

**A comprehensive reference book for those with interest in, or need to know,
how operations in the world's factories work,
and how common products, components, and materials are made.**

Handbook of Manufacturing Processes

How Products, Components and Materials Are Made

James G. Bralla

**With Contributions by a Distinguished
Editorial Board**

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EDITORIAL BOARD—HANDBOOK OF MANUFACTURING PROCESSES

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DEDICATION

This book is dedicated to the thousands of people, worldwide, who keep all the manufacturing processes described in this book operating productively. These people come from all walks of life with varied amounts of education, ranging from the grammar school level to PhD's and even post-PhD's. All, however, share certain attributes. One is dedication to the task of keeping their process in operation, with willingness to stay with a problem—beyond normal working hours, if necessary—until it is solved. A second attribute is extensive self-education in the workings of the equipment for which they are responsible. A third is an innate knack for analyzing a process problem, finding the root-cause of the problem, and the ingenuity, when necessary, to devise a quick fix. They may realize, for example, that a certain linkage is sticking, that there is too much play in some moving parts, that a detector is not signaling the condition for which it is designed, that the workpiece material is out of spec, or whatever one of the thousands of things that can go wrong is causing the malfunction of the equipment. Then they have the energy to try different approaches, to disassemble a device to find out what is wrong, to research a problem with others, or from source documents, to find out what could be amiss. After all this, they have sufficient skill to do what has to be done to put the equipment back into productive working order. This may involve such skills as machining, to make or modify a critical part, to replace electronic devices or printed circuit boards, to add a simple sheet metal shim, to design or build a tool or fixture, or to have the ability to work with others who provide the specialist skills necessary. The net result of their efforts and skills is the continuing operation of the equipment that they care for, so that we all can benefit from the products and goods that they make.

This book is also dedicated to Steve Bralla, my son, who happens to be one of the gifted people noted above, except that his particular field is the operation of sophisticated earthquake detection apparatus, rather than production machinery. Steve was faced last year with a diagnosis of acute myeloid leukemia, a devastating and frequently fatal disease. But through his courage, strength and willingness to undergo the lengthy and debilitating ordeal that a cure involves, the support of his family, and with the guidance of talented and dedicated medical specialists, he now tests to be cancer-free. I salute him and all those who keep the world's production machinery in operation, and dedicate this book to them.

James G. Bralla
North Jackson, PA

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Readers are invited to call to my attention any errors that may have crept into the information presented in this book. Please address e-mail to info@industrialpress.com.

James G. Bralla

HOW TO USE THIS HANDBOOK

The book is in two sections: (I), the Process Section, in which common manufacturing processes in 17 key industries are described, and (II), the Products, Components and Materials Section, which explains how many of these are made.

Section I explains how each manufacturing process works, detailing what happens to the materials or workpieces that are being processed. Usually, these explanations are in general terms as they are not limited to a particular component or material. However, the description also identifies the normal components or materials to which the process applies.

Section II deals with specific products, components, and materials, outlining the manufacturing sequence and processes used for making each. It often refers the reader, using the designation of any applicable text entry, to where more detailed descriptions of the operations mentioned can be found in the book. This is done by showing, in parenthesis, the chapter and text entry designation from Section I, where the basic operation is described. For example, in the description of the manufacture of a metal part that requires case-hardening heat treatment, the description may include “(8G3b)” to tell the reader that the case-hardening heat treatment used on the part is described at greater length in entry G3b of Chapter 8.

The handbook text in Section I is organized in a typical outline structure to aid the reader in finding relevant information easily. Related processes are grouped together and sequential operations are covered in sequence when possible. Major topics are given an upper-case letter designation such as A, B, C, etc. Important sub-topics are designated with the capital letter and a number (for example, A1, B1, C1, etc.) Sub headings under these topics are indicated by adding a lower-case letter to the designation (e.g., A1a, A1b, A1c, etc.) The descriptions of further process variations may be given designations such A1a1, A1a2, A1a3, etc. For example, Chapter 1 is devoted to metal casting processes; section B in Chapter 1 covers sand-mold casting methods; entry B5 describes methods of making sand molds, B5e describes those methods that utilize a machine for the operation, and B5e1 describes one specific machine method, the jolt-squeeze method.

For ease of reference, the same designations used to identify text entries are also used to identify accompanying illustrations. For example, Figure 9B2 illustrates the process described in text entry B2 in Chapter 9. Figure 1B5e1 illustrates the jolt-squeeze machine described in entry B5e1 of Chapter 1.

Section II is simply arranged in alphabetical order by the name of the product, component, or material whose manufacturing method is described. Section II includes descriptions of manufacturing processes used in making each product, component, or material listed, though sometimes, if the process for that item has already been described in Section I, the Section II entry simply refers to the applicable entry in Section I. Thus, for the manufacture of gasoline, whose manufacturing process is described under “Petroleum Processing” in Chapter 11, the listing in Section II simply refers to (11H)—Petroleum Refining and Processing—where gasoline manufacture is described in considerable detail.

When an entry in Section II is referred to elsewhere in the book, the name is shown italicized to tell the reader that there is a description in Section II of how the item is manufactured. Thus, for example, if the reader sees a name such as "*detergents*" in italics, he or she knows that there is a description in Section II that tells how detergents are made. (Italics are also used in the text of the book to designate processes of particular importance.)

HOW TO FIND A HANDBOOK ENTRY

For a process description, if the usual process name is known, the reader can refer to the Index at the back of the book. If the reader is uncertain of the name of the process, he or she can refer to the table of contents, find the major heading where the kind of operation of interest is shown, and, by visually scanning the entries below the major one, find the listing and page number for the particular operation in mind.

For a product, component or material manufacturing description, the reader can refer directly to Section II of the book, where entries are arranged in alphabetical order or can refer to the Index to locate its page number. (Both Section II and the Index are arranged in alphabetical order, but Section II includes considerable descriptive material, and does not include listings of processes, equipment, methods, or operations by name, as does the Index.)

PREFACE

This is a reference book. It was prepared to serve as a concise, easy-to-read, source for those who need to gain an intelligent insight into the workings of manufacturing processes. It is also for those who want or need to know how particular products, their components, or their raw materials are made.

Many books that are currently available give some very worthwhile instruction about the methods used in specific industries; others present good information over some range of industries, but these are textbooks rather than reference books and none have the breadth of coverage that is included here. This book gives descriptions of key operations in the major production industries: Metalworking, including Casting, Metal Forming and Machining, and the Plastics, Ceramics, and Woodworking Industries. There are chapters on Joining and Assembly, and on Product Finishing. The Paper and Printing Industries, Textiles, Garment-Making, Chemicals, Food Processing, and Electronics are all included in this book.

There are other books that describe how some products are made, but they are usually aimed at the general public, especially younger readers, and are quite limited in both scope and the depth of information provided. There is no reference book on this subject with engineering-level information. This book is intended to fill that void.

An objective of the book is to provide clear, easily readable and concise explanations, so that the reader can easily gain an understanding of what is involved and how each process works. Although the book includes much technical detail, we have tried to avoid including non-essential complexities of any process, but to explain it concisely in simple terms, so that the reader, even if not technically trained, can understand and, if necessary, explain the method to others. The text has been prepared to be explanatory, straightforward, to-the-point, and practical (rather than theoretical). To aid in this end, descriptions have been liberally supplemented with illustrations. The objective of each illustration is to present a clear, easily understood view of the workings of the method covered. To this end, most illustrations are schematic, concentrating on the basic principles of each process and stripped of unnecessary detail.

WHO SHOULD USE THE BOOK

People for whom the book was prepared include the following:

manufacturing engineers, those who design, build, plan, execute and maintain the equipment, tools, and processes that make the things that the public buys and uses.

process engineers, those who plan and engineer the manufacturing steps, equipment and tooling needed in production.

manufacturing executives, managers, and supervisors who need to know and understand what their employees are doing and why, and what new processes and equipment should be considered to improve their operations.

students interested in a career in manufacturing and especially those pursuing a career in manufacturing engineering, who can use this book for current instruction and for future reference.

product design engineers and draftsmen, who should have this book available for reference so that they understand how the products that they design are made.

government officials who are responsible for operational safety (OSHA), environmental conditions, and other regulatory matters. They can gain a better understanding, with this book, of the factory operations that they regulate.

consultants who have, or wish to have, manufacturing clients and want to be sure that they understand what is happening in their client's operations. These consultants should have this book available for reference.

salesmen and sales managers who deal with customers that are involved in manufacturing, and who need to know more about their operations.

faculty of engineering schools

engineering societies involved in manufacturing or related subjects should have a copy of this book in their libraries and should offer it to their members.

state, city, county, town and college libraries, for their constituencies.

purchasing people who buy manufactured components and products.

quality control managers and specialists who can gain, with this book, a better understanding of the processes, whose products they monitor.

maintenance and reliability managers and technicians who can similarly benefit from a better knowledge of the processes they are responsible for.

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Section I

Manufacturing Processes

Chapter 1 - Casting Processes

A. Melting Metal for Casting

A1. ***cupola melting*** - Now much less common due to environmental factors, this method utilizes a furnace in stack form as shown in Fig. 1A1. Fuel and metal to be melted are in direct contact. The stack is lined with refractory material and alternate layers of coke and metal are placed in it. Some minerals, primarily limestone (CaCO_3), are included with the metals to be melted. Air is blown through the stack from the bottom through openings called tuyeres. The bottom layer of coke is ignited initially. Heat from the burning coke melts the metal, which flows to the bottom of the cupola from where it can be removed by opening a tap hole. Slag is also removed from the bottom, from an exit hole just above the one used to remove molten metal. As the coke is consumed and the metal charge melts, the burning gradually proceeds upward. The upper layers are preheated by the flow of hot gases. Additional metal, coke, and limestone can be added from a charging door in the upper part of the stack as the operation proceeds. Metal charges may consist of steel scrap, cast iron scrap or pig iron, or, more commonly, a combination of them. The molten metal absorbs carbon from the coke, so cupola melting is generally restricted to cast, malleable, and ductile iron (though the electric arc method is preferred for the latter).

A2. ***electric arc melting*** - In this method, an electric arc similar to the one used in arc welding but

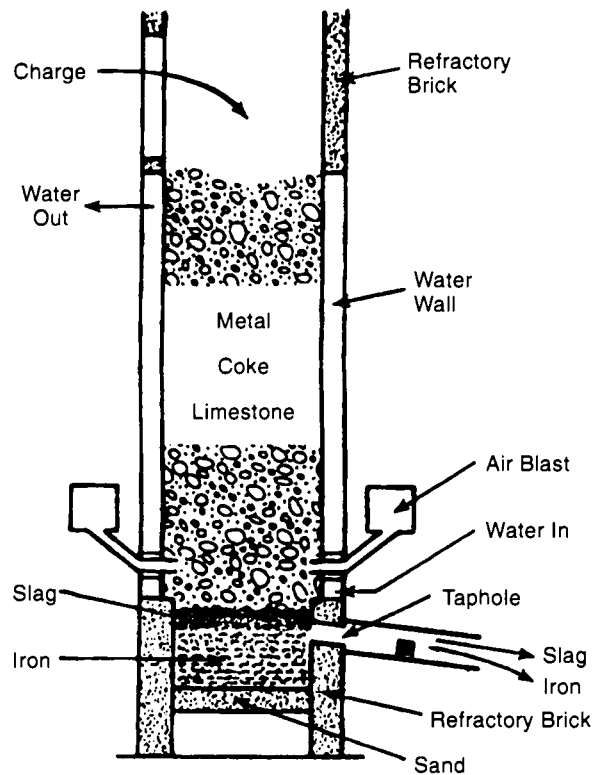


Fig. 1A1 Cross-sectional view of cupola melting cast iron. The metal charge (pig iron and scrap iron and steel) is in direct contact with burning coke. When the metal melts, it flows to the bottom of the cupola where it can be withdrawn. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

much larger and more powerful, is used to provide the melting heat. In the *direct-arc* method, there are two arcs, one from an electrode to the metal and another from the metal to the second electrode. In the *indirect-arc* method, the arc extends from one electrode to another and the heat is transferred to the metal by radiation. Electrodes normally are made of carbon although, when molybdenum and other high-melting-temperature metals are processed, the electrodes may be of the same metal as that being melted. This variation is known as *consumable arc melting*. Fig. 1A2 illustrates the direct-arc method. This method can also be used with three electrodes and three-phase current. Electric arc melting is used extensively for in the production of alloy and carbon steels, and for malleable iron, ductile iron, tool steel, and high-strength cast iron. Control of environmentally undesirable emissions is easier with electric furnaces than with cupolas. An indirect arc is used in brass and bronze production.

A3. crucible melting - This method employs a cup-shaped, refractory-lined, metal furnace which is normally heated by gas or oil and sometimes by electrical resistance or induction. It has an inner crucible to hold the metal charge. The crucible is

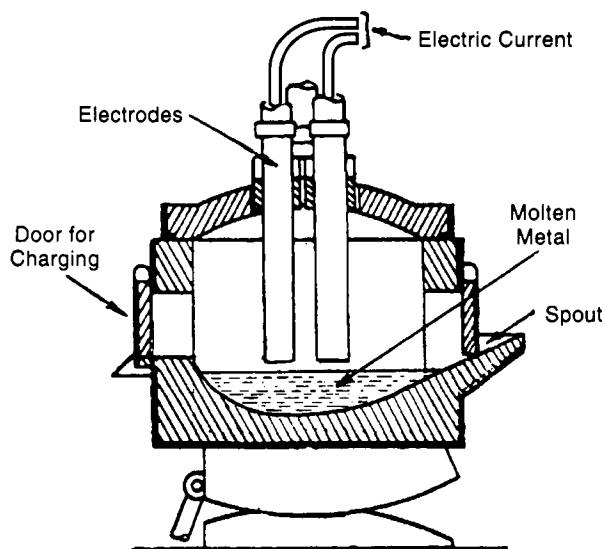


Fig. 1A2 A direct-arc furnace for melting steel or iron for castings. The arc passes from one electrode to the metal and back from the metal to the other electrode, providing heat that melts the metal.

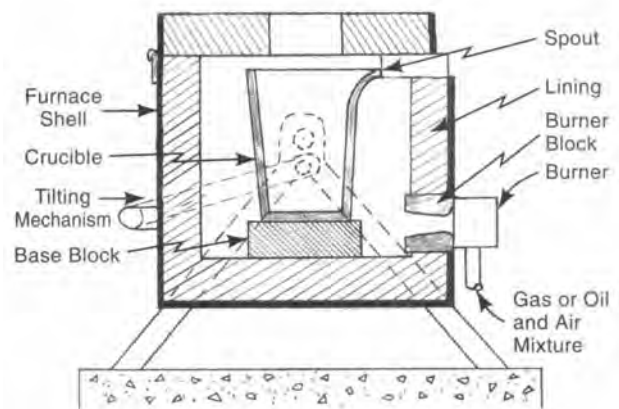


Fig. 1A3 Cross-section through a crucible furnace.

made of either a clay-silicon-carbide or a clay-graphite mixture. The furnace can either tilt for pouring or the crucible can be lifted out. Fig. 1A3 illustrates a tilting type with a lift-out crucible. The crucible method is used to melt brass, bronze, aluminum, and magnesium for sand castings. Except for induction heating, ferrous metals are not usually melted in this kind of furnace.

A4. air furnace (reverberatory) melting - has similarities to open-hearth melting. Fig. 1A4 shows a typical air furnace. Oil or pulverized coal is burned in one chamber and the charge is placed in another. Heat from the burning fuel passes over and is absorbed by the charge, melting it. There is no direct contact between the metal and the fuel, allowing carbon content to be closely controlled. Oil or finely pulverized bituminous coal are used as fuels. Some smaller furnaces use natural gas. This type of furnace is used in the production of castings from malleable and gray cast iron, brass, and bronze.

A5. induction melting (high frequency and low frequency) - With this method, alternating electric current in a coil creates a magnetic field that induces corresponding secondary electrical currents in the metal charge. The resistance of the metal in the charge causes its temperature to rise to the melting point. Melting can be very rapid and there is no pollution or contamination from the heat source. Induction melting is used for steel, brass, bronze, aluminum, and magnesium.

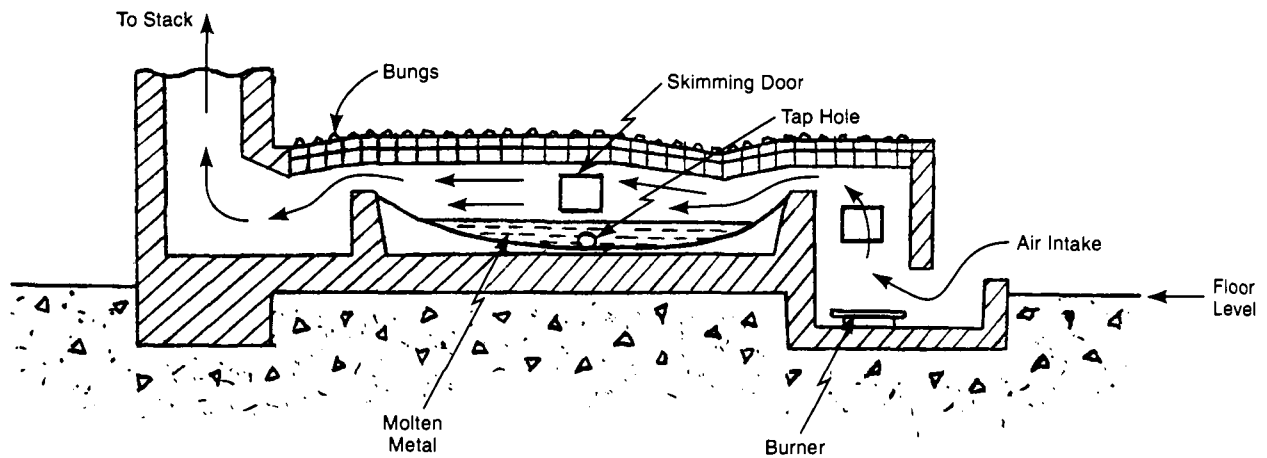


Fig. 1A4 An air reverberatory furnace.

With the *coreless* method, which commonly - but not always - is utilized at high frequencies, the coil surrounds a crucible containing the metal. The coil is made from copper tubing and water is circulated through the tubing to prevent the coils from overheating. Typical frequencies vary up to 10,000 Hz. but coreless furnaces can also operate at low frequencies (e.g. 60 Hz). The most common range is 250 to 3000 Hz. Melting is rapid. At the lower frequencies, the induction provides a stirring effect. At higher frequencies, higher power levels are possible. Brass, aluminum, cast iron, and steel are melted in coreless induction furnaces. Fig. 1A5 illustrates a typical coreless furnace.

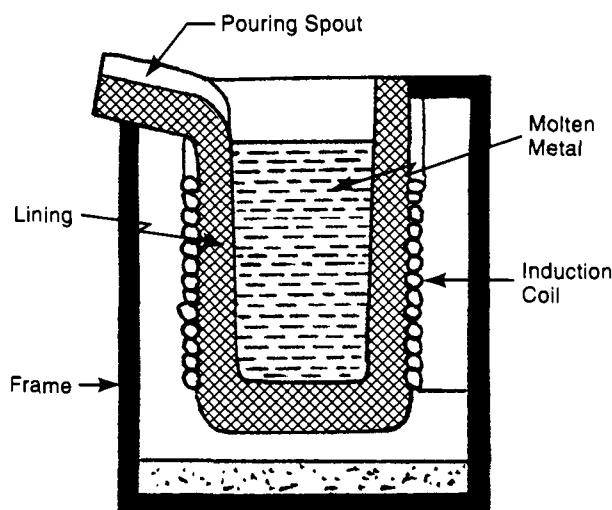


Fig. 1A5 A coreless induction furnace.

With the *channel* type of induction, the melting container itself forms a loop but only one portion of the loop is surrounded by the coil. The metal in this loop is heated by induction and the heat is transferred to the balance of the metal by convection and induction. The arrangement is shown in Fig. 1A5-1. Channel type furnaces operate at low frequencies. The melting rate is very high with this method and the temperature can be controlled accurately. However, there must be liquid metal in the channel for the induction effect to take effect, so an initial charge of enough melted metal to form a loop is required. Solid material can then be added. Low-frequency cored furnaces are often used as holding furnaces. Channel furnaces are used for brass and aluminum, and as duplex or secondary furnaces

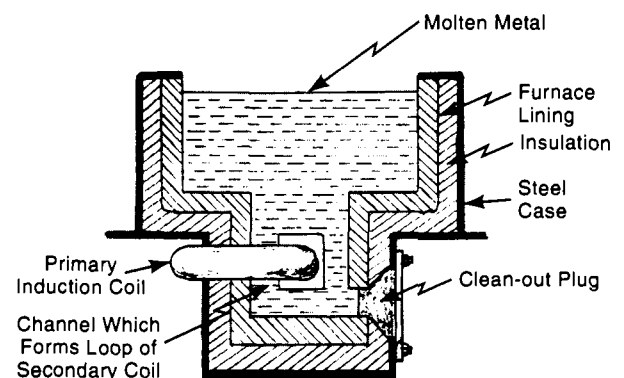


Fig. 1A5-1 A channel-type induction furnace. The molten metal in the furnace becomes the loop of a secondary induction coil.

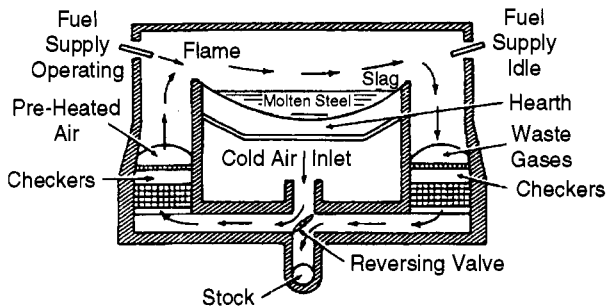


Fig. 1A6 Sectional-view of an open-hearth furnace. (Courtesy Steel Founders' Society of America, Barrington, Illinois)

for iron. In the latter case, molten cast iron from a cupola is fed to a channel induction furnace where the composition can be adjusted to meet specifications.

A6. open-hearth melting - This method, used in the production of steel and cast iron, is also used to supply molten metal for casting operations. Foundry open-hearth furnaces are usually smaller than those found in steel mills. Fig. 1A6 illustrates a typical open-hearth furnace which is both reverberatory and regenerative. Metal in the furnace is heated by a flame passing over the charge. The flame comes from the combustion of gas, oil, tar, or pulverized coal. The low roof of the furnace reflects heat downward to the metal in the furnace. Both fuel and air are fed from one side into the central area where the flame and heating take place.

The chambers on the opposite side are heated by the flame and exhaust gases moving through them. The pool of molten metal in the furnace is shallow, which provides the maximum area for heat transfer per unit volume of metal. After a period of time, the direction of flow is reversed. The chambers heated from the previous cycle, in turn, heat the incoming fuel and air. Most open hearth furnaces are chemically basic (rather than acidic) as determined by the material of the brick furnace lining. The basic furnaces remove sulfur, silicon, carbon, and manganese from the charge metal. The charge used in making structural steel includes iron ore, lime-stone, scrap, and, later, molten pig iron. Additions can be made to the steel to produce the desired composition. Oxygen may be added to the furnace combustion area to reduce the process time and the amount of fuel required. Finished metal is removed from a hole in the rear of the furnace and transferred to a ladle.

A7. pouring - Metal is usually tapped from the melting furnace into either a ladle from which it is poured by gravity into the mold, or into one that is used to transfer a quantity of metal to a pouring ladle. Such transfer ladles are usually covered to reduce heat loss during transfer. Pouring ladle capacities range from about 60 lb (27 Kg) up. Ladles are frequently transported by overhead cranes. There are three basic types of ladles, as illustrated in Fig. 1A7: open-lip ladles that pour by

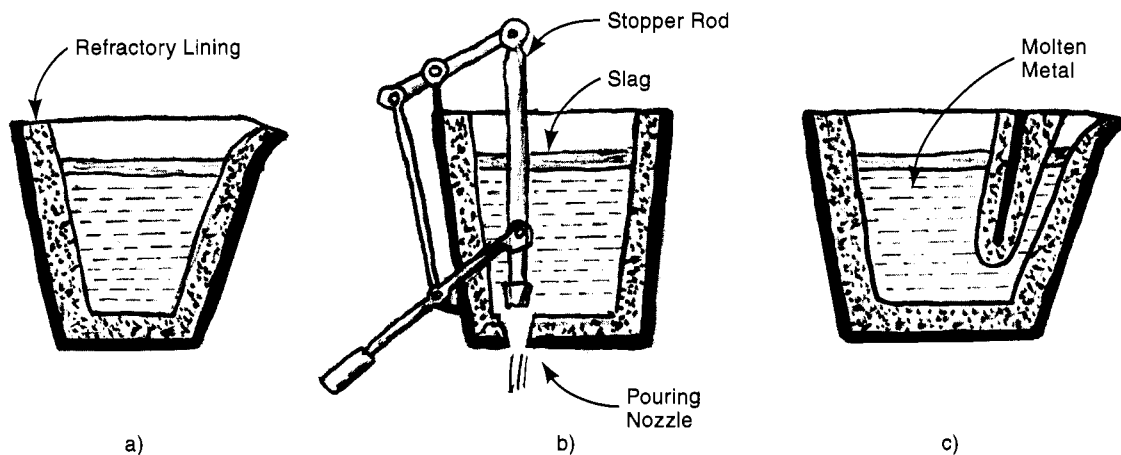


Fig. 1A7 Three different types of pouring ladles: a) a standard open lip-pour ladle. b) a bottom-pour ladle that avoids including slag in the metal poured. c) a "teapot" ladle that pours metal from near the bottom, avoiding the inclusion of slag in the casting.

tilting, “teapot” ladles that also pour by tilting but which avoid pouring slag, and bottom-pour ladles which also avoid pouring slag. Tilting ladles often utilize worm-gear tilting systems to provide better control and prevent the ladle from tipping too much or too fast. Numerous automatic pouring systems, designed to accurately meter the amount of molten metal poured, are also used. Some consist of mechanized or robotic dip-and-pour ladles. Others pour directly from a larger holding pot, using either stopper rods as shown in Fig. 1A7, or sliding gate valves. Some pouring vessels are fitted with electrical heating apparatus to maintain the metal at the proper pouring temperature. (The ideal pouring temperature involves a “superheat”, a metal temperature sufficiently high to ensure that all parts of the mold are fully filled before solidification starts.) Other pouring systems include machine vision to sense when the mold is full, or weight controls to pour a prescribed amount, by weight, into the mold.

B. Sand-mold Casting

In sand mold casting the mold is made of packed sand. Molten metal is poured into a cavity in the sand. When the metal cools and solidifies, it has the shape of the cavity. The sand is removed, normally by a shaking action that is vigorous enough to cause the mold to break apart. The casting is then cleaned of sand; flashing and sprues are cut off and any jagged or sharp edges are ground smooth. (See snagging, B8g.)

The sand mold includes binders to hold the packed sand together and other additives. Bentonite clay is one of the most common binders. Organic materials and a certain amount of water are also used. The sand is either shoveled into the mold flask, dropped or blown from an overhead chute, or thrown by a sand slinging machine. The sand mixture is packed around a pattern which duplicates the shape wanted in the cast part. Various hand and machine approaches are used to compact the sand. Ramming, squeezing, slinging, and jolting are described below. After the sand has been compacted, the pattern is removed, leaving a cavity that retains the inverse of the pattern’s shape. The sand is held together strongly enough so that it withstands the pressure and any eroding effects of

the melted metal; is porous enough to allow gases to escape; yet it is weak enough to yield to shrinkage forces when the metal solidifies, and can be broken up and removed easily from the finished casting. The pattern can be of almost any material. In low quantity production situations, it may be made of wood. For repetitive manufacture, steel is more common. Plastics, aluminum, and other materials are also used. The pattern has the same shape as the desired cast part, but is slightly larger to provide a shrinkage allowance for the metal as it cools.

A typical sand mold is shown in Fig. 1B, and is normally made in two halves. The pattern is correspondingly split. The top half of the mold is called the “cope”; the bottom half the “drag”. Both are held in a box-like container called “flasks”. An entrance channel for the molten metal into the mold is provided by a basin and sprue formed in the cope half. Runners and gate are normally in the drag half. If the casting has some hollow or undercut elements, one or more additional sand pieces, called “cores” may be used. If a core is used, it is inserted in the mold cavity. The cope half of the mold is made similarly to the drag half and, after the pattern is removed, is inverted and placed over the drag. Pins in the flask insure alignment of the mold cavity. The two mold halves are held together with a clamp or weight. Sand mold casting can be used to make simple and complex parts from a wide variety of metals, though cast iron is the most common. Shapes with undercuts, contours, re-entrant

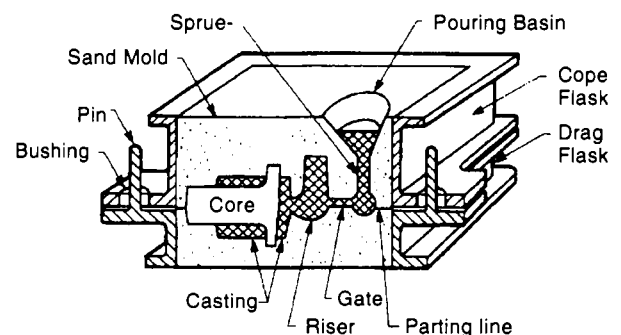


Fig. 1B A typical mold arrangement for sand-mold casting showing a typical core, pouring basin, riser, gate, and cope and drag flasks. (From James G. Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

angles and other complications of shape can be cast. Castings weighing only one ounce to those of many tons can be cast with the process. Typical applications of sand mold casting are: automotive engine blocks, cylinder heads, connecting rods, crankshafts and transmission cases, machine tool bases and other mechanical components.

B1. *green sand casting* - is the basic sand-mold casting process described above. The green sand mixture consists of sand (usually silica), 6 to 8 percent clay binder (usually bentonite), 2 to 3 percent water and additives (sea-coal, starches, cellulose). ("Green" refers to the mixture, not the color.) It is moist and is not dried out before the molten metal is poured into the mold. The ingredients are mixed together thoroughly in a sand muller machine. The green sand process is inexpensive and has great versatility in regard to the metal that is cast and the size and shape of the castings made. Other sand-mold processes may give greater accuracy and smoother surface finish, however. The sand can be reclaimed and used again many times. The green sand method is the most common and least expensive sand casting process. Castings up to about 500 lb (230 kg) are commonly made with this approach. Automotive engine blocks, transmission cases, differential housings, railroad parts, and machinery components are all typical parts. Metals cast include gray cast iron, malleable and ductile iron, cast steel, aluminum, brass, bronze, and other non-ferrous metals.

B2. *dry sand casting* - In this process, the green sand mold is dried or baked before it is filled with molten metal. Typically, the mold is heated to 300°F (150°C) or higher, by baking or forced hot air until most of the moisture is evaporated. This approach produces a stronger mold and there is less gas (steam) generated when the molten metal is poured into the mold. One or more coatings of refractory material - silica, zircon, or graphite - are usually applied to the mold surface in a water or solvent carrier. Dry-sand molds can withstand more handling and longer storage, and have better resistance to the pressure of molten metal. The dry-sand process is normally used for medium-size to very large, multi-ton castings where greater mold strength is needed to withstand the mass of the molten metal. Dried sand gives a better surface

finish but is more costly than green-sand molding because of energy, space, and equipment costs. With dry-sand casting, pitch is most commonly used to provide carbon instead of the sea coal used with green sand. Gilsonite, glutrin, corn flour, and molasses are other additives. These materials become thermoset at the baking temperature, adding to the strength and rigidity of the mold. Coarser sand is used to facilitate natural venting. Strong flasks and reinforcing bars, which extend into the sand, are also used to insure rigidity of the mold. Large castings in dry sand molds are cooled slowly to reduce internal stresses in the casting and the possibility of cracking.

B2a. *skin-dried casting* - To reduce the lengthy drying time of dry-sand casting, the drying is often limited to a depth of only about 1/4 to 1/2 in (6 to 13 mm). The patterns are usually first coated with a wash of refractory material. Heat for drying is supplied from a torch, from infra-red lamps, or from hot air. The mold is then referred to as a *skin-dried mold*. The dried skin is backed up with a mixture of green and dry sand. The approach is used extensively for the casting of steel, which involves higher pouring temperatures, and has also largely replaced dry sand molding for other applications. The casting surface is improved by elimination of the moisture in the facing sand, which could cause pin holes in the casting. Shake out is also facilitated. Additional binders such as linseed oil, corn flour or molasses may be used in the facing sand to improve the strength of the dried mold skin.

B3. *other sand-mold casting processes*

B3a. *shell mold casting* - In this process, the mold sand is mixed with phenolic or another thermosetting plastic resin, either in liquid or solid form, with a catalyst. There is no clay binder but some other additives may be included for specific purposes. The mixture, when used, is dry and free-flowing. The pattern that forms the sand mold is heated to about 400 to 600°F (200 to 300°C), and clamped to a container of sand, which is then inverted, dropping the sand on to the heated pattern. When the sand is in contact with the heated pattern for a short period, the resin melts and then begins to polymerize, becoming hardened enough

to bind the sand particles together. Coated sand particles that are not in contact with or near the pattern do not get heated sufficiently and do not bond together. Thus, a layer of bonded sand is formed next to the pattern. The pattern and sand are then re-inverted and the loose, non-bonded sand drops free. The pattern and the shell of bonded sand are heated additionally to complete the polymerization. The shell, normally from 0.2 to 0.4 in (5 to 10 mm) thick, is removed from the pattern by ejector pins and the flat faces of the two shell halves are fastened together with adhesive. Loose sand, gravel, or metal shot may then be used to support the mold during casting. This method is adaptable to

large-scale production conditions and can produce castings of high complexity and accuracy but of limited size. The surface finish is smoother than that attainable with other sand casting methods because of the effect of the resin and the finer sand normally used.

The process is also used for making cores for molds used with other sand-mold processes. When shell cores are made, the core box is metal and is heated to cure the phenolic resin. Production is rapid. Cores can be made hollow by removing the sand from the center of the core before it has received enough heat to melt and cure the resin. The shell molding process is illustrated in Fig. 1B3a.

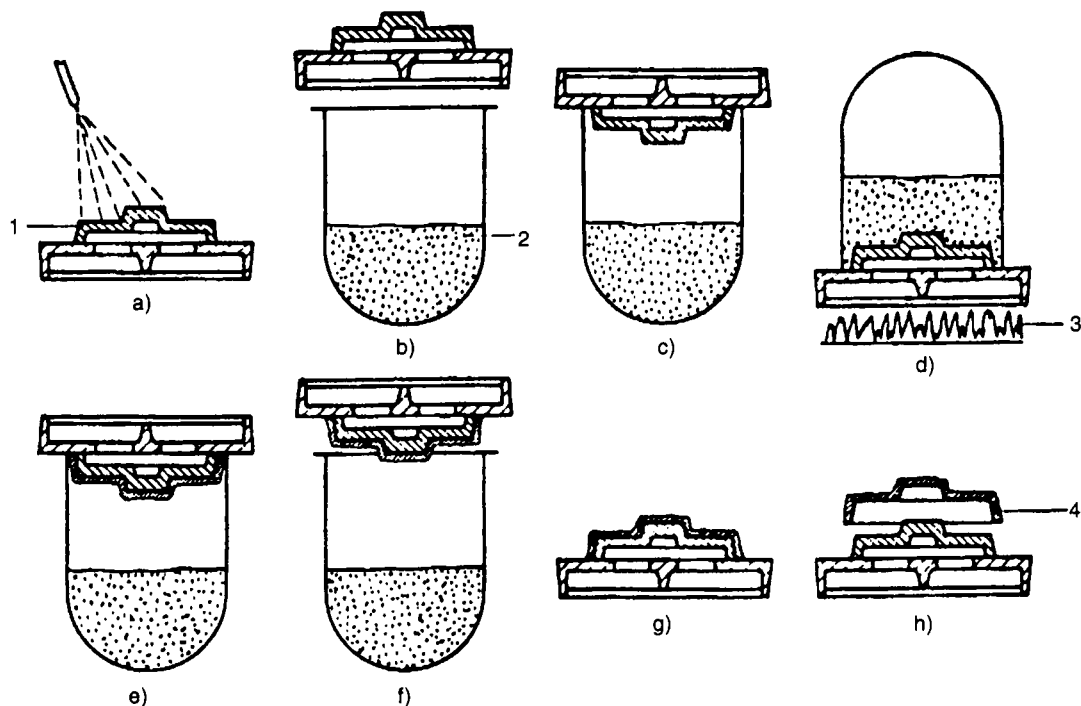


Fig. 1B3a The shell molding process. a) A silicon parting agent is sprayed on the preheated pattern. b) The preheated pattern is then brought to a dump box that contains a sand-resin mixture. c) The pattern is inverted and clamped to the top of a dump box. d) The dump box is inverted, sand falls against the pattern and is further heated for a short period. The resin in the sand mixture next to the hot pattern starts to set, causing sand particles to adhere together. e) The dump box is turned upright and the sand not in contact with the hot pattern or near to it, being unaffected, falls away. f) The pattern and the sand-resin shell are removed from the dump box. g) The pattern and shell are baked to fully cure the resin. h) The pattern is withdrawn from the shell. Two shells are fastened together, placed in a flask and supported with back up sand or metal shot. Molten metal is poured into the cavity formed by the two shells. Identified items: 1 - pattern, 2 - sand-resin mixture, 3 - burner, 4 - shell mold half. (from Davidson, *Handbook of Precision Engineering*, Vol. 10, McGraw-Hill, New York)

B3b. lost foam casting - This process is also called *full mold casting*, *evaporative casting* or *disposable pattern casting*. It differs from conventional sand mold casting in that the pattern is made of foamed polystyrene plastic (See 4C4.) instead of conventional pattern materials and is consumed in the process. The polystyrene pattern is coated with a slurry of permeable refractory material by dipping, spraying or brushing. This coating is dried before the pattern is placed. The mold is made by placing the pattern - which is made complete with sprues, risers, runners, and gates - in a flask and packing sand around it. The foam pattern remains in the mold during pouring and melts and vaporizes immediately on contact with the molten metal. Thus, it is not necessary to remove the pattern from the sand prior to pouring. The molten metal takes the place of the foam plastic pattern and fills the space it occupied in the sand. The sand mold is in only one piece; there is no cope or drag, hence the

name, "full mold casting". Because gas is produced from the vaporization of the foam pattern, the sand mixture must be highly permeable to allow these gases to escape. Hence, there is no bonding agent for the sand. Loose sand is flowed into the flask to surround the pattern. Then, the filled flask is vibrated to compact the sand. If the pattern is of such a shape that the sand can fill the openings in it, no separate core pieces are required. Therefore, there is much less need in the process for separate core pieces. On the other hand, since the pattern is consumed during the process, an additional pattern has to be made for each casting in the lot. If the quantities are large, the foam pattern is molded by the normal methods used for polystyrene foam (See 4C4b). If quantities are limited, or if the casting shape is such that the pattern cannot be molded in one piece, the pattern may be fabricated by gluing together machined or molded polystyrene foam blocks. Pouring of a lost foam casting must be

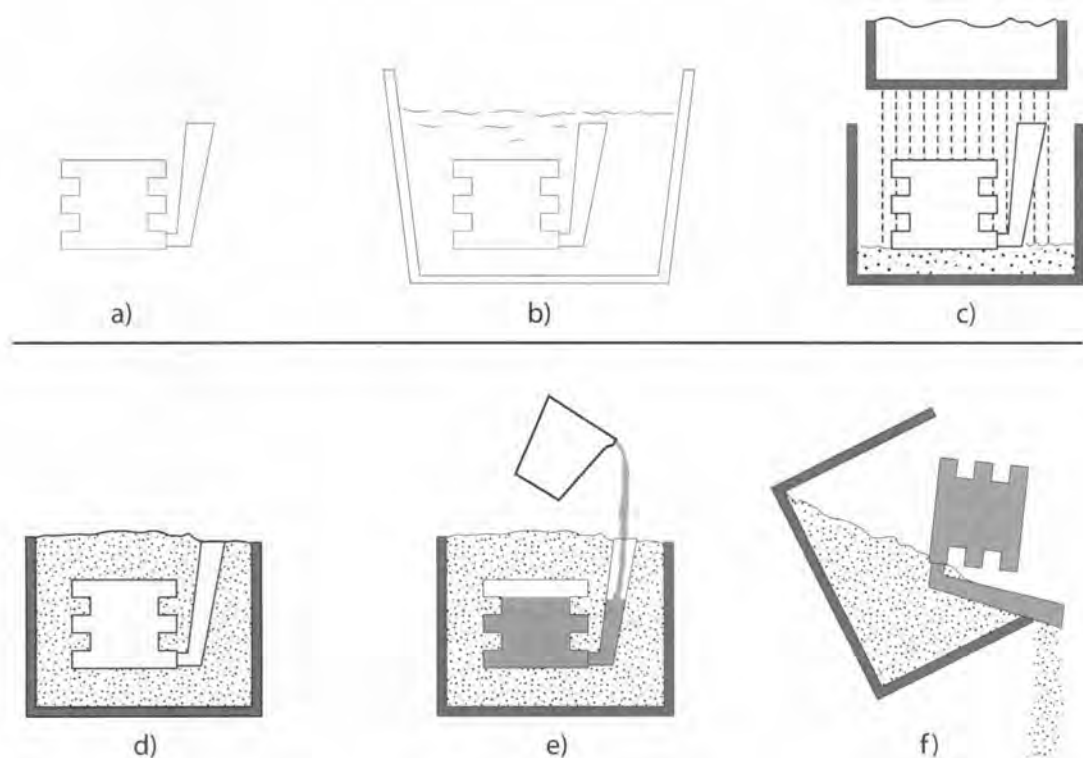


Fig. 1B3b Lost foam casting. a) The pattern is made of polystyrene foam. b) The pattern is dipped in a refractory slurry, c) The pattern is placed in a flask and surrounded with unbonded sand, d) The filled flask is vibrated to compact the sand. e) Molten metal is poured onto the pattern, vaporizing and replacing it. f) The solidified casting is removed from the flask; the sand is recycled.

controlled to maintain pressure in the unbonded mold so that it does not collapse. After pouring, the mold is allowed to cool and the metal to solidify. The flasks are then moved to a shakeout area where they are inverted to dump the loose sand. Castings are then cleaned by conventional methods. The lost foam process is suitable for complex shapes with undercuts and other irregularities. Complex castings can be made more easily than with other sand casting processes. Cleaning is also simpler than with other sand mold processes; there is no parting line, and the sand, being unbonded, is more easily recycled. The process has come into widespread use for automotive castings and is illustrated in Fig. 1B3b.

B3c. *magnetic molding* - is a variation of lost foam casting in that a polystyrene foam pattern is used and there is no cope or drag. However, instead of the sand used to back up the mold, iron powder with particles of 0.004 to 0.020 in (0.1 to 0.5 mm) in diameter is used. This iron is compacted by vibrating the flask and then is magnetized with a magnetic field to hold it in place during pouring. The magnetic field is turned off after the poured metal has cooled and solidified. The casting is then easily shaken out and the metal powder can be reprocessed. The heat conductivity of the iron powder results in a finer grain structure of the casting. The process has been used for casting steels, copper-based alloys and cast iron.

B3d. *V-process casting (vacuum molding)* - is another process that uses loose sand to back up a mold. In this case, the sand is contained between two plastic sheets, one of which is in the shape of the mold cavity. There are two such pairs of sheets filled with sand, one for each mold half. A vacuum is drawn between each pair of sheets to hold them against the sand. The outer plastic sheet, holding the sand, is flexible and essentially flat and does not require forming. The inner sheet is formed to cavity shape by conventional thermoforming processes as described in chapter 4, and this is the first step of the casting process.

Fig. 1B3d illustrates the operation sequence. Thermoforming and mold making take place at one location as a single operation sequence. The forming die for each inner plastic sheet stays in place beneath the sheet until a mold flask is put into position over it and is filled with sand. The mold flask

has a vacuum connection. The equipment is vibrated to compact the sand, excess sand in the flask is removed, a pouring basin and runner are formed in the sand as needed, and the remaining sand is leveled and covered with the outer sheet of plastic film. A vacuum is applied to the sand so that atmospheric pressure, acting against the outer sheet and the formed sheet, holds the sand in position, producing a mold of high hardness. The flask is then lifted from the forming pattern while still under vacuum with the plastic sheets and is assembled with a similar flask for the other mold half. The mold halves are kept under vacuum during pouring and until the cast metal has solidified. The formed plastic sheets vaporize from contact with the poured molten metal. When the vacuum is released, the sand falls away and a clean casting remains. The process is used for production of medium-large castings at moderately high production levels.

B3e. *cement-sand molding* - simply involves the use of about 10 percent Portland cement (plus water) as a binder for the sand mold. This process variation is used for large parts/large molds where the improved strength of the cement in comparison with other binders is important. The sand-cement-water mixture is formed into mold halves immediately after mixing but full curing requires another 24 to 72 hours. The molds may be stored for extended periods. A disadvantage of the high strength of the cement-sand molds is that they are less apt to yield to shrinkage forces and some casting shapes and materials may be susceptible to tearing.

B3f. *loam molding* - is suited for large castings of circular shape. Patterns are not used; the mold cavity is made to approximate shape manually using a structure of bricks or wood to hold the sand. A slurry of coarse sand, with a high percentage of clay and water, is worked into the cavity over the structure to further form the approximate shape. Then, as shown in Fig. 1B3f, a profile board is swept from a central upright spindle through the rough cavity to scrape away excess sand and produce a cavity of the required shape. The mold is heated and thoroughly dried and a coating of refractory material is applied.

The cope half of the mold is made from a series of cores placed side by side around the central axis. Alternatively, if there is a flask of sufficient size

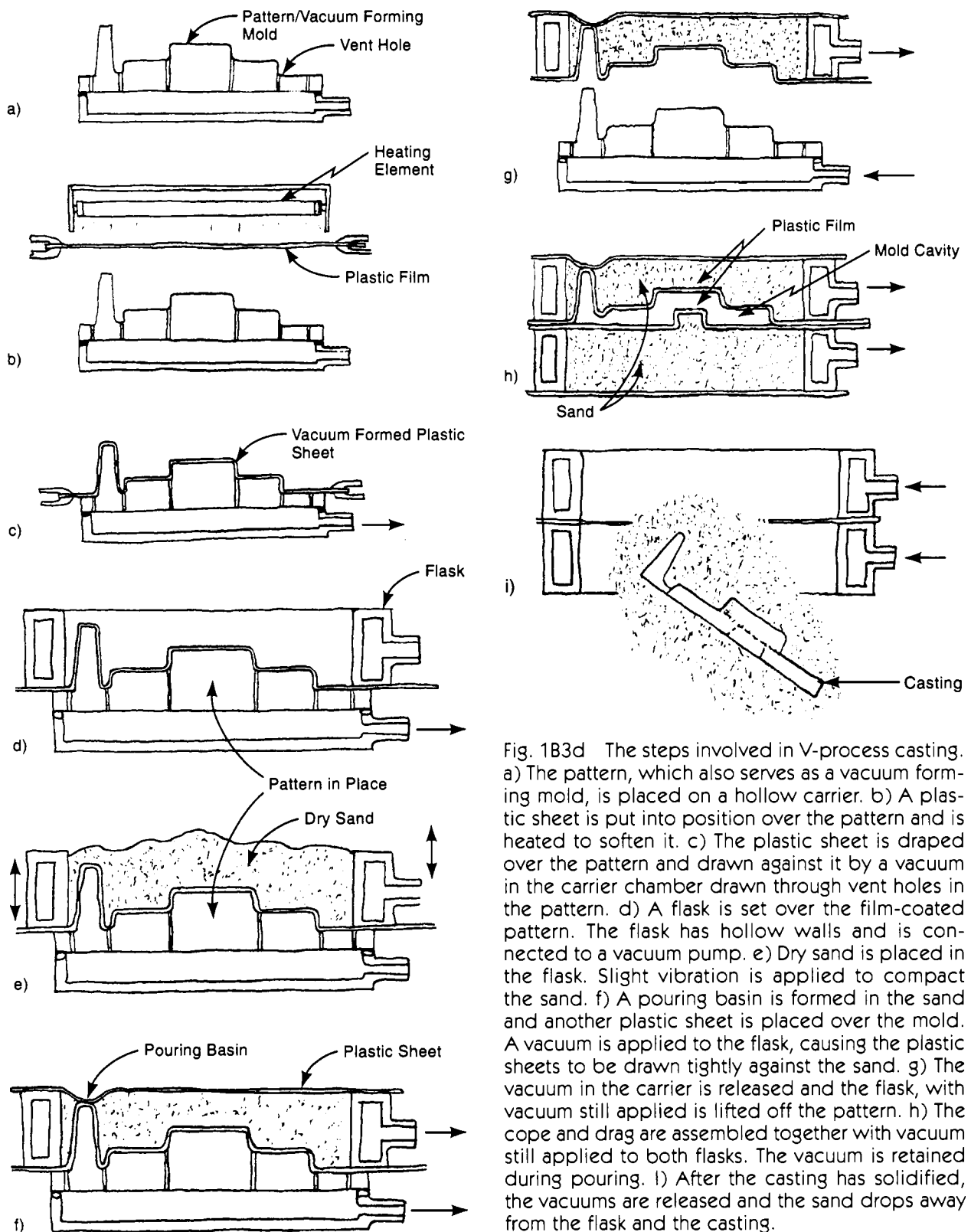


Fig. 1B3d The steps involved in V-process casting. a) The pattern, which also serves as a vacuum forming mold, is placed on a hollow carrier. b) A plastic sheet is put into position over the pattern and is heated to soften it. c) The plastic sheet is draped over the pattern and drawn against it by a vacuum in the carrier chamber drawn through vent holes in the pattern. d) A flask is set over the film-coated pattern. The flask has hollow walls and is connected to a vacuum pump. e) Dry sand is placed in the flask. Slight vibration is applied to compact the sand. f) A pouring basin is formed in the sand and another plastic sheet is placed over the mold. A vacuum is applied to the flask, causing the plastic sheets to be drawn tightly against the sand. g) The vacuum in the carrier is released and the flask, with vacuum still applied is lifted off the pattern. h) The cope and drag are assembled together with vacuum still applied to both flasks. The vacuum is retained during pouring. i) After the casting has solidified, the vacuums are released and the sand drops away from the flask and the casting.

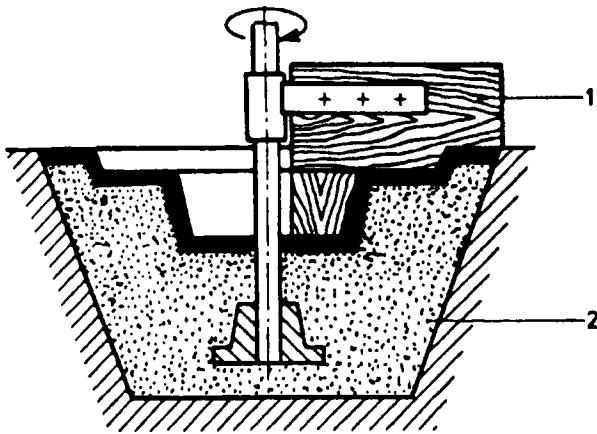


Fig. 1B3f Loam molding with a sweep, rotating about a central axis to form a round shape. 1) wooden sweep. 2) pit mold. (from Davidson, *Handbook of Precision Engineering*, Vol. 10, McGraw-Hill, New York)

and the necessary handling equipment is available, the cope can be made by methods similar to that for the drag, or by conventional methods and fitted in place over the drag. Skilled workers are required for satisfactory results. Equipment is not extensive: a bed plate, cover plate, spindle, and arbors for cores are needed. Straw, hay, cloth strips, or sawdust, may be used to reinforce the sand mixture. These materials burn off during casting. Large bells, cylinders, and rolls are cast with this method. Loam molding is currently in only limited use.

B3g. flaskless mold casting - is a high-production, automatic green-sand process. Casting rates of over five hundred pieces per hour are feasible. A typical mechanized sequence includes mold-making, core placement, pouring, cooling and shake-out, all automatic and all linked together by a conveyor in one production area. The flaskless process uses a four-sided mold chamber in which the molds are formed. The chamber is filled with a sand mixture from above by gravity and air pressure. The molds are formed and maintained with the parting line between mold halves in a vertical position. The pattern plates are supported vertically in the molding chamber with a plate for half of the mold cavity on each side of the chamber. The sand is compacted between the two plates by horizontal squeeze pressure. Each mold, then, has a half-cavity

on each side, the cope half on one side and the drag half on the opposite. Cores, if needed, are inserted automatically.

One of the patterns swings out of the way and the molds are pushed together side-by-side, providing a complete cavity between them and, as the operation proceeds, forming a continuous line of molds. There are no flasks; the weight of the molds pushed together and the bonding of the sand is sufficient to resist any sideways thrusts. Sand is firmly compacted by air and hydraulic pressure to provide the holding strength needed without flasks. Pouring is automatic. The metal enters a basin and sprue, formed by the pattern, at the parting line of the two mold halves. As the operation proceeds and more molds are added to the side-by-side line of molds, the metal cools in those that have been filled, and the castings solidify. They are conveyed to a section where they are separated automatically from the sand and then to a cleaning area. The sand is recycled. Fig. 1B3g illustrates the mold making steps and how the molds are pushed together, side-by-side. Needless to say, a considerable investment is required for a complete flaskless molding operation. Gas stove grills, sewing machines, pipe fittings, and valve bodies are cast with this method.

B3h. Antioch process - In this process, gypsum plaster is used as a binder for the sand. Talc, sodium silicate, bentonite, Portland cement and terra alba may also be used to provide certain characteristics to the mixture. Water is added to the dry mixture and the resulting slurry is piped or poured around the pattern in the mold flask. A typical mixture is 50 percent sand, 40 percent gypsum, and 8 percent talc, plus water equal to half the weight of the dry mixture. After the material sets, it is air dried, heated with steam for 6 to 8 hours in an autoclave at 15 lbf/in² (103 kPa), air dried again for about 14 hours, and then oven heated to 450 to 475°F (230 to 250°C) for 12 to 20 hours. This sequence results in a mold permeability much greater than that achievable with regular plaster molds while retaining a smooth surfaces. Close tolerances can be maintained in the casting but the process is limited to non-ferrous metals. Alloys melting at 1900°F (1040°C) or less are suitable. Applications include the casting of aerospace parts and critical automatic transmission parts for automobiles.

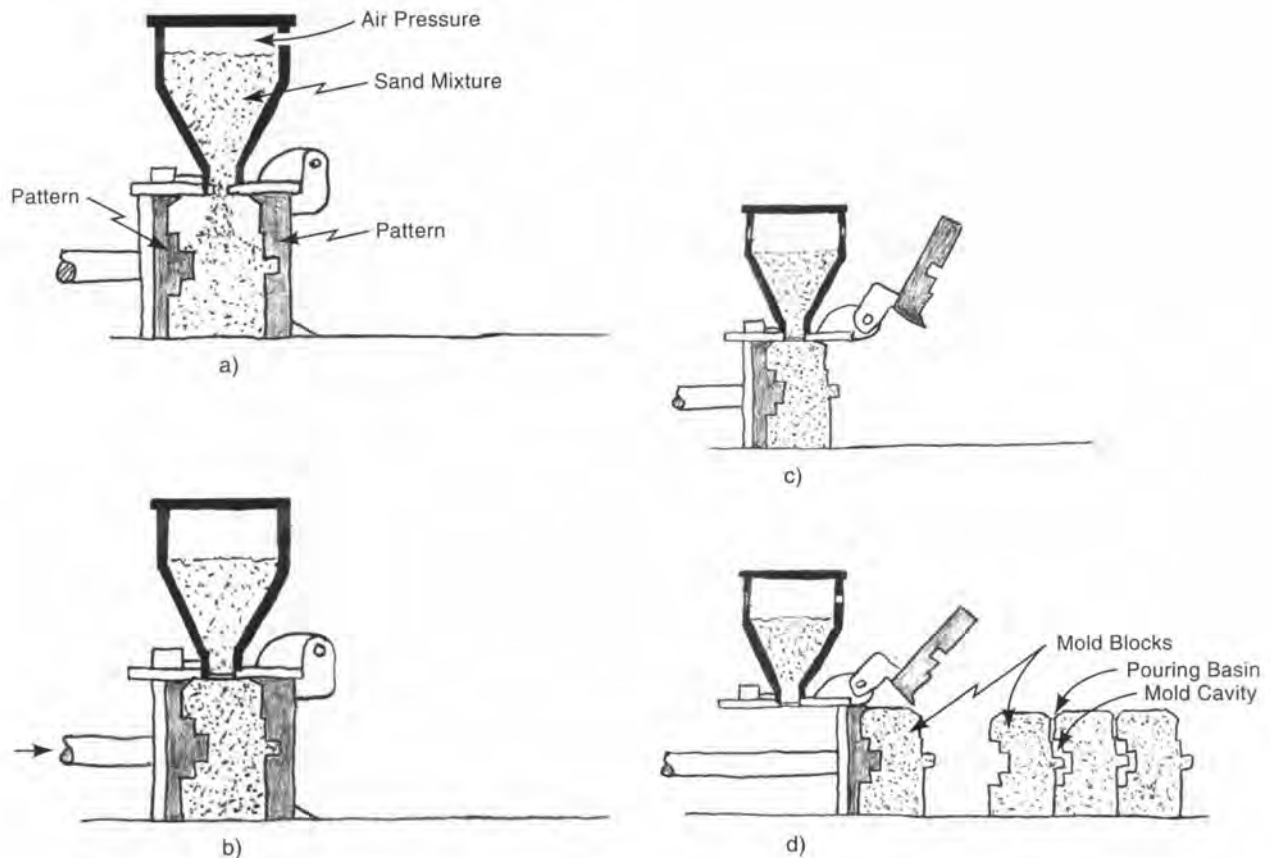


Fig. 1B3g Flaskless molding. a) Sand is blown between two pattern plates in a molding chamber. b) The sand mixture is squeezed to form a dense mold block which has half the mold cavity on each side. c) One of the patterns is withdrawn so that the newly formed mold block can be moved. d) The mold block is pushed tightly against previously made mold blocks. The pouring basin, sprue, and mold cavity lie at the vertical parting line between mold blocks.

B4. core making - Cores are used whenever there is an undercut, opening, or hollow area in the casting that cannot be made by the mold. Cores, sometimes called *dry-sand cores*, are separate pieces made to the shape of the opening, and are supported by the external mold. Fig.1B shows the placement of such a core in a sand mold. Cores are made from sand mixed with a binder to hold the sand grains together strongly enough to allow handling and placement of the core in the mold. One or more of a variety of binders may be used including linseed oil or other oils, phenolic resin, sodium silicate, bentonite, or other clay, and cereals. Core sand, with the binder, is compacted in a metal, wood, or plastic mold, usually called a "core box". After

the core is removed from the core box, baking may be employed to set the binder. Some binders are activated by a reactive gas without additional heat. Another binder needs no external heat or reactive gas: the binder ingredients react and cure without external agents. Which process is selected depends on a number of factors: the size and shape of the core, the production quantity of the casting requiring the core, the metal being cast, and the mold-making process involved. Finished cores are placed in the mold before the two mold halves are placed together. *Core prints*, recesses in the mold, or *chaplets*, small metal pieces that will fuse with the molten metal and become part of the casting, are used to properly locate and hold the

core in the mold. Sometimes, complex or large cores are made by gluing two or more simpler or smaller cores together. Typical cast parts requiring cores are: exhaust manifolds of internal combustion engines, and cylinder heads and engine blocks with cooling channels.

B4a. *green sand cores* - are not cores in the sense that a core is a separate piece inserted in the mold. They are appendages of the green sand mold that form openings or holes in the casting. When a center hole is needed in a casting for pulley, gear or other round part, the hole may be formed by a green sand element of the mold itself. The term, "green sand core" is sometimes used for such elements with "dry sand core" referring to those that are separate and made independently from the mold. Green sand cores are weaker than dry sand cores, require draft, and are suitable only for short, large, openings.

B4b. *core blowing* - is a pneumatic process for filling and compacting core sand in core boxes in production quantities. The premixed sand and binder are added to a chamber that is then sealed except for ports that are placed in line with inlet ports of the core boxes. The sand is "blown" with a sudden blast of high pressure air (40 to 100 lbf/in² (275 to 690 kPa) from the chamber and into a core box. The kinetic energy of the air/sand/binder mixture provides the force needed to pack the sand. The method used for hardening the binder depends on the chemical nature of the binder, but phenolic resin-coated sand is a common approach and the phenolic is cured with heat. All steps in the operation are automatic and production is rapid. Blown cores are used for applications requiring mass production of small or medium-sized cores.

B4c. *core baking* - The binder for the core sand is hardened by drying or polymerizing it in an oven of controlled temperature. Core-oil binders using linseed or vegetable oil are commonly oxidized and hardened by baking. Urea-formaldehyde and phenolic resins are also oven baked. These cores are formulated with the flour of corn or another cereal and/or clay and water, which coat the sand and provide sufficient green strength so that the cores can be handled. They are then removed from the core boxes before curing and

placed in an oven. Ovens may be continuous, with a metal mesh conveyor, or stationary, the choice depending on the production level and size and complexity of the core. Baking is for one hour or longer at 400 to 500°F (200 to 260°C), the time depending on the thickness of the core section. When fully cured, the cores are removed from the oven and allowed to cool to room temperature.

B4d. *oil-oxygen process* - for core making. In this process, a combination of oils and additives is used with the sand. The oils polymerize when they contact oxygen-bearing activators (perborates, percarborates, permanganates, peroxides), and bond the sand particles together. Dry sand, additives, and activators are mixed together. The sand mixture flows easily into core boxes and does not have to be rammed. Depending on the amount and nature of the additives and activators, as well as the temperature and the presence or absence of metallic dryers, the additives begin to gel. When they are sufficiently hard, the cores can be removed from the core box, and are usually baked in ovens at 400 to 450°F (200 to 230°C) until polymerization is complete. The resulting cores are stable dimensionally, and sufficiently strong. After the casting has solidified, the core sand is easily removed. The process is used for a wide range of ferrous and non-ferrous casting alloys. However, its principal use is in large castings made in small quantities. Large gears, steam turbine impeller wheels, and bridge construction components, are typical applications.

B4e. *uran no-bake core process* - Furans are a family of thermosetting resins that, when cured, act as binders for core sands. Curing takes place at ambient temperature and begins when two or more of the binder components are mixed together with the core sand. Curing is slow enough that the sand mix is flowable and workable for a period of time so that core boxes can be filled. After an additional period, curing has progressed enough so that the cores can be removed from the boxes. The curing then proceeds to completion. (Although baking is not strictly required, it may be used to speed curing and drying.) The time required for both preliminary and final curing can be varied from a few minutes to a number of hours, depending on the resin formulation. Both fural acid and phenolic acid resin systems can be used with this approach.

B4f. carbon-dioxide process¹ - This process uses 3 to 6 percent sodium silicate as a binder for the core sand. Sand compaction in the core box is by blowing or other conventional methods. The compacted sand - mixed with sodium silicate - in a corebox is exposed to carbon dioxide gas for from 5 to 15 seconds. With small cores, the core box is double-walled or the pattern is hollow, to allow a closed conduit for the gas. With larger cores, lances are used to inject the gas into holes made in the core. In both methods, the gas permeates the core sand and causes the sodium silicate to gel and harden. Cores then are stored for 24 hours or more, while the hardening of the silicate continues, producing a core strength of about 100 to 200 lbf/in² (700 to 1400 kPa) so long as the atmosphere is not too humid. No baking is required; the operation can be performed at room temperature. [However, baking at 400°F (210°C) is sometimes done after the CO₂ treatment.] Surfaces of the cores are often coated with a graphite or zircon refractory coating using an alcohol wash. Most of the sand can be reclaimed for further use after pouring and shake-out. Iron, steel, copper, and aluminum alloys are cast with these cores for many applications.

B4g. shell process for cores - is essentially the same as the process used to make shell molds. See B3a above.

B5. sand mold methods

B5a. ramming - is the packing of sand in a mold. The term usually refers to the hand operation performed with a hand tool, a *rammer*, which provides weight and a small, flat, packing surface to aid the operation. Pneumatic hand-operated rammers are also used. Hand ramming is labor-intensive, produces more variable results, and is slower than mechanized methods but is suitable when production quantities are too small to justify mechanized methods. Ramming is also useful to supplement sand slinging in large floor and pit molding operations.

B5b. bench molding - For small castings, the mold making and pouring may be done on a workbench where the work surface height is more convenient.

B5c. floor molding - When larger castings are to be made, it is common for the mold making and casting operations to take place on the factory floor. Sand compaction may be done by hand ramming, sand slinging, or large machines of other types. Sand is applied in layers and each layer is carefully knitted to the adjacent layers. The use of very hard sand compaction is necessary because of the weight of the casting and the amount of molten metal poured, especially if large flasks are not available to contain the sand. (When flasks are used they are normally so large that they require the use of an overhead crane. Otherwise, the cope may be made up of a series of side-by-side cores.) Dry-sand molding is often used. Cement-bonded sand or loam molding may also be employed.

B5d. pit molding - is used when the castings are too large to fit in flasks that would hold the cope and drag. Instead, a pit in the foundry floor takes the place of the lower half of the mold. The pit is filled with the sand to be used. An upright pattern is lowered and pressed into the sand, and additional sand is rammed tightly around it. Sets of cores, arranged side by side, are used to provide the cope half of the mold. These large castings are cooled slowly, sometimes over several days, before the mold is opened, in order to minimize internal stresses.

B5e. machine methods - In production situations, several machine methods are available to supplement or automate the sand mold-making operations, which would otherwise be manual. Mechanized methods typically provide more uniform sand densities than manual ramming. Often, the machines not only compact the sand, they invert the mold and remove the pattern from the sand. Mechanized methods include jolting, squeezing, jolting-squeezing, sand slinging, and flaskless casting.

B5e1. jolt-squeeze methods - use a machine that packs sand around a pattern by raising the pattern plate and flask with sand for a few inches and then allowing them to fall to an abrupt stop. The inertia of the falling sand packs it around and against the pattern. The operation is repeated until the desired density of compaction of the sand is achieved, but some hand or pneumatic ramming

may also take place. Then, the machine uses pneumatic or hydraulic pressure to lift the table and force the packed sand in the flask against a flat plate that is fixed in position. The pressure further densifies the sand packing in the flask. In rollover machines that process both mold halves using a match-plate pattern (See B5e4 below), the double flask is inverted, sand is added, and the operation is repeated for the other mold half. The flasks are separated (The cope is lifted.), the pattern is removed, and the cope is lowered onto the drag to complete the mold. Fig. 1B5e1 shows some of the key steps of the sequence. The degree of mechanization and automation of the operations, other than jolting and squeezing, varies with the installation. High production volumes and large sizes of the molds make mechanization of lifting and inverting and other

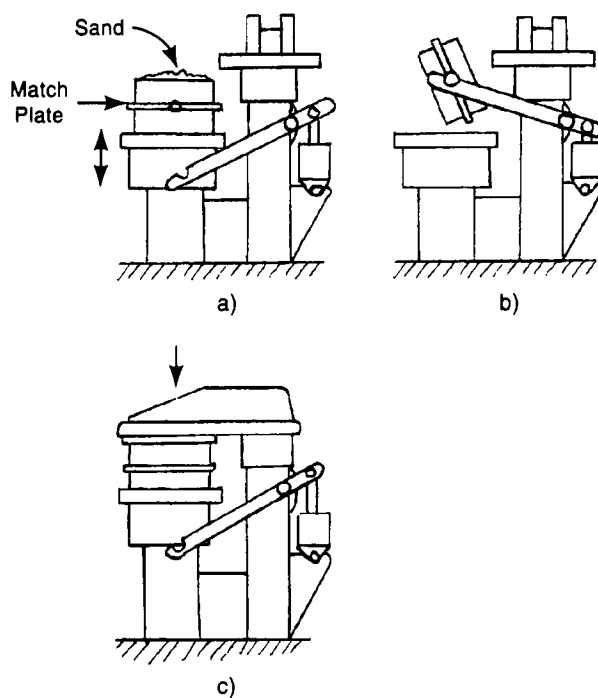


Fig. 1B5e1 A typical jolt-squeeze-rollover machine with a match plate pattern. a) The sand in one mold half is jolted by rapid up and down motions of the machine table to compact it around the pattern. b) Rollover - The mold is inverted after the drag is completed so that the cope half can be filled. c) The head of the machine indexes over the mold and the squeezing cycle takes place to fully compact the sand.

steps more economically justifiable. After the completed mold is assembled, it is normally placed on a conveyor that transports it to the foundry pouring area. Jolt-squeeze sand compaction works best when molds are not too deep and the casting shape is somewhat shallow and horizontal. Both *jolting* and *squeezing* may be performed as single operations on either jolt or squeeze machines, depending on the casting involved. Squeeze machines are limited to molds only a few inches thick. Some squeeze machines use a rubber diaphragm and air pressure to squeeze the sand.

B5e2. sand slinging - compacts the mold sand by slinging or throwing it at high velocity against the pattern in the flask. Centrifugal force from a rotating impeller provides the high velocity. The operation is fast and can produce uniform compaction. However, when sand slinging is used in jobbing foundries, considerable skill on the part of the machine operator may be necessary to insure consistent results and uniform mold density. Supplemental hand ramming may sometimes be employed but the process provides very dense and hard molds. For larger molds, the slinger machines are portable and are brought to the mold location.

B5e3. rap-jolt machines - are similar to jolt squeeze machines but, instead of jolting the pattern plate and flask, a weight strikes the underside with a controlled force at rapid intervals. The pattern plate and flask do not move up and down but the rapping causes the sand to densify. Squeezing is part of this method also and it may take place simultaneously with the rapping. The method provides dense, hard molds.

B5e4. match-plate molding - has patterns for the cope and the drag mounted on opposite sides of a single metal plate. Fig. 1B5e4 shows a typical match plate pattern. When these patterns are used, both the cope and drag halves of the mold are made in one operation, one on each side of the plate. Gravity fill, followed by a pressure squeeze, is one method used to supply and compact the sand. Sand fills the flask on one side of the plate, a plate closes the flask, the flask is rotated, and the other side is filled by gravity. Then the two sides are compacted by the same squeezing operation. Another approach is to blow the sand in

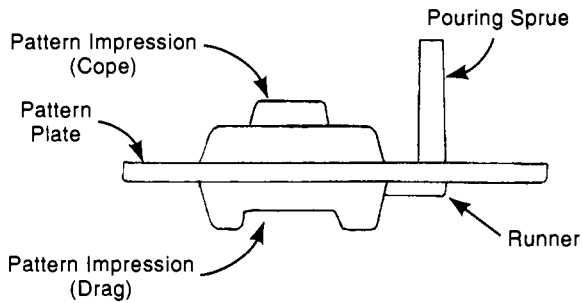


Fig. 1B5e4 A typical match plate pattern. Note that the two half patterns, for the cope and drag cavities, are placed on opposite sides of the plate. Sprues, runners and risers are also included in the pattern.

on both sides of the pattern plate at the same time. Then the two halves are squeezed simultaneously. After squeezing, the mold halves are separated and the pattern is withdrawn, a core is placed, if applicable, and the cope and drag are assembled together in preparation for pouring. (Also see jolt-squeeze mold making above.) Match plate molding is suitable for high production situations. Gates and runners are normally included as part of the pattern.

B6. sand processing

B6a. sand mulling - or mixing is performed by a machine, a sand muller. Sand, and for green-sand molding, water, clay, carbonaceous material, and other additives are loaded into the machine. The muller has two rollers (muller wheels) at the ends of a horizontal arm that rotates. The rollers with two plow-like blades, break up agglomerates of sand and binder and distribute binder, water, and additives throughout the mixture. The machine operates at a low speed. Fig. 1B6a illustrates a typical batch type sand muller. There are also continuous mullers in which ingredients are fed into the equipment at one end and exit at the other end after being blended. One such continuous muller uses two connected side-by-side mullers similar to the one illustrated. When sand is processed after it has been used in casting, ingredients are replenished as needed and are blended. (Casting sand is re-used but is normally blended with a certain amount of fresh material.) After mixing, the sand is typically

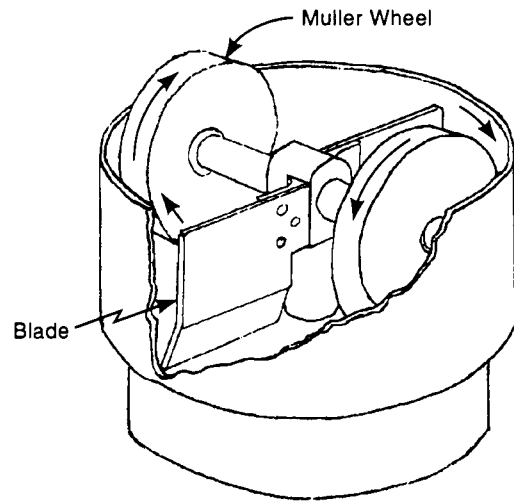


Fig. 1B6a A typical batch-type sand muller. Both the muller wheels and blades move and mix the sand, binder, and other ingredients.

conveyed to an aerator that separates the sand grains and improves flowability and thence conveys it to hoppers serving the molding operations. Other types of equipment are available for sand mixing, some of which can operate with shorter mixing times than the conventional unit pictured in Fig. 1B6a.

B6b. reclamation of sand - is increasingly important in light of the increasing costs involved in the disposal of used sand. Reclamation is a feasible alternative, but is more difficult if several types of binder are mixed. Three reclamation methods are in current use: *mechanical reclamation*, *thermal reclamation* and *wet reclamation*. After these methods are used, additional sand, binder, and other additives are provided to insure that the sand mixture, including reclaimed material, meets specifications.

B6b1. mechanical reclamation - uses the sand muller described above to break up lumps so that only particles the size of sand grains remain. However, the process also involves several other steps such as the separation and removal of metal using magnetic or screening methods, and scrubbing, which hurls the sand against a target plate, either with high volume air flow ("pneumatic scrubbing") or centrifugal force ("mechanical

scrubbing"). The sand grains impact against each other and against the target plate. This tends to remove the residue of bonding resin from the grains. A dust collection system removes the resin husks and various fine particles from the sand. If necessary, the sand is kept in the system for repeated action until the desired degree of removal of unwanted material has taken place. The processed sand is cooled, if necessary, and is screened or air classified to remove any further foreign or undersized material. Sometimes, both mechanical and pneumatic scrubbing is performed in sequence on the same lot of sand. Make-up sand is added as needed and is blended with the reclaimed sand. Typically, the finished product will be 80 percent reclaim and 20 percent new sand.¹

B6b2. *thermal reclamation* - uses similar steps but includes heat processing. The sand is heated in a rotary kiln to a temperature high enough to ignite and burn off organic resins used in the shell molding process - about 1470°F (800°C). The burning of the resins contributes to the heat required for the operation. One method utilizes a refractory-lined rotary drum with an elevated feed end. Burners inside the drum at both ends are directed at the cascading sand flowing through the drum or, in other designs, external burners provide sufficient heat to ignite the resins. The drums are relatively inexpensive but have high heating costs and some weaknesses in control of material flow and air for combustion.

Fluidized bed machines are also used for thermal reclamation. Such machines, have a combustion chamber with provision for flow of air and hot gas from the bottom sufficient to fluidize the sand in the chamber. Burners are located below the chamber in the flow of incoming air and also in the chamber with the sand. Sand is introduced through a higher port of the chamber and withdrawn from a lower port. All resins and other hydrocarbons are burned off with this system. A second combustion zone above the chamber burns off any waste gases. This approach requires a larger investment than a rotary kiln but provides better energy efficiency and better control of the operation.

Clay-bonded sands can also be processed thermally. After the sand is crushed and metal residues are removed, it is fed into a calciner, which heats the mixture to a temperature sufficient to calcinate the

clay but not high enough to cause the clay to fuse to the sand particles. Temperature control is critical. Following this step, the sand is cooled and processed with the scrubbing steps described above.

B6b3. *wet reclamation* - is used for sand mixtures bonded with silicates. A water wash replaces the heating cycle of thermal reclamation. It removes the silicate residues. The first step, however, is the breaking and crushing of lumps in the mixture. Then the water wash takes place, followed by sand and liquid separation. The sand is dewatered and dried. The liquid is treated to agglomerate the residues and allow separation by settlement. The water is then treated to permit safe disposal. When properly performed, all the sand processed can be re-used. The only new sand needed is to make up any that is lost.

B6c. *metal separation from sand* - It is necessary to remove smaller pieces of metal from the sand. These include sprues, runners, etc. that are separated from the casting in the shakeout operation. With iron and steel castings, these tramp metal pieces can be removed magnetically. A common approach is to use a belt conveyor for the sand and to place magnets both above and at the end of the conveyor. (See 11C8d.) With non-magnetic metals, screening is the most common method, using multiple screens of successively finer mesh. Other machines, whose method is based on the density difference between the metal and the sand, are also available.

B6d. *cooling of sand* - is necessary after use because hot sand causes moisture and other problems. Bentonite clay does not function as a binder if the temperature is above about 115°F (45°C). Sand does not conduct heat well and a mass of sand in storage will remain its heat for a long period. Cooling is accomplished by spraying the green sand with water and blowing air through the sand. Evaporation of 1 percent water content cools the sand by 45°F (25°C).³ Water is sprayed on the sand, and air is blown through it in either a rotary drum or through a screen that retains the sand. In the latter method, the sand becomes a fluidized bed. With both the drum and fluidized bed methods, sand is fed from one side of the device and exits at the other, thus providing a continuous

operation. Both air flow and moisture addition must be carefully controlled so that the sand mixture is not made too wet and that the amount of desirable fine materials carried away with the cooling air is not excessive. In some arrangements, many of the fine particles carried away by the cooling air are returned to the sand mixture.

B7. *pattern making* - Patterns are made to produce the proper sizes and shapes of cavities in the sand molds. Except for some very simple shapes, usually those that are circular, a pattern is necessary if the mold cavity is to have the correct shape and dimensions. Patterns are typically made from wood, plaster, plastics, various metals, and, for lost foam castings, from polystyrene foam. For investment castings, patterns are made from wax or plastics. Aluminum, brass, and cast iron are common metal pattern materials. The greater the production required, the harder and more wear-resistant the pattern material should be. Pattern-making may be costly because the process is lengthy and largely manual. Patterns must be slightly larger than the casting they will produce because of the shrinkage of metals as they change from the liquid to solid state and cool to room temperature. The initial operation for many pattern materials is contour milling. The pattern is typically rough contour milled with the machine under either hand, template, or computer control. It is then finished by hand with filing, sanding, and polishing operations.

Metal patterns are often produced by first making a wooden pattern and then casting a metal replica. Wood patterns are usually varnished to provide a moisture seal and smoother surface. Some of the available rapid prototyping methods are useful for making patterns suitable for various casting methods, chiefly for investment casting of smaller quantities. (See Chapter 14.) The laminated object method (LOM)(14A5a) is used to make wood-like casting patterns.

B8. *post-molding operations*

B8a. *shakeout* - is the operation that separates castings from the sand mold. It is the first operation that takes place after castings solidify and cool in the mold. The basic method employed in the operation is to subject the mold and casting to a strong

vibrating motion, which causes the sand mold to break up and fall from the casting. The sand falls through a grating that supports the casting but allows the sand to fall to a collection bin or conveyor below. Fine dust is collected by a cyclone-type dust collector. There are four prime methods by which shakeout is carried out: 1) *vibrating conveyor* - The molds containing castings are placed in a pan or trough that moves the casting with a vibratory motion as the sand falls away. 2) *shakeout table* - or deck, which processes the castings on a batch basis. This approach is used for lower quantity production. The frequency of vibration is lower, but with greater amplitude for larger, sturdier, castings and at a higher frequency and lesser amplitude for thin-walled or otherwise weaker castings. 3) *rotary shakeout* - This uses equipment that tumbles the molds and castings in a rotating cylinder. Castings are fed into the cylinder at one end and exit at the other. Sand also normally exits at or near the end but sand discharge openings can be at other points along the cylinder. Light castings with thin walls may not be suitable for this method. 4) *vibrating drum* - a large drum with a bottom grating allows the sand to fall as the drum vibrates. The drum does not rotate but the vibration imparts a rotary motion to the mass of sand and castings in the drum.

These devices all provide some degree of cooling to the sand and castings in the drum. Rotary shakeout machines may be equipped for water addition to provide increased cooling. Shakeout machines remove almost all the mold sand from the castings. Abrasive blast cleaning, which follows shakeout, removes whatever sand remains on the casting surfaces after the shakeout operation.

B8b. *core knockout* - Aluminum and other non-ferrous castings are poured at a lower temperature than iron or steel castings and the metal temperature may not be sufficient to burn out organic binders in molds and cores, making them less easily removed from the castings in shake out. This is particularly true with cores for hollow sections, which are protected by metal sections of the casting from shake out and tumbling forces. It is more common, in non-ferrous castings, to have a separate operation to remove core sand. One method involves the use of a manually operated chisel, which vibrates pneumatically. The impact of the

vibrating chisel blade breaks up the core sand, which falls away. Another method uses a chisel or other tool that is mounted on a frame and pushes the core sand from the casting, or breaks it up. The casting is handled manually but the machine holds, advances, and retracts the vibrating tool. Other machines, sometimes designed or arranged for use on a specific casting, provide vibration to either tools or the whole casting to break up and remove the core sand. Holding fixtures are used to position the casting for maximum effect. Some machines use high-frequency mechanical vibration rather than pneumatic oscillation to create the forces needed. High pressure water jets, shot blasting, and vibrating media are used in other equipment. These vibration methods tend to generate high noise levels and some dedicated machines include acoustic enclosures.

B8c. blast cleaning - is a fast method for removing residual sand and scale from a casting after shake out. It also improves the surface finish of the casting. The blast medium is either sand, metal shot, grit, or glass beads, which are propelled against the casting by air, water nozzles, or mechanical means. Centrifugal wheels provide the most common propulsion method. See Fig. 1B8c-1. The shot, grit, or sand is fed to a rapidly rotating wheel, that has vanes to pick up, accelerate, and expel the media. The wheels can deliver larger quantities of media than nozzles, but nozzles can deliver the media more selectively to recesses and other areas needing special attention. The blasting operations produce dust, which must be contained except when water is used as the carrier for the media. The castings may be tumbled in the blast chamber to expose all surfaces, may be on a turntable, or may be carried on an overhead hook-type or other conveyor. Smaller quantity production can be processed in batch-type tumble blasting machines, as shown in Fig. 1B8c-2.

High production equipment utilizes a belt conveyor with means to tumble the castings as they pass under the blast nozzles. High production equipment may also have multiple blast sources arranged so that they reach all surfaces of the workpiece. Robots are now used to handle and position castings so that the blast medium strikes all necessary surfaces. For aluminum castings, the blast cleaning process can provide a more uniform surface finish, an improvement

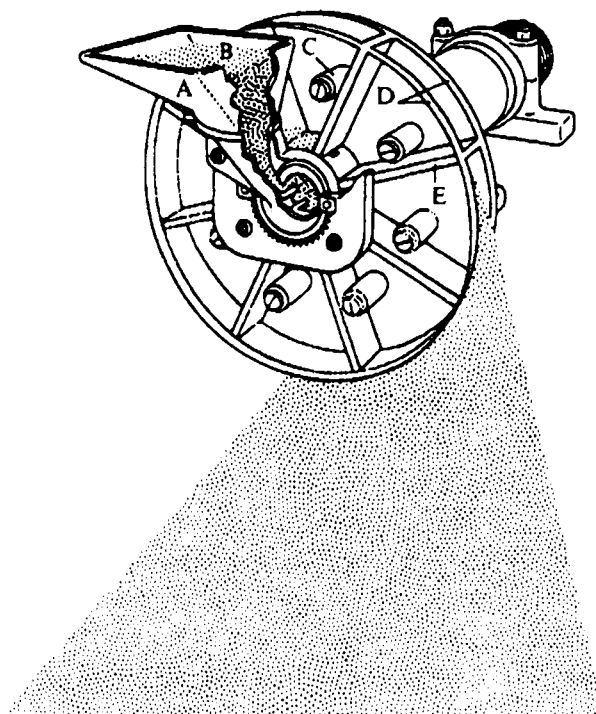


Fig. 1B8c-1 The wheel mechanism that uses centrifugal force to propel the grit, metal shot, glass beads, or sand in a blast cleaning machine. (Courtesy Wheelabrator. Wheelabrator is a registered trademark of Wheelabrator Technologies, Inc.)

in appearance, and closure of surface porosity in addition to the cleaning effect.

B8d. tumble cleaning - Castings small enough to be placed as a group or lot in a rotating tumbling barrel can be cleaned of sand residues, scale, and fins by tumbling. Star shaped pieces of iron are included in the barrel with the castings and they abrade and burnish the castings as the barrel rotates, removing the sand and smoothing the surfaces. Sometimes water and a caustic are also included to hold down dust. Brass and bronze castings are tumbled with steel or iron balls, sand, or pumice, with water and detergents to improve their surface finish². Tumbling can also be combined with blast cleaning as noted above for smaller castings. The tumbling action exposes all sides of the casting to the blast.

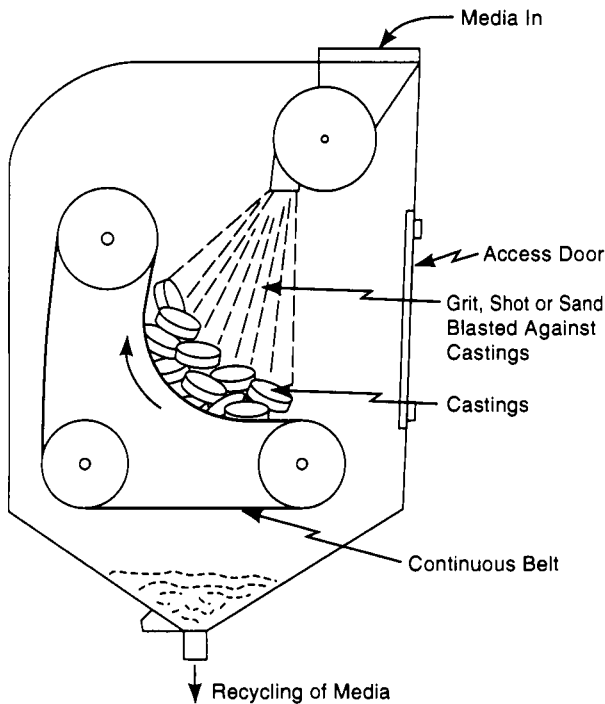


Fig. 1B8c-2 A tumble blasting machine for cleaning castings. The continuous conveyor causes the castings to tumble while being subjected to the blast of media, which removes sand and scale from the surfaces of the casting.

B8e. wire brush cleaning - is often used on aluminum, brass, and bronze alloy castings. It can produce a shiny surface on the casting. Various types and hardnesses of brushes can be selected, depending on the cast material, its shape, and the results desired. Power-driven rotating brushes are usually used. The operation may be performed robotically.

B8f. gate, riser and fin removal - This operation is sometimes referred to as *fettling*. It can be accomplished with any of a variety of metal cutting devices such as band saws, shears, abrasive cut-off wheels, flame cutting torches, and pneumatic hammers. Flame cutting is more common on steel castings if the gates and risers to be removed are large. Powder-assisted flame cutting (See 3H1 and 3H2) is sometimes used on alloys that are oxidation-resistant. The operation may be performed by robots.

B8g. snagging - utilizes portable and powered grinding tools, stationary stand-grinders, or swing-frame grinders, to remove excess metal from castings manually. The operation provides rough grinding only; further machining is required to produce accurate surfaces. Fins and flashing are often removed by snagging and the operation is also applicable to forgings. Hand chipping tools, including pneumatic hammers, are also used.

C. Other Expendable Mold Processes

C1. ceramic mold casting - The ceramic mold process has similarities with investment casting, sand mold casting, and plaster mold casting. It is similar to plaster mold and sand mold casting in that two-piece, cope and drag molds are used. The process is similar to investment casting in that it uses a ceramic mold material rather than sand or plaster, so that steel and alloys with high melting temperatures can be cast (whereas plaster molds are limited to non-ferrous materials having lower melting temperatures.). The pattern is not expended as in investment casting; normally a precision made, re-usable wood or metal pattern is used. The first step in the process is to pour a thick slurry of ceramic mold material around the pattern, which incorporates gates and risers and is mounted on a match plate. Fine-grain zircon and calcined, high-alumina mullite are commonly used refractory mold materials. The pattern is removed after the mold material gels but before it sets completely. This prevents bonding of the mold to the pattern. The other mold half is made similarly, and when both halves have set, they are assembled. The assembled mold is fired at approximately 1800°F (980°C) and is filled with molten metal while still hot. Castings can be considerably larger than typical investment castings but have the advantages of a fine surface finish, sharp detail, and high dimensional accuracy, except that dimensions across the parting line require somewhat greater tolerances. A disadvantage of the process is the high cost of the ceramic material, which is expended in the process. Ceramic molds are used for dies and die parts, cast from tool steel, to eliminate much of the machining that otherwise would be required of these difficult-to-machine alloys. Die casting and forging dies, thread rolling dies, injection molds for plastics,

stamping dies, and cutting tools are cast in ceramic molds. Parts cast by this method include components for aircraft, chemical processing, and food equipment, using stainless steel, and many parts for marine and architectural applications made from copper alloys. Cast iron, ductile iron, aluminum, nickel, cobalt alloys, and titanium are also cast in ceramic molds.

C2. *ceramic-shell process* - To reduce the cost of the mold, with its loss of ceramic material, the ceramic mold process can be modified to make only a facing layer of ceramic around the pattern, with the balance of the mold made up of less expensive fireclay. This approach is used when the castings are large and a conventional ceramic mold would be too expensive. The Shaw and Unicast processes, described below, are two of several methods that can be used to make ceramic-shell molds.

C3. *Shaw process* - is a ceramic mold process that uses two different types of molds: 1), an all-ceramic mold with a process quite similar to that described above and used primarily for small castings and 2), a mold consisting of a ceramic facing $3/32$ to $3/8$ in (2.3 to 9.3 mm) thick, backed up by a larger amount of inexpensive fireclay. The economics of the use of ceramic material limits the size of castings in the first process; there are no size limitations to the second process. Both process variations produce castings with fine detail, smooth surface finishes, fine grain, and a high level of soundness and accuracy. Both approaches use a variety of mixes of refractory powders and a liquid carrier of hydrolyzed ethyl silicate in a proprietary formulation. These materials are mixed with a gelling agent to produce a slurry that can be poured over the pattern to produce a cope or drag.

In the all-ceramic approach, the slurry of refractory material with hydrolyzed ethyl silicate is poured over the mold pattern, which can be wood, metal or plaster. The mold is stripped from the pattern when the material has gelled but before it is fully set, as in regular ceramic molding. The mold, at this point, is quite rubbery, so some undercuts and back drafts are feasible. The volatile materials in the mold are burned off by torch heating before the mold is baked in a furnace for four to five hours. The burning operation produces microcrazing in the cavity surface, which allows

the gases and air to escape without being large enough to allow the molten metal to penetrate. The resulting mold is strong enough to withstand the expansion forces from hot molten metal while still being sufficiently porous. The molds may be preheated before pouring. They can be filled gradually so that turbulence is avoided, improving the structure of the casting.

The composite mold process uses four patterns if the cavity extends into both the cope and the drag. Two of these patterns are oversized and are used to form the backup material for the cope and drag. The other two are sized for the casting dimensions and are used to produce the ceramic facing. The backup is formed by ramming or vibrating the fireclay mixture over the backup pattern. (In some arrangements, only one pair of patterns is needed; a felt or flexible plastic sheet is placed over the facing pattern, equal in thickness to the ceramic facing, so that the fireclay backup can be formed.) Both the facing and backup patterns include locating members so that both halves of both mold portions can be assembled in correct alignment. The backup mold portions are hardened by placing them in bell jars and diffusing carbon dioxide gas through them for about 20 seconds. The facing mold portion is formed by pouring the ceramic slurry through a pouring channel in the backup and over the casting pattern, in the gap between the pattern and the backup. Fig. 1C3 illustrates the arrangement. Gravity pouring of the slurry is used but a vacuum chamber can be employed to remove trapped air if the casting details are critical. When the material gels after 2 or 3 minutes, the mold is stripped from the pattern. As with the all-ceramic molds, the flexibility of the mold at that stage allows it to be stripped from the pattern even if there are mild undercuts. The composite mold is then subjected to torch heat, which ignites and burns off the volatile materials. The mold halves are then assembled.

C4. *Unicast process*¹ - is similar to the Shaw process. It differs primarily in the treatment of the ceramic material (in both the all-ceramic and ceramic-facing alternatives) after it has gelled but before setting is complete. In the Shaw process, alcohol in the ceramic mold material is burned off before microscopic cracks in the mold surface, which are desirable if kept small, can become

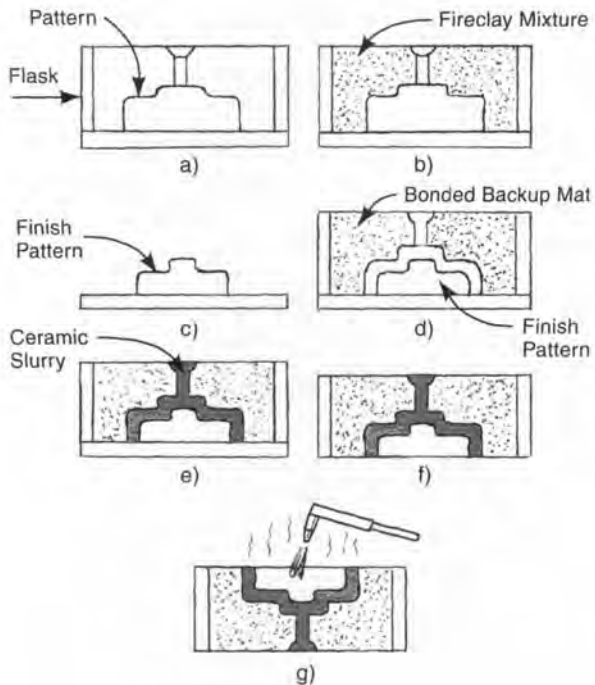


Fig. 1C3 The Shaw process for making composite molds. Two patterns are used, one to form the finish cavity, the other to form a somewhat larger cavity. The ceramic slurry poured between the larger cavity and the finish mold forms a ceramic shell suitable for accurate castings of many materials. a) The pattern for the backup material is placed in a flask. b) A fireclay mixture is introduced to the flask and is compacted by ramming or vibration. Containing sodium silicate, the mixture is bonded by gassing with carbon dioxide. c) The finish pattern on a pattern plate. d) The finish pattern and the bonded backup material are assembled in the same flask. e) Ceramic material in slurry form is poured into the opening between the backup material and the finish pattern. f) The finish pattern is removed. g) The mold half is inverted and heated by torch to burn off volatiles. Two mold halves, thus formed, are assembled together and are ready for pouring.

excessive or too large. In the Unicast process, the alcohol is dissolved in a liquid or vapor solvent, usually by spraying the solvent on the mold for 15 or 20 minutes. Application of the solvent limits the crazing and facilitates the hardening and stabilization of the ceramic material. Following this step, the hardening is completed by heating the mold in

an oven at 1800°F (980°C). The cured mold is then ready for pouring. Another difference between the Unicast and the Shaw processes is the means of making composite molds. With the Unicast process, the ceramic facing slurry is applied to the pattern first. It gels almost immediately and a slurry of backing material is poured into the flask until it is full. Thus, only a single set of patterns is required. Very fine refractory material is used in the facing mixture and extremely sharp detail can be produced in the casting. The mold is also well vented with natural porosity permitting the casting of thin sections. Iron, steel, and a variety of non-ferrous alloys are cast with the process.

C5. plaster mold casting - This process is similar to sand-mold casting except that the molds and cores are made of a type of plaster of Paris rather than packed sand. The mold is made in a metal or wooden frame that contains the pattern. A liquid mixture of about 60 percent water and 40 percent metal-casting plaster is poured over the pattern. (Metal-casting plaster includes 20 to 30 percent talc and some other ingredients to speed setting.) The mold is vibrated lightly to ensure complete mold filling. After the plaster achieves an initial set, the frame and the pattern are removed, sometimes with a vacuum assist. Cores, if any, are added and the two mold halves are assembled together. The mold is then baked at a temperature ranging from 350 to 1600 °F (175 to 870 °C) to remove moisture, including the chemically-combined water, and to improve its permeability. Pouring of molten metal takes place with the mold hot and subject to a vacuum, to further remove the water of hydration. Fig. 1C5 illustrates a typical plaster mold before it is filled.

The process is used for non-ferrous metals with a melting temperatures of 2000°F (1100°C) or below. Aluminum, magnesium, zinc, and copper alloys are plaster cast. Cast parts can have an excellent surface finish, fine detail, and good dimensional accuracy. Intricate parts can be cast. However, production rates are lower and costs are higher than with sand mold processes. Typical parts include valves, pistons, cylinder heads, gears, cams, handles, pump parts, rubber tire molds, and plumbing fittings.

C5a. foamed plaster mold casting¹ - is conventional plaster mold casting with a foaming

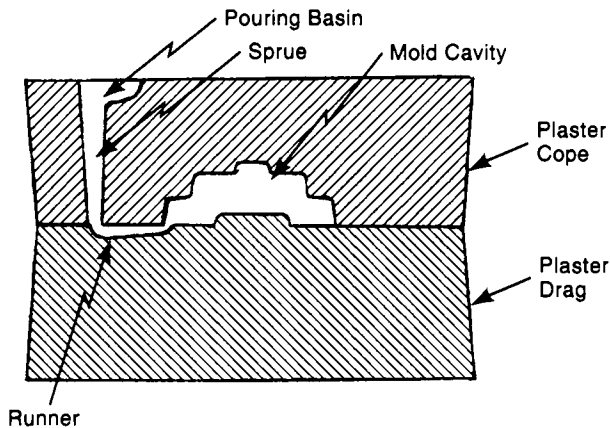


Fig. 1C5 A typical plaster mold before it is filled.

agent added to the plaster mix. The foaming, after the mold is completed, results in a permeable mold since the air cells tend to connect during the mold drying operation, providing an escape path for any gases generated during casting. The process differs from conventional plaster mold casting in that the foaming agent is added to either the dry plaster mix or to the slurry and there is intense mixing of the slurry. Proper mixing insures that the air cells are fine, no larger than about 0.01 in (0.25 mm) in diameter. Small air cells provide a mold surface that is smooth and strong enough to withstand the casting pressure. Otherwise the casting surface smoothness would suffer. The ideal amount of foaming produces 50 to 100 percent of volume increase. Drying of the foamed plaster molds before casting is done at the lower range of temperatures normally used for plaster molds because the insulating properties of the foam can result in cracking if the outer portions of the mold are overheated. Aluminum-magnesium alloys are most suitable for the process, but all-aluminum casting alloys can also be cast.

D. Permanent Mold Processes

D1. permanent mold casting - Permanent mold casting involves the use of reusable metal molds instead of the single-use molds of sand, ceramic, or plaster. The mold halves are usually hinged or mechanically guided together to permit quicker mold assembly. Filling with molten metal is by gravity. The process, then, falls between sand-mold

and die casting. Molds are usually made of cast iron and are given a coating up to 0.12–0.03 in (0.30–0.75 mm) of refractory, suspended in liquid to prevent overly-fast cooling of the casting and to protect the mold surface. Powdered graphite is also sprinkled on the mold surface every few shots to facilitate release of the casting from the mold. The process is most practical for metals that melt at lower temperatures. Aluminum, magnesium, and copper-based alloys are the ones most frequently cast. Steel and iron can be cast in metal molds of suitable high-temperature alloys but this method is less common. Graphite molds are sometimes used, but they do not have a long life. Sand or metal cores may be used, depending on the shape required. (When sand cores are used with metal permanent molds, the process is known as *semi-permanent mold casting*.)

Molds are usually preheated before pouring and water cooled after pouring. Since the metal molds are not porous, small vent holes or channels to release displaced air and gases are usually incorporated in the molds. The process provides surface finishes and dimensional accuracy superior to those of sand-mold casting and denser structures than die casting. It is most suitable when shapes are not highly intricate. Since pressure is not used to force metal into the mold cavities, wall thickness must be greater than that used in die castings, typically 1/4 inch (6.3 mm) or greater. Fig. 1D1 illustrates a typical permanent mold ready for casting. Typical parts cast by this method are: automotive pistons,

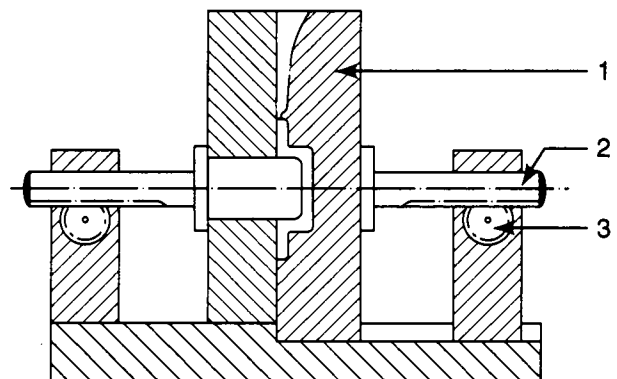


Fig. 1D1 A typical permanent mold. 1) movable mold half, 2) rack gear, 3) pinion gear. (from Davidson, *Handbook of Precision Engineering*, McGraw-Hill, New York)

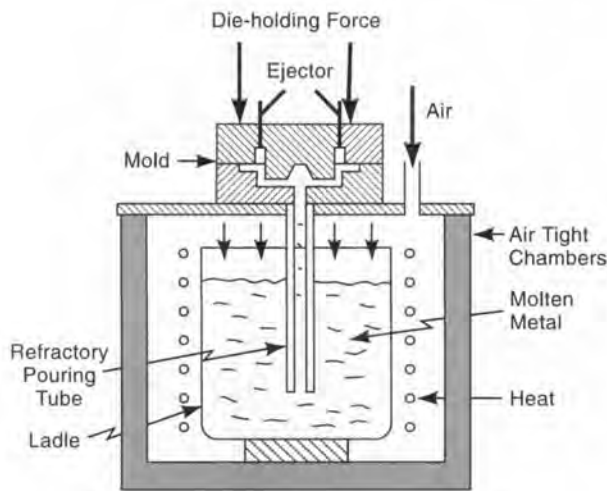


Fig. 1D2 Schematic view of low-pressure permanent mold casting. Air pressure forces the molten metal to flow upward against gravity and fill the mold. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

waffle irons, wheels, electric irons, pipe fittings, and gear housings.

D2. low pressure permanent mold casting - uses gas pressure to fill the mold and is a step more sophisticated than conventional permanent mold casting which uses gravity. Fig. 1D2 illustrates the low-pressure permanent mold process (LPPM). Gas pressure of about 5 to 15 lbf/in² (35 to 100 kPa) admitted to the chamber above the molten metal, forces the metal up through a filler tube and into the mold cavity. This approach provides a dross-free filling of the mold since the metal entering the mold comes from beneath the surface and is not in contact with the atmosphere. The method also can provide a highly controlled, non-turbulent, fill rate because the air pressure in the chamber can be controlled. A vacuum may be applied to the mold to ensure more complete filling. The process is suitable to higher production levels and produces high-quality castings. With graphite molds, the process can be used to produce ferrous castings.

D3. slush casting - This process is used for hollow objects of zinc-, lead- or tin-based alloys. It does not require a core. The molten metal is poured into

a permanent mold and retained there long enough so that a shell of solidified metal coats the mold walls. The mold is inverted before all the metal has solidified. The still-liquid metal in the interior of the mold flows out and is returned to the melting pot. The mold is then opened and the casting removed. The process is suitable only for components whose interior dimensions are not critical, since the interior surface is irregular and rough. Statues, lamp bases, and other decorative objects are cast with this method.

D4. pressed casting - is similar to slush casting. The permanent mold is partly filled with a metered amount of molten metal. A closely-fitting core member is inserted into the molten metal, displacing it and pressurizing it enough to make it flow into the remainder of the mold cavity. When the molten metal has cooled and solidified, the core is immediately retracted, leaving a hollow casting. The process is used for components similar to those produced by slush casting but differs in that the inner cavity of the casting has controlled dimensions. As with slush casting, the process is used in the manufacture of ornamental objects.

D5. vacuum casting - is another permanent mold process, chiefly used for casting ingots, though parts can be cast also. Melting, reducing, and casting all take place in the same vacuum chamber, which contains the mechanisms necessary to transfer the molten metal from the melting pot to the mold. Centrifugal force may be applied to the molds if required by the nature of the part being cast. The vacuum prevents atmospheric contamination of the alloy and removes any entrapped gases. Induction is the most common heating method for melting but electric arc, electron beam, and plasma arc are also used. Vacuum chamber pressures are on the order of 10 μ m. Vacuum casting is used for various alloys including those that are to be forged. Titanium requires a vacuum process when it is cast.

E. Centrifugal Casting

All centrifugal casting processes utilize rotation of the mold about a central axis and the resultant centrifugal force to drive the molten metal in the

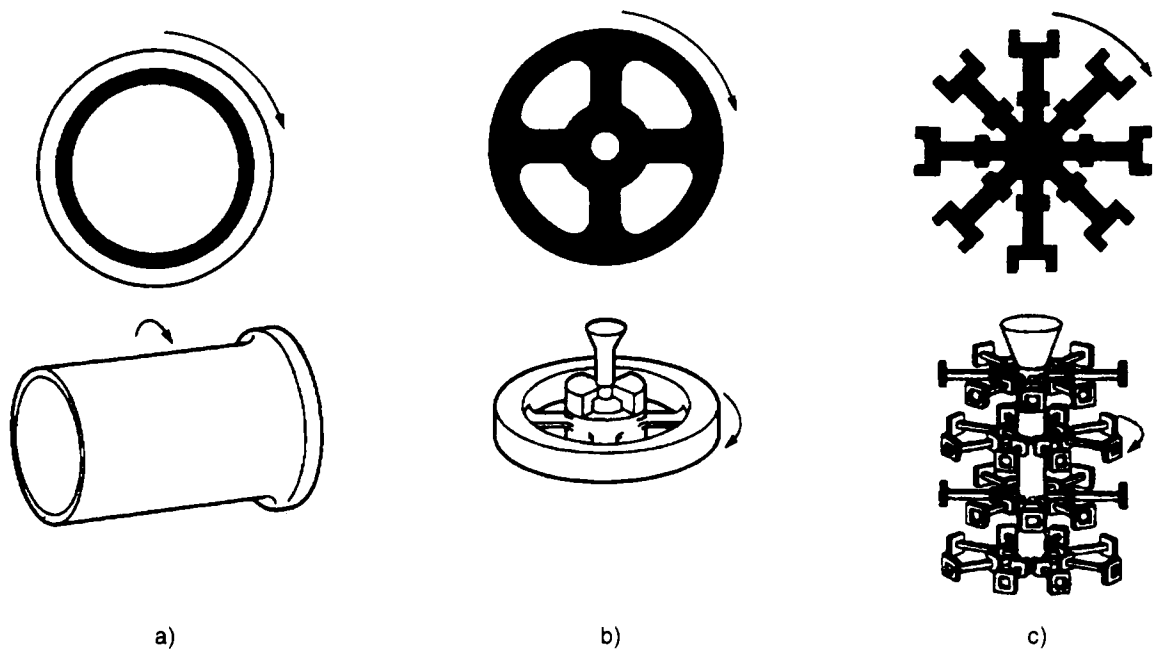


Fig. 1E Three types of centrifugal castings. (a) true centrifugal (b) semi-centrifugal, (c) centrifuging. (from David C. Ekey and Wesley P. Winter, *Introduction to Foundry Technology*, McGraw-Hill, New York)

desired portion of the mold. The cast metal is then relatively dense. Slag and other impurities cluster near the central axis and can be disposed of or removed more easily. Fig. 1E illustrates three common processes.

E1. true centrifugal casting - is used to manufacture piping, specialty tubing, cylinder liners, and other cast objects of cylindrical shape. Centrifugal force holds the molten metal against the outer walls of the rotating mold. The volume of metal in the mold determines the wall thickness and internal diameter of the part. No core is used except to form the bell ends of cast pipe. The mold is made of metal but may be sand-lined. If sand is employed, one of a number of binders may be utilized. Graphite is also used for some molds. The pouring spout may move axially as the mold rotates, providing a helical path to the flow of liquid metal. As the mold continues to rotate, the molten metal spreads evenly on the mold surface and solidifies. The rotation of the mold produces centrifugal force up to 100 times the force of gravity, the amount being partially dependent on the angle of orientation

of the axis. The inner surface of the casting tends to collect dross and other impurities. Fig. 1E, view a), and Fig. 1E1 illustrate the process.

E2. semicentrifugal casting - In this process, parts that have a symmetrical shape around a central axis are cast, including wheels, gear blanks, nozzles, and similar parts. (See Fig. 1E, view b.) The rotational speed of the mold is less than that used in true centrifugal casting. Several molds may be stacked on the same axis and all filled from the same pouring source. A core may be used for the center hole, if any, or the sprue may be left in the center of the casting. In either case, the hole is machined to provide the necessary accuracy and surface finish. The outer portion of the casting has a dense structure.

E3. centrifuged casting - This process is used for smaller, intricate parts. Centrifugal force provides the pressure that ensures complete filling of the mold cavities. Molds are located radially about a central sprue or riser, which acts as the axis of rotation. Rotation can be about a vertical or horizontal

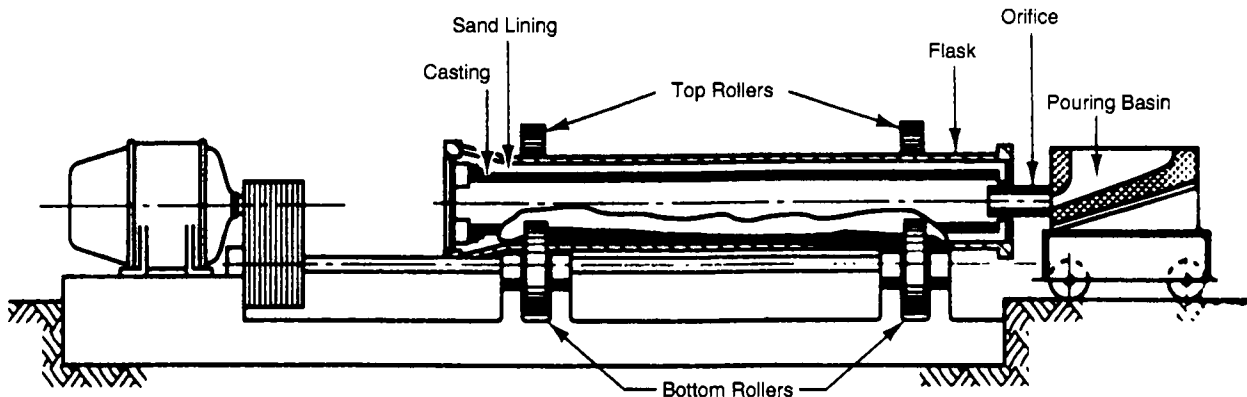


Fig. 1E1 A horizontal centrifugal casting machine equipped to make cast iron pipe. (Courtesy American Cast Iron Pipe Company)

axis and is at a relatively low rotational speed. Fluid pressure of the molten metal is proportional to its distance from the axis and the square of the speed of rotation. Molds may be stacked as shown in Fig. 1E, view c). Casting shapes that otherwise might present feeding problems can be cast with this process. Small caps and brackets, and dental inlays are among the components cast.

F. Die Casting

Die casting is a permanent mold casting process wherein the molten metal is forced into the mold at high velocity and under high pressure. That pressure is maintained until the metal solidifies. The molds, referred to as “dies”, are water-cooled and are usually made from a hardened steel alloy that can withstand the pressure and heat of the process. Dies are in two halves and often have side cores if the part shape includes undercuts. These cores are actuated by cams, gears, or separate hydraulic cylinders. The dies are usually lubricated for each cycle prior to the clamping of the two halves together. The lubricant may be accompanied by water to cool the die and compressed air to remove any extraneous metal pieces that may remain on the die. Pneumatic, hydraulic, or mechanical force is used to close the die halves and to actuate the plunger that moves the molten metal into the die cavity. Because die filling is very rapid, some air may be trapped in the die cavity and result in some porosity in the casting. This porosity is normally

limited to the interior of the casting, but surfaces tend to be dense. Vents and small overflow wells are incorporated in the die to allow trapped air and excess metal to escape. After the casting metal solidifies, the die halves part and ejector pins remove the workpiece. Cycle times range from just a few seconds for small zinc parts to 30 or 40 seconds for larger aluminum parts. The maximum practical casting size is about 40 lb (18 kg). A trimming operation is frequently needed after casting to remove flash, sprues, and overflow material. Although some ferrous die casting is being done, the process is primarily limited to non-ferrous alloys. Zinc, aluminum, magnesium, tin, and lead alloys are most commonly cast. Some die casting of copper-based alloys also takes place. The high-velocity filling of the dies permits the production of thin-walled and intricately shaped parts. Close tolerances can be held and post-casting machining is normally less than that required after other casting processes. Because the cost of equipment and tooling are high, the process is most suited to high-production conditions. Typical die cast parts are used in appliances, automobiles, hand tools, and builder’s hardware.

F1. hot-chamber die casting - In this process, the plunger that forces the molten metal into the die is immersed in the molten metal at all times. Fig. 1F1 shows the “gooseneck” configuration of the plunger and injection channel. Prior to injection, molten metal is allowed to flow by gravity into the injection cylinder. The plunger is then actuated by either

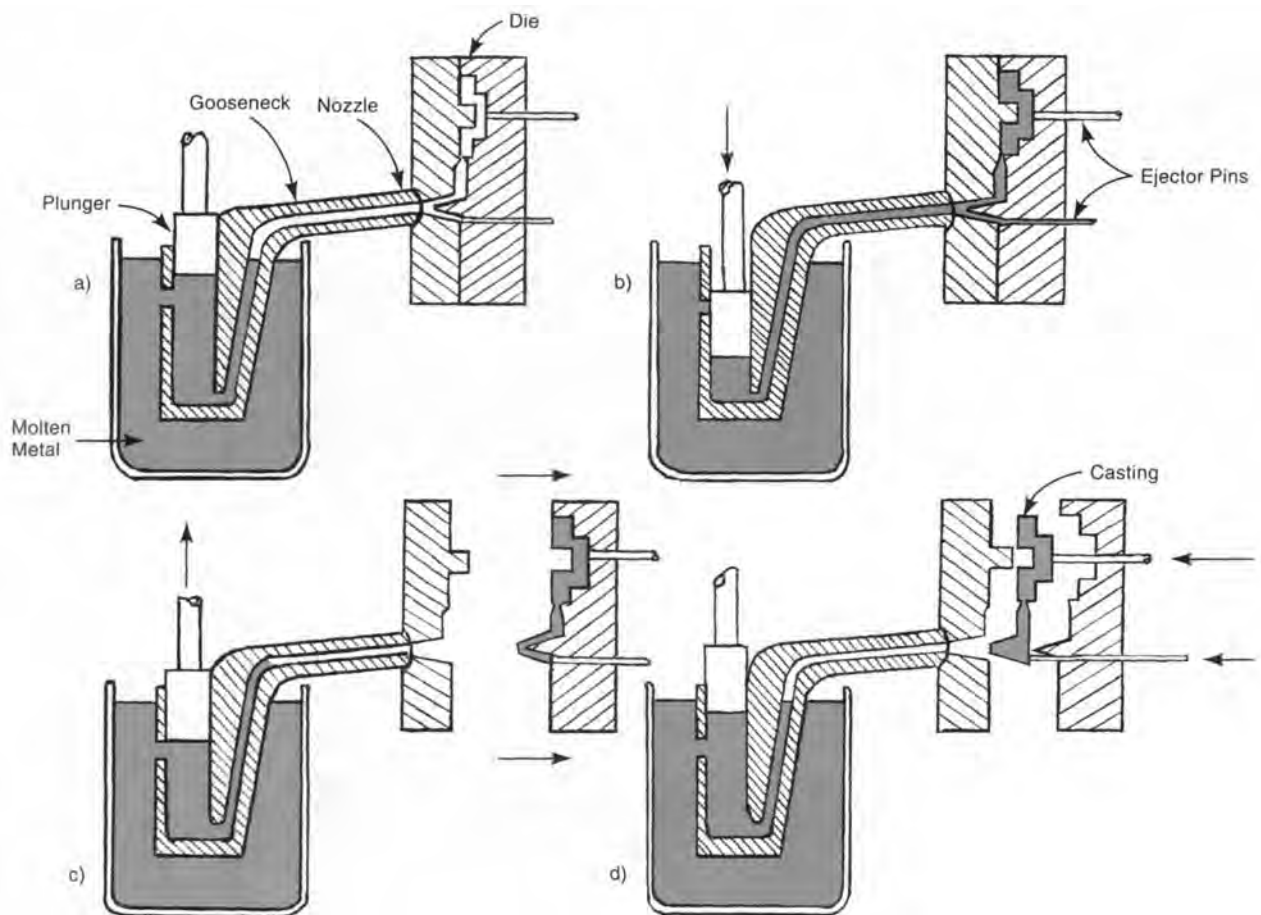


Fig. 1F1 Hot-chamber die-casting. a) The die is closed and the hot chamber (at the gooseneck) is filled with molten metal. b) The plunger descends and forces molten metal through the gooseneck and nozzle and into the die cavity. Metal is held under pressure until it solidifies. c) The die opens. The casting stays in the one half of the die. The plunger retracts, pulling molten metal back through the nozzle and gooseneck. d) Ejector pins push the casting out of the die. As the plunger uncovers the inlet, molten metal refills the hot chamber for the next cycle.

mechanical or pneumatic force to move the molten metal into the die. (There is no external transfer of molten material to the injection cylinder.) The cycle is automatic and, with small parts, can often repeat as fast as every 4 or 5 seconds. However, the constant contact of the injection equipment with molten metal causes difficulties with aluminum and other higher melting temperature alloys which attack the steel components of the injection system. As a result, hot-chamber die casting is used mainly with zinc, tin, lead, and, more recently, magnesium alloys.

F2. cold-chamber die casting - In this process, as illustrated in Fig. 1F2, molten metal is ladled

into the horizontal injection cylinder from a separate melting and holding pot so that the metal contacts the injection mechanism only during the injection portion of the cycle. After ladling, the metal is immediately injected into the die and, as in the hot-chamber method, is held under pressure during solidification. This approach is not quite as rapid as hot-chamber die casting but nevertheless still provides high productivity. The process is used with aluminum, copper, and magnesium, which are not well suited to hot-chamber die casting because constant contact with these metals may result in short life of the injection equipment. The cold-chamber method limits the time

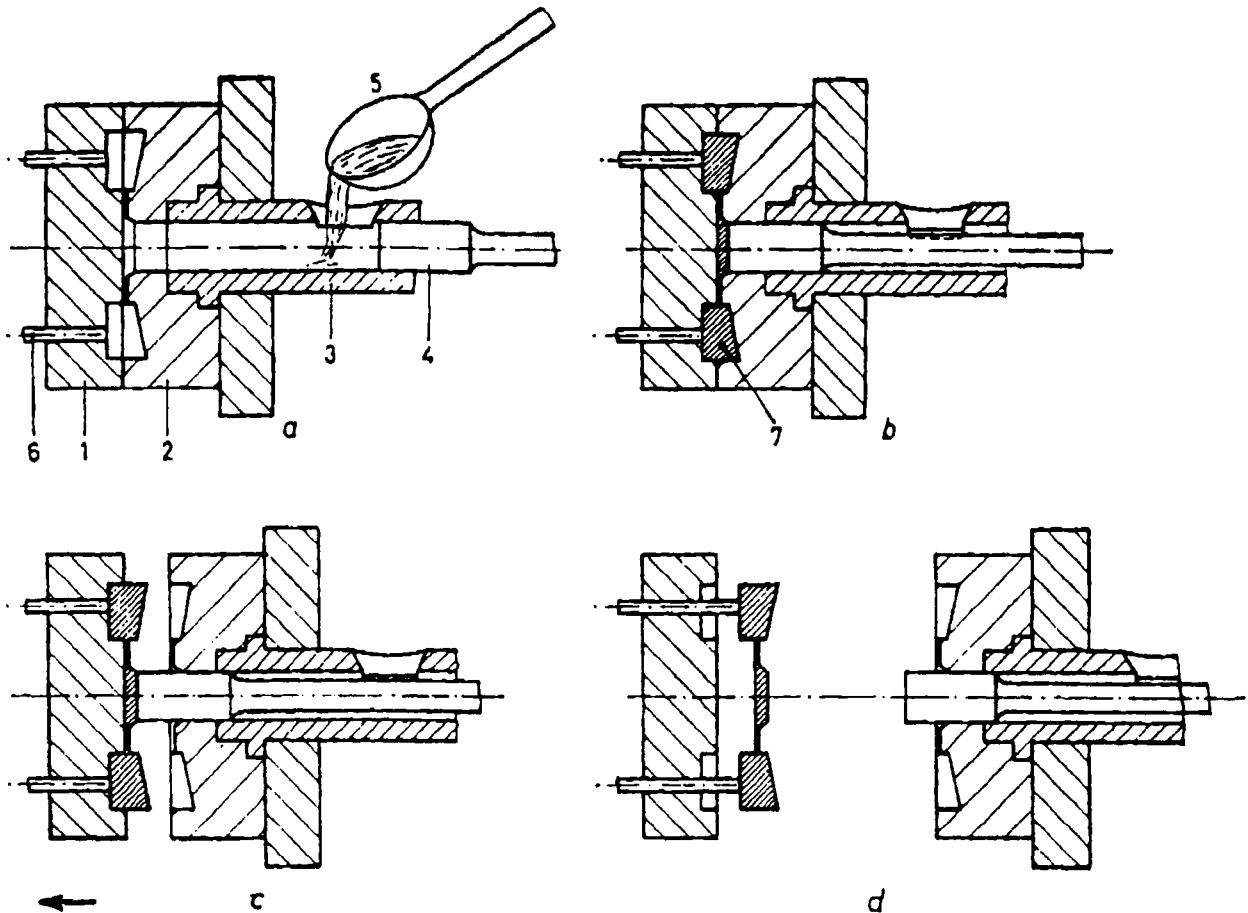


Fig. 1F2 Cold-chamber die casting. a) The mold is closed and molten metal is ladled into the injection cylinder ("cold chamber"). b) The plunger advances, forcing molten metal into the die cavity. c) The mold opens. d) The casting is ejected. Machine components: 1 - stationary die half, 2 - movable die half, 3) cold chamber, 4 - plunger, 5 - ladle, 6 - ejector pin, 7 - die casting. (from Davidson, Handbook of Precision Engineering, McGraw-Hill, New York)

of exposure of system components to the molten metal. The cold-chamber method is also used when ferrous alloys are die cast. Cold-chamber machines are of rugged construction because of the higher casting pressures needed with the alloys mentioned.

F3. **trimming** - of die-cast parts normally follows casting to remove flash, overflow material, gates and runners. The common method uses a hydraulic or mechanical press and a trimming die, made to fit the outline shape of the part. The operation is often performed immediately after casting when the

workpiece is hot and more easily sheared. Trimming can also be a manual operation but the high production normally involved with die casting also justifies the use of dedicated tooling and production equipment. Grinding may also be employed in trimming operations.

F4. **impregnation of die castings** - is another operation that may follow die casting if the product application requires pressure tightness. The die casting is impregnated with organic material or sodium silicate to fill any pores that could affect the ability of the parts to hold pressure. The impregnation

process involves the following steps: cleaning, placement of the workpieces in a suitable vacuum chamber, drawing of a vacuum in the chamber, introduction of the sealant to the chamber, pressure in the chamber to drive the sealant into any pores that exist on the workpiece, removal of the castings from the chamber, heating or baking to cure the impregnated material, if necessary, and washing and drying.¹

G. Investment Casting (Lost Wax Process)

This process uses a one-piece mold made of ceramic material, the same material that is used in ceramic casting. The mold is made by surrounding an expendable wax, plastic, or frozen mercury pattern with the ceramic material in slurry form. When the mold material solidifies it is heated and the wax, plastic, or mercury replica of the part is melted out, leaving a cavity corresponding to the shape of the desired part. The mold is baked to remove all residues of the pattern and to fuse the ceramic. Molten metal is poured into this cavity. When the metal solidifies, the ceramic mold is broken free and removed from the casting. There are two basic variations of this process, the *flask*, *solid mold* or *monolithic method* which uses a metal flask to hold a solid mass of the ceramic mold material, and the *shell method* in which a thin (about 1/4 in - 6 mm) shell of ceramic without a flask surrounds the pattern. Investment casting is used extensively for intricate, usually small, precise parts of high strength alloys. Turbine blades, sewing machine and gun parts, valve bodies, wrench sockets, and gears are typical parts. Larger parts are also now produced weighing up to about 80 lb (35 Kg) per casting.

G1. *flask method* - The sequence for the simpler, but much less used, flask method is as follows:

1. The wax or plastic patterns are injection molded, often in a low-cost nonferrous mold.
2. A number of patterns are assembled together on a "tree" of the same wax or plastic so that a number of parts can be cast at one time. The tree consists of a central sprue and branch runners to which are attached the individual patterns.

3. The "tree" is precoated by dipping it in a slurry of refractory material and then is dried thoroughly.
4. The tree is inserted in a flask and investment material is poured around it. The worktable is usually vibrated to settle the investment material and drive out air pockets. The investment material is allowed to set and then air dry for six to eight hours.
5. The flask is inverted and placed in an oven to melt out the wax or plastic. Typically temperatures of about 375°F (190°C) are used for about 12 hours.
6. The flask is heated gradually, then held at about 1800°F (980°C) for about 4 hours to melt and "burn out" the wax or plastic residue and to fuse the investment material.
7. Molten metal is poured into the mold cavity. Gravity is the prime filling method but air pressure and centrifugal force may also be used. The metal cools and solidifies.
8. Shake-out takes place. The casting in "tree" form is removed from the flask and the investment material is broken away from it.
9. The tree is descaled by immersion for 10 to 15 min in a molten salt bath at 1100°F (600°C) followed immediately by a cold water dip and cleaning and neutralizing immersions.
10. The parts are cut from the tree.
11. Gates and runners are removed from the castings by abrasive or other machining methods. Fig. 1G1 illustrates the mold making portion of this process.

G2. *shell method* - This method has a very similar sequence to that of the flask method. The chief difference is that, instead of pouring a solid mass of investment material around the thinly-coated tree pattern, it is coated with a series of dip coats of ceramic slurry until the desired thickness of shell is built up. This thickness is usually about 1/4 in (6.3mm), and no flask is then required. About six or seven dips may be required, depending on the size of the part. The sequence of operations is illustrated in Fig. 1G2. The shell method has become the predominant method, though the flask method may give somewhat better surface definition to the casting since the molten metal cools more slowly. Less surface decarburization occurs with the shell process. It also has a shorter cycle time.

PREPARING A MOLD FOR INVESTMENT CASTING

The "Lost Wax" or precision casting process

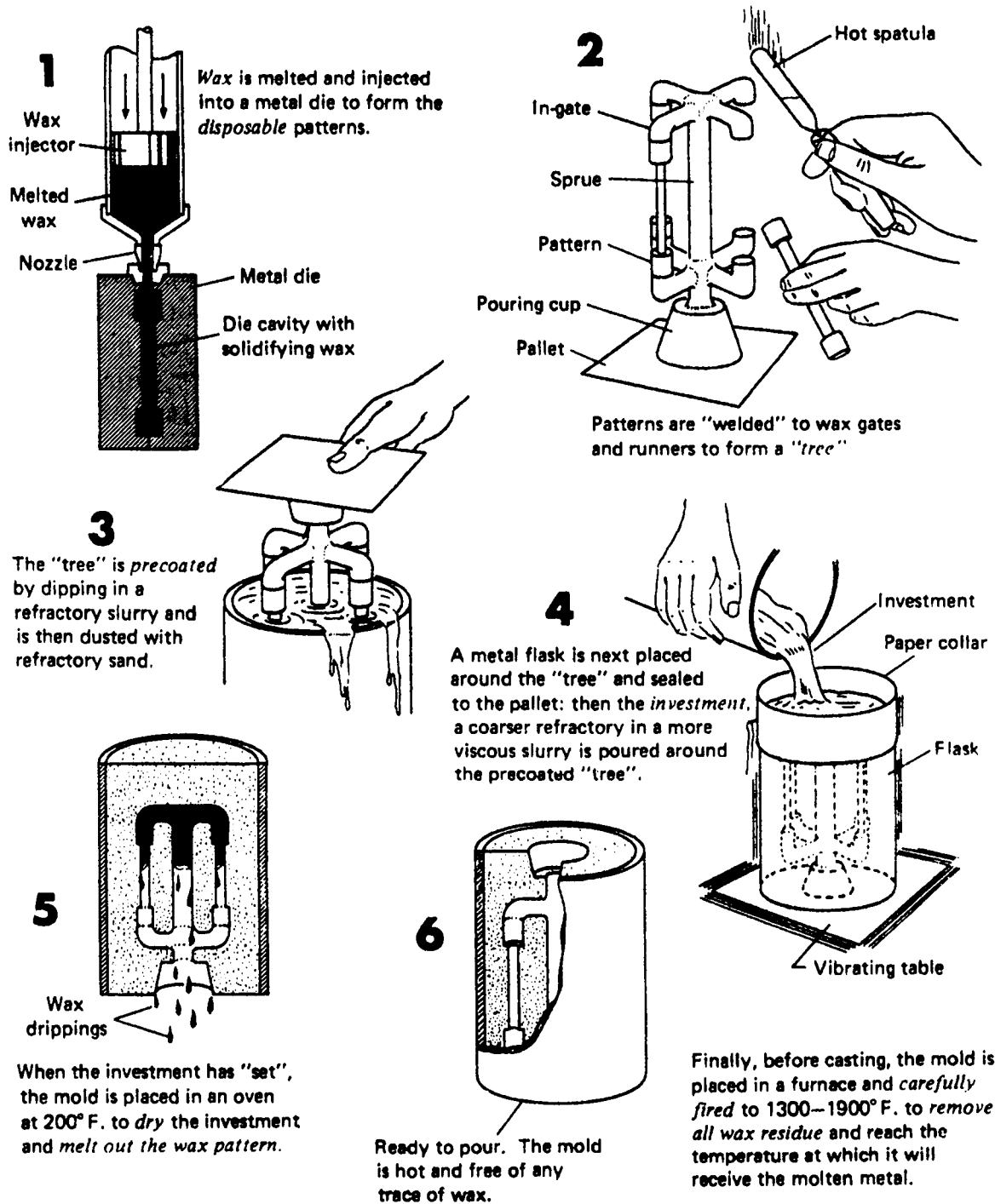


Fig. 1G1 The process for making a mold for the flask method of investment casting. (from Niebel and Draper, *Product Design and Process Engineering*, McGraw-Hill, 1974, New York)

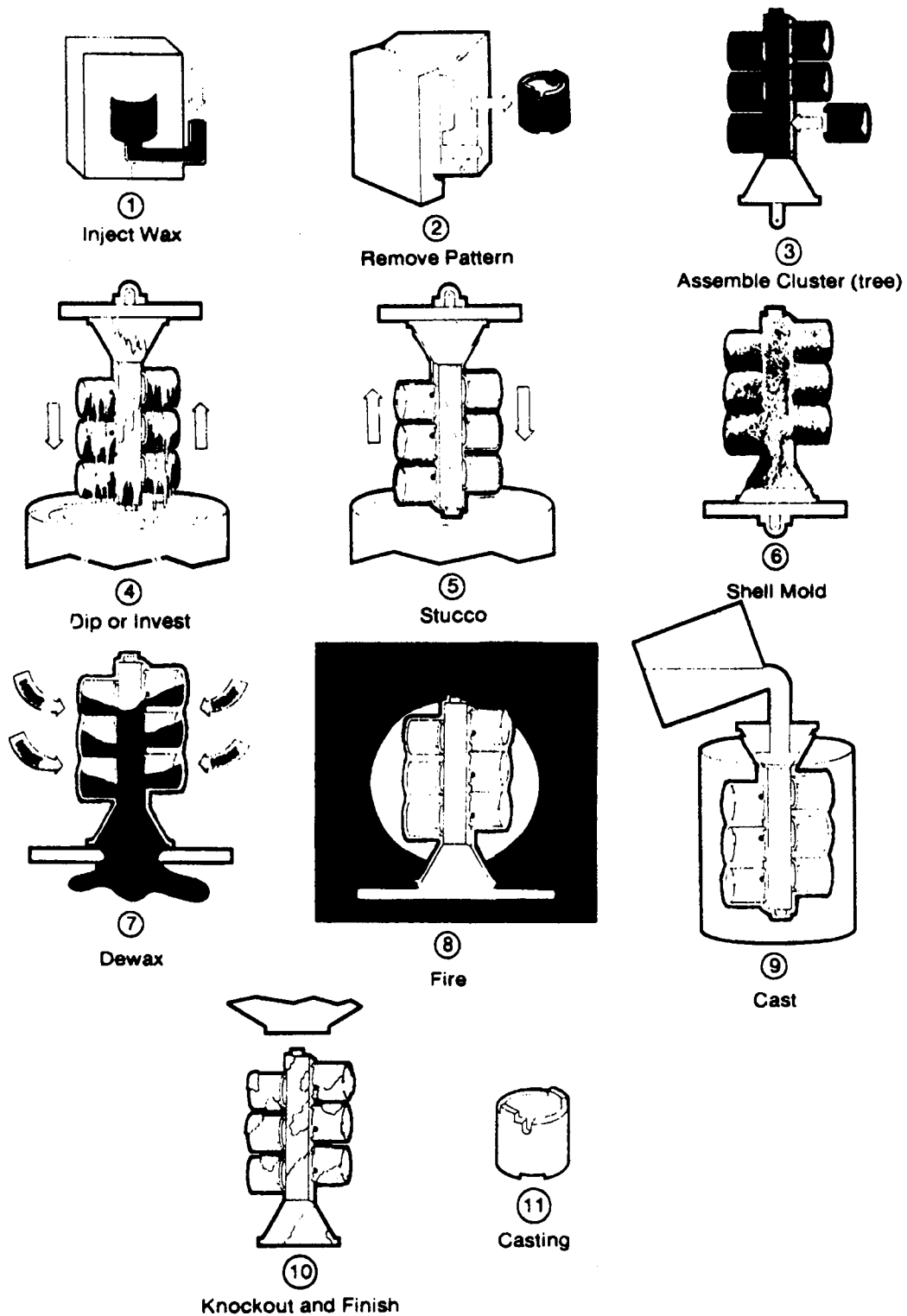


Fig. 1G2 A typical sequence of steps for the shell method of investment casting. (Courtesy Investment Casting Institute, Dallas)

H. Continuous Casting

Continuous casting is primarily a mill method for producing ingots, rather than discrete cast parts, but it is used for producing some long parts of constant cross section such as piping or tubing. The method solves certain quality difficulties that are more prevalent with conventional ingot casting and is more cost effective for mill-quantity production. The molten metal is continuously solidified as it is poured and its length is not determined by the length of the mold but by the length of time that the pouring and solidifying continues. The mold position is most commonly vertical with an open top and bottom. The material flows

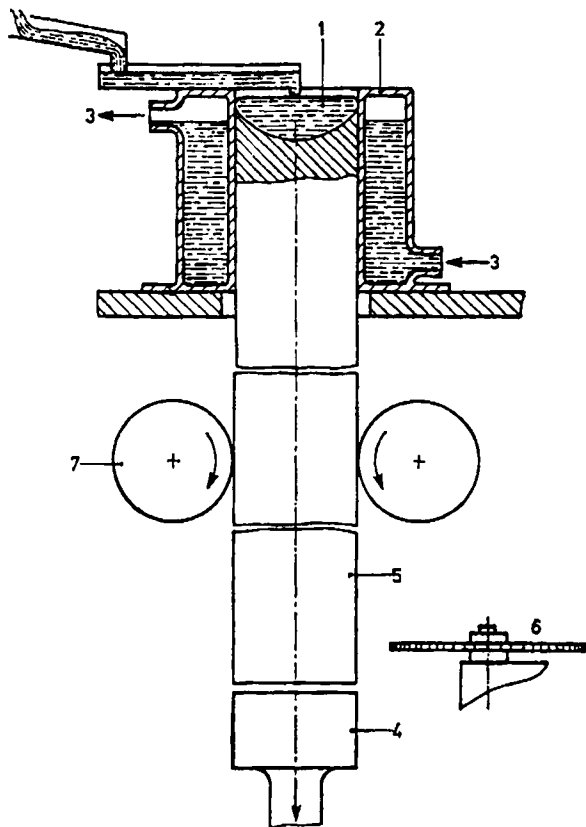


Fig. 1H Continuous casting of a solid bar with a vertical continuous casting machine. 1) molten metal, 2) water-cooled mold, 3) cooling water inlet and outlet, 4) (not shown) movable mold base which descends at a controlled rate to start the operation, 5) cast bar, 6) flying cutoff saw, 7) rollers to control movement of the cast bar. (from Davidson, *Handbook of Precision Engineering*, McGraw-Hill, New York)

downward through the mold, which shapes it. As it starts to solidify and exit the bottom of the mold, space is created for additional molten metal at the top. Fig. 1H illustrates a typical arrangement.

The casting sequence is as follows:¹ 1) molten metal is delivered to the casting equipment. 2) The metal flows from a tundish (temporary container) into the mold; flow is controlled by a suitable stopper or slide gate valve. 3) The molten metal cools and partially solidifies as it passes through the water-cooled mold (which is often made from copper); the mold oscillates and is lubricated to prevent the casting from adhering to it. (When casting aluminum, air pressure and an electromagnetic field may be used to keep the metal from contacting and adhering to the mold.) 4) The section is supported and guided below the mold by opposed rolls that contact the cast section whose surface is solid but whose interior may still be molten; water spraying provides further cooling action. 5) The opposed rollers withdraw the solid cast section to a station where it is cut to length by flame cutting or a shear. It may, alternatively, be reheated and rolled before being cut to length. First utilized in the production of primary non-ferrous metals, this method is now used extensively in steel production as well. Non-ferrous metals are continuously cast as tubing and other special shapes; steel is more difficult to cast into special shapes.

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Chapter 2 - Metal Forming Processes

A. Hot and Warm Forming Methods

(Note: Many metal forming operations can be performed with the workpiece metal either hot or cold. The operations discussed in this section are normally - but not always - performed on workpiece material that has been heated to make it more malleable for the operation involved. Metals that are to be hot formed are heated above their recrystallization temperature, one that varies with each material but is normally about 0.6 times the melting temperature on the Kelvin (absolute temperature) scale. For example, steels require a temperature above about 1800°F (980°C). Warm forming involves heating to a temperature 30 to 60 percent of the melting point, while cold forming takes place when the metal temperature is below 30% of the melting temperature².)

A1. **hot rolling** - is commonly applied to convert steel ingots to blooms, billets, or slabs, and to make these shapes into salable forms. In the process, heated metal is passed between two rollers whose spacing is less than the thickness of the metal. The rotation of the rollers moves the metal forward, squeezing and elongating it. Fig. 2A1 illustrates the process. The process extends and refines the grain structure of the rolled material. A number of passes may be required, depending on the thickness desired and the thickness of the entering material. Reversing rollers are often used to facilitate

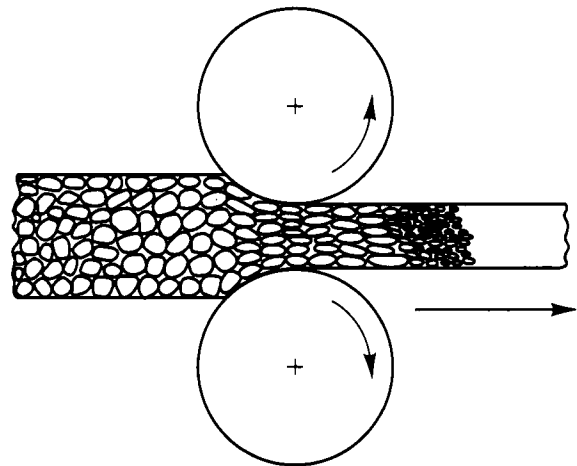


Fig. 2A1 The hot rolling process. The grain structure of the metal is deformed and then recrystallized.

multiple passes. Thin sheet or foil is best rolled with small-diameter rollers that are backed up with larger rollers to provide the necessary rolling force. As many as twelve rollers in a cluster may be used. Shaped rollers can produce material with various cross sections including those of structural shapes or special cross sections. Low-alloy or plain-carbon steel is heated to about 2200°F. (1200°C) before rolling and after being preheated in a soaking pit. In addition to ferrous metals, aluminum, copper and copper alloys, magnesium, nickel, titanium, and zinc alloys are hot rolled.

A2. hot drawing or cupping - is a process for making cup shapes of some depth (more than several times stock thickness) and thick and seamless tubes and cylinders from blooms, flat plate, or sheet. The process is similar to cold deep drawing of sheet metal (except that the material may be thinned during the operation whereas in deep drawing the material flows into the die and tends to thicken). Tubular parts can be made when the cup formed in one such operation is reheated and redrawn to a narrower diameter; then reheated and pushed through a series of draw bench dies that further reduce its diameter and extend its length. Fig. 2A2 illustrates both the cup-forming and redrawing operations. In addition to the redrawing that produces cylinders and seamless tubing, the process is used for forming relatively simple shapes, usually cylindrical, in thick material.

A3. extrusion - In this process, metal is forced through a die opening that gives it a uniform cross-sectional shape. Although the operation can be performed with many cold metals, the usual procedure is to preheat the metal to the plastic range to ease the transition. A heated ingot or billet is inserted in a chamber called a "container". A ram, normally hydraulically powered, forces the material through the die opening. As it flows through the die, the metal takes the shape of the die opening and closely conforms to its dimensions. It is quickly cooled as the metal exits the die so that the shape is maintained. Fig. 2A3 illustrates the process.

Aluminum, copper, magnesium, tin, lead, and their alloys are commonly extruded. Steel, including alloy and stainless varieties, and nickel alloys, are more difficult to extrude but can be processed by the Sejournet and related processes (See A3b below.)

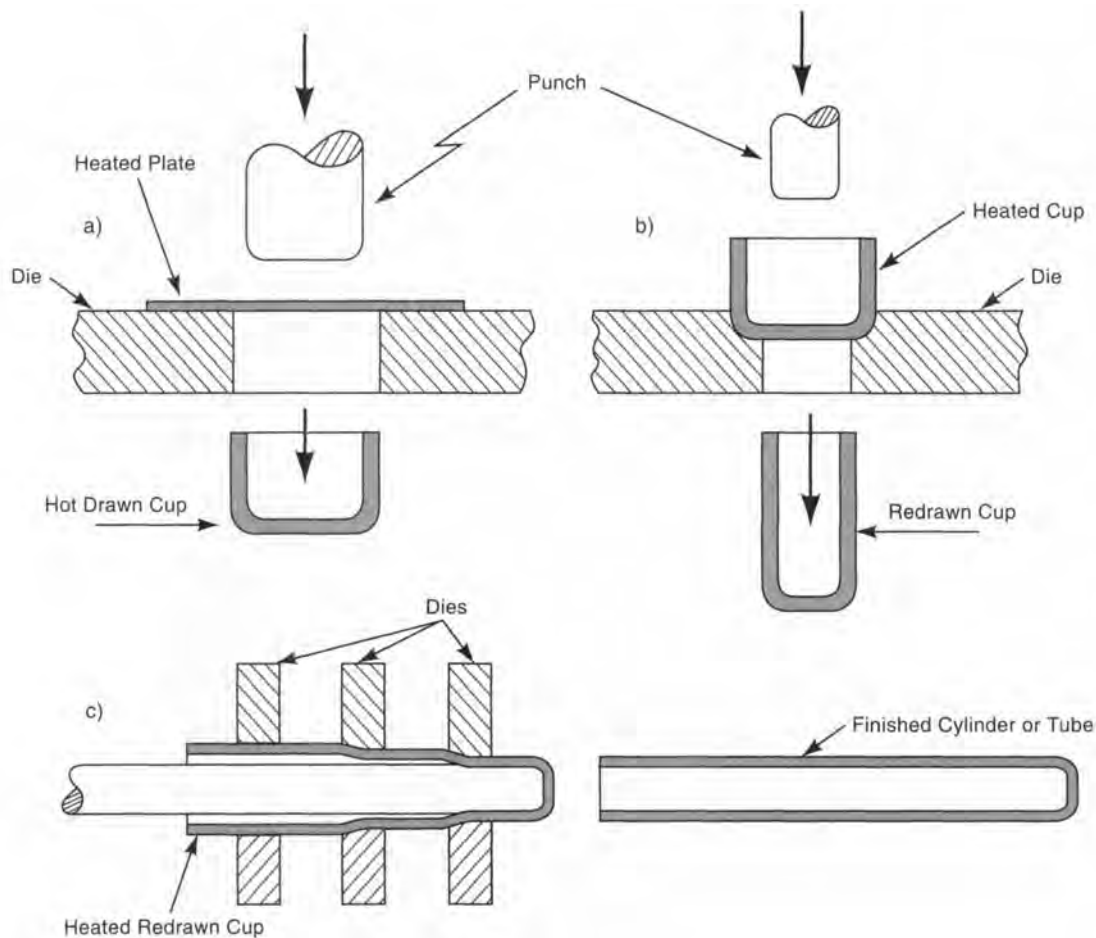


Fig. 2A2 Hot drawing or cupping. a) first draw, b) redraw, c) multiple die redrawing on drawbench.

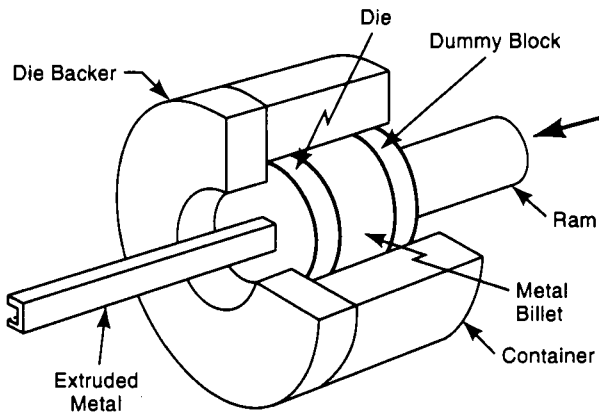


Fig. 2A3 Direct extrusion.

After extrusion, sections may be stretch-straightened to remove twist and camber that may exist. Extrusion is suitable for almost any part that has a constant cross section and is made from the above materials. A wide variety of complex shapes such as tubing and other hollow objects, door and window frame elements, ladder members, and structural sections can be extruded. A similar process is used to make like-shaped components in plastics or other materials (See chapter 4, section 4I.)

A3a. indirect extrusion - In this process variation, the ram is hollow and the metal is forced backward through a die and into the ram. Friction is reduced because the metal does not have to flow along the extrusion chamber walls, but the difficulty in supporting and removing the extrusion makes the process awkward. (See Fig. 2A3a.)

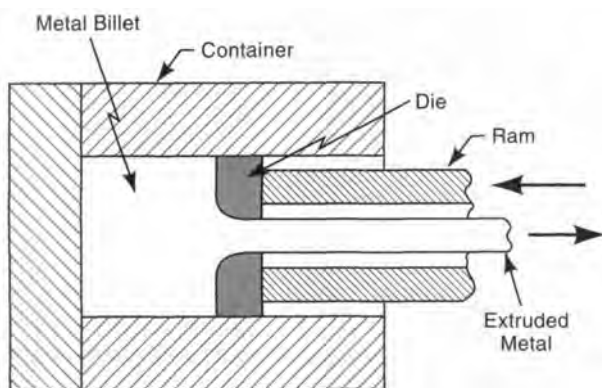


Fig. 2A3a Indirect extrusion.

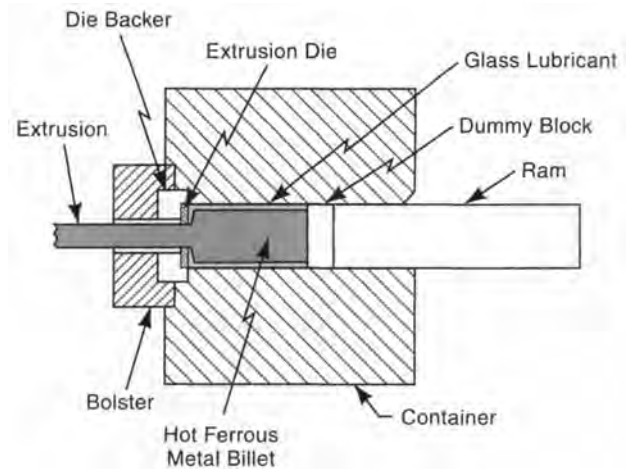


Fig. 2A3b The Sejournet process for extruding ferrous metals uses molten glass as a lubricant and insulator.

A3b. Sejournet process - is used for the extrusion of ferrous metals. The operation is the same as that for other metals except that the steel billet to be extruded is heated to the recrystallization temperature range and then coated with molten glass that lubricates and insulates the metal as it is pushed through the die. See Fig. 2A3b. The workpiece is usually stretch-straightened afterwards to remove camber and twist that may result from the process.

A4. forging - is a process in which a metal slug undergoes plastic deformation into a useful shape, usually at an elevated temperature. Repeated strokes or extended pressure may be used. The process refines the grain structure of the material and improves the physical properties of the part. Equipment capable of applying compressive forces is required. Dies are often heated to a temperature between 300 and 400°F (150 and 200°C) or higher. Metals commonly forged include steel, aluminum, magnesium, brass, bronze, copper, stainless and alloy steel. Aluminum is typically forged isothermally at a temperature of 600 to 850°F (320 to 455°C). Many machine components that require high strength are produced by forging. Examples are aircraft landing gear components and other aircraft and aircraft-engine parts, connecting rods, spindles, couplers, parts for earth moving and agricultural equipment, valve bodies, ordnance parts, gears, turbine parts, and levers.

A4a. open-die drop-hammer forging (hammer, flat-die, or smith forging) - involves repeated blows with a powered flat-faced hammer or tools of simple shape. The workpiece is not confined. Except for the powered press strokes, the operation is the same as that traditionally performed by a blacksmith in that the operator positions and orients the workpiece for each blow. The process is often a preliminary one, used to provide an initial shape prior to further forging and other operations. The process is also used for forgings that are too large for impression dies, and for small quantities and situations where time schedules do not permit the fabrication of dies. It is illustrated in Fig. 2A4a. Simple shapes such as discs, shafts, or rings, are commonly produced. Steam, compressed air, or gravity ("drop forging"), provide the necessary force. The operation can be computer controlled to reduce dependency on operator skill and to ensure more accurate workpiece dimensions.

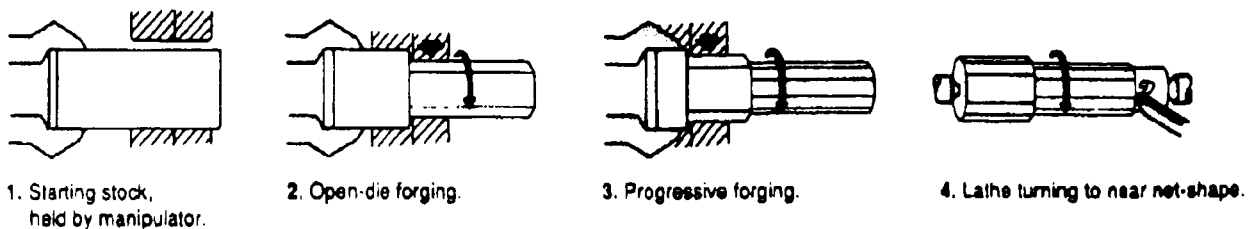
A4b. impression die forging (closed die forging) (die forging) - differs from hammer or smith forging in that the dies are closed. There are two die halves, one of which is fastened to the ram of the forging press and the other to the machine

bed. Repeated press strokes or heavy hydraulic or mechanical pressure cause the workpiece metal to flow into the die cavities, taking their shape, as shown in Fig. 2A4b. If the part is complex, several different die sets may be used before the final shape is attained. The operation produces surplus metal called "flash" around the edges of the forging. The flash cools and hardens before the balance of the forging and aids in filling the unfilled portions of the die. The flash is removed in a secondary trimming operation.

Typical metal temperatures for impression die forging per Ostwald¹ are: steel - 2000 to 2300°F, (1100 to 1250°C), copper alloys - 1400 to 1700°F (750 to 925°C), aluminum alloys - 700 to 850°F (370 to 455°C), and magnesium - 600°F (315°C). The process results in particularly strong parts per unit of weight because it produces favorable orientation of the metal grains.

A4b1 - drop forging - is impression die forging using a drop hammer. A drop hammer is a machine that uses gravity, air, or steam pressure to make repeated blows against a workpiece. With gravity drop hammers, a heavily weighted ram is lifted above the forging die and then released.

SHAFTS



DISCS

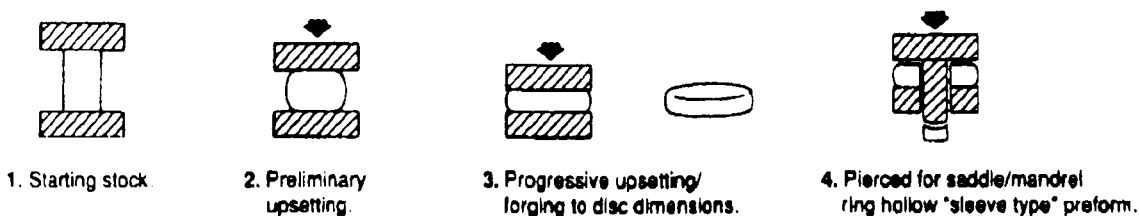


Fig. 2A4a Open-die forging of shafts and discs. Repeated press strokes with a flat or simple-shape die form the workpiece. (Courtesy Forging Industry Association.)

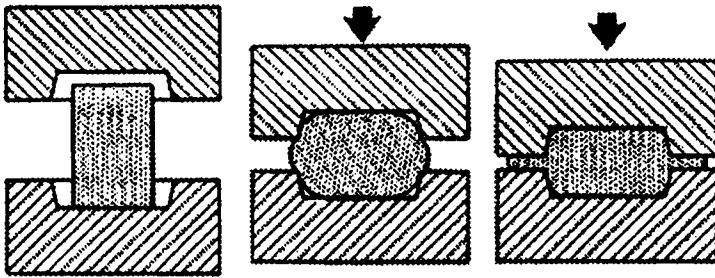


Fig. 2A4b Conventional impression-die (closed-die) forging sequence. (Courtesy Forging Industry Association.)

The press action is then repeated until the workpiece has attained the desired shape. Impact force aids the forging operation. Powered drop hammers use air, steam, or hydraulic pressure to add to the downward force.

A4b2 - precision forging - is a variation of impression die forging with a closely-controlled, more extensive forging process, accurately controlled blank sizes, and carefully designed dies, so that the forgings produced are close to the net shape required. The process greatly reduces the amount of post-forging machining required. This is because it can reduce side-wall draft to from 0 to 1° and permit thinner forging walls, smaller radii, and smoother surfaces. Since there is little or no machining, the grain flow patterns are not disturbed, extra metal does not have to be added to compensate, and strength-to-weight ratios are improved. A key approach in the process is to provide forging blanks of just the right size and shape with accurate and consistent dimensions. A certain amount of trial and error is usually required to develop a blank that will just fill the die completely without requiring excess metal in any area. A preformed (preforged or pre-machined) blank may be used. One method sometimes used to provide accurate blanks is the use of powder metal preforms since the powder metal process can provide accurate and consistent forging blanks. Very close attention to all process details is required: workpiece temperature throughout the billet, descaling, die temperature (dies are heated), press pressure and stroke, and lubrication, are all of vital importance.

The precision forging process is often used to produce forged gear blanks. Aluminum is a metal commonly precision forged. The metal is heated to about 800°F (425°C) and the die temperature is maintained at 700 to 800°F (370 to 425°C) to

insure proper metal flow⁹. It should be noted that precision forging usually requires higher pressures and stronger dies than other forging methods, and, because the dies are typically run hot, they have a shorter die life.

A4b3. flashless forging - is characterized by an absence of the excess metal (flash) that normally escapes between the die halves in closed-die forging. Excess metal is often necessary to insure proper filling of all portions of the die cavity, particularly when the operation requires high deformation of the forging billet. One approach used to eliminate flash, although not all excess metal, when the part has a center hole (eg., a gear blank) is simply to confine the excess metal to that center hole. There, it is more easily removed with a punch-press operation. The principal approach in making flashless forgings, however, is to carefully size the billet and control its weight, so that there is no excess metal. There is an overlap between precision and flashless forging methods, and the process refinements and controls used in precision forging may also help to eliminate flash. Precision forging usually minimizes and sometimes eliminates flash³. However, precision forgings are not necessarily flashless, and flashless forgings are not necessarily precision forgings. The advantage of flashless forging, of course is the reduction of metal required and the elimination of the post-forging trimming operation.

A4c. press forging - differs from drop forging in that the forging action results from a slow squeezing action rather than a hammer-like impact. This squeezing action produces deformation more uniformly throughout the workpiece, resulting in greater dimensional accuracy and less need for sidewall draft. The dies may need to be preheated to reduce heat loss from the billet, and to promote

finer surface detail. The presses used for press forging are normally hydraulic. This process is most suitable for more complex shapes; less intricate, simpler shapes may be more advantageously produced by drop forging.

A4d. upset forging - is an operation that increases the diameter of a workpiece while shortening its length. It is the hot-material equivalent of cold heading. The workpiece material is normally in the form of a bar, on which a head or other larger-diameter portion is produced by the process. One part of the die holds the bar while another part of the die is forced against it axially, causing the metal to flow and fill the die cavity. Normally, only the part of the bar to be upset needs to be heated. Making bolt heads is the most common application.

A4e. roll forging - involves placing heated bar stock between two cylindrical or semi-cylindrical powered rollers that have shaped cavities on their surface. The workpiece is reduced in diameter or thickness, increased in length and often changed in shape. Die rollers can have multiple cavities, side-by-side, when the forging operation requires successive passes with different dies. Fig. 2A4e shows typical shaped rollers. Levers, shafts, and axle blanks are typical roll-forged parts.

A4f. isothermal forging - is a forging operation during which the workpiece metal temperature remains uniform and constant. This is achieved by heating the dies to the same a temperature as that of the forging material. The dies then do not chill the forging, allowing it to be forged with very slow strain rates. The approach overlaps and has the same purpose as precision forging - to produce forgings that are closer to the net shape of the finished parts. Aluminum, nickel, and titanium are the most common materials to be forged by this process, and are used particularly in the manufacture of aerospace components.

A4g. swaging - is described in sections 2D12 and 2F1 and is normally a cold-forming operation. However, in some situations, it is performed on heated workpieces. The surface finish then is inferior to that achieved in cold swaging but some work-hardenable materials perform better when swaged hot.

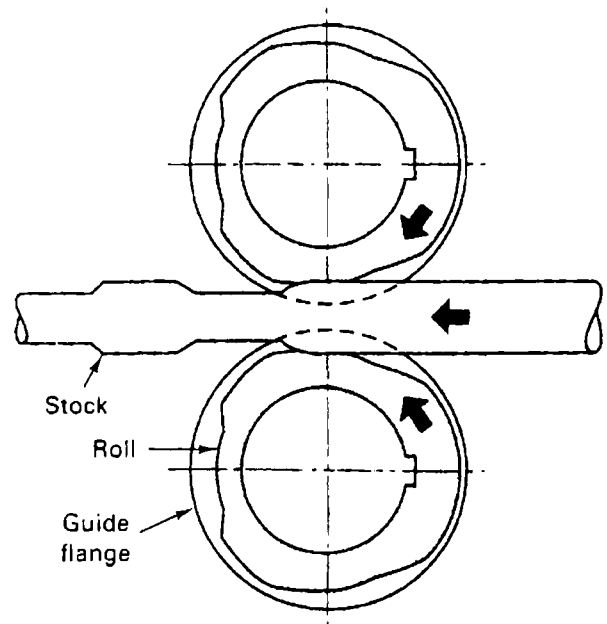


Fig. 2A4e The roll forging process. The stock is formed between two shaped rolls. (Courtesy Forging Industry Association.)

A4h. ring rolling (mandrel forging) - is a process for making ring-shaped parts of particular cross sections by rolling a ring-shaped blank between rollers that control the diameter, width, height, and cross-sectional shape. The ring cross sections may have rectangular or contoured elements. See Fig. 2A4h.

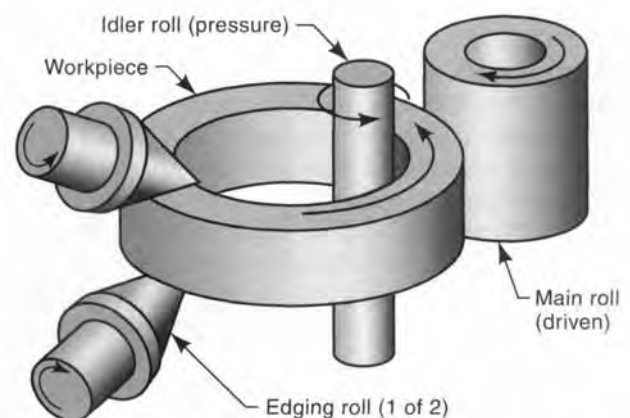


Fig. 2A4h Horizontal ring rolling to make a ring-shaped part with a rectangular cross section. (Courtesy Forging Industry Association.)

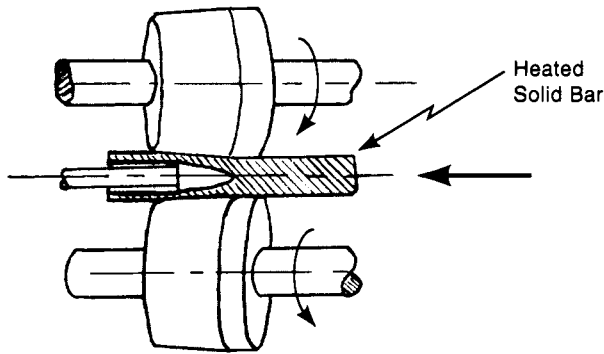


Fig. 2A5 Hot piercing, the first step in a method for making seamless tubing.

A5. piercing - as a hot working operation is different from that performed on cold sheet metal (section 3C5). Piercing, sometimes called **rotary piercing**, is a process for manufacturing thick-walled seamless tubing. The process is illustrated in Fig. 2A5. In this process, a heated bar is passed between two tapered rollers that are canted at opposing angles of about 6 degrees from the axis of the heated bar. The bar is pushed forward against a pointed mandrel. The pressure and taper of the rollers tends to flatten the bar and cause a small crack to develop in the center. The pointed mandrel enters this crack and forces the metal to flow into a tubular shape. As the heated bar advances, a length of seamless tubing is formed. Various secondary operations are performed to size and straighten the tubing and to change the wall thickness. Seamless tubing up to about 150 mm (6 in) in diameter is made with this process but, when the piercing is used as a secondary operation on existing tubing, diameters up to 610 mm (24 in) are feasible¹.

A6. pipe welding - involves making pipe from heated strip (called "skelp" in this process) by roll forming it into cylindrical shape and pressing the heated edges together with enough force so that they fuse together to form a butt weld. The operation can also be performed by pulling the skelp through a tapered cylindrical die. The skelp can also be roll formed so that the edges overlap and form a lap joint. The rolls force the overlapping material against an internal mandrel where it fuses together. In all cases, additional rollers size and shape the welded pipe. Diameters for butt-welded pipe range from 3 mm

(1/8 in) to 75 mm (3 in) and in lap welding from 50 mm (2 in) to 400 mm (16 in). Product length in the lap method is limited to about 7 meters (23 ft) because of the need for an internal mandrel².

A7. hot spinning - is metal spinning (section F6) with heated instead of cold material. Two common applications are the closing of the ends of tubing or cylindrical containers and the spinning of heavy plate stock.

A8. creep forming - relies on the property of some metals to flow at a slow rate when put under stress and heated. The stress level is below the yield point and the temperature is below that which anneals or otherwise heat treats the material. The process is used in the aerospace industry for large, thin components that require shallow contours. The manufacture of airplane wing skins is a common application. Aluminum sheet material is clamped in a fixture. Then the fixture with the clamped part is placed in an oven for a number of hours, typically between 4 and 8 hours. An alternative is to supply heat directly to the fixture. The sheet metal gradually assumes the shape of the tooling without significant internal stresses and retains the shape after the cycle is completed. Titanium and beryllium are also processed by this method with shorter holding times.

A9. warm heading - is the same as cold heading, described in section I2 below, except that the metal is heated to increase its ductility. The amount of upsetting possible per press stroke is increased. The work metal is heated to between 300 and 1000°F (150 and 540°C)⁵. The temperature depends on the metal to be headed, but is below the recrystallization temperature. The process is used chiefly for materials such as austenitic stainless steels, higher carbon steels, and other metals that are difficult to cold head because of their rapid work hardening characteristic³.

B. Primary Cold-working Operations

B1. rolling - Cold rolling is a common process in the production of sheet, strip, bar, and rod forms of steel and other materials. It is similar to the hot rolling described in section A1 except that the

metal is at room temperature. The material is passed between opposing rollers, sometimes with back-up rollers or in clusters of rollers, that compress the material and reduce its thickness - up to about 50%. Improved surface finish and dimensional accuracy are provided by the operation. With shaped rollers, various cross-sectional shapes can be produced and the operation can be a substitute for extrusion or machining. Cold-rolled material may exhibit improved yield strength because of the work hardening effect of the rolling operation. All malleable metals can be cold rolled.

B2. cold drawing - is a common method for reducing the size of wire, bar, tubing, and other shapes and is a different operation than the drawing (or deep drawing) of sheet metal. It may also be performed in conjunction with cold rolling or extrusion to produce special cross-sectional shapes. The material is forced through a die whose opening is smaller than the size of the entering metal. Except

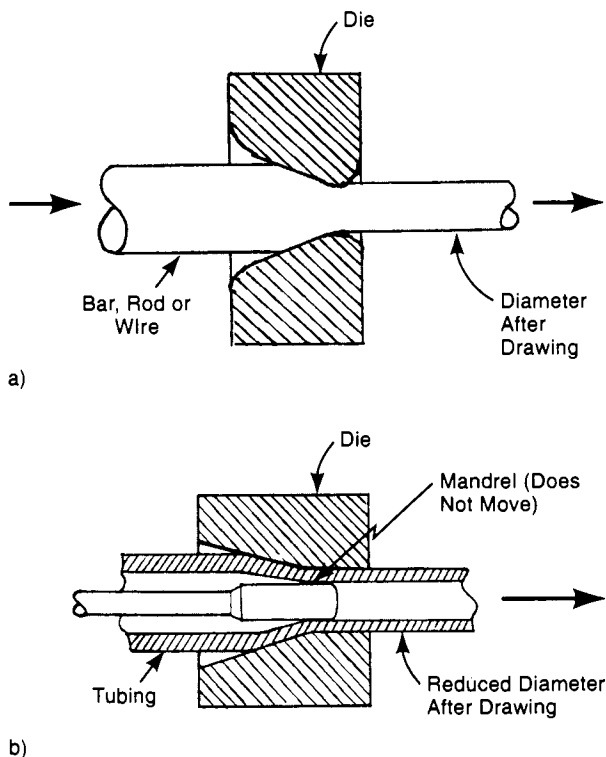


Fig. 2B2 Cold drawing. a) wire, b) tubing. The material is pulled through the die to reduce the diameter.

at the start, a pulling force is used to move the material through the die. The operation, illustrated in Fig. 2B2, improves the surface finish and dimensional accuracy of the material processed as well as reducing its cross sectional dimensions and sometimes, slightly changing its shape. Several dies are usually used in series, each progressively smaller than the preceding one. With some materials and depending on the size reduction and shape, intermediate annealing may be required between draws. Scale and dirt, if any, must be removed from the metal before drawing, and lubricants are normally employed to facilitate the operation. Cold finished steel usually is processed by cold rolling and drawing, but turning, grinding, polishing, and straightening operations may also be involved. The operation is performed on both solid wire (Fig 2B2, view a) and tubular material (Fig. 2B2, view b).

C. Sheet Metal Cutting Operations

C1. shearing - often refers to the cutting of sheet metal in a straight line without the generation of chips and without melting or oxidation. However, the cut may be curved as well as in a straight line. In many sheet metal operations such as blanking, punching (piercing), notching, parting, slitting, trimming, and lancing, the cutting action consists of shearing. The basic process is illustrated in Fig. 2C1. In the usual shearing process, the sheet metal lies on a lower tooling member, the die. The other tooling

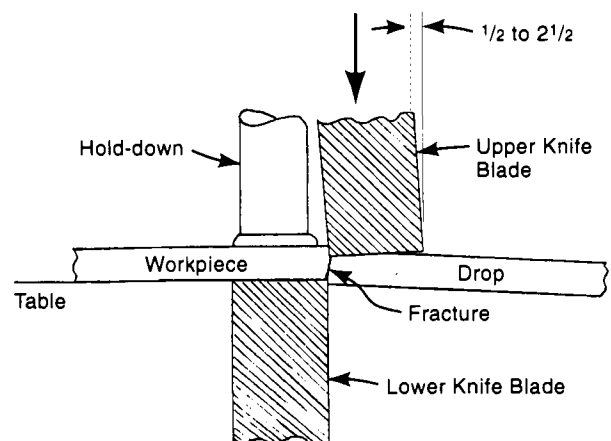


Fig. 2C1 A simple shearing operation is performed on a squaring shear.

member, the punch, has a sharp edge that is approximately opposite the sharp edge of the die. (There is a slight clearance between the two). Cutting takes place when the punch descends downward into the sheet metal workpiece. The sheet is cut and also deformed in a downward direction. When the force of the punch entering the workpiece exceeds the strength of the metal, the workpiece fractures. Fig. 2C4 shows the shearing action of a hole punch or blanking die. The edge of the sheared metal shows a slight depression at the one edge, where the punch or die has deformed it. There is an area of a smooth metal edge, the sheared portion, adjacent to which is an area of rough surface, the "break-away" portion. Fig. 2C4 shows the edge of a typical sheared or blanked sheet metal piece. Note the three portions of the edge.

C1a. squaring shears - are machines that perform the shearing operation. Fig. 2C1a illustrates a hydraulic squaring shear. The sheet to be cut is positioned on the machine table under the ram, which has a blade attached. The blade and the cutting edge

of the machine table are in close alignment. When the ram descends, a set of clamping fingers or a clamping bar descend with it and hold the workpiece sheet firmly. The blade then moves down further to sever the workpiece. Usually, the blade is fastened to the ram at a slight angle to the horizontal so that the shearing action is progressive from one side to the other as the blade descends. The ram movement is usually machine-powered except for small machines, which may utilize human arm or leg power to lower the ram. The method makes accurate straight cuts on sheet. Sheet metal up to a maximum of about 1.5 in (38 mm) in thickness, and up to 20 ft in width, can be processed on the largest machines.

C1b. alligator shears - get their name because the pivoting action of the blades is reminiscent of the motion of an alligator's jaws. The shearing action is similar to that of scissors. These machines have somewhat shorter cutting blades than squaring shears and therefore are best adapted and most used for shearing rods, bars, and sections, rather than sheet, though they can cut sheet and plate material.

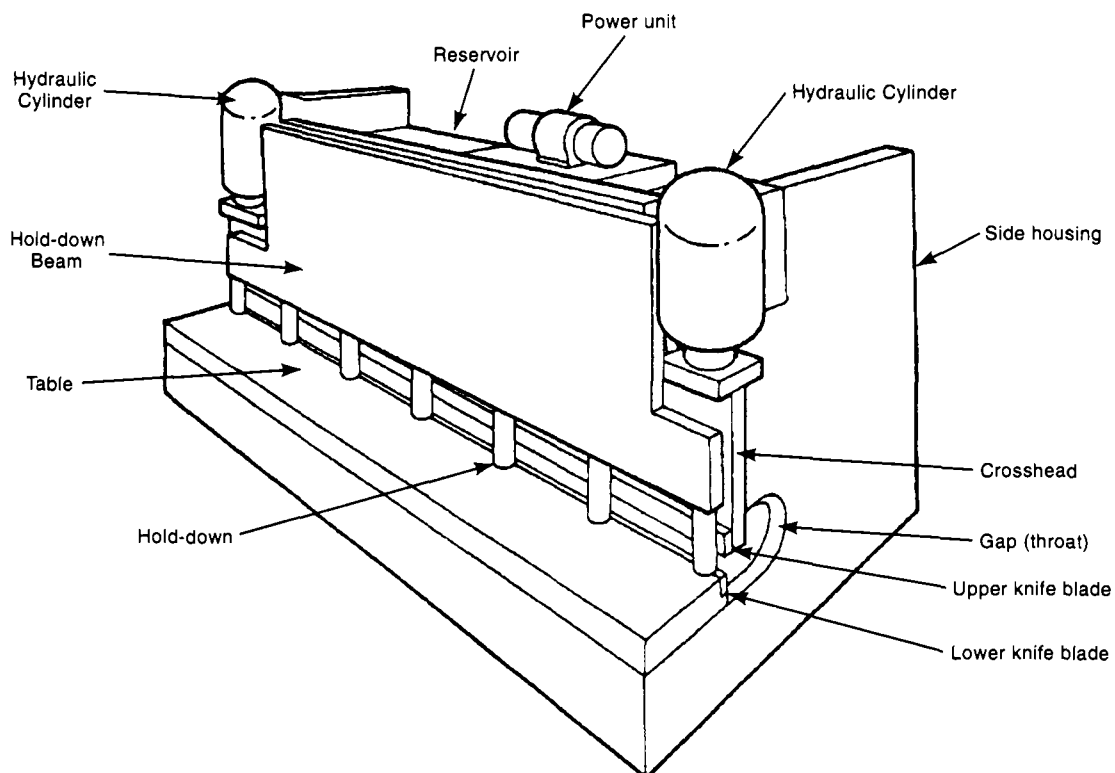


Fig. 2C1a A hydraulically-powered squaring shear. (Courtesy Pacific Press Technologies.)

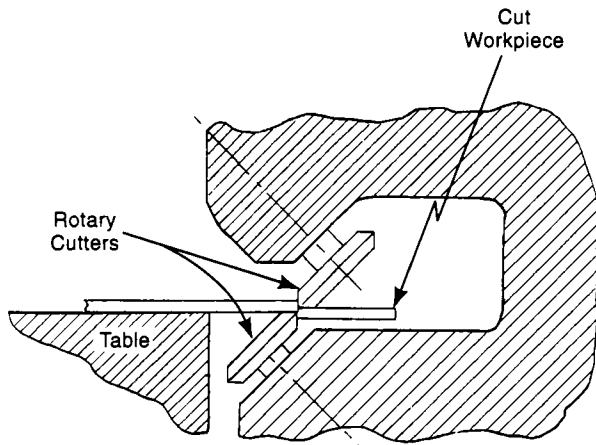


Fig. 2C1c A rotary shear used to make curved cuts in sheet material.

C1c. rotary shears - use two opposed and canted rollers, ground at an angle, that roll across sheet or plate and produce a shearing action. The arrangement is shown in Fig. 2C1c. The upper cutter is powered for both rotation and position. Steel plate up to about 1 in (25 mm) in thickness can be cut this way. Shearing can take place along a straight or curved path, and irregular parts can be cut out with this method. It is adaptable to low-quantity production.

C2. nibbling - is a sheet metal operation in which a long cut is made by punching a series of overlapping holes or slits in the workpiece. The nibbling

press typically operates at 300 to 900 strokes per minute³. This approach permits complex cuts to be made, including blanking with simple standard tooling. The method works best when controlled in a CNC turret punching machine but can also be controlled manually, and by less sophisticated automatic equipment.

C3. slitting - is a shearing operation that divides sheet or coiled sheet metal into narrower widths. Circular shearing tools in a slitting machine, illustrated in Fig. 2C3, are mated cutters. The raised circular cutters on one arbor match a space between circular cutters on another arbor. Sharp edges perform the slitting operation. The operation is normally performed in a line of machines that feed coiled sheet material to the slitting machine and re-coil the stock after slitting. Edges are commonly slit to insure accurate width of the slit material.

C4. blanking - is a pressworking operation used in the production of parts from sheet metal. In the operation, a flat workpiece of the desired size and shape is cut out completely around the periphery in one press stroke with a punch and die set. The punch's cross-section and the die opening match the shape of the desired blank and differ in size only to the extent of the clearance between them. The punch descends and shears the sheet stock to sever the blank from the sheet, leaving stock entirely around the blanked workpiece. Fig. 2C4 illustrates the process.

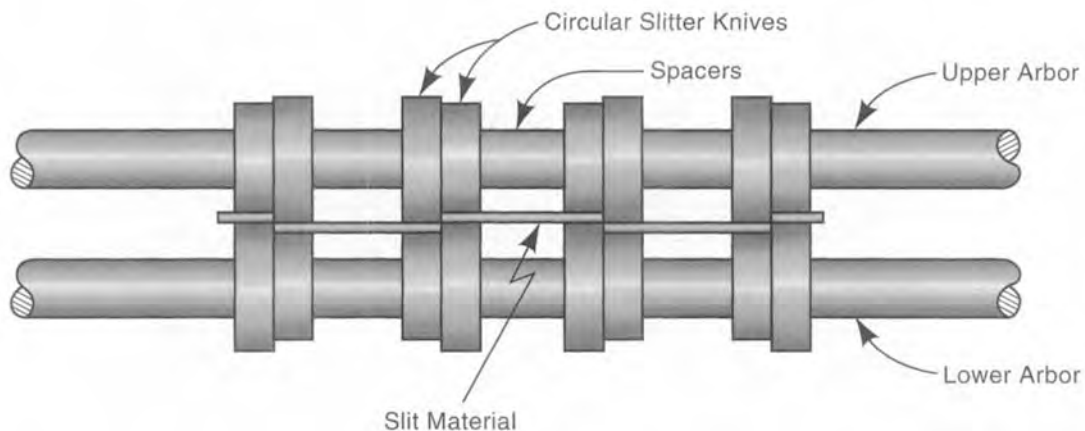


Fig. 2C3 Rotary slitting. Sharp edges of the circular slitting knives shear the sheet material.

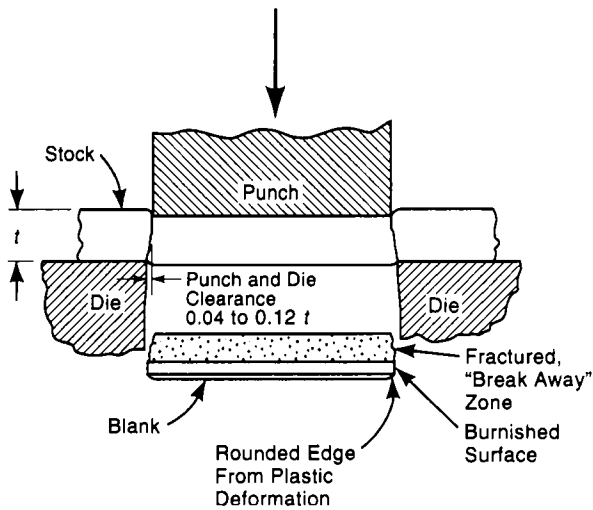


Fig. 2C4 The shearing action of a blanking punch and die. Note the edge of the blank which is typical of all sheared, blanked, or punched parts. There are three different edge areas: 1) the area of plastic deformation where the die edge first impinges the sheet, 2) the burnished area where pure shearing takes place, and 3) the breakaway area where the metal sheet fractures.

C4a. steel rule die blanking - This method is particularly suited to lower-quantity production of parts made of softer materials such as leather, rubber, plastic sheet, fibre, and paperboard. Dies are somewhat similar to cookie cutters. They consist of a thin strip of hardened steel bent to the shape of the blanked part and held in a base of wood or other material. The exposed edge of the strip is sharpened. The die is mounted on a press ram. On the opposing surface on the press bed, there is a hardened steel punch made from flat stock and cut to the shape of the blank. When the press ram descends, the steel cutting edge penetrates the work material and there is a shearing action between the steel rules and the punch. Although the materials noted above are most suitable, this method has allowed steels up to 3/8 inch (10 mm) and aluminum to 0.55 in (15 mm) to be blanked in short runs. Blocks of rubber in the die serve to strip the blanked work-piece from the die. Fig. 2C4a shows the elements of a typical steel rule die.

C4b. dinking - is similar to steel rule die blanking in that the cutting is performed by a knife-like

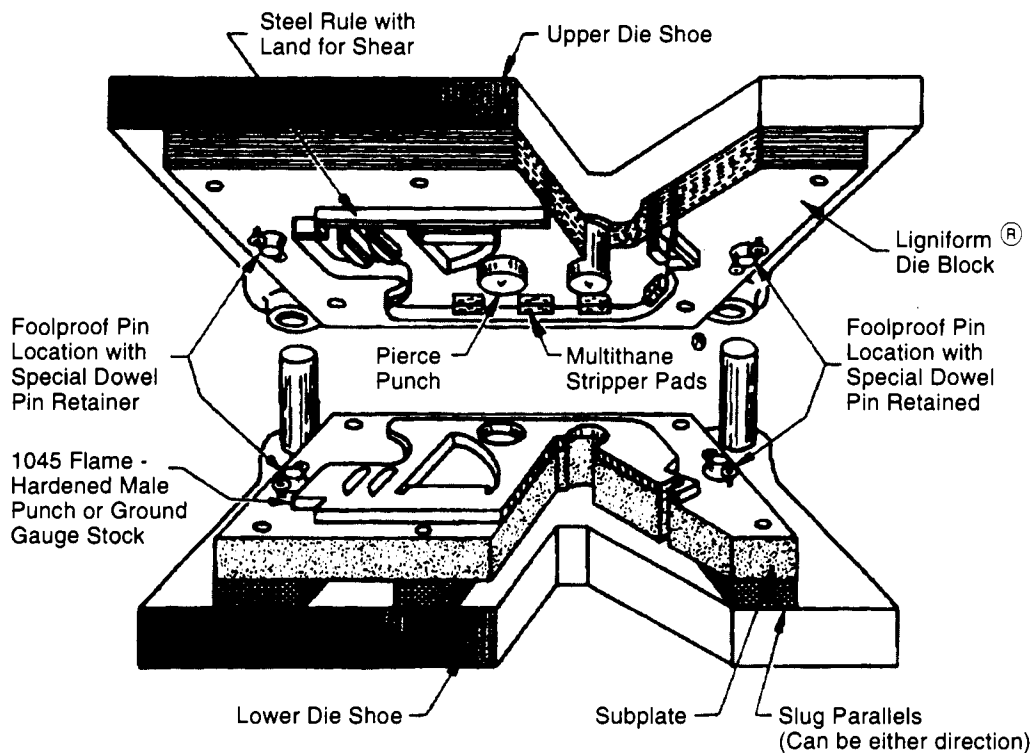


Fig. 2C4a Cross-section of a steel-rule blanking die. (Courtesy J.A. Richards Co.)

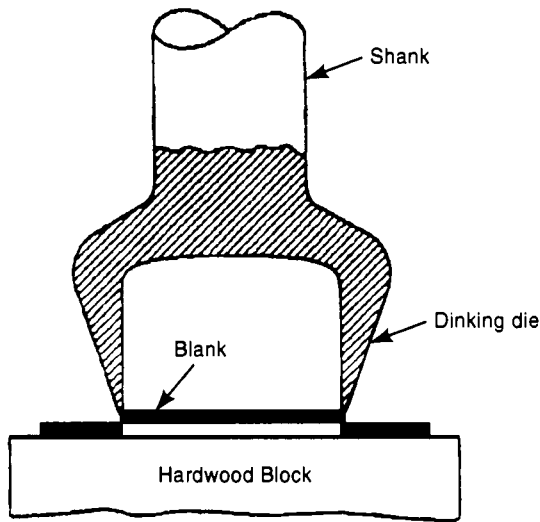


Fig. 2C4b Cross-section of a typical dinking die. The work material is cut when the die presses it against the hardwood block. (from Niebel, *Product Design and Process Engineering*, McGraw-Hill, NY 1974)

edge that can bear against a flat surface. In this variation, the knife-like punch and its holder are all made from one piece of steel, hardened and sharpened at the edge. The process is illustrated in Fig. 2C4b. The process, like most steel rule die blanking, is used for cloth, fibre, rubber, and other soft materials.

C4c. cutoff - a stamping operation to sever a part from a sheet or strip of stock, normally with a single line cut. The operation is frequently the last one of a progressive-die sequence where a number of blanking, piercing, forming, and other operations are best performed on a work piece while it is still attached to the stock and the cutoff operation is the final one to create a discrete part.

C4d. parting - is similar to cutoff in that a part is severed from strip material except that the term, *parting*, implies that some material is removed in the operation whereas cutoff implies a cut only along a single line. Fig. 2C4d illustrates the operation.

C4e. photochemical blanking - See chapter 3, paragraph S4.

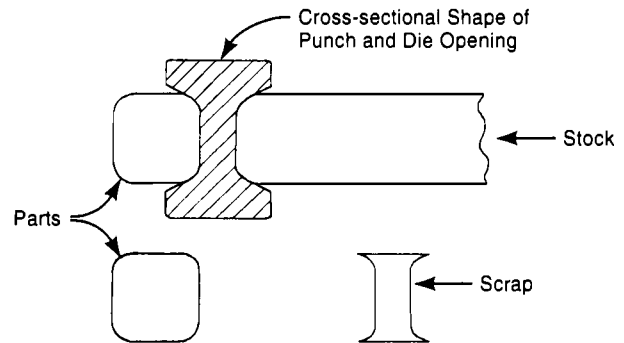


Fig. 2C4d A parting punch is used to make separate pieces from strip material when the end edges do not mate.

C5. punching - often called *piercing*, is a press-working operation used to produce holes in sheet materials. The operation is a variation of blanking (2C4), being identical in that a separate piece (or pieces if multiple holes are punched in one press stroke) is sheared from another piece in one press stroke with a punch and die set, but different in that the purpose of the operation is to create a hole rather than a new part. The piece that is removed is scrap rather than a useful part. The hole punched can be circular or any other shape, according to the shape of the punch and the matching die opening.

C5a. turret punching - is performed on a machine that has two synchronized indexing tables, one containing punches and the other containing matching dies. The machine also has a free floating table to which the work piece is attached. The flat work piece can be moved, either manually, often with the aid of a template, or by computer-numerical control to position the work piece under the operating punch. When the press is actuated, the punch descends and punches a hole in the work piece. When there are several holes to be produced, the work piece is moved in succession to the designated locations and the press is tripped at each position. When there are holes of several sizes, the turret mechanism can index to present a different size punch and die. Notching, nibbling, lancing, louver forming, slotting, embossing, and other operations are also feasible with the appropriate tooling. This equipment is used for work pieces that are too large to be punched with a single die

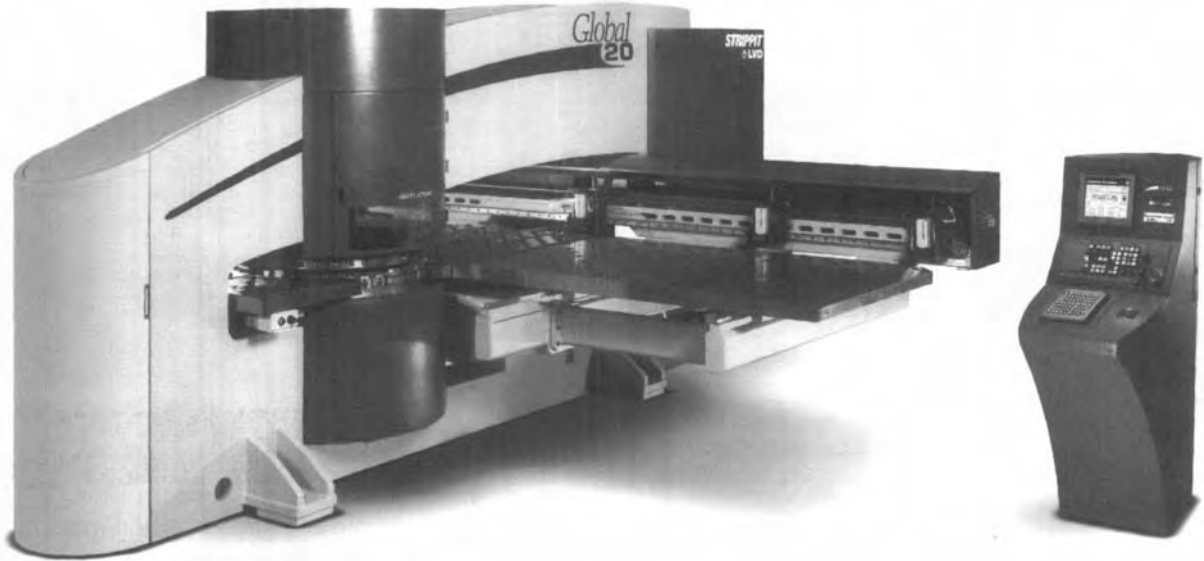


Fig. 2C5a A CNC turret punching machine. Movement of the sheet, changes in punches and dies through rotation of the turret, and the punching action, are all controlled automatically. (Courtesy Strippit LVD, Akron, New York.)

set or parts made in such low quantities that they do not justify an investment in dedicated tooling. See Fig. 2C5a.

C5b. notching - is punching or piercing performed at the edge of the work piece. The edge of the strip or blank becomes part of the perimeter of the piece that is removed. The operation is performed

when the shape of a blank is too complex to fully incorporate in a blanking die, for low-quantity work when complex tools are not justifiable, to free material for a subsequent forming or drawing operation, or to remove material that would otherwise be distorted in a subsequent operation. A work piece with several notching operations performed is illustrated in Fig. 2C5b.

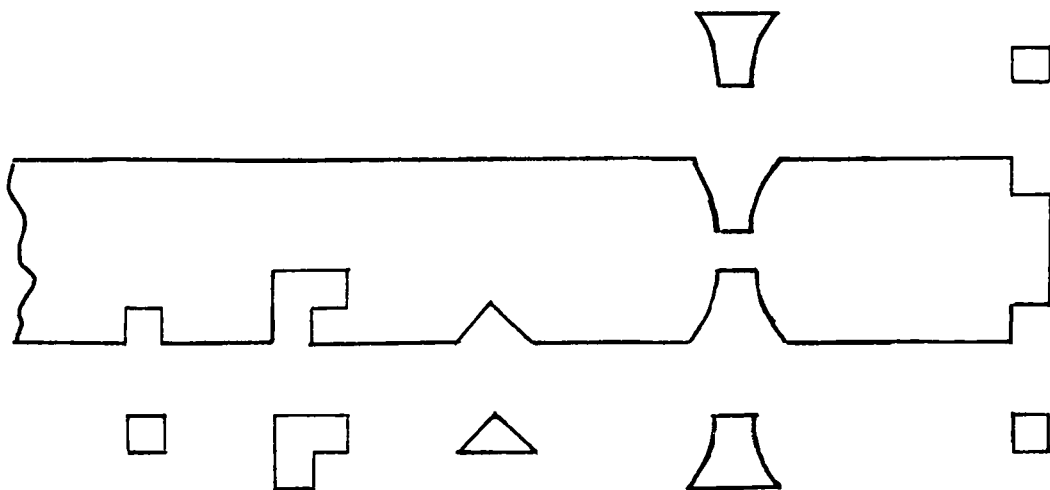


Fig. 2C5b Metal strip with various notches made to provide the desired workpiece shape or to facilitate a subsequent bending or forming operation.

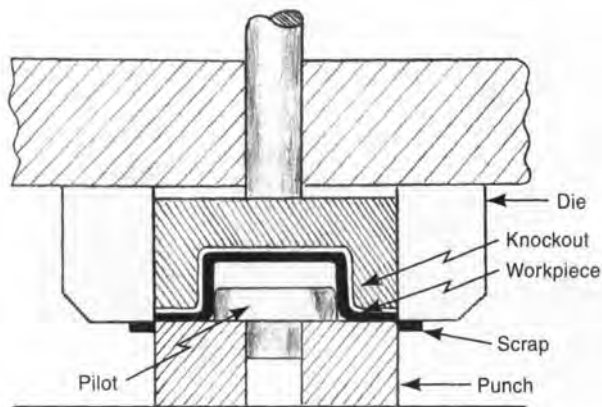


Fig. 2C6 Trimming a drawn cup. This method is intended to leave a flange at the top of the cup.

C6. *trimming* - is a stamping operation used to remove unwanted material that occurs as a result of some other process such as casting, forging, forming, or deep drawing. The operation is similar to blanking except that the workpiece is a semi-finished part instead of a flat piece of sheet stock, and the trimming die is shaped to contain the shape of the part. In die casting, trimming removes sprues, flash, and runners. In deep-drawing and some forming operations, trimming removes flanges left where the material was gripped or held. A workpiece with this trimming operation is illustrated in Fig. 2C6.

C7. *shaving* - is a secondary operation performed on sheet metal workpieces after blanking or piercing. Its purpose is to refine the edge finish or the dimensions of the blank. The process is similar to blanking except that the fit between the punch and die is very close. Very little metal, only a few thousandths of an inch, is removed from the part. The edge of the workpiece, after the operation, is sheared smooth through about 75% of the stock thickness, with reduced rounding or "pull-down" and very little rough breakaway area. Sometimes, a second shaving operation is performed on the workpiece to further improve the straightness and length of the smooth portion. Before the advent of fineblanking, the process was used to produce smooth-edged stampings. Stamped gears are a typical application.

C8. *lancing* - is a sheet metal operation that makes a slit or cut that is not long enough to produce a separate piece. No scrap is produced because the

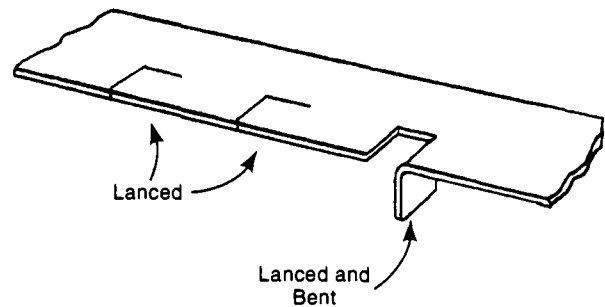


Fig. 2C8 A workpiece with lancing cuts, and one bending operation.

cut does not extend from edge to edge. The usual purpose is to facilitate a subsequent forming operation on the workpiece by allowing the material to flow more easily. A workpiece with this kind of cut is illustrated in Fig. 2C8.

C9. *fineblanking* - is a method for producing smooth edges and other improved features on stamped metal parts. It involves both blanking and forming. The method requires closer control and several features in presses and tooling compared to those in conventional stamping. These features include a more precisely controlled press stroke, a closer fit between punches and dies, the use of a shaped pressure plate with a v-shaped impingement ring surrounding the die to hold the workmaterial and provide compressive stress in the part, a floating ejector pin to provide pressure on the material and against the punch force, and somewhat slower press speeds. Another difference is that the close-fitting punch does not enter the die. A typical fineblanking operation is shown in Fig. 2C9-1. The operation requires a press with the following characteristics: separate actions for the punch, v-ring pressure, and counterpressure; capability for a fast approach stroke, a slow shearing speed, and a fast ram retraction rate; control of the shut-height setting within 0.0004 in (0.01 mm) to insure that the punch stops at precisely the correct point; and sufficiently accurate guideways that the punch-die clearance can be maintained within half percent 2% of the stock thickness. Fig. 2C9-2 illustrates the difference between the edges of conventionally blanked and fineblanked parts. Fineblanking is utilized in the manufacture of precision parts that otherwise may require machining or other secondary

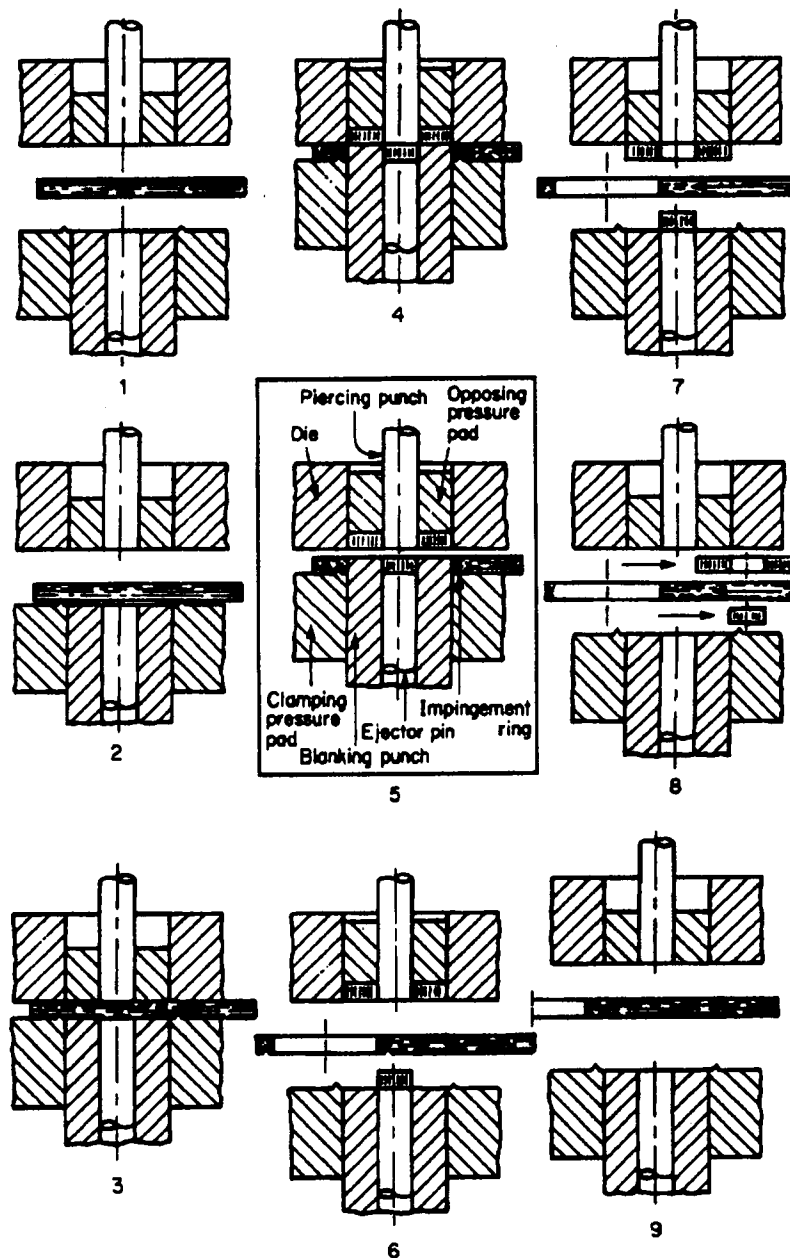


Fig. 2C9-1 The sequence of steps in a typical fine-blanking operation with a compound die that both blanks and pierces the sheet material: 1) The material is fed into the die. 2) The ram lifts the table, die set, and material to the die face. 3) The tool closes and the v-ring is embedded in the material. The counterpunch clamps the material against the blanking punch face inside the shear periphery. 4) The v-ring pressure and counterpressure are held constant while the punch moves upward, shearing the part into the die and the inner slug from the punch. At the top dead center position, all pressures are shut off. 5) The ram retracts and the die opens. 6) The v-ring elements moves upward, stripping the punch from the skeleton material and pushing the inner slugs up out of the punch. The material feed begins. 7) The counterpressure is reimposed, stripping the part from the die. 8) The part and the slugs are ejected from the die by either air jets or by a removal arm. 9) The cycle is complete and ready to repeat. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

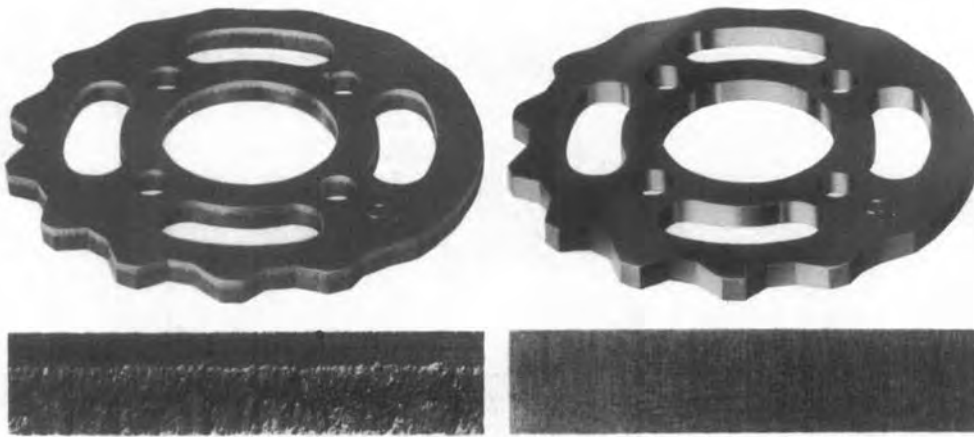


Fig. 2C9-2 Comparison of the edge surface produced by conventional stamping (left) and fine blanking (right). (Courtesy Feintool New York, Inc.)

operations after blanking, and for making parts that may not be feasible by conventional stamping methods. Stacked gears, cams, sewing machine and business machine parts are examples. The method is not limited to blanking: forming, piercing, coining, embossing, etc. may also be performed on the workpiece with a separate operation or with compound and progressive dies, when required.

C9a. semi-piercing - is piercing with a shortened punch stroke so that the piece that would otherwise be removed from the part is offset rather than severed. If done properly, there is no fracture in the workpiece metal. In fact, the metal joining the offset and the base material is strengthened by the cold working it receives. The offset part can function as a cam, a stop, a rivet, or a locating pin. Fine-blanking is particularly suited for producing strong and accurate semi-piercings as illustrated in Fig. 2C9a.

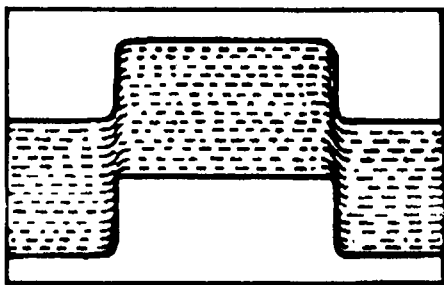


Fig. 2C9a Cross section of semi-piercing in sheet metal. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

D. Press Bending and Forming Operations of Sheet Metal

D1. bending - is the deformation of material about a straight axis. There is little or no change in surface area of the workpiece. Material on the outside of the bend tends to be stretched and material on the inside tends to be compressed. Bending is a very common sheet metal operation. When performed as an individual operation, usually in smaller quantity production, it can be done on a bending brake (sometimes called a bar folder), as shown in Fig. 2D1-1, if the sheet is about 1.5 mm (0.060 in) or less in thickness. Press brakes are used for thicker stock. Bending as a punch press operation is often carried out with wiper dies as illustrated in Fig. 2D1-2.

D1a. press brake bending - Press brakes, as illustrated in Fig. 2D1a, are mechanical or hydraulic presses with long, narrow, stationary

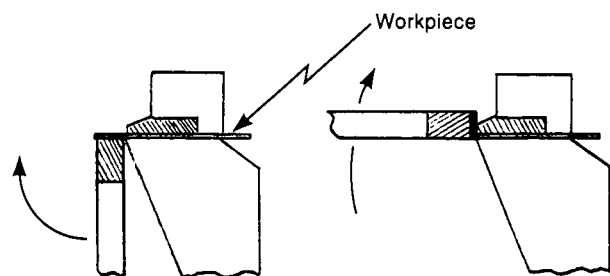


Fig. 2D1-1 The bending action of a manually-operated bending brake (bar folder).

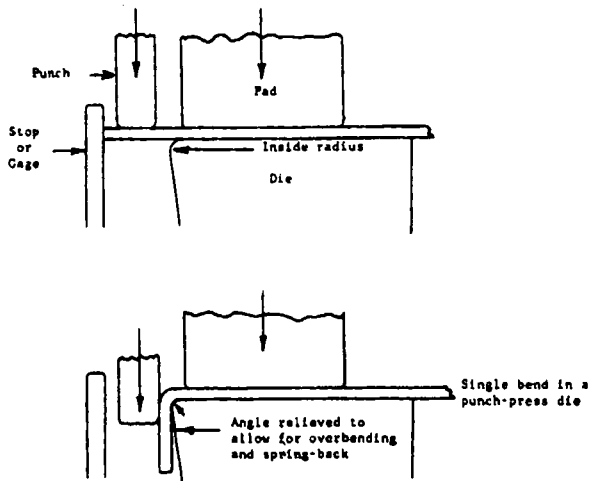


Fig. 2D1-2 Bending sheet metal with a punch press wiper die. (from Niebel, *Product Design and Process Engineering*, McGraw-Hill, NY 1974)

beds. Bed lengths range from 2 or 3 ft to 30 ft and press tonnages from 10 to several thousand. The ram stroke is short but adjustable. Dies are long, narrow, and often simple V-dies. Both sharp and

gentle bends can be made, depending on the shape of the dies. Piercing, notching, forming, shearing, edge curling, beading, hemming, corrugating, and tube forming can be performed with suitable dies. In bending, sheet metal, placed between the bed and the ram is most commonly bent once with each press stroke. The bend occurs when a shaped punch, attached to the press brake ram, descends against the workpiece, forcing it into a suitably-shaped die, fastened to the press brake bed. Multiple bends are made by repositioning the workpiece sheet between press strokes. Press brakes are used in the bending of long, narrow workpieces and for other workpieces made in small quantities where standard press brake tooling can be employed.

D1b. V-die bending - V-block dies are commonly used in press brakes. The die half has a V-shaped cavity and the punch has a corresponding V-shape of the same or somewhat lesser angle. The punch and die extend over the entire width of the press. The angle of the bend is the same as that provided by the V-block less any spring back.

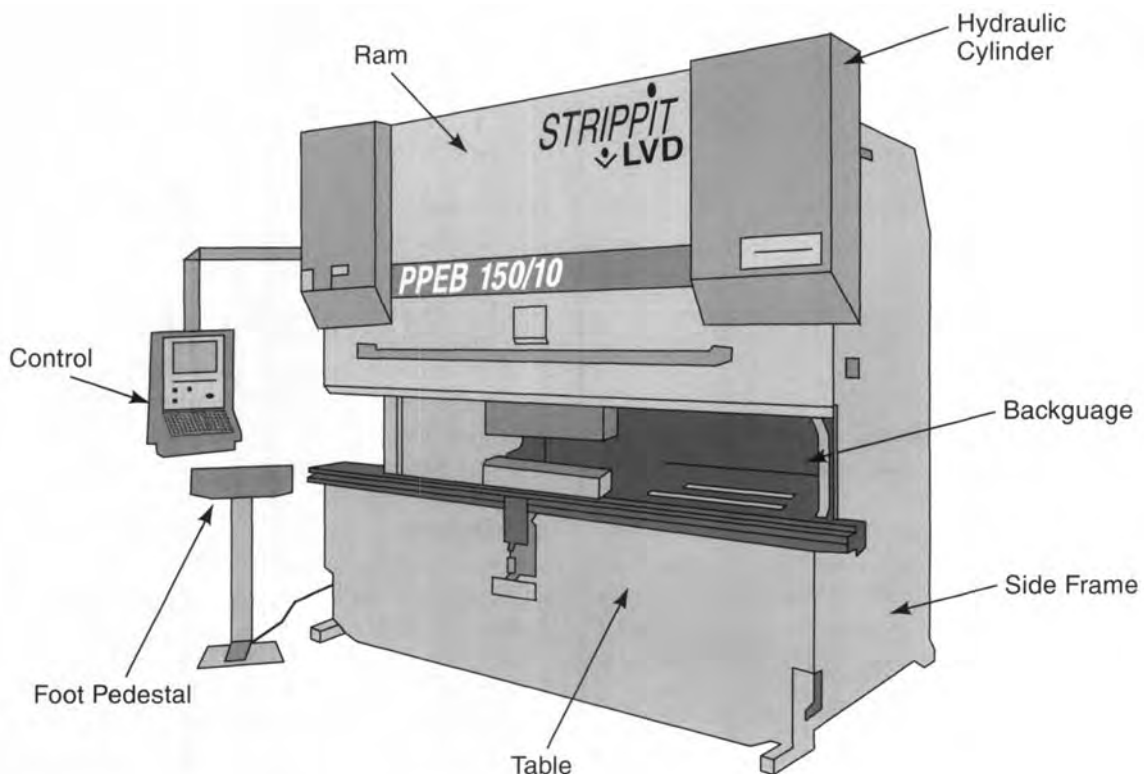


Fig. 2D1a A typical powered press brake. (courtesy Strippit LVD, Akron, New York)

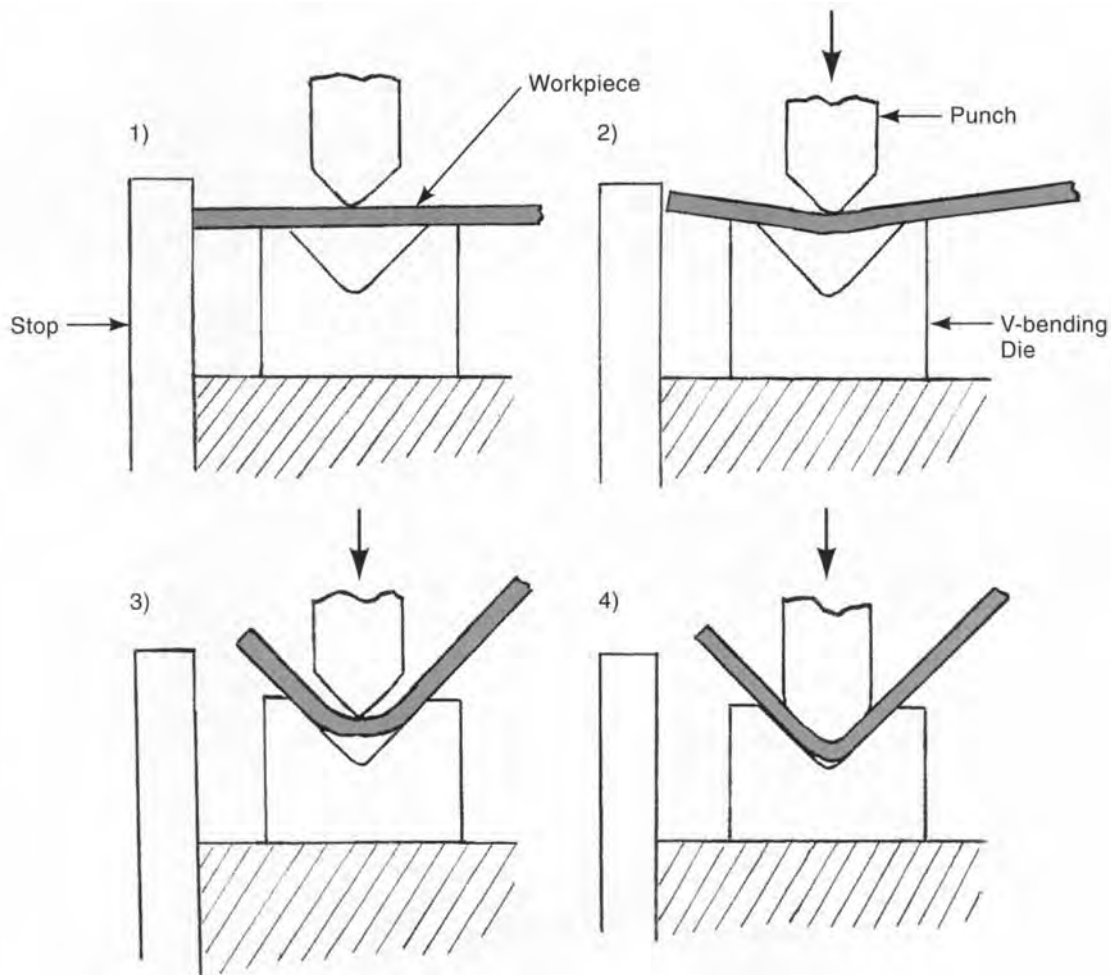


Fig. 2D1b Making a 90 degree bend in a V-die in a press brake.

Typical examples of V-dies are shown in Figs. 2D1b, 2D1c, and 2D11.

D1c air bending - In air bending, the upper die in a press brake set does not bottom in the v-block. The degree of bend depends on the depth of movement of the upper die, as shown in Fig. 2D1c. This approach has the advantage that adjustments can be made in the process to accommodate variations in materials and that one die set can be used for bends of a variety of angles. However, the results may not be as consistent as they are when the upper die bottoms in the V-block.

D1d. punch press (bending die) bending - all the bending operations feasible with press brakes

can also be made in regular punch presses, though not over as great a length. Dies similar to the V-block dies commonly used in press brakes are sometimes used but other die configurations are more common. Dies dedicated to a particular part permit high-production bending of one or more bends, often in combination with other press operations. Again, the descending stroke of the press ram typically carries a punch that pushes the workpiece against an adjacent form block, bending one or more sides of the workpiece.

D2. forming - is any operation that changes the shape of a solid-state workpiece by force or pressure. Forming operations have one thing in common: permanent useful deformation or plastic

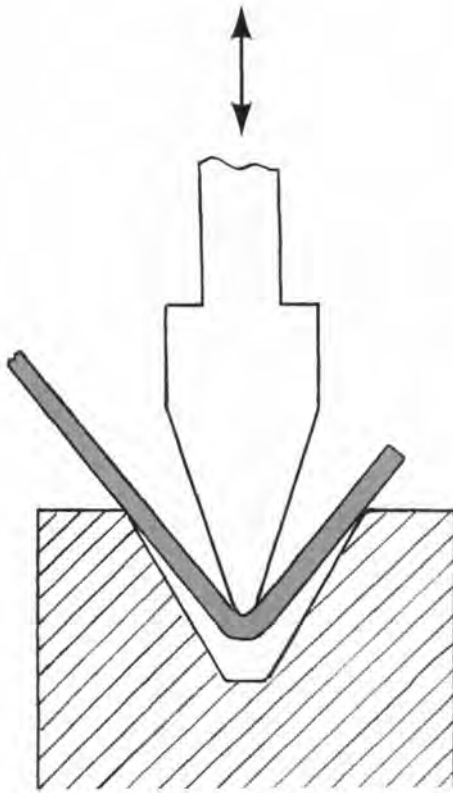


Fig. 2D1c Air bending sheet metal, using a V-die in a press brake.

flow of the workpiece material as a result of forces applied to it. This definition covers operations such as bending, rolling, forging, cold heading, extrusion, metal spinning, swaging, coining, and deep drawing. It applies to sheet metal and material of other shapes. Casting and machining, however, are not forming operations. In sheet metal operations, however, the term, forming, is often applied to operations that involve somewhat more deformation than simple bending but that do not fall into another clear-cut category such as deep drawing, coining, embossing, or rotary swaging, especially if the operation is intended to change the thickness of the part. Included in the term, forming, then would be the production of dish-shaped parts, flanges or other bends along curves or at corners and other miscellaneous sheet metal operations. Fig. 2D2 illustrates a simple tooling arrangement for forming a sheet metal workpiece.

D3. forming with rubber tooling

D3a. rubber tool forming (rubber pad forming) - is a method of bending and forming that simplifies the tooling required by substituting a confined rubber pad for one half of the die. The other half of the die consists only of a simple block around which or against which the part is formed. The confined rubber pad acts like hydraulic fluid exerting force in all directions as it is compressed. The tooling tends to be quite simple and the forming blocks can be made of low-cost materials including non-metals. The process is suited for short-run production since tooling costs are low. The process is commonly used in making aluminum parts in the aircraft industry.

D3b. Guerin process - is a common rubber-tool forming process that also can be used to blank parts. A rubber pad of fairly soft durometer, usually 6 or more inches thick, is fastened to the press ram and is surrounded on the sides with steel or cast iron walls strong enough to contain the rubber against the pressure of forming. The forming block is fastened to the press platen. When the press ram descends, the rubber pad forces the workpiece against the forming block and, as the workpiece bends, rubber surrounds the workpiece and applies horizontal as well as vertical pressure to force it against the forming block. The process is illustrated in Fig. 2D3b. The maximum feasible depth of the formed portion is about 1.5 in (37 mm).

When blanking is required, the edges of the lower blocks are hardened and have sharp edges. The blocks can be as little as 3/8 in (10 mm) thick. The pressure of the rubber pad causes the workpiece metal to be sheared by the sharp edge. Rubber of higher durometer is used when blanking is included in the operation. Aluminum sheet up to about 0.050 in (1.3 mm) thick can be blanked.

D3c. Marform process - is a rubber-tool process that uses a deeper rubber pad in the press ram and adds a flat steel holder plate, supported hydraulically or by springs to act as a blankholder during the downward movement of the rubber pad. The arrangement permits deeper forming and drawing of irregular parts. Drawing depths equal to the workpiece diameter are feasible.

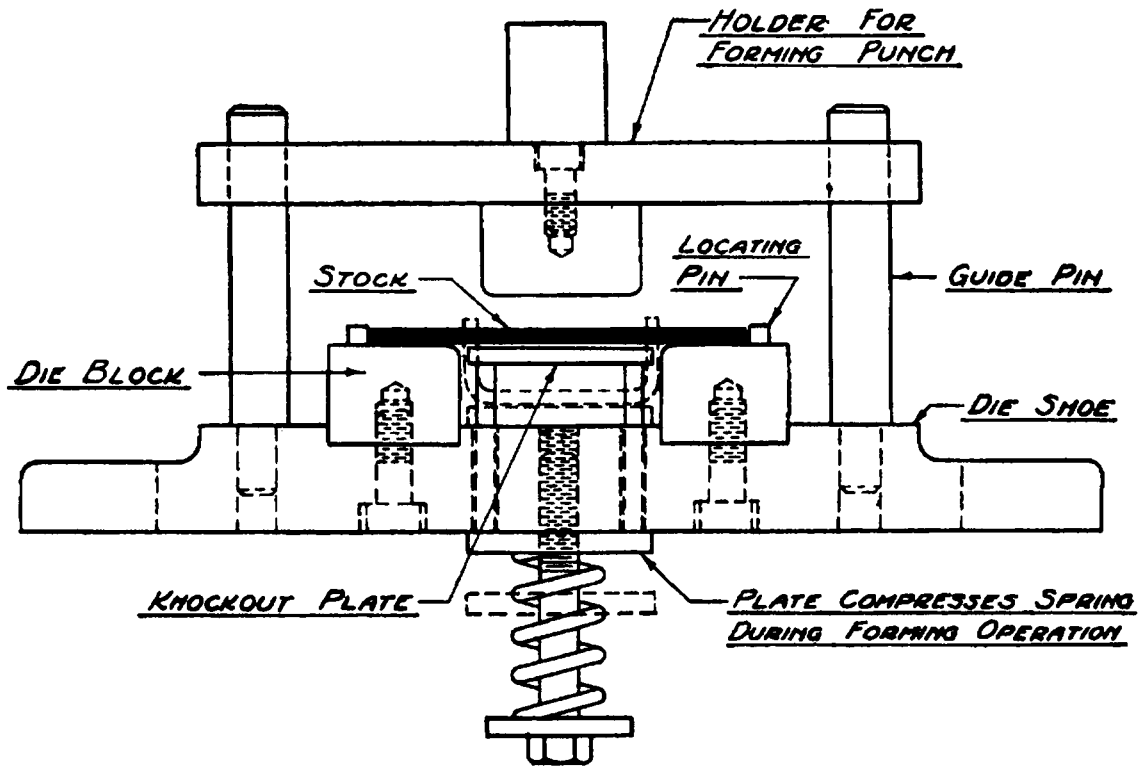


Fig. 2D2 A punch and die made for a forming operation.

D3d. **rubber diaphragm forming (hydro-form process) (fluid forming)** - in this process, the rubber pad is replaced by a hollow flexible rubber diaphragm which contains hydraulic fluid. This

fluid provides improved sideways pressing capabilities so the process can be used to form deeper parts. The forming block is attached to a hydraulic cylinder that forces it upward against the diaphragm, raising

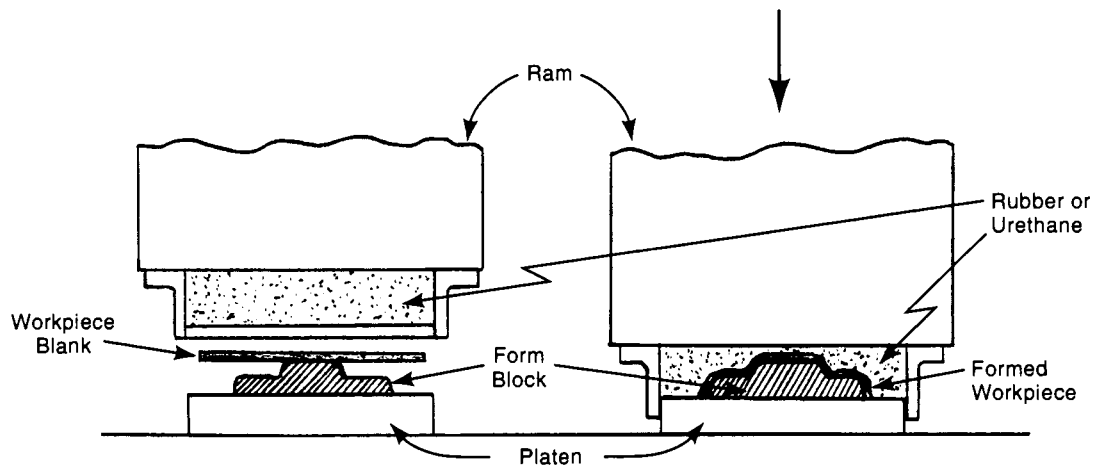


Fig. 2D3b The Guerin process for rubber tool forming. The rubber takes the place of one half of the forming die that would otherwise be required.

the pressure in the system. Hydraulic pressures up to 15,000 psi (100 MPa) may be used. Fig. 2D3d illustrates the process.

D3e. **Verson-Wheelon process** - is another rubber-diaphragm process. There is no press stroke. Instead, hydraulic pressure is applied directly to a diaphragm that forces a rubber pad against the work-piece. The process is applicable only for relatively shallow formed parts, similar to those processed

with the Guerin process, but can produce somewhat greater detail and variety of forms. Fig. 2D3e shows how the process works.

D4. **drop hammer forming** - uses repetitive strokes of a drop-hammer press to form sheet metal parts. (See drop forging, A4a.) The process is particularly suitable for parts with shallow, smooth contours and generous radii, including parts with double curvature. Beaded parts can be produced.

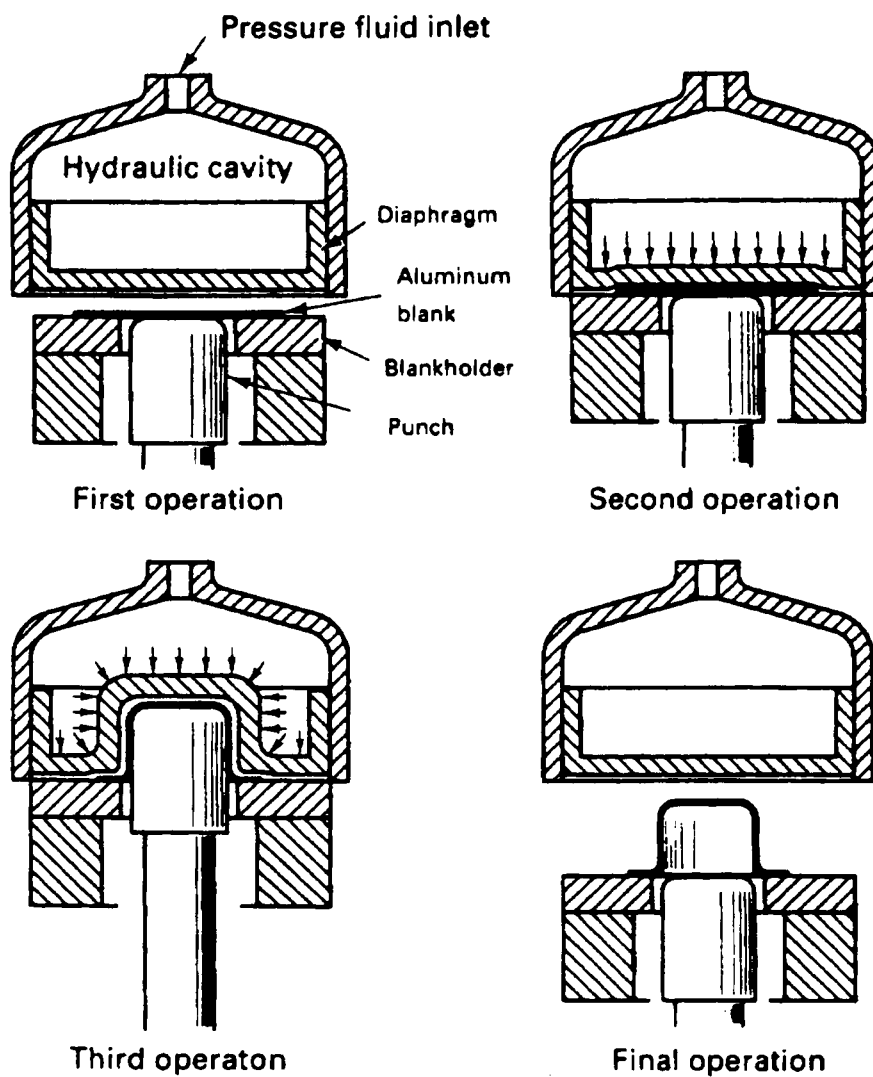


Fig. 2D3d A schematic view of the rubber diaphragm forming process (hydroform or fluid-forming process) showing: 1) the blank in place ready for forming, 2) the press closed and the cavity pressurized, 3) the ram advanced into the cavity and, 4) the pressure released and the ram and press retracted. (Courtesy Aluminum Association, Washington, DC)

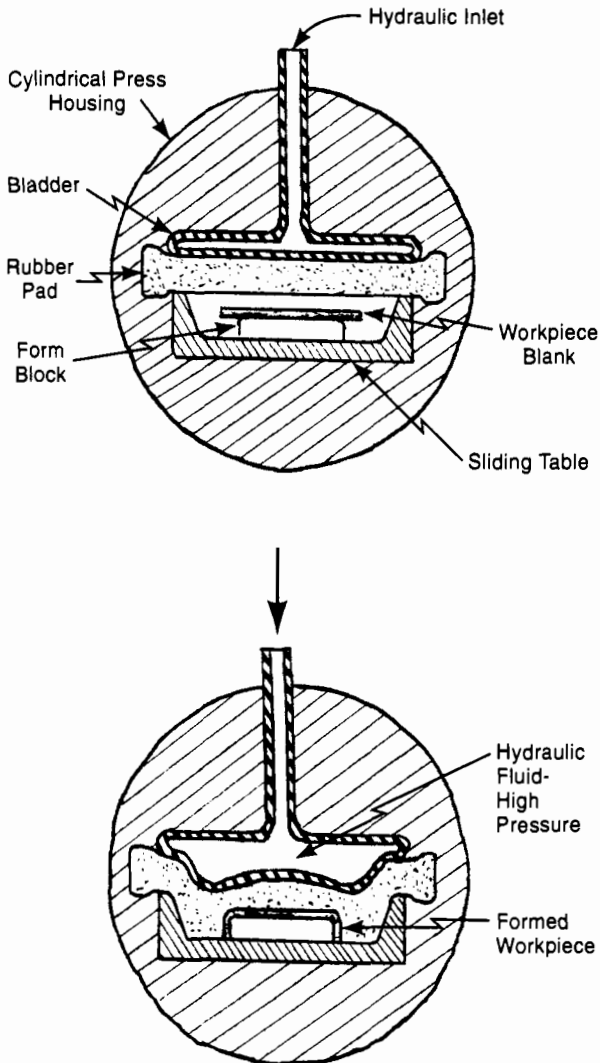


Fig. 2D3e The Vernon-Wheelon process which uses a rubber bladder and hydraulic pressure to provide the forming force.

The tooling is simple and can be cast from low-melting-temperature alloys. Since tooling costs are relatively low, the process can be economical for limited production quantities. Applications are normally limited to sheet metal thinner than 0.064 in (1.6 mm). Dimensional tolerances are wide.

D5. drawing (sheet metal parts) - is a process that forms a recess in a flat sheet-metal workpiece. The process can produce cup, cylinder, and box-shaped parts with a depth considerably greater

than the diameter. (It is then called, "deep drawing".) When the press ram descends, a punch attached to the ram pulls or draws the metal into a die cavity over the die cavity's rounded edge. The operation involves flowing rather than stretching the sheet material. To control the operation, the drawing die or press includes a blank holding device. The blank holder (pressure pad) restricts the movement of the workpiece and keeps it from wrinkling but allows it to flow toward the punch and die cavity. Blankholder pressure is typically about one third of the pressure required for drawing. Thinner metal requires greater blankholder pressure⁴. The thickness of the sidewalls of the part normally increase during the operation. A close fit between the die cavity and the punch can be used to "iron" the sidewalls, maintaining their shape and reducing the thickness. Fig. 2D5 illustrates the operation. When the depth of draw is more than three-quarters of the diameter or width of the part, two or more draws, with annealing between draws, are usually required. The need to control the blank movement by holding it, usually

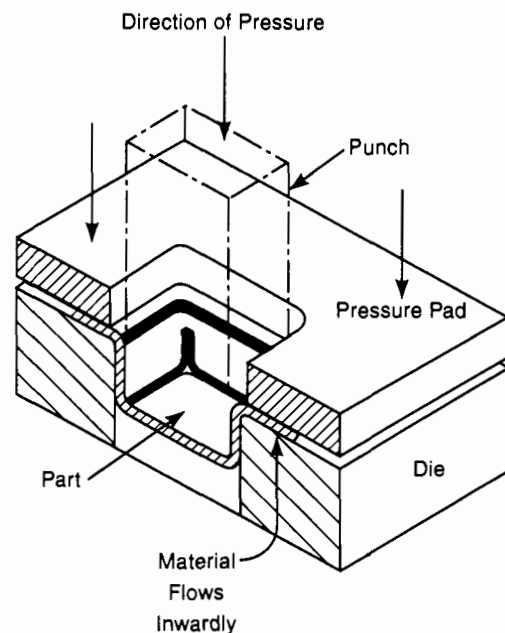


Fig. 2D5 Schematic of deep drawing showing the blank holder (pressure pad). (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

results in excess material that needs to be trimmed off in a secondary operation. Typical parts made by drawing are: beverage cans, artillery shells, cartridge cases, auto body panels, and pots, pans, and other containers.

D5a. shallow drawing - commonly refers to a drawing operation when the depth of the part is less than one half its diameter.

D5b. deep drawing - commonly refers to a drawing operation when the depth of the part is greater than one half its diameter. One or more redrawing operations and, with some materials, annealing before redrawing, may be required.

D5c. redrawing, direct and reverse - Sometimes a drawn part is run through a second drawing operation to increase the depth and reduce the diameter of the part. The drawn part is placed in a die recess and a punch, smaller in diameter than that used in the previous drawing operation, pulls it into the die. The blank-holding function is also involved to control the metal flow. Annealing may be required between the original and the redraw operations if the workpiece metal is the type that work hardens.

In direct redrawing, the operation proceeds in the same direction as the original drawing. The punch is made in two parts, an inner punch that determines the inner diameter of the part after the operation, and a sleeve that surrounds this punch. The outer diameter of the sleeve is about the same diameter as that of the drawing punch in the first operation. This sleeve enters the workpiece first and serves the same function as the blank holder in the first drawing operation. As the inner punch strikes the workpiece, it pulls it downward around the sleeve into a smaller diameter. See Fig. 2D5c, view a). A double-action press provides both the holding action and the drawing action.

Reverse redrawing performs a similar operation, but the workpiece is inverted in the die and the die again is configured with a two-piece punch which provides both holding and drawing operation. The advantage of reverse drawing is that the workpiece is not subjected to severe stress in one direction and then the other. This allows a greater percentage diameter reduction in the operation and lessens the need for annealing

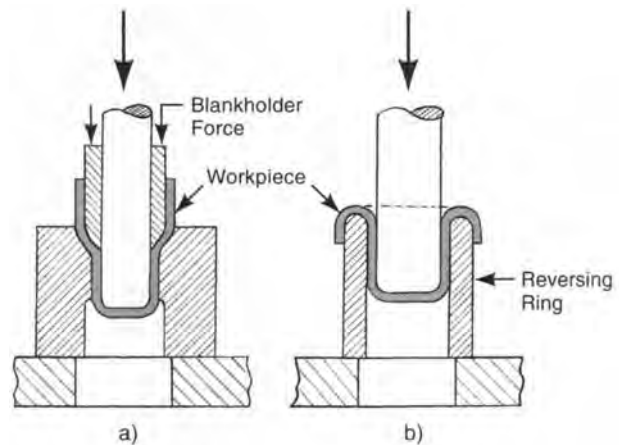


Fig. 2D5c Redrawing a drawn part: a) direct redrawing, b) reverse redrawing.

between operations. Fig. 2D5c, view b), illustrates reverse redrawing.

D6. coining - is an operation that changes the thickness of a sheet metal part, usually to create visible designs, markings, or other configurations on the surface. Very high compressive forces, and dies that confine the workpiece so that it doesn't flow in the lateral direction, are required. The workpiece thickness changes locally and its surfaces are formed to match accurately whatever design exists on the die surfaces. Fig. 2D6 illustrates the effect of the process and contrasts it with embossing. One difference is that coining permits the opposite surface of the part to have a different design. Coining is used to produce coins, jewelry, tableware, medals, and other parts where markings on both sides, or thickness changes, are required. Pressures as high as 100 tons per sq in (1400 MPa) may be required. Knuckle-joint mechanical presses are frequently used for the operation because they can provide the high pressure with a slow squeeze and dwell at the bottom of the stroke. Ductile materials, including low-carbon mild steel, are suitable for the operation. (Note: Also see roll coining, F4.)

D6a. drop hammer coining - is a process in which the high pressures required for coining are provided by the impact force of multiple blows of a drop hammer rather than by a high-force, slower-acting,

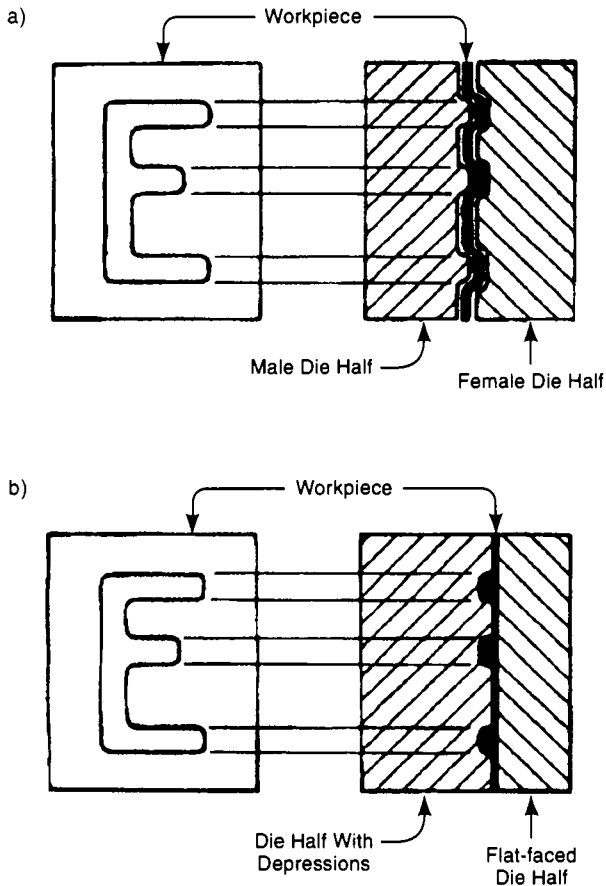


Fig. 2D6 A comparison of embossing (a) and coining (b) to imprint a surface design on a sheet metal part. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

punch press. Tableware is often coined with drop hammers.

D7. *embossing* - is a process, usually performed on sheet metal, that results in raised areas on one side of the sheet and depressed areas opposite them on the other side. The operation is basically a shallow drawing operation that does not significantly change the thickness of the sheet. It is frequently performed to create a pattern in the surface of sheet metal workpieces. Reinforcing ribs and identification markings on stamped parts, tags, jewelry, and nameplates are typical applications. The height of the raised area is normally no more than three times the material thickness. Fig. 2D6 illustrates the

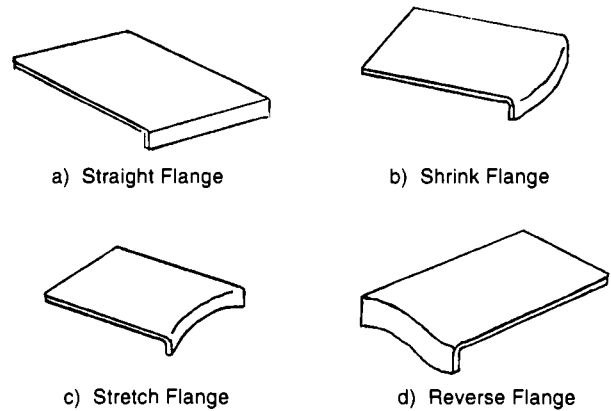


Fig. 2D8 Various types of flanges: a) straight flange, b) shrink flange, c) stretch flange, d) reverse flange.

process, and contrasts it with coining. (Note: Also see rotary embossing, F5.)

D8. *flanging* - is a bend of approximately 90 degrees near the edge of a sheet metal part, usually for reinforcement. If the bend is along a straight line, a simple bending operation is all that is required; if there is an inside or outside curvature to the bend, as shown in Fig. 2D8 b), c), and d), more extensive forming is required because metal will be forced to flow as the bend is made.

D9. *beading* - forms a shallow round trough of uniform width in a sheet metal workpiece. The trough can be depressed or raised, and can be in a straight line or can be curved or circular. Its purpose is to provide stiffening or decoration in the part produced. The thickness of the sheet does not change. The process is similar to embossing except that embossing implies a more complex pattern of formed material. A simple stiffening bead is illustrated in Fig. 2D9, where view a) shows the cross section of a press brake die for making a simple stiffening bead and view b) shows the bead itself in section and plan views.

D10. *hemming and seaming* - Hemming is the bending of a sheet edge back 180 degrees on itself to provide a rounded edge or reinforcement. The bend can be produced by roll forming, or by two bending operations, or in one operation with a

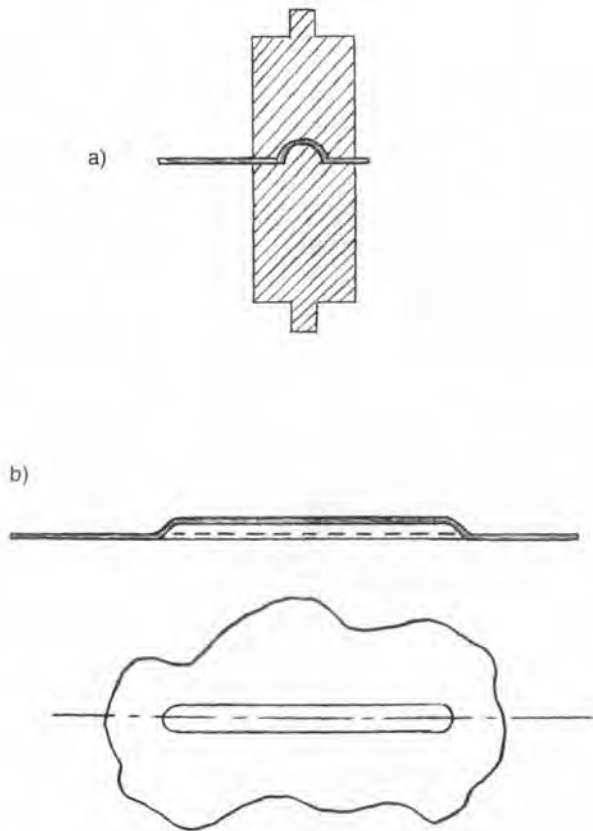


Fig. 2D9 A simple stiffening bead in a sheet metal part. The operation used to form the bead is very similar to that used in embossing.

cam-operated or compound die. Seaming is the joining of two opposite edges of a workpiece with interlocking hems or other interlocking bends. It is frequently used in the manufacture of containers such as pails, drums, and cans. Special machines are often used for the operation, particularly in high production applications. Fig. 2D10 illustrates both hems and seams.

D11. edge curling - provides a coiled or partially-coiled edge on the workpiece for reinforcement or to provide a smooth edge. On straight edges, curling can be performed with two press brake dies as illustrated in Fig. 2D11. On curved edges the operation is more complicated because curling reduces the diameter of the curved section and provision must be made for removal of the punch. Punch removal may be provided for by using a

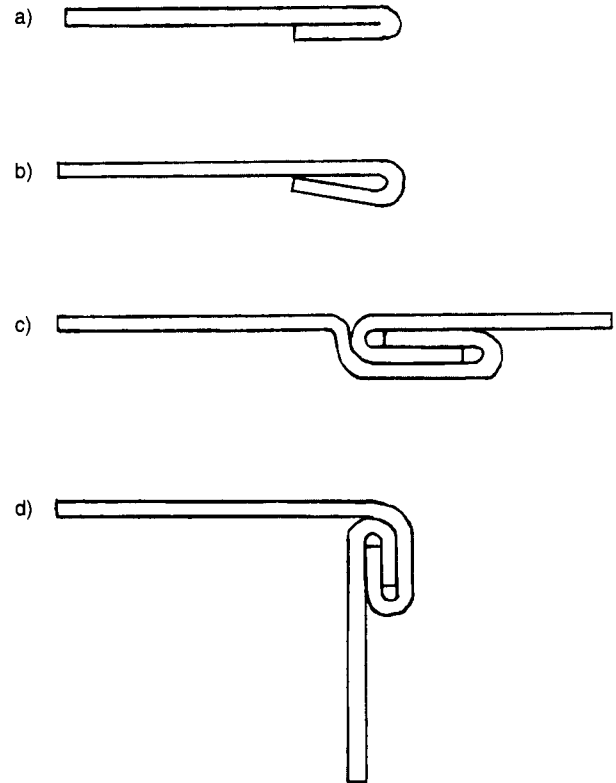


Fig. 2D10 Hems, a) and b), and seams, c) and d), on sheet metal parts. Seams are formed by interlocking hems on the edges of two sheets.

segmented punch. When the punch is to be removed, a segment is retracted so that the punch diameter is reduced.

D12. swaging - has several meanings. As a press operation, sometimes called *flat swaging*, it compresses a workpiece severely to reduce the thickness of all or part of it, to flatten it, or otherwise changes its shape. The process is similar to coining, but does not form the workpiece as completely as coining does. However, the term *swaging*, is most commonly used to refer to rotary swaging described in F1.

D13. sizing - is a press operation that improves the dimensional precision of a workpiece by subjecting it to high force in an accurate die. Perhaps the most common example is the re-pressing operation

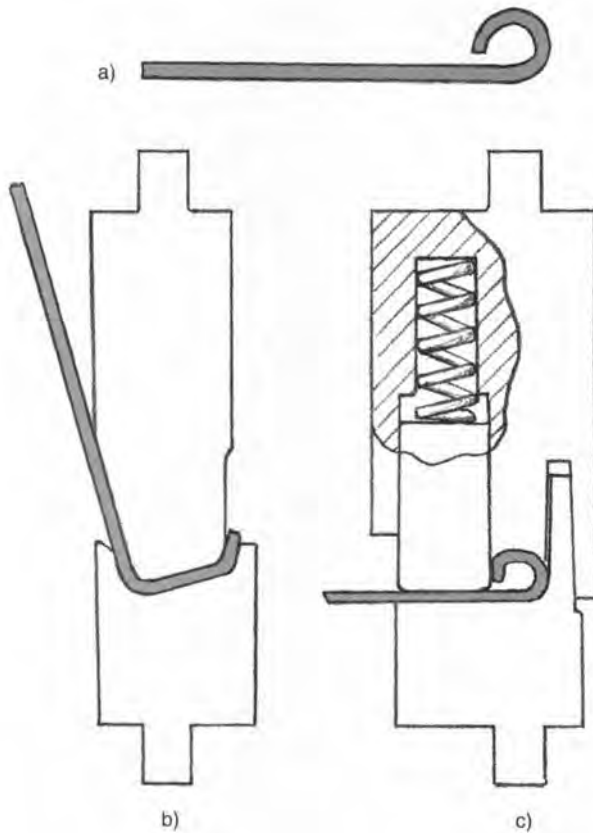


Fig. 2D11 Edge curling. a) cross-section of a sheet with a curled edge. b) and c) show the two-step sequence of forming a curled edge with press brake dies. The second die includes a member to hold the sheet from shifting during the final curling step.

performed on powder metal parts (See below.) Sizing is also performed on forgings, castings, and various cold-formed parts. With sheet metal parts, the operation is similar to coining in that the thickness of the workpiece may be reduced, except that the part is not confined in the die as it is in coining. The operation is used to flatten and sharpen the edges of stampings.

D14. ironing - is an operation that smooths and thins the walls of a cup-shaped part by forcing the part through a die with a punch. The operation works the material severely, so that annealing may be required afterward. It is illustrated in Fig. 2D14.

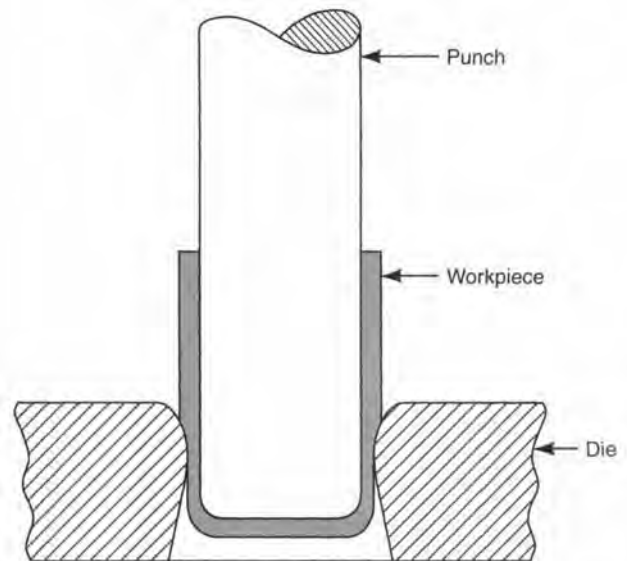


Fig. 2D14 Ironing a drawn part smooths the side walls, reduces their thickness, and lengthens the workpiece. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

E. Multiple Die Stamping Press Operations

E1. progressive die operations - In this metal stamping method, the work material moves from station to station through the die in step-by-step increments. There can be two or more stations in the die and, often, ten or more. After each movement of the work material, the press ram makes a stroke and a stamping action takes place. Once the front end of the work material has moved all the way through the die, a finished piece is produced with each press stroke. Stamping operations take place at all die stations with each press stroke (except for die stations left blank to facilitate material flow or for other reasons). Complex stamped parts can be produced with this method at rapid rates. The approach is widely applicable but sufficient production quantity is needed to provide economic justification for the cost of the tooling. Operations at each die station can run the full gamut of stamping including piercing, notching, lancing, blanking, forming, drawing, and trimming. Pilot holes to assure alignment at subsequent stations are

typically punched at the first station. Typical parts produced with this approach include a wide variety of mass-produced products and components such as laminations for electric motors, metal kitchen tool parts, automotive parts, aluminum cans, and all kinds of mass-produced sheet metal parts. In the last station, the part is cut away from the strip or sheet material. Fig. 2E1 illustrates a typical, but simple, progressive die operation.

E2. transfer die (transfer press) operations - Transfer dies consist of several separate die stations for sequential operations on a particular part, all positioned on one press bed and are all actuated with the same press stroke. The workpiece can be manually moved from die to die between press strokes, but the major benefits of the system occur

when the transfer press is equipped to move the workpiece from die-station to die-station automatically. The operation is similar to that of progressive dies except that the parts are severed from the strip stock before all the operations on it are complete, and the transfer mechanism then moves the workpieces. The transfer mechanism consists of parallel rails with grippers, fingers, cam-actuated slides or levers, that move and position the workpieces. Each die-station is independent and can be adjusted separately from the others, but all perform an operation with each press stroke, unless deliberately made idle. Blanking, piercing, shearing, bending and forming operations can be performed. An advantage of the transfer die approach is that it can be used to perform secondary stamping operations on parts already formed and may reduce material loss since

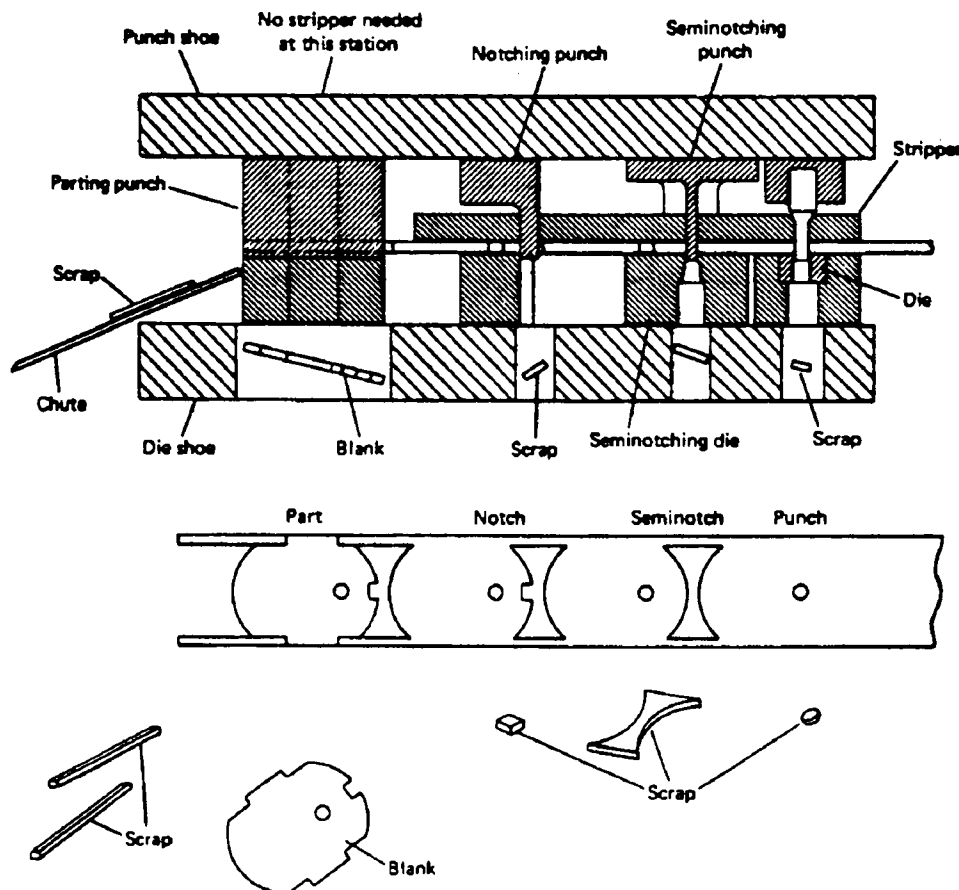


Fig. 2E1 A typical simple four-station progressive die that blanks and punches a part. (from Niebel, *Product Design and Process Engineering*, McGraw-Hill, NY 1974)

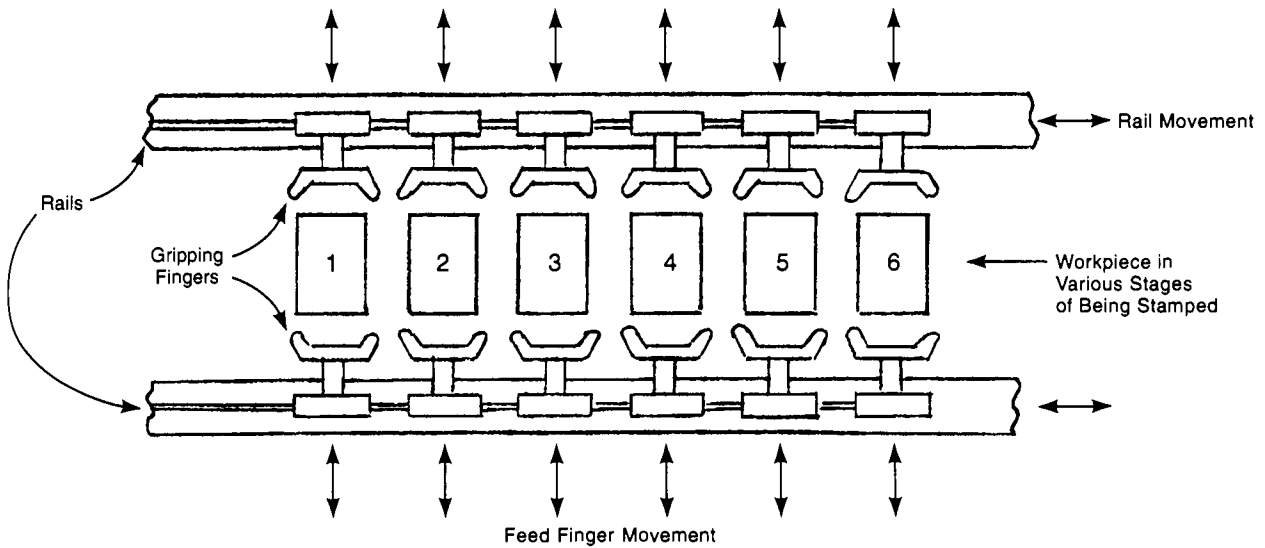


Fig. 2E2 A schematic view of the transfer mechanism used in a transfer press with six stamping stations. Gripping fingers move forward to grasp the workpiece at each station; the rails then move to the right to the next station; fingers then retract and the press makes another stroke. The cycle is then repeated. After station no. 6, the workpiece is deposited in a take-away chute; new workpieces are loaded at station 1 after each press stroke.

the alternative method, progressive die stamping, requires the use of some stock material to hold the workpieces as they are moved from station to station. The transfer material then becomes scrap. The transfer die process is useful in making parts that are difficult to form when they are connected to the stock, as in progressive die stamping. Making small rings, cylinders, and cups, from strip stock are common applications. The approach depends on high quantity production to amortize the high costs of tooling, equipment, and set-up costs involved. Fig. 2E2 shows a typical transfer die operation.

E3. compound die operations - Compound dies perform several operations on the workpiece at one die location and in one press stroke. Typical combinations are blank and bend, blank and form, blank and pierce. An example would be an operation in which the part is first blanked and then, as the press ram continues to descend, die elements perform a bending operation on a portion of the blank that was just created by blanking. Another common use is to blank a part and simultaneously punch an opening in it, as illustrated in Fig. 2E3. The advantage of a compound die operation is that it eliminates the

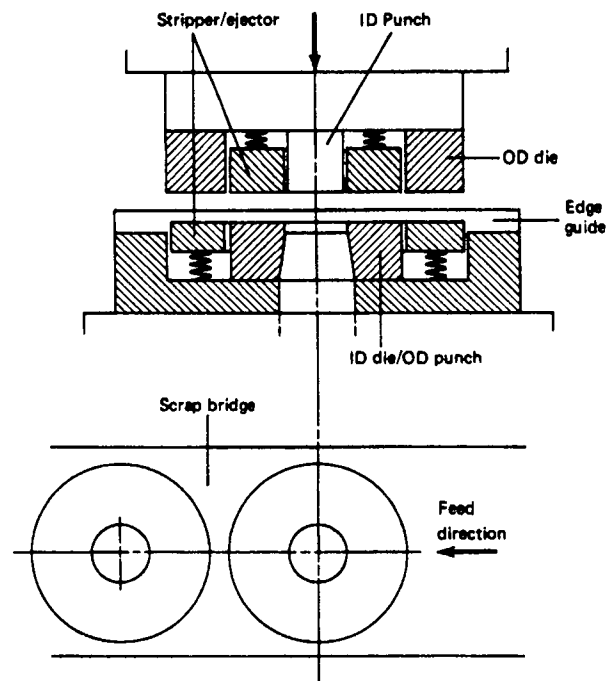


Fig. 2E3 A simple compound die that blanks and punches a part in one press stroke. The blanking punch contains the die for punching. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

need for two or more separate press operations and is normally more accurate than two operations on separate dies. Compound die operations are also usually better from the cost and accuracy standpoints than operations with progressive dies. However, since compound dies are more complex and usually more expensive than several single-operation dies, a greater level of production is usually required to amortize the die expense.

F. Sheet Metal Operations Performed on Equipment Other Than Presses

F1. *rotary swaging* - is an operation to reduce the cross-sections of tubes, bars, rods, and wires. It is accomplished by a rapid series of controlled blows from the die elements of a rotary-swaging machine. The machine, illustrated in Fig. 2F1, contains one

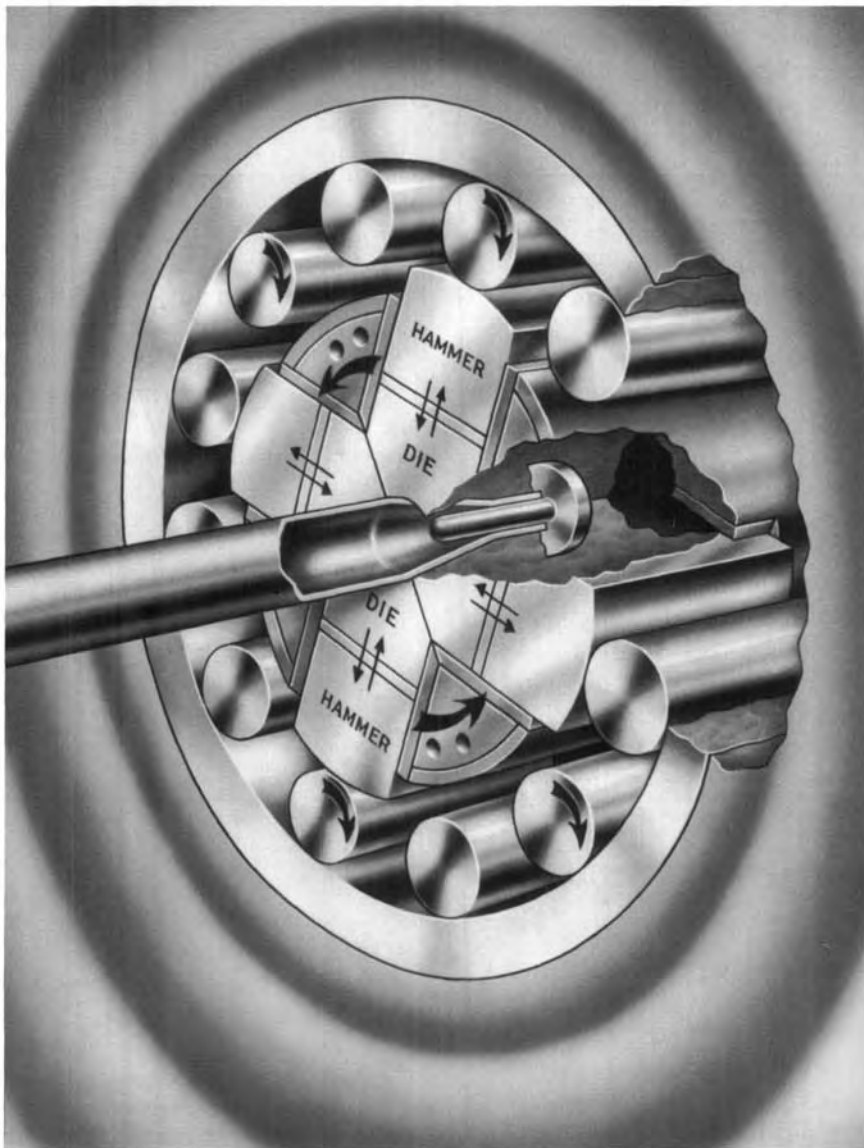


Fig. 2F1 A conventional rotary-swaging die reducing the diameter of a tubular workpiece. (Courtesy Fenn Manufacturing Co.)

or more pairs of opposed dies that strike the workpiece repeatedly as the machine spindle and the dies rotate. Centrifugal force throws the die members outward, where they encounter a series of rollers that force them to move inward and strike the workpiece. A common operating speed is 1000 blows per minute. The workpiece is inserted axially between the dies, held in place during the die blows, and then removed. For some workpieces it is necessary to have a mechanical assist or mechanical feed to move the workpiece against the taper of the dies. An internal mandrel may be used with tubular workpieces to control internal dimensions, to control wall thickness when it is reduced, to prevent collapse of thin walled tubing, and to form internal shapes.

The operation can produce tapers, pointed ends, and other shape changes, as well as diameter reductions. The method is also used to fasten fittings to cable, wire, and hose. Sewing machine needles, golf club shafts, and automotive torque tubes, are typical rotary-swaged parts. Tubing up to 14 in (375 mm) and bars up to 4 in (100 mm) in diameter have been rotary swaged³.

F1a. stationary die swaging - is a variation in rotary swaging used when the workpiece does not have a round cross section. The operation is the same as conventional rotary swaging except that the dies do not rotate and are configured to conform to a non-round workpiece shape. The machine head does rotate, along with the rack of rollers, so that the rollers strike the back ends of the dies, driving them into the workpiece. The process has the same applications as conventional rotary swaging except that the workpiece develops a square, rectangular, or other non-round cross section.

F2. three-roll forming - See roll bending, section H2f.

F3. stretch forming - involves the stretching of a length of sheet metal (the workpiece) as it is wrapped around a form block. Stretching is achieved with two or more pairs of gripping jaws equipped to provide tension in the sheet. The combination of movement of the forming block and stretching of the material causes the material to be stressed beyond the elastic limit (typically, 2 to 4 percent total elongation). Simple tooling is involved because only a

form block is required and there is no need for close alignment and fit of two die halves. Form blocks can be made of wood, plastics, and cast iron, as well as steel. The method is particularly applicable to large parts with small or modest amounts of forming, but it is not feasible for sharp contours. Tooling is inexpensive, so the method is justifiable for low-quantity production, despite the need to trim off material held in the gripping jaws. The method is best suited for producing shallow contours. Sheet aluminum components for aircraft are a common application, as are sheet steel body parts used in the truck and automobile industries. The method can also be used to make longitudinal bends in roll-formed or extruded sections. It is illustrated in Fig. 2F3.

F3a. stretch draw forming - is stretch forming when a mating female die also engages the workpiece on the form block. This permits more severe forming to take place. Automotive panels and door posts are made with the process. Stainless steel and titanium sheet, as well as the more common steel sheet can be processed. There is material loss and secondary trimming since the material in the grippers is trimmed from the workpiece, as in conventional stretch forming.

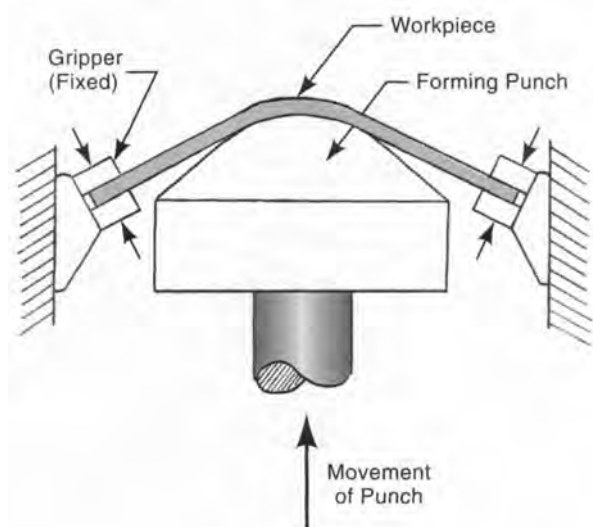


Fig. 2F3 Stretch forming with gripping jaws and a form block. Relative motion between the form block and jaws stretches the material just beyond its yield strength. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

F3b. stretch wrapping (stretch wrap forming) - uses the stretch principle and a rotary table to make stretch-formed parts without scuff marks on the workpiece surface. The rotary table allows the workpiece to be wrapped around the form block without sliding motion between the two. When reverse bends are needed, additional form blocks on the table are utilized. The process with three form blocks is illustrated in Fig. 2F3b. In this illustration, after initial stretching, the table rotates, creating a first bend in the workpiece. Additional movable blocks advance, and the table rotates in either direction, depending on the configuration to be made.

F3c. compression forming - is one of the family of stretch forming operations, but the force,

instead of being used to stretch the material, is used to press it against the forming block. A roller or shoe, machined to match the cross-sectional shape of the workpiece, is used. The workpiece, which can be a metal strip or part with some cross-section, is pressed firmly, with hydraulic force, against the rotating form block. The compression forming method enables small radius bends to be made without exceeding the elongation limits of the outer portion of the workpiece. It also helps maintain the cross-sectional dimensions of the workpiece. The method is similar to stretch forming with a rotating form block except that only one end of the workpiece is gripped and the only workpiece stretching is that which results from the forming. Fig. 2F3c illustrates the process, which is used for vehicle bumpers and various structural members.

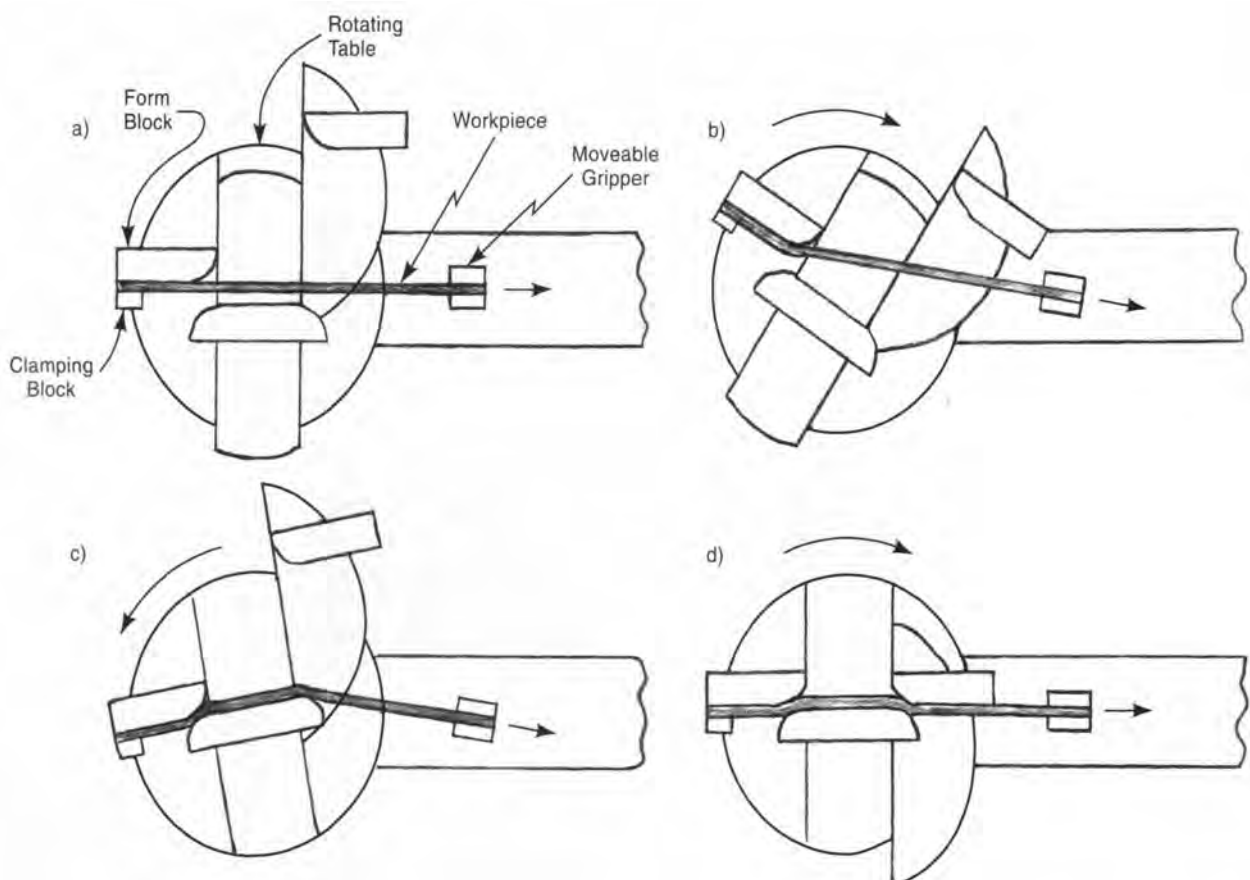


FIG. 2F3b Stretch-wrap forming of a part to make two reverse bends. The operation takes place on a rotary table with form blocks on slides. a) starting position, b) first forming operation, c) second forming operation, d) third forming operation.

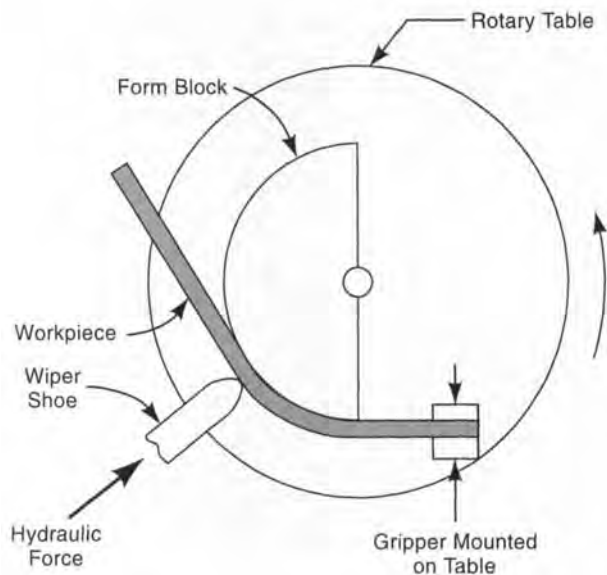


Fig. 2F3c Compression forming. The wiper shoe presses the workpiece against the form block. As the block rotates, bends are made in the workpiece.

F3d. radial-draw forming - is another stretch forming operation. It is similar to compression forming described above except that the workpiece is kept in tension. The method is used in bending extrusions and other workpieces with non-flat cross-sectional shapes. There are three points of application of hydraulic force: on the two ends of the workpiece and on the wiper shoe that presses the workpiece against the form block. Parts with a twist as well as a bend can be formed with this method by incorporating a twisting motion in one of the grippers, at the appropriate time during bending. See Fig. 2F3d.

F4. roll coining - is similar to rotary embossing, described below, in that the work is fed between two opposed rollers that have the desired surface shape. The process can be more rapid than press coining but normally is limited to small parts produced in large quantities from metals of lower yield strength. Interlocking fastener strips, made from jewelry bronze, are an example.³

F5. rotary embossing - Embossing, normally a press operation, can also be performed by passing the work material through a pair of opposed rollers that

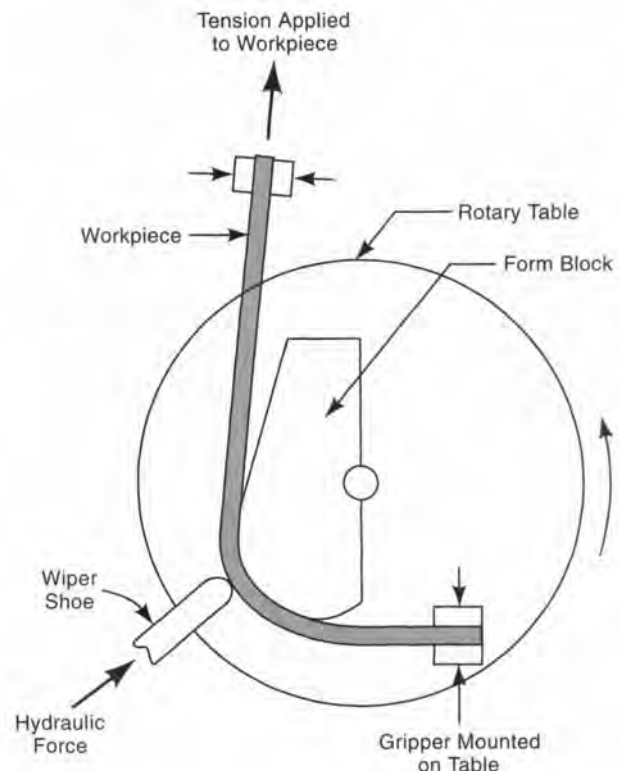


Fig. 2F3d Radial-draw forming. Similar to compression forming but the workpiece is stretched as it is pressed against the rotating form block.

have the desired surface shape. The roller approach is particularly applicable with thinner metals and foils at high production levels, when continuous strip is fed to the rollers and the embossed parts are separated from the strip in a subsequent operation.

F6. metal spinning - is an operation that forms a disc of sheet metal into various seamless circular shapes by pressing it against a form while it rotates. The disc is clamped against a form block of circular cross section, held in the headstock of a lathe, so that the two rotate together. As the disc rotates it is pushed with localized pressure against the form block, with suitably shaped spinning tools, and gradually assumes the shape of the form block. The motion and pressure of the pressing tool can be provided manually or with mechanical power. This method is used in the production of various circular sheet metal objects such as reflectors, lamp bases, bowls, bells, cooking pans, funnels, metal drinking

glasses, and conical parts. Tooling is very simple; form blocks, called “chucks,” can be made from wood, wood fibre, cast iron, steel, or other metals. The operation is therefore economical for prototypes and low-quantity production, particularly when manually powered. Some deeply-formed parts may require several passes, sometimes with blocks of different shapes, before the part is completed. With some metals, annealing between successive spinning operations is required. Intermediate form chucks are sometimes referred to as “breakdown chucks.”

For parts that are narrower at the open end than at the closed end, and other parts with re-entrant contours, a one-piece chuck would be trapped in the part after forming. These shapes can often be produced, however, if a segmented chuck is used, i.e., one that can be removed, piece-by-piece, after the spinning is completed. Another approach, more common with higher production levels, is to use a smaller diameter, off-center, contoured roller, that can be withdrawn from the workpiece after spinning.

Spinning may be combined with deep drawing if the part has considerable depth. Deep drawing takes place first and the part is then spun to its final shape.

F6a. manual spinning - Metal spinning can be performed manually as long as the metal used is thin and ductile enough to respond to manually-applied pressure. Pressure is applied to the workpiece by the rounded end of a wooden or metal (e.g., aluminum-bronze) lever held by the machine operator but supported by a tool rest on the lathe's cross slide. The operator often also uses a “back stick”, a second tool to guide the workpiece material and prevent wrinkling. Lubricants such as: grease, petroleum jelly, beeswax, or brown laundry soap, facilitate the operation. Tooling costs are very low, but skill is required in order to assure uniform results. Sheet steel up to about 1/8 in (3 mm) in thickness can be formed by manual spinning. Fig. 2F6a illustrates the process schematically.

F6b. power spinning , “flow turning” or “shear spinning” - refer to a variety of methods that apply powered forming pressure to the spinning process. Rollers are usually used to contact and shape the workpiece. These methods work the material more severely than hand spinning and reduce its thickness. Heavier parts can be produced

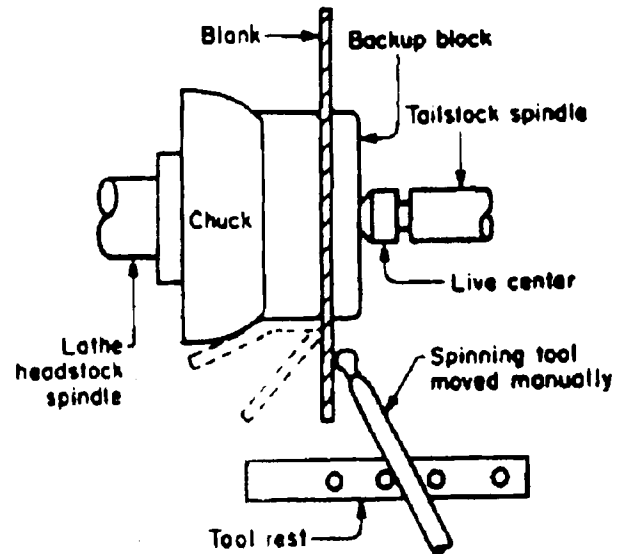


Fig. 2F6a Schematic illustration of manual metal spinning. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

in this way and the operation, with a metal form block, can be applicable to high production levels. However, shapes may be more limited than those attainable with manual spinning. With repeated operations, closed-end cylindrical parts can be produced. The method has been applied to workpieces as thick as 1 in (25 mm) and 240 in (6 m) in diameter³. Typical parts produced are: conical light fixtures, air deflectors, and domed tank ends. In shear spinning, the workpiece metal is subjected to shearing deformation, being pushed ahead of the forming roller and compressed between the roller and the forming block. The operation is illustrated in Fig. 2F6b.

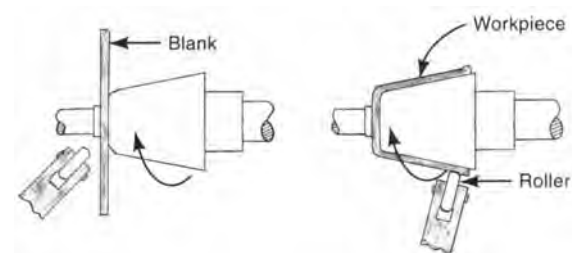


Fig. 2F6b Schematic illustration of power spinning, also known as “shear spinning” or “flow turning”.

F7. roll forming (contour roll forming) - is a method for forming tubing, channels, pipe, roof gutters, siding and roof panels, metal joists and studs, metal picture frames, curtain rods, toy train tracks, decorative strips on railroad cars and trucks, and other shapes of constant cross-section from strip material. The strip is guided through a series of contoured mating rollers, mounted in tandem, which progressively make longitudinal bends in the strip as it passes through the sets of rollers, called "stands". Quite complex shapes can be produced in very long lengths. Only bending takes place; the stock thickness does not change. Typically, from one to 40 stands are employed. The process is an alternative to extrusion in some applications, and is illustrated in Fig. 2F7. Steel and other sheet metals are processed with the method including prepainted and preplated metals in thicknesses from about 0.005 in (0.13 mm) to 3/4 in (19 mm) but standard machines are limited to about 5/32 in (4 mm) thick steel. All metals that can be bent by other methods can be roll formed. The operation is rapid [about 100 ft (30 m) per min and sometimes much faster], and suited to high-volume production. Roll sets must be changed when the section to be produced is changed. When a particular section requires welding, a resistance welding station can be incorporated

at the end of the forming rolls. Notching, piercing, embossing, and other operations can be performed if suitable equipment is added to the roll forming line, though these usually slow the roll-forming operation. Straightening rollers or guides may be placed at the exit end of the machine to correct for any twist distortion that may occur in the operation. Flying cut-off equipment can be placed at the end of the line of rollers to cut the workpieces to the desired length.

F7a. roll forming of tubing and pipe - When tubing and pipe are made by roll forming, a welding unit is incorporated in the process. The metal strip, as it moves through the machine, is formed into a circular cross section. The edges of the strip are brought together as they exit from the forming rolls and are arc or resistance welded together. Typically, 10 pairs of rollers are required to bend, finish, and size the tubing. The welding station normally limits the speed of the operation. An interlocking seam joint can also be produced (with thinner sheet) by the rolling operation. Welded tubing of from 1/4 to 24 in (6.3 to 625 mm) in diameter can be produced⁴. Straightening and cutoff equipment are normally part of the production line.

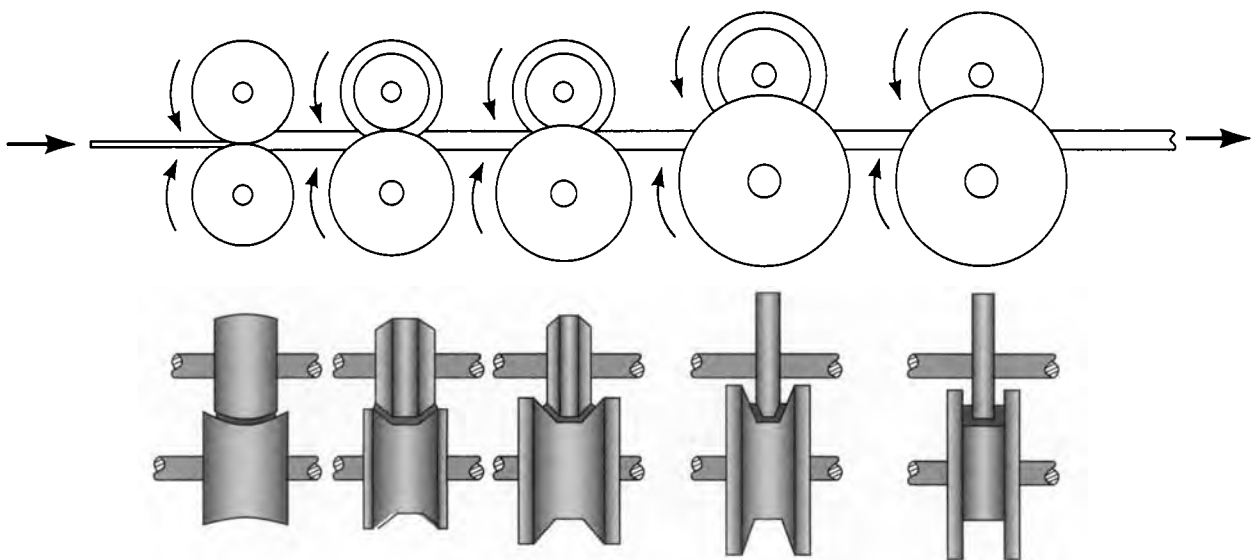


Fig. 2F7 The stages of contour roll-forming a U-shaped channel.

G. Wire Forming Operations

G1. wire forming - Components made from bent and formed wire are useful when an open configuration, such as those used in baskets and fan or machine guards, is required. In many other applications, wire can provide an economical configuration, sometimes with a spring effect incorporated and sometimes as a rigid member. Bending methods used for sheet metal, rod, tube and other cross-sections are normally also applicable when the work-piece material is wire. Other operations that can be performed on wire include swaging, cold heading, resistance, arc or gas welding and threading.

G1a. manual forming of wire parts - Wire can be bent with hand-powered bending brakes, kick presses, or various fixtures with hinged or pivoted elements, since forces required are low. Bending tools similar to tube benders can be used. Hand-bending may be applicable when quantities are limited.

G1b. wire forming in power presses and special machines - All bending operations performed

by presses, press brakes, four-slide machines, and other equipment can be performed, with suitable tooling, on wire workpieces. See sections C1, D1, D2, D12, H2, I2 and K. Additionally, wire is formed into springs of various shapes. (See *springs*.) In high production situations, the wire is fed from continuous coils and is formed and cut off automatically.

G2. forming in four-slide machines - is applicable to parts formed from wire or sheet metal strip. Four-slide machines have a forming area with four press slides set 90 degrees apart and driven by cams. There is also a center post that can be shaped to facilitate forming. Tools on the slides are designed to blank, pierce, notch, bend, form, emboss, and cut off the wire or strip as it progresses through the machine. Mechanisms feed the material (from coil stock) and eject the workpiece where appropriate. Rollers are often positioned on the machine to straighten the stock prior to the blanking or forming operations. One or two small, horizontal punch presses can also be mounted on the machine upstream from the four-slide area to perform additional operations.

Fig. 2G2 shows the layout of a typical four-slide machine for forming one typical part. Very complex

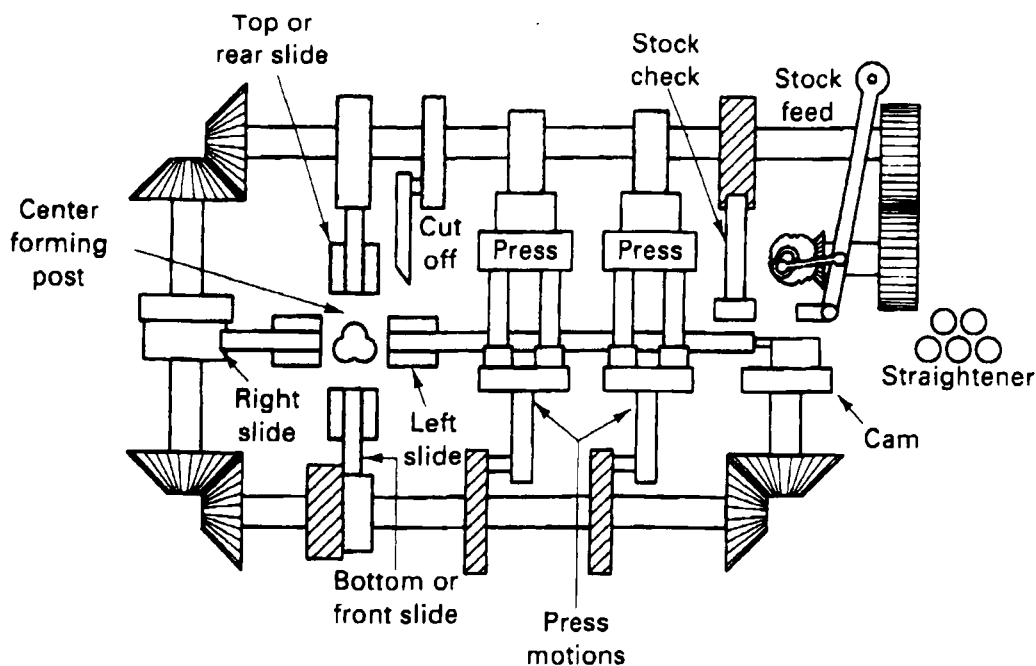


Fig. 2G2 Schematic view of a four-slide machine. Various blanking, punching, forming, and cut-off operations are performed as the stock passes through the machine (from right to left in this illustration). (Courtesy U.S. Baird Corporation, Stratford, CT.)

parts can be produced with this process and they are often completely fabricated in one four-slide operation. Production is rapid, but large lot sizes are needed because set up is lengthy. Resistance welding, and drilling and tapping, are sometimes added to the operation by mounting the appropriate head on the machine. Four-slide parts, though often of quite a complex configuration, are generally on the small size because of machine limitations. Deep draws and severe coining are not normally found. Clips, rings, hooks, bobby pins and electrical contact and switch parts are made with the process.

G3 spring forming - see *springs*

G4. Turk's-head rolling of wire - is used to change the cross-section of round wire. Rectangular, square and special shapes can be imparted to the wire by passing through opposed rollers arranged so that the opening between them is the shape of the cross-section desired. Fig. 2G4 illustrates the roller arrangement used to produce square wire. The operation is rapid, up to about 600 ft (180 m)

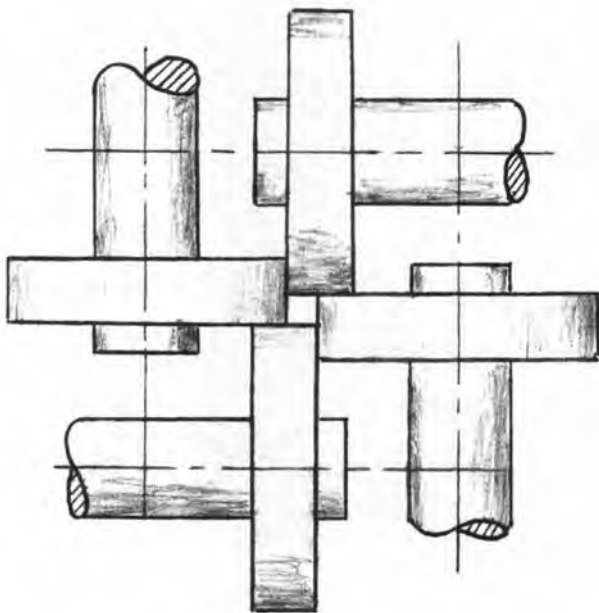


Fig. 2G4 Turk's-head rolling of wire into a rectangular cross-section. By moving the rollers to slightly different positions, rectangular wire can be rolled. Contoured rollers can be used to make wire of other cross-sections.

per minute. Contoured cross-sections can be produced so long as the shape desired can be ground into the rollers.

H. Tubing and Section Operations

H1. tube spinning - Tubes can be spun to provide tapers or flanges by using metal spinning methods similar to those used in spinning sheet metal. Other uses are to thin the walls and increase the strength of tubular members. Internal mandrels are normally used to provide support for the workpiece metal. Hollow mandrels external to the tubing can be used when the tubing is expanded or flared at the end. All ductile metals can be processed with this method. Two different methods can be employed: forward tube spinning and backward tube spinning.

H1a. forward tube spinning - sometimes called tube stretching, is a means for increasing the depth of cooking pots or the length of cylindrical parts or tubing. The diameter is constant. The power-spinning method is equivalent to shear spinning, and forces the metal to flow axially along a mandrel, increasing the length of the workpiece while decreasing the thickness of the sidewalls. The forming tool moves in the same direction as the lengthening of the workpiece, away from the headstock of the spinning lathe, as illustrated in Fig. 2H1a.

H1b. backward tube spinning - is the same as forward tube spinning except that the forming tool moves in the direction opposite to that of the expansion of the workpiece. ie., it moves toward the headstock of the spinning lathe and the workpiece metal flows away from the headstock as shown in Fig. 2H1b. This arrangement enables the tool travel distance to be less than the eventual length of the workpiece because the workpiece material flows along the mandrel beyond the forming roller. However, distortion can take place in the workpiece.

H2. tube and section bending

H2a. draw bending - is used in bending tubing, sections, and bars. The workpiece is held against a bending form by a shaped clamp. As the bending

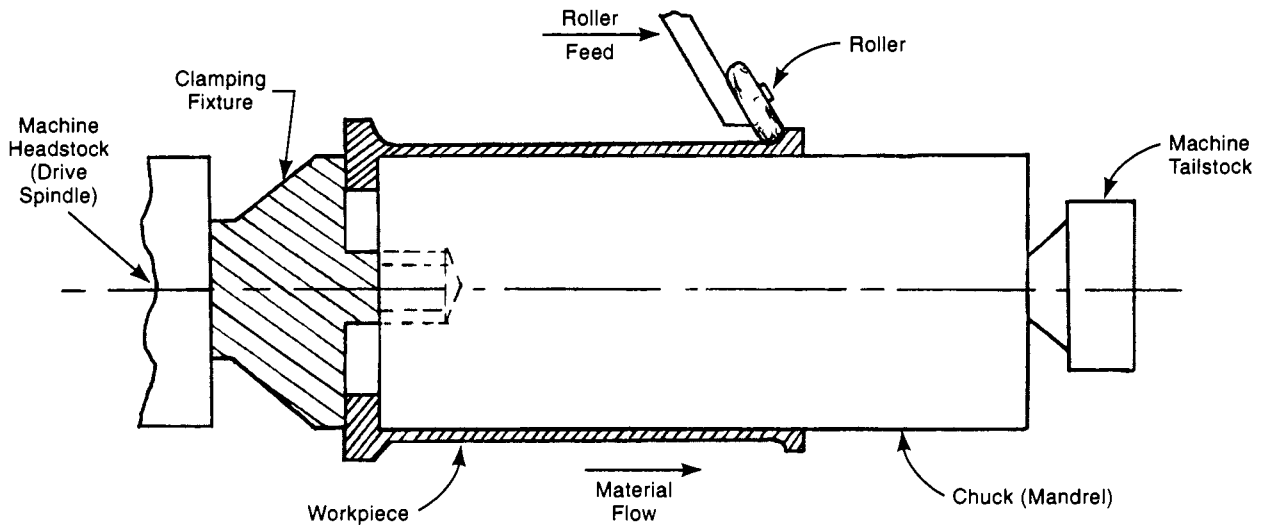


Fig. 2H1a Forward tube spinning. The illustration shows the second or third pass of several required, the number depending on the metal used and the length and wall thickness desired. An opposing roller used to balance forces is not shown in this illustration.

form and clamp rotate together, the workpiece is pulled or drawn around the form and against a pressure die whose form also matches the cross section of the workpiece. The pressure die can be either stationary or movable along its longitudinal axis.

An accurate bend is produced by this method, which is illustrated in Fig. 2H2a. Internal mandrels may be used to prevent or minimize flattening. Typical flexible mandrels are illustrated in Fig. 2H2a-1. The operation is often power driven, and ultrasonic

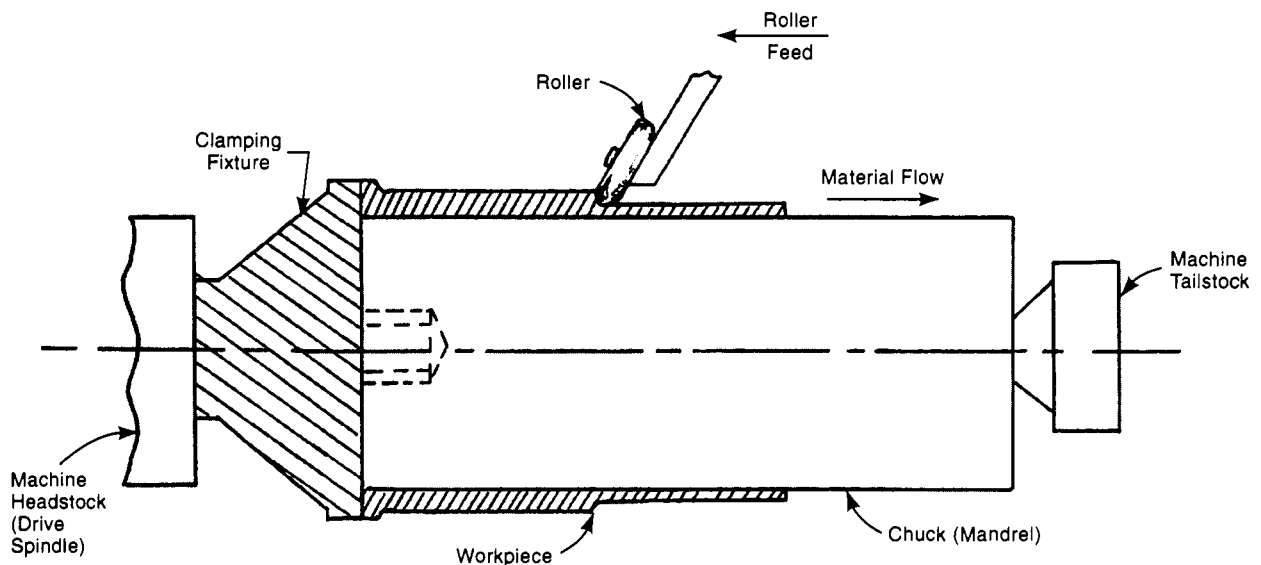


Fig. 2H1b Backward tube spinning. The material flows in the opposite direction from that of the pressure roller. The illustration shows the second pass of the roller. An opposing roller used to balance forces is not shown in this illustration.

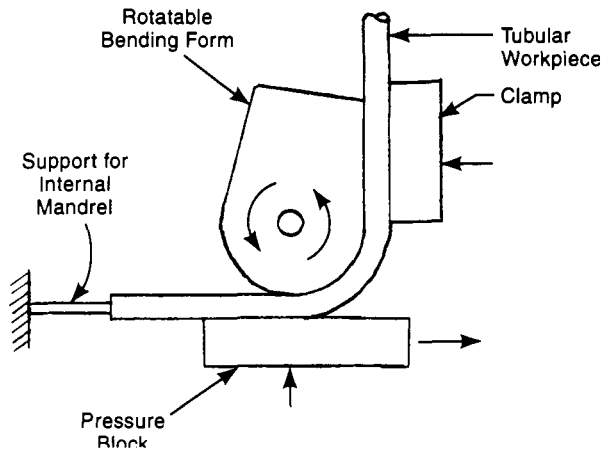


Fig. 2H2a Draw bending of tubing. The form block rotates with tubing clamped to it. A mandrel is often used to prevent collapse of the tubing.

vibration may be applied to the tooling or workpiece to reduce friction. The method is applicable to tubing of 1/2 inch to 10 in (12 to 250 mm) in diameter and bends to 180 degrees. Draw bending provides better control over the workpiece shape than other tube bending methods. With use of a

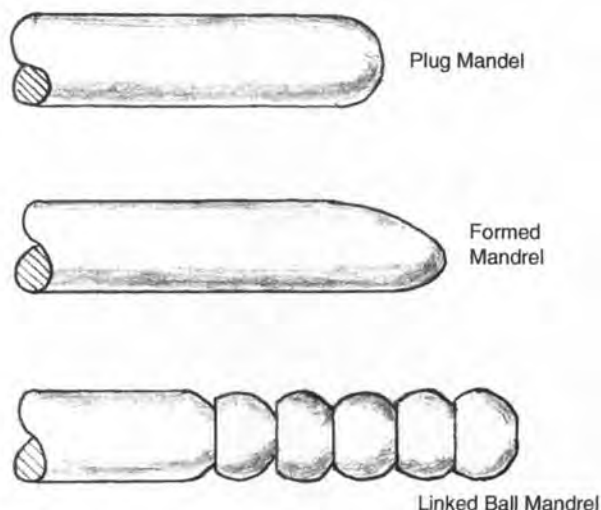


Fig. 2H2a-1 Mandrels used in tube bending to prevent collapse of the tubing during bending. The linked balls in the mandrel shown at the bottom can pivot to provide support to the tubing wall throughout a tight precision bend.

mandrel and care in the operation, thin-walled tubing can be bent with little wall collapse to a center line radius as small as one tube diameter.

H2b. compression bending - is similar to draw bending, but the forming block and clamp do not rotate. Instead, the pressure die is replaced by a wiper shoe or fitted roller which moves along the periphery of the stationary bending form, causing progressive bending of the workpiece. No internal mandrel is used. Except for the outer surface, the tubing is subjected to some compressive stress. The operation is normally manually powered. The method is less applicable to thin-walled tubing than draw bending.

Center-line bend radii as small as about 2.5 times the tube diameter are possible, but 4 times is a more common minimum. Bends in tubing to 170 degrees are feasible. The method is useful when multiple bends in a workpiece are close together, but bends may have more distortion than draw bends made with a mandrel. Painted tubing can be compression bent because there is little stretching of the outer surface. Fig. 2H2b illustrates the process.

H2c. ram-and-press bending - is a method applicable to tubing, bar, and other sections, and is illustrated in Fig. 2H2c. A forming block is attached to the ram of a hydraulic press. Wing dies below the ram hold the tubing and pivot to wrap it

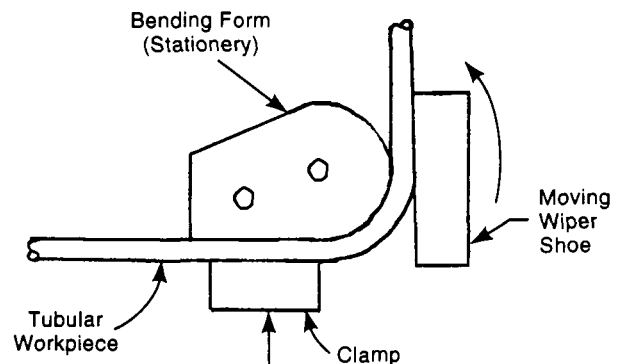


Fig. 2H2b Compression bending of tubing. A moving tool compresses the workpiece against a stationary form. (from Schey, *Introduction to Manufacturing Processes*, McGraw-Hill, New York, 1987)

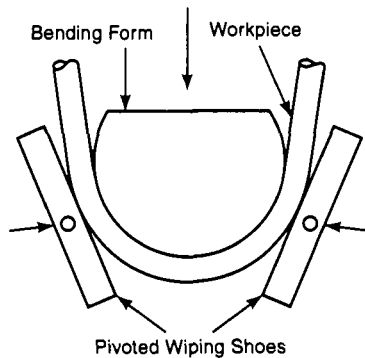


Fig. 2H2c Ram-and-press bending. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

around the forming block as the press ram descends. A wiping action of the wing dies controls the flow of metal and provides a compression bend. The length of the press stroke determines the angle of bend. Typically, hydraulic presses, in which the press stroke can be stopped at any point, are employed. No mandrel is used. There is less control over the workpiece than that provided by draw or compression bending, but the operation is relatively rapid. This method can be used to make successive bends if the tubing is repositioned between press strokes. Bends to 165 degrees can be made. Automobile exhaust pipes and other tubing components used in large quantities are commonly bent by this method.

H2d. stretch bending - The stretch forming method for sheet metal, described above in section F3, also is applicable, with variations, for bending of tubing and other sections. The workpiece is stretched longitudinally to the yield point and then is wrapped around a bending die or form. A mandrel is not needed, but the method is not rapid. It is applicable to bends of non-uniform radius. More than one low-angle bend can be made in one operation. The ends of the workpiece may have to be trimmed off after the bending operation because of distortion from the gripping jaws that provide the stretching tension. One common application of the process is the bending of structural members made from angle or channel sections when such members require a curved shape. The frames of

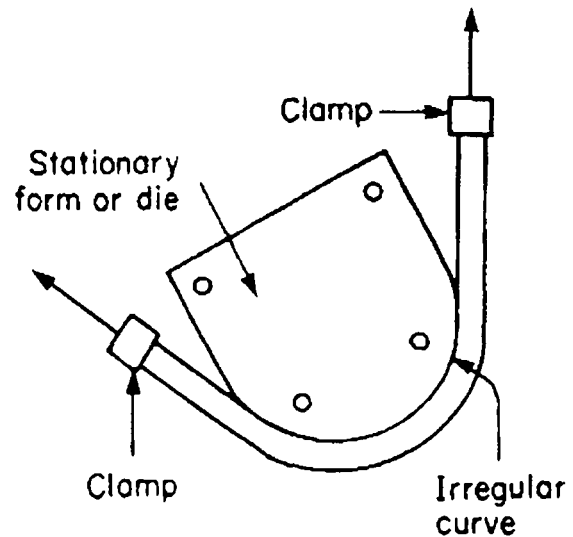


Fig. 2H2d Stretch bending of tubing. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

rockets and other aerospace vehicles are bent this way. See Fig. 2H2d.

H2e. wrinkle bending - is a method for bending large, heavy-wall, tubing or pipe. It is applicable to field conditions since it can be done by hand with no special tooling. One side of the tubing is heated locally by gas torch to the point where the tubing wall softens. A compressive force is applied to the pipe, causing the soft area to wrinkle and the tubing to shorten on that side, producing a shallow bend. The operation is repeated at another point a short distance from the first wrinkle and then successively until the desired degree of bend has been achieved.

H2f. roll bending - is a means of putting gentle bends in tubing, pipe, bars, rolled or extruded shapes, plates and sheets. It is illustrated in Fig. 2H2f. Usually, three parallel rollers are provided in a triangular arrangement with the lower two being mechanically driven. The third is placed above and between them at a height that can be varied, depending on the diameter or thickness of the workpiece and the desired degree of curvature. This upper roller usually is not power driven. Sometimes, more than three rollers are employed. When workpieces

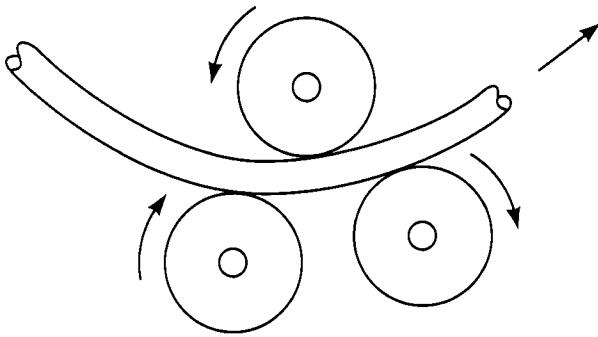


Fig. 2H2f Roll bending of tubing.

other than sheets or plates are bent, the rollers are grooved to fit the cross section of the workpiece. When used for pipe or tubing, the process is limited to heavier-walled workpieces with bend radii usually not tighter than 6 times the diameter though 4 times is possible. Pipe up to 8 in (200 mm) in diameter can be bent with this method. Rings and coils can be produced. When the process is used with sheet metal, a common application is the production of cylindrical parts.

H2g. roll extrusion bending - This method is used for large, heavy-walled pipe. One wall of the pipe is swaged from the inside, causing it to elongate and the pipe to bend. Pipes of 5 to 12 in (125 to 300 mm) can be bent with this method to a minimum bend radius of 3 times the diameter. Successive bends in different planes can be made with this method but a straight section must be allowed between bends.

H2h. bulging, mechanical - is an operation that expands a portion of a tubular or cylindrical part. When done mechanically, a segmented die - with segments held together by springs - is inserted into the tubular part. During the press stroke, a tapered punch pushes the segments apart and they, in turn, push out the walls of the workpiece. The process produces a patterned expansion (flat spots around the tubing) because of open spaces between the die segments when they are expanded. These flat spots can be minimized by rotating the segmented die and repeating the operation. However, the method is otherwise straightforward and well suited to production conditions.

H2i. bulging, hydraulic - expands tubing, pipe, or a cylindrical part, by applying internal force with a pressurized liquid or an elastomer (low-durometer rubber or polyurethane) punch. The workpiece is contained by a die that is split so that the bulged part can be removed after the operation.

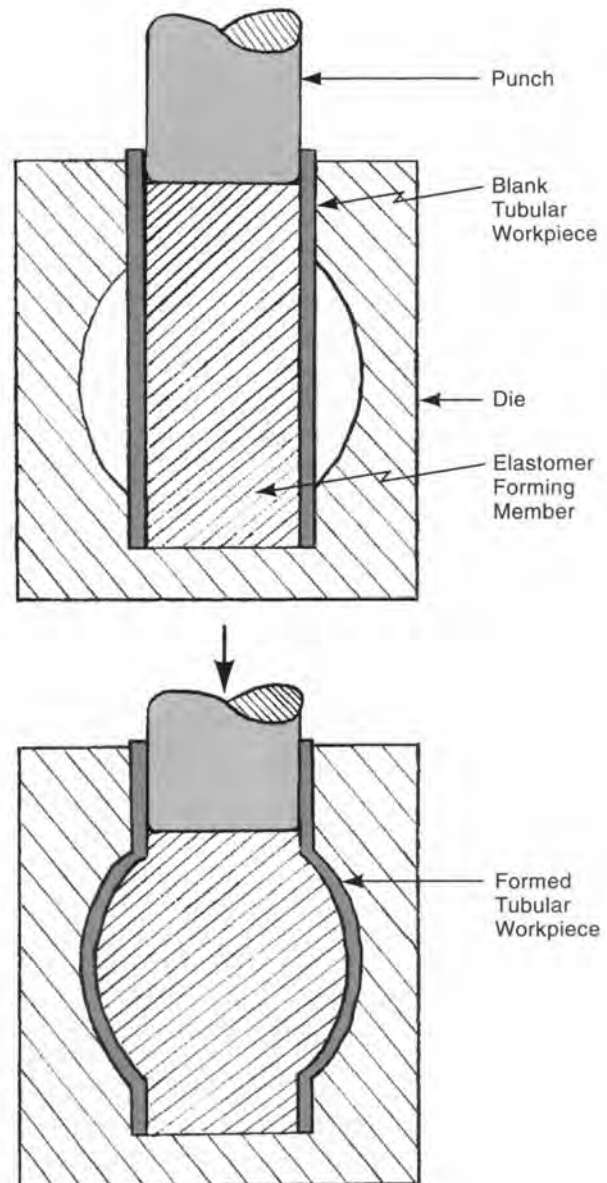


Fig. 2H2i Hydraulic bulging of tubing with an elastomer. The elastomer is deformed by the descending punch and forces the tubular workpiece outward into the die.

With direct hydraulic forming, the tubing is filled with water, sealed at the ends, placed in the die and pressurized. Water pressure forces the tubing walls outward to conform to the shape of the external die. With the other variation, an elastomer punch is commonly used since there are no leakage problems with it and it is wear resistant. As the press ram bears against it, the elastomer deforms but does not compress significantly; the compressive force of the press is transferred outward, forming the workpiece. When the press ram withdraws, the material springs back to its original shape and can be removed from the workpiece. Fig. 2H2i illustrates hydraulic bulging with rubber or polyurethane.

H2j. *other methods of bulging tubing* -

Most of the high-energy-rate forming methods described in section J can be employed to expand tubular workpieces.

I. Non-sheet Forming Operations

I1. *shearing of bars and other non-flat shapes* -

Alligator shears (see Section C1b), are commonly used for shearing bars and other sections to length. Guillotine shears, vertical presses, permanently fitted with short shear blades, are another alternative in shops where there is much bar shearing. The blades of guillotine shears may be notched or grooved to aid in maintaining the location of the workpieces during cutting.

I2. *cold heading* - a process for *upsetting* (enlarging and shaping) the end of a rod, wire, or bar. It is commonly used for the production of bolts, rivets, nails, and screws, and is illustrated in Fig. 2I2. One or more blows of a heading tool against the end of a rod or bar displace some portion to change its shape and enlarge its diameter. Material is usually fed from coil stock. The material upset is that portion of the workpiece that extends from a stationary die. A series of blows with different punches may be required in order to produce the desired head shape. As can be seen in Fig. 2I2, upsetting can take place in the punch, in the die, in both the punch and die and between the punch and die. Production rates can exceed 500 parts per minute. The part is cut off by shearing

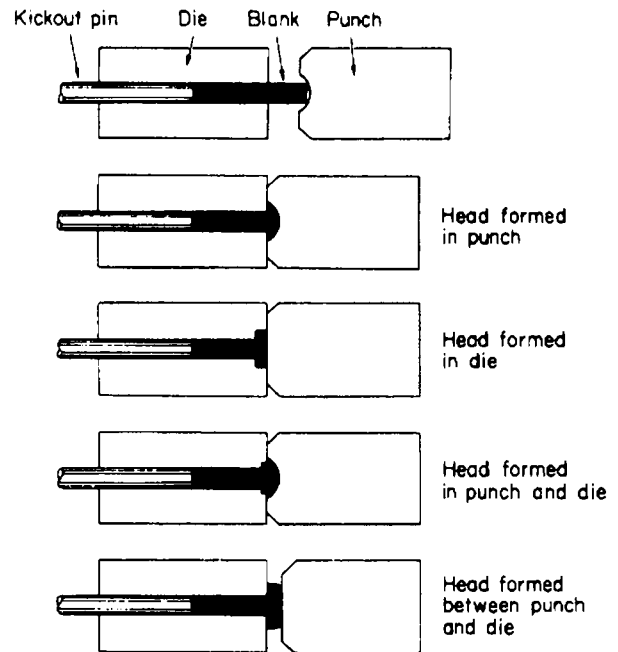


Fig. 2I2 Cold heading. Upsetting the end of the workpiece material can be achieved by a moving punch, in the stationary die, or in both punch and die and between the punch and the die. (Courtesy National Machinery Company)

either before or after heading, and other operations may be performed after heading, often automatically when the production quantities are large. Machining, bending, and flattening are examples, but thread rolling is probably the most common accompanying operation. No material is wasted in the operation, burrs are not produced and grain flow provides improved mechanical properties. Although fasteners are the major application, a wide variety of parts of different shape can be formed in this process. Valves, knobs, rollers, shafts, spark-plug bodies, gear blanks, and hose fittings are examples. Upsetting within the length of the part rather than the ends is also possible. Cold heading is particularly economical when production quantities are large. The operation can be performed upon heated workpieces if the material involved is difficult to form or work hardens quickly. The operation then is referred to as warm heading. High carbon steels and austenitic stainless steels may be processed with this approach.

I3. **thread rolling** - See screw threads.

I4. **impact/cold extrusion** - forms a part of some length by plastic flow of metal under compressive stress into an opening of limited size. The process is normally referred to as *impact extrusion* when non-ferrous metals are involved and *cold extrusion* when the workpiece is ferrous. A blank is placed in the die and a punch puts pressure on the blank, causing metal to flow in the desired direction. The press used can be either mechanical or hydraulic. With the rapid force of a mechanical press, the term, "impact extrusion" is appropriate. There are three varieties of the process: forward extrusion, backward extrusion and combined extrusion. Impact/cold extrusion produces parts with smooth surfaces, with no loss of material in the form of machining chips. The process is fairly rapid and is suitable for mass-produced components used in

quantities of 100,000 pieces per year or more. Cylindrical and near-cylindrical shapes are typical parts made with the process. Collapsible metal tubes are made with the process. Aluminum, copper, lead, and magnesium alloys are the most commonly extruded, along with low and medium-carbon steels.

I4a. **backward extrusion** - In this process, shown in Fig. 2I4a, a metal blank is placed in the die, and the metal is compressed by the punch and forced to flow backwards around the punch to form a hollow object. The side wall thickness of the part depends on the amount of clearance between the punch and the die. Depending on the shape of the bottom of the punch and the bottom of the die, various shapes at the closed end of the part can be produced. The thickness of the base depends on the press stroke and is independent of the wall

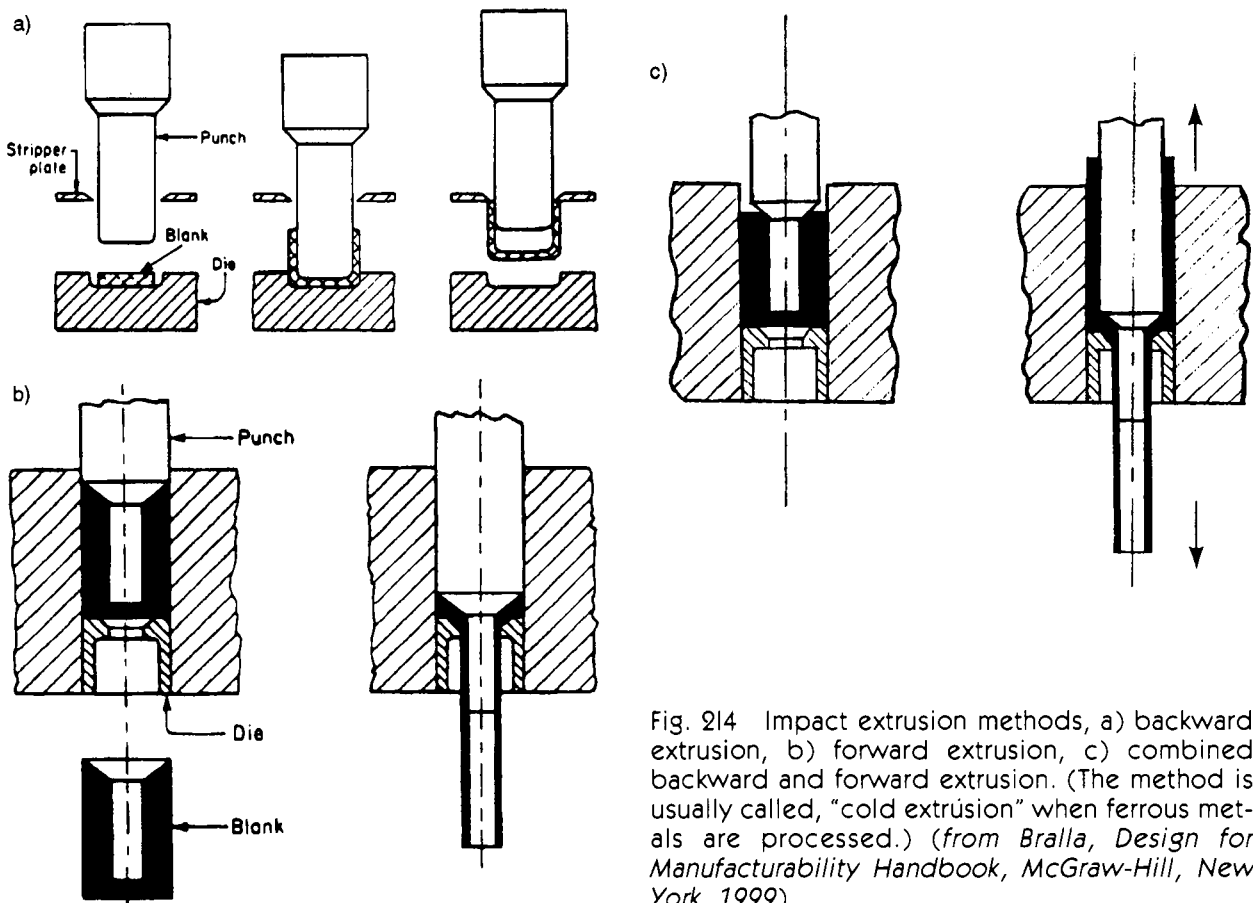


Fig. 2I4 Impact extrusion methods, a) backward extrusion, b) forward extrusion, c) combined backward and forward extrusion. (The method is usually called, "cold extrusion" when ferrous metals are processed.) (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

thickness. The process is most frequently used with softer non-ferrous metals such as zinc, lead, tin, and aluminum to form cans and collapsible tubes for toothpaste, paint pigments, shaving cream, and other materials.

I4b. forward extrusion - In this process, sometimes called the *Hooker process*, the workpiece metal flows forward (normally downward) through an orifice rather than upward around the punch. A close fit between the upper portion of the punch and the die prevents the upward flow. Hollow parts are produced by providing clearance between lower portion of the punch and the die orifice. The process differs from conventional extrusion described above in section A3 in that, with this method, a discrete part is produced that has one end closed or is of a particular shape. However, open- or closed-end tubes can be produced with the process. The operation is also sometimes part of a sequence that also involves cold heading. Preformed blanks are often used to provide a desired shape in the finished part. Fig. 2I4 (view b) shows the process.

I4c. combined extrusion - is both forward and backward impact extrusion at the same time on one part, as shown in Fig. 2I4c. The backward extrusion can have a different solid or hollow shape than the forward extrusion. Typical parts have a central flange with different cross sectional shapes above and below it. Fig. 2I4 (view c) illustrates the process.

J. High-energy-rate Forming Methods

HERF methods, sometimes referred to as HVF (*high velocity forming*) methods are useful in the forming of large workpieces and difficult-to-form metals through the application of large amounts of energy in a very short time period. These processes are characterized by the high velocity of the forming action (more than 50 feet per second⁴) and the use of a pressure wave rather than a forming punch to effect the change in the workpiece (except for pneumatic-mechanical forming described below). Energy is supplied by explosive charges, detonation or combustion of gas mixtures, spark discharge, exploding bridge wire, electromagnetic pulses, and the sudden release of compressed gas.

Water may be used to transmit the shock wave. Except for pneumatic-mechanical forming, tooling and equipment are relatively simple and less expensive compared to that required with more conventional forming methods. The processes are often advantageous for prototype and limited quantity production. However, safety aspects of the process used must be dealt with.

J1. explosive forming - uses an explosive charge to provide the energy necessary to effect the forming operation. Normally, the explosion takes place in water and the water pressure then forces the workmetal against the die walls, but rubber, sand, glass beads, oil, molten salts, and air can also be used as a pressure transfer medium. (Air is an inefficient medium.) The pressure wave travels at several hundred feet per second. Only a female half die is required to form depressed shapes. For short-run production, dies made of concrete, fiberglass/plastic, sheet metal, or cast epoxies can be used. Another advantage is that there is little or no springback after the operation. Fig. 2J1 illustrates explosive forming, a) with a water medium and free forming and b), with a confined system. One common application is the forming of steel plate components for large storage tanks. Blanks to 13 ft (4 m) in diameter have been formed with this method. The method is useful when the workpiece material, eg., stainless steels, have work hardening properties. Most such operations are performed outdoors. The tank used to hold the medium must be strong enough to withstand the force of the explosions. The explosive charge is sometimes affixed to the workpiece ("contact operation") and sometimes separated from the workpiece ("standoff operation") as illustrated in Fig. 2J1.

With smaller parts, a confined system can be used. This is one which has a die that completely encloses the workpiece. The method is practical for forming and sizing tubular parts and other smaller parts where the cost of a fully-enclosing die is not too expensive. Applications for explosive forming include aircraft and jet-engine components, ducts, panels, and housings⁵.

J2. combustible gas forming - With this HERF process, hydrogen, methane, or natural gas, mixed with air, oxygen, or ozone, when ignited, provide the pressure wave that forms the sheet metal workpiece.

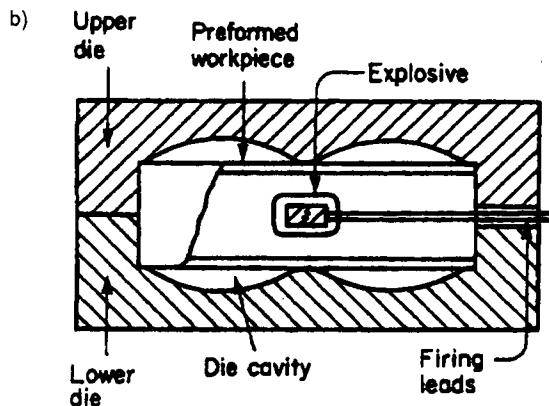
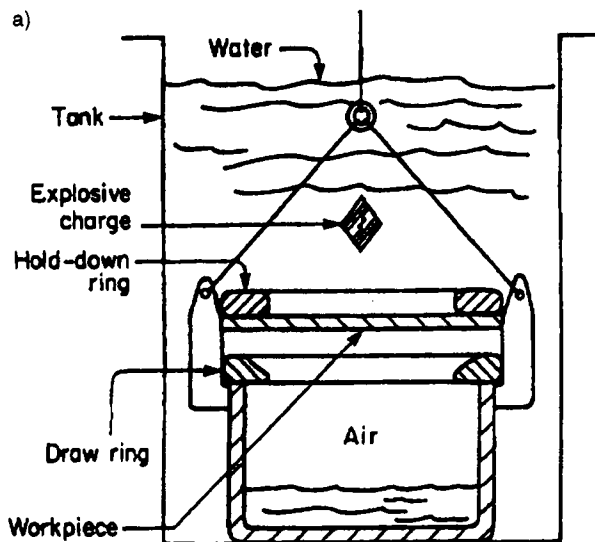


Fig. 2J1 Typical explosive forming arrangements: a) free forming with a water medium and b) with a confined system. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

The speed of the pressure wave is considerably less than when high explosives are used, and its duration is shorter but still measured in milliseconds. The pressure wave occurs in the ignited gas rather than in water or some other medium. The process is more suited for in-plant operation and for larger production quantities than high-explosive forming. More complex shapes can be produced. Large parts of sheet metal are feasible. Fig. 2J2 illustrates the process.

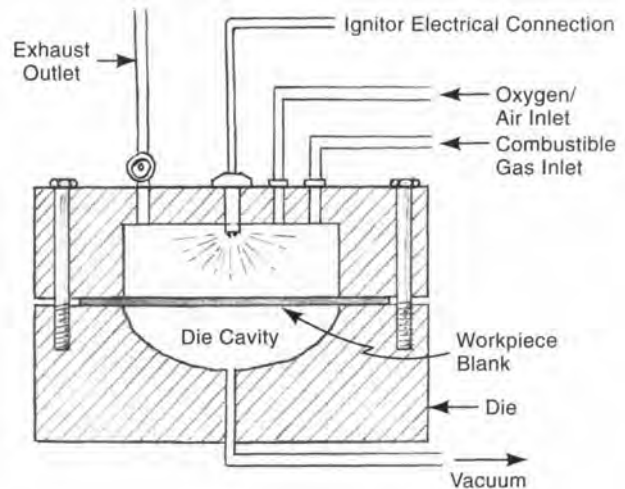


Fig. 2J2 Typical arrangement for combustible gas forming.

J3. electromagnetic forming (EMF) (also known as **magnetic-pulse forming**) - uses the electromotive force generated by a sudden electromagnetic pulse to form conductive sheet metal workpieces. A magnetic coil, placed adjacent to the workpiece, is subjected to sudden electrical current flow from the discharge of a bank of capacitors. The magnetic field thus produced in the coil induces a secondary current in the workpiece and there is a repulsive force between that current and the primary current in the coil. This repulsive force drives the workpiece metal against the die or other part and stresses it far beyond its yield point. There is no contact between the coil and the workpiece, and the magnetic energy will pass through non-conductive materials such as fibre, rubber, plastics, etc. The operation works best with highly conductive workpiece materials such as copper, brass and aluminum. Low-carbon steel can also be processed. Materials of low electrical conductivity can be formed if a "driver", a sheet of conductive material, is placed between the coil and the workpiece. Equipment consists of a storage capacitor, a power supply to charge the capacitor, and switches. The magnetic pulse lasts only 10 to 100 μ s. One common application is to contract (swage) tubing around fittings or tubular fittings around pipe, cable, or hose. This requires a coil around the part to be swaged. In all electromotive forming, the coil must be physically strong enough to withstand the

repulsive force, but otherwise, tooling is simple and inexpensive. The operation is illustrated in Fig. 2J3. It can be used for embossing, forming, expanding tubing, piercing, and blanking, as well as swaging, but there are limitations to the complexity of shapes that can be produced.

J4. spark-discharge forming (electrospark forming) - Both this method and electrohydraulic forming, described below, use electrical energy stored in a bank of capacitors to create a shockwave, which is transferred through a liquid medium. In spark-discharge forming, the energy released is in the form of a spark across two electrodes. Switching circuits instantaneously discharge that energy to the two electrodes. The intense energy emanating from the spark sends a shock wave

that forces the workpiece material against the die walls. The equipment set up is similar to that depicted in Fig. 2J1 a) and b) except that the explosive charge is replaced with spark discharge. The liquid medium used must be non-conductive because the electrodes generating the spark are in the same liquid. The use of a spark discharge permits careful control of the energy intensity. Repetitive cycles can be employed without removal of the workpiece when successive blows can aid the forming operation. Tooling and equipment costs are low so the process can be economical even with small production quantities.

J5. electrohydraulic forming - is very similar to spark-discharge forming except that the energy is released from an exploding bridgewire connecting

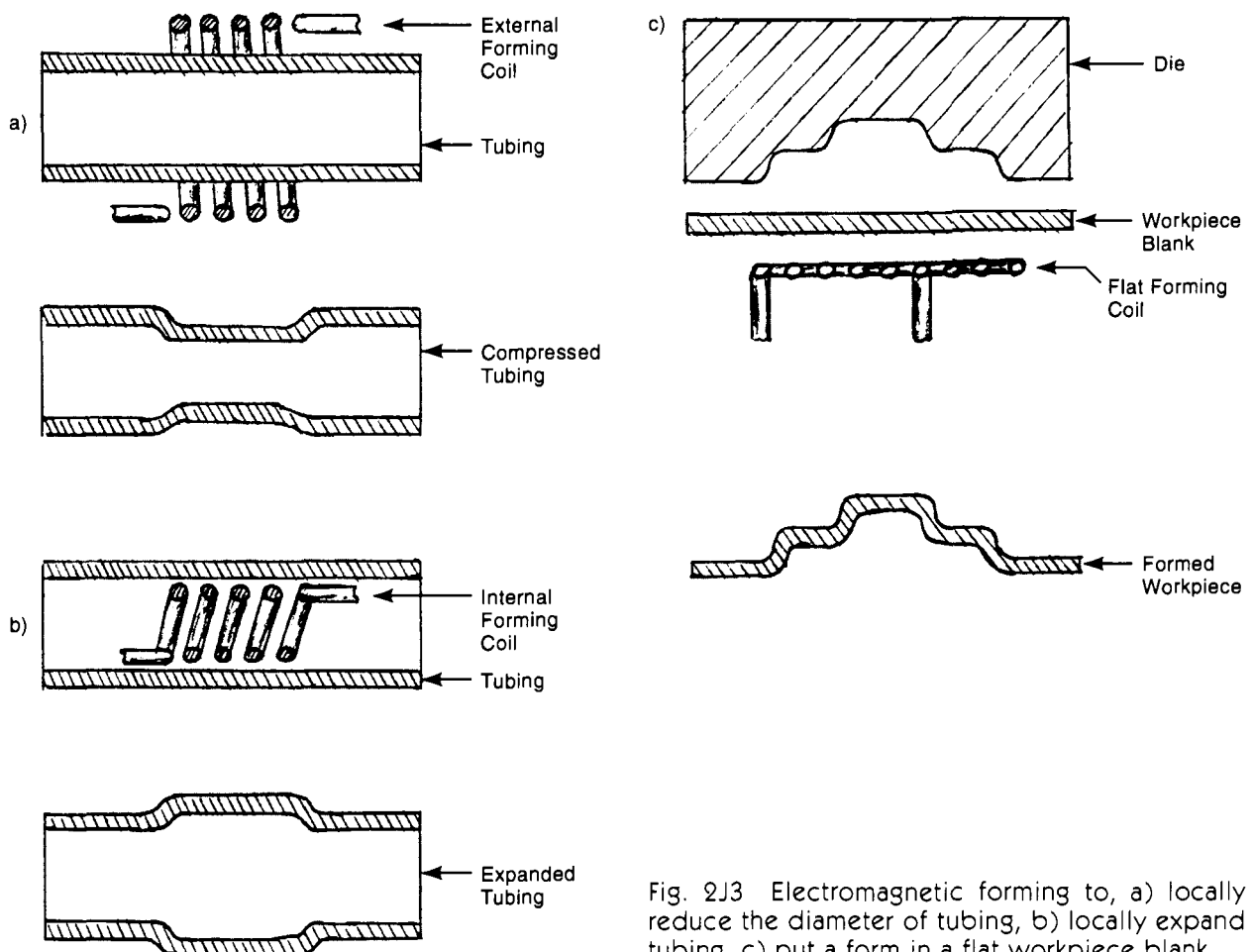


Fig. 2J3 Electromagnetic forming to, a) locally reduce the diameter of tubing, b) locally expand tubing, c) put a form in a flat workpiece blank.

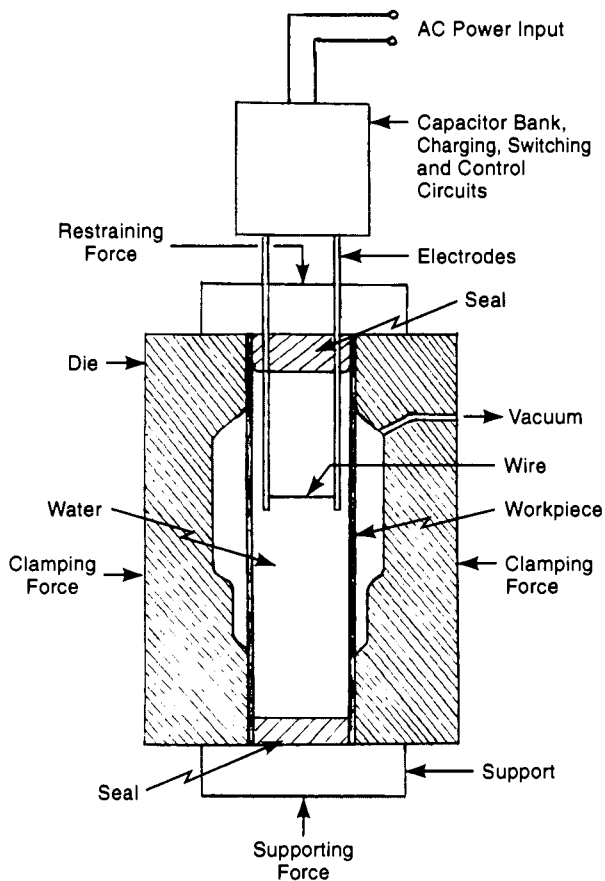


Fig. 2J5 Tooling arrangement for use of electro-hydraulic forming to change the shape of a tubular workpiece.

two electrodes. Water transfers the force that forms the workpiece. The operation cannot be repeated as easily as spark-discharge forming but it does provide somewhat greater forming force. The process, illustrated in Fig. 2J5, is most suited to expansion forming of tubular parts. The process is effective; however, if the operation can be performed by more conventional methods, they are usually more economical.

J6. pneumatic-mechanical forming - can be considered a variation of drop hammer forging. Compressed gas stored in a pressure tank, or the energy released in the form of gas from combustion of a fuel-oxidizer mixture, is used to drive the press ram to a high velocity, two to ten times that of conventional drop hammers⁴. The best application of

the process is the forging of parts having thin vertical dimensions and a high level of detail. The process is advantageous with workpiece materials of high unit cost when the forging can be produced in sufficient detail so that material wastage is minimized. Otherwise, conventional forging will probably be more economical.

J7. peen forming - is a forming process that does not require any dies and can be performed at room temperature. Sheet metal is impinged on one surface with a stream of metal shot as illustrated in Fig. 2J7. Each shot piece acts as a very small hammer stroke, compressing the surface vertically but elongating it horizontally. The shot is delivered by either nozzle or centrifugal wheels. The total effect is the generation of a gentle compound convex curve. The process is useful when the form required does not involve abrupt curvature changes. It is used in the aircraft industry to produce wing panels. An advantage is that both the top and bottom surfaces have residual compressive stresses, which aid in providing fatigue strength. Workpieces with some reinforcing structure can be processed. Sometimes a preload is applied to the surface to assist in producing the desired final shape. Aluminum sheet from 0.050 to 0.200 in (1.25 to 0.5 mm) and steel from 0.016 to 1.00 in (0.40 to 25 mm) thickness can be processed.

K. Straightening

Straightening is required when the workpiece material is not in the form required for subsequent operations (eg., coiled rather than straight) or has undergone some deformation from stresses induced by prior operations. Several methods are available.

K1. manual straightening - covers a variety of operations performed with surface plates, levers, vises, anvils, hammers, twisting tools, grooved blocks, and heating torches. Typically, the workpiece is clamped at one end or where there is no deformation, and the deformed portion is moved in the opposite direction of the distortion. The workpiece is overbent so that it springs back to a straight orientation. Hammer blows or heat sometimes aid in the process.

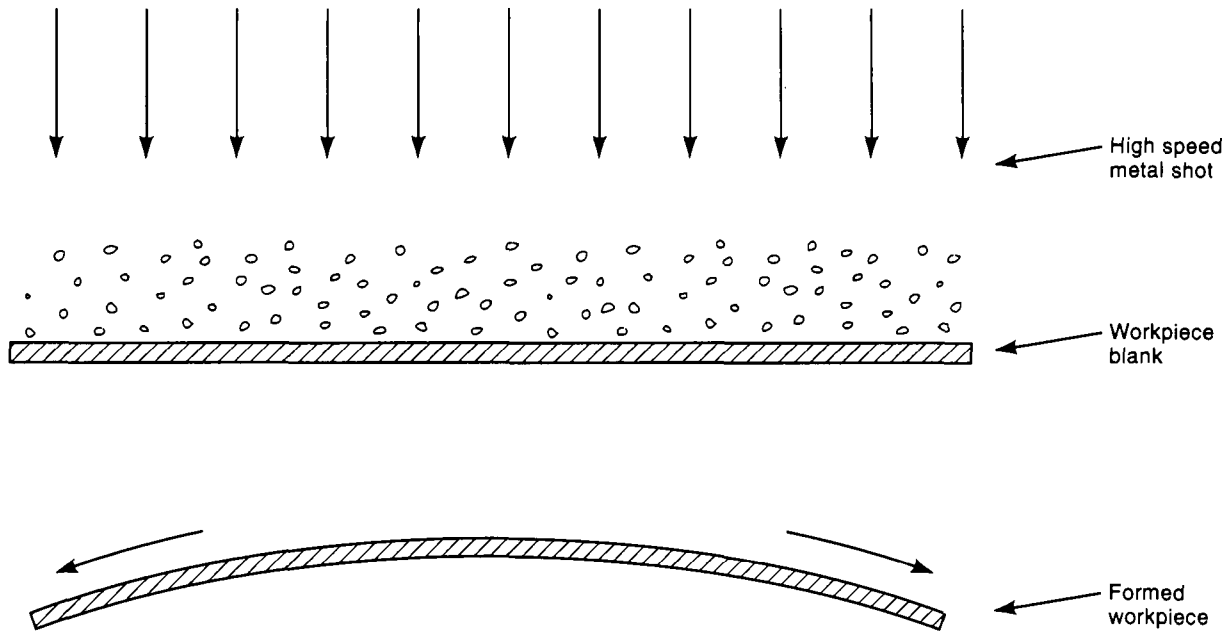


Fig. 2J7 Peen forming. High velocity shot striking the upper surface elongates the metal grains of a sheet and creates a convex shape.

K2. press straightening - uses an arbor or hydraulic press to make the corrective bends. Typically, the deformed workpiece is placed on support blocks in the press bed so that the convex area is on the upward side. The ram descends and bends the workpiece in the opposite direction far enough so that the elastic limit of the material is exceeded. If done properly, the workpiece will spring back to a straight position. Indicators and blocks may be used to find the high points in the deformed areas and to measure the effect of press strokes. Heat may also be applied to the area of deformation. The process works best with materials of Rockwell C hardness less than 40³.

K3. parallel roll straightening - illustrated in Fig. 2K3, is used on sheet, rod or wire. A series of parallel rollers on opposite sides of the workpiece subjects the workpiece to progressively decreasing reverse bends as it passes through the rollers. As the metal is bent back and forth, it is stressed slightly beyond the yield point, exiting from the rollers with a reasonably flat or straight shape. The operation is rapid since it is continuous.

K4. rotary straightening - is a method for straightening round rods and bars. It uses two or more rollers with axes at an angle to each other and at an angle to the axis of the part. One of the

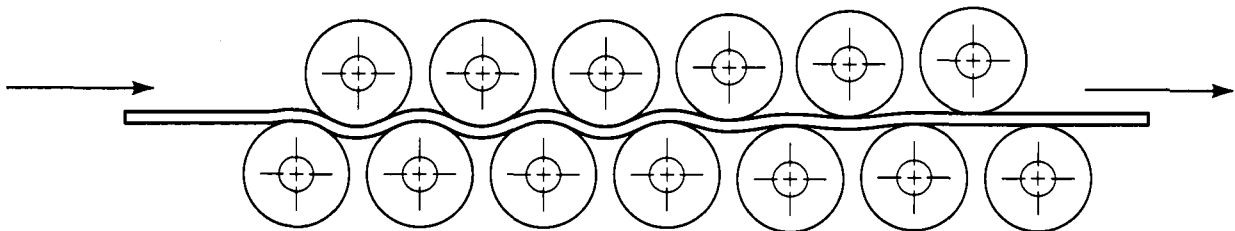


Fig. 2K3 Straightening of workpiece material by passing it through a set of straightening rolls that reverse-bend it a gradually decreasing amount as the material passes through.

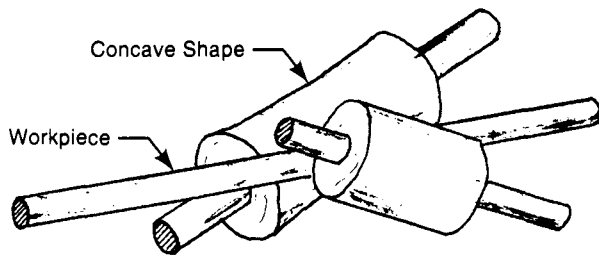


Fig. 2K4 Rotary straightening of bar material. The workpiece moves axially. Alternating compressive and tensile stresses straighten the workpiece. (Guides for the workpiece are not shown.)

rollers has a concave shape, as shown in Fig. 2K4, while the other is cylindrical. There are guides to position the direction of the rod to be straightened. Both rollers are driven and they rotate the workpiece and cause it to move axially. As the workpiece moves, the curvature of the concave roller(s) puts the workpiece surface into alternate stresses of compression and tension. The angles of the rollers and the pressures that they apply are both adjustable. The method is particularly applicable to short workpieces that are more difficult to straighten by other methods. Workpieces of from 1/16 to 10 in (1.6 to 250 mm) long have been straightened with this method³.

K5. *epicyclic straightening* - is a proprietary process for straightening axles, tubular driveshafts, and propeller shafts, I-beam and other sections, and symmetrical forgings. The workpiece is supported on its ends and is rotated. A powered arm, attached to the center of the workpiece, deflects the center of the workpiece so that it is stressed in all directions beyond its elastic limit. The powered arm reduces the magnitude of deflection gradually so that the neutral axis of the part describes either a circular or elliptical spiral toward the center.

K6. *stretch straightening* - The workpiece is gripped mechanically and stretched in a straight line beyond the yield point. Twist deformation can also be corrected; when this is needed, the workpiece is reverse-twisted when it is stretched. The process is normally limited to workpieces of constant cross section. It also results in some material loss since the ends damaged by gripping must be removed.

L. Other Forming Processes

L1. *powder metallurgy (P/M) processes* - metal powders mixed with certain solid lubricants are compacted under pressure to form the desired shape (See L1c.); they then are heated to a temperature sufficient to bond the particles strongly together (See L1d.). The sintered part may be pressed a second time to improve dimensional accuracy and surface finish and, sometimes, to modify the shape. (See L1e.) Typical powder metal parts are rather small (About 3 square inches in cross-sectional area is a typical maximum because of the high press forces involved.). The process is used for a variety of precision mechanical parts, but bearings, and other parts with surfaces that have are metal-to-metal sliding contact are good applications because the porosity inherent in these parts provides space for a reservoir of lubricating oil. Almost all metals can be processed by this method. Iron, steel, bronze, copper, brass, nickel alloys, and stainless steels, are the most commonly used. Small gears, cams, small levers, sliding blocks, sprockets and pawls are other applications. Further applications are parts made from alloys that are otherwise difficult to machine or fabricate such as carbide cutting tool inserts, and tungsten lamp filaments. Parts requiring dual materials such as graphite-carbon motor brushes, copper or silver and tungsten electrical contacts, and tin-copper bearings are other examples. The process tends to be limited to high-production situations since the tooling required is not inexpensive. However, the labor content is low, particularly in comparison with applications that otherwise would require machining. The process works best with parts having straight sides, although tapers and curvature of sidewalls are possible over short distances if properly designed. Undercuts and holes in sidewalls are not feasible and must be produced by secondary machining operations.

L1a. *metal powder manufacture* - See *powders, metal*.

L1b. *powder blending and mixing* - The ideal powder for parts making may contain a mixture of powders of different metals or alloys, non-metals, different particle sizes, lubricants, and binders.

Lubricants, eg., stearic acid, lithium stearate, and graphite, provide better compressibility and flow characteristics. Binders improve the “green strength” of the unsintered part. Both binders and lubricants are burned off or volatilized in the sintering process. Blending of these ingredients may take place either wet or dry. Water, or other solvents facilitate the mixing and reduce dust. Mixing usually is performed as a batch operation. The mixing cycle should be short to prevent damage to or work-hardening of the powder particles. Drum, double-cone, cubical-shaped, V-shaped, and conical mixers, with rotating screws are commonly used. Fig. 2L1b shows the shape of several common mixers.

L1c. pressing (compacting) - Metal powders, normally at room temperature, are introduced to, and fill, a die cavity of precise shape, with side-walls that are usually straight. A punch of the same cross-sectional shape as the die, and with a close fit to the die cavity, descends into the die and presses the metal particles together. A lower punch, which rises to aid in the compaction and later ejection of the part, is common. Parts with stepped shapes or flanges may have more than one lower and upper punch. (Multiple punches are required because the powder does not behave like a liquid; friction between particles and die sidewalls reduces the density of areas away from the punch face. Almost all compaction is vertical, and pressures of up to about 1600 MPa (230,000 psi) are used. The pressing operation forms a “green” part of sufficient strength for further handling (but not enough strength for functional use.) The die and press motions are summarized in the caption accompanying Fig. 2L1c. Note that there is an upward force and motion applied from the bottom punch. This is advisable to provide more uniform compaction, overcoming die wall friction. Multiple-action presses with multiple-motion punches may be used to provide the necessary compaction in all portions of more complex workpieces. In one pressing method variation, the basic die is not fixed; instead, its motion during the operation provides the equivalent effect of a moving bottom punch. This variation, called *withdrawal-die pressing*, is shown in view (b) of Fig. 2L1c.

L1d. sintering - The “green” compact is heated to an elevated temperature in a controlled atmosphere.

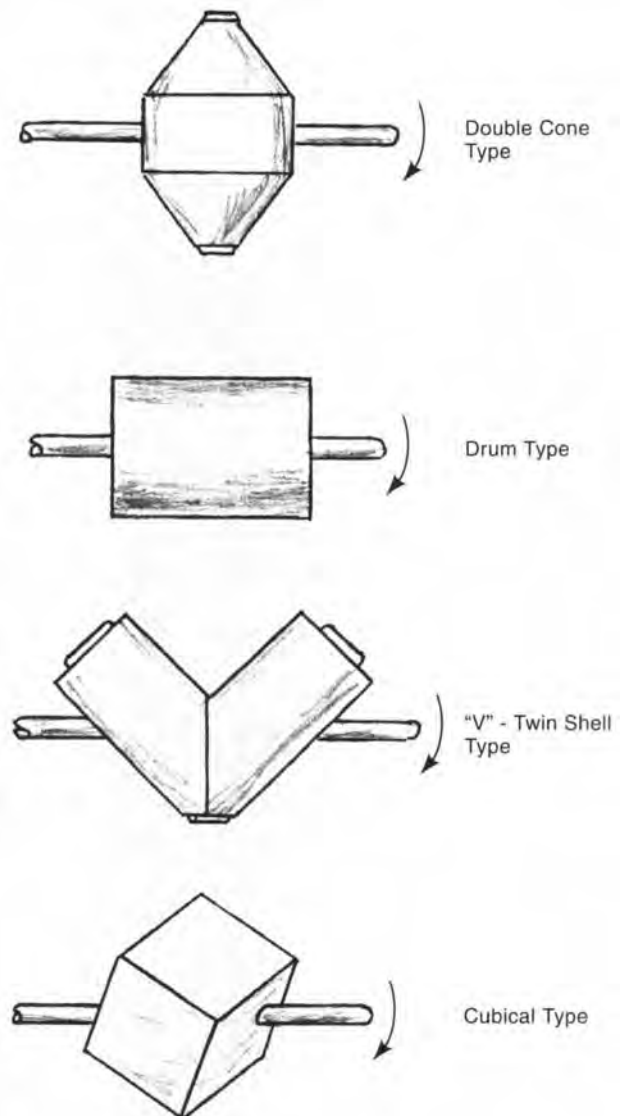


Fig. 2L1b Four types of rotating mixers used to blend metal powders.

Either a batch-type or continuous conveyor furnace may be used. The furnace temperature is well below the melting point of the alloy involved but high enough and maintained for a long enough period so that diffusion bonding of the metal particles takes place. The metal particles bond securely together and there may be some increase in density but the resulting part is not 100 percent dense. Densities of 75 to 90 percent are typical.

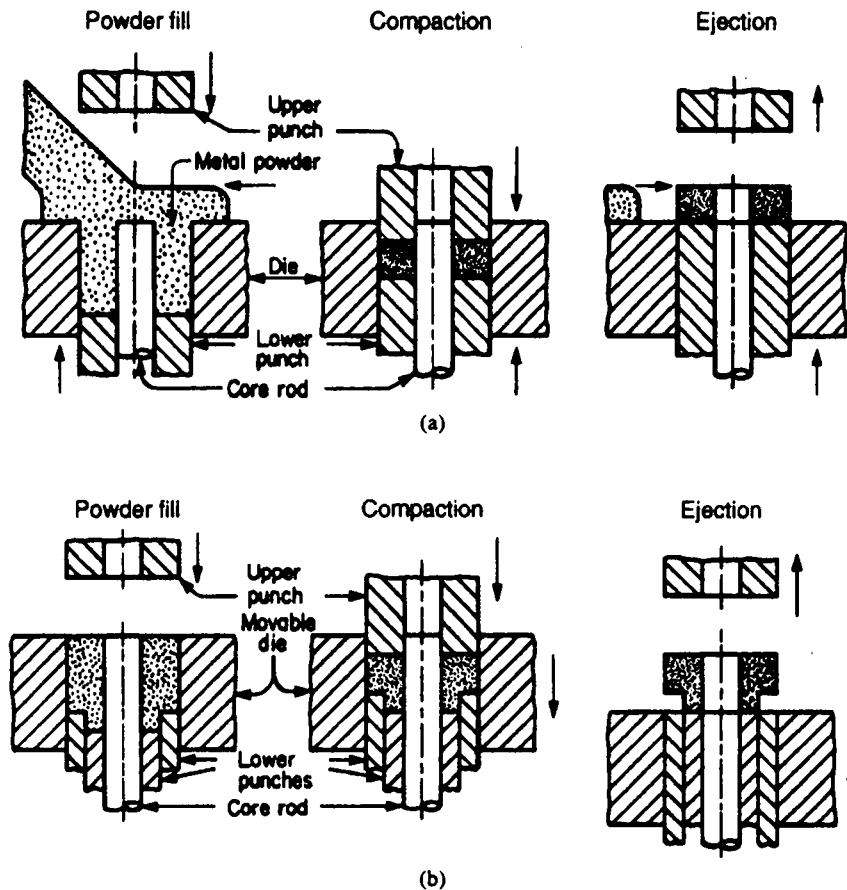


Fig. 2L1c The pressing sequence for powder metal parts, (also applicable to ceramic parts. See chapter 5.) (a) **Fixed-die system.** The die is fixed in the press table. The lower punch is withdrawn when the feed shoe (not shown) is over the die cavity. The excess metal powder is pushed aside. The upper punch lowers the die. The upper and lower punches move simultaneously. Powder is compacted. The upper punch is then withdrawn. The lower punch continues to rise, ejecting the newly compacted part from the die. The feed shoe moves across the face of the die, pushing the part to a collecting station. The cycle is repeated. (b) **Withdrawal die pressing system.** The main lower punch is fixed; the die is movable. The die is filled. The upper punch enters the die. The die is withdrawn at half the speed of travel of the upper punch. When two lower punches are employed, one lower punch is fixed and one is movable. When the movable punch has completed its compaction motion, it is allowed to move to enable compaction of the second level to occur. When compaction has been completed, the upper punch is raised. The die is further withdrawn to effect ejection by stripping the die from the component. The feed shoe moves across the face of the die, pushing the part to the collection station. The die rises to allow it to fill from the feed shoe. The cycle is repeated. (from Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, New York, 1999)

The sintering process actually has three phases:

1. burn off, which removes air and volatilizes binders and lubricants as the temperature of the compacted part gradually increases. The volatilized materials must be removed from the
2. furnace atmosphere before the second phase begins.
2. a high-temperature stage during which the diffusion bonding takes place. This can require a period of minutes or several hours. For iron-based parts, the temperature ranges from

1850 to 2100°F (1010 to 1150°C); copper, bronze, and brass parts allow somewhat lower temperatures⁴.

3. cooling phase, which lowers the temperature of the sintered workpieces while maintaining the controlled atmosphere.

The atmosphere used is commonly one with oxide-reducing properties. Dissociated ammonia, hydrogen, or cracked hydrocarbons, are most often used, though the atmosphere may also be inert, especially with nitrogen. Vacuum sintering is utilized with stainless steel, refractory alloys, and titanium. Fig. 2L1d shows a typical continuous type furnace.

L1e. repressing - The sintering process results in parts with some shrinkage from the green state as binders and lubricants are removed from the parts. There is also some inevitable distortion from the thermal expansion and contraction that takes place during sintering. To improve the dimensional accuracy of the parts, to improve surface finish, to sharpen certain details, and sometimes, to reduce the porosity of the parts, they may be subjected to an additional pressing (or "calibrating") operation. With some parts, repressing can take place in the same die that was used for compacting; for other parts, separate dies are used. The parts are pressed severely enough to cause plastic flow of the material. In addition to the improved dimensions and surface finish, the parts gain some strength from being cold worked and densified.

L1f. secondary operations - Powder metallurgy parts can be machined, thread rolled, heat treated, and surface finished after fabrication. Machining takes place when undercuts, side holes, screw threads, and other features not feasible with the powder-metallurgy process, are needed. Techniques are straightforward but the effect of porosity must be considered. It is usually not recommended to machine bearing surfaces if impregnated lubricants are planned to be used, since the machining will tend to close the surface pores of the workpiece. Heat treating with liquid-cyanide is not recommended for PM parts because the liquid salts can be trapped in the pore structure, leading to corrosion. Similarly, electroplating and other surface treatment chemicals can be trapped in these pores; pretreatment with materials that close the pores permits electroplating and other chemical treatments.

L1g. powder metal forging - In this process, the sintered powder metallurgy part becomes a blank for forging. The operation involves more drastic deformation than conventional repressing, and the P/M part is heated to forging temperature beforehand. This process has the advantage that the forging blank can be made to optimum size and shape, eliminating or greatly reducing wasted material, and permitting the production of more complex forged shapes with reduced necessity for machining after forging.

Forgings made from P/M blanks can be more precise than conventional forgings. No flash is produced

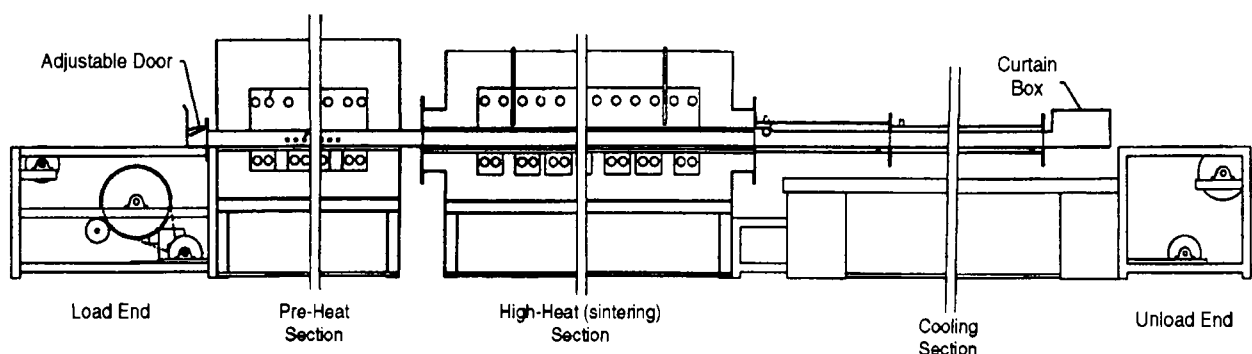


Fig. 2L1d Conveyorized, continuous-type, sintering furnace for powder metal parts. The furnace includes a preheat section, a high-heat sintering section and a cooling section. (Note: The lengths of the sections are considerably longer than shown here. The drawing was shortened to fit the page.) (Drawing courtesy Abbott Furnace Co.)

and draft is not necessary. The part is stronger than a conventional repressed P/M part because it gains the benefit of the improved grain structure that forging provides, and the density is increased to as much as 99 percent. Cams, gears, splines and connecting rods are typical parts made with this process. To prevent oxidation, protective atmospheres are used during the heating and forging cycles or the workpiece is coated with graphite.

L2. *electroforming* - Electroforming is a process that utilizes electroplating (See 8C.) techniques to make a formed sheet component. Whereas, in electroplating, the deposited material is very thin and is left on the surface of the plated workpiece, in electroforming, the deposited material is much thicker and is separated from the substrate after plating to produce a separate part. There are three steps, then, in the process:

1. Preparation of a mandrel,
2. Electroplating of the mandrel to the thickness needed, and
3. Separation of the electroplated material from the mandrel.

The process is particularly suited to complex shapes where very high accuracy and great detail are needed. One common application is dies used in production of compact audio and video discs. The accuracy and detail produced depend on the precision of the pattern or mandrel onto which the plated material is deposited. The electroformed part takes on the detail and accuracy of the mandrel. Therefore, it is necessary for the mandrel to be made with the accuracy and surface smoothness wanted in the electroformed part. Casting and molding methods can sometimes be used in making the mandrel. This may have to be repeated for production of multiple parts if the mandrel is expendable, that is, if it is made of materials that are melted or dissolved to separate the electroformed part and the mandrel.

Typically, the wall thickness of the electroformed material will range from the minimum needed to maintain the part's integrity to as much as 5/8 in (15 mm). Nickel, copper, and silver are metals most easily used for the electroformed parts, with nickel probably being most common. Iron can also be processed. The mandrel can be made of

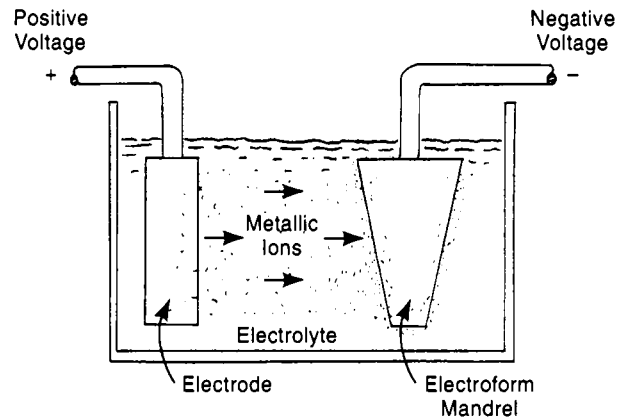


Fig. 2L2 Schematic representation of electroforming. The part is formed from a build up of electroplated coating on a mandrel.

either non-metals or metal, though the former require a conductive coating so that electrodeposition can take place. Plastics, glass, and even wax, can be used for mandrels in addition to metals such as aluminum or stainless steel. Surface finishes down to $2\mu\text{in}$ are feasible on the interior surface of the part. (The other surface may be quite irregular, but this condition is seldom critical because compensations can be made on the mating parts, if necessary.) Fig. 2L2 shows the process schematically and Fig. 2L2-1 shows a typical electroformed part.

Electroforming can be used to "weld" several pieces together. The weld is stress-free because it is made at room temperature; melting of the fillet or the base materials is not involved. The fillet is developed by electrodeposition of metal on plating the joint area to a sufficient thickness.

L3. *metal injection molding (MIM)* - is a process somewhere between standard powder metal forming and injection molding, as used with many plastics (See 4C.). A mixture of fine metal particles and binders that usually include a thermoplastic, wax, plasticizers, and dispersants, is heated enough to provide a paste-like consistency and is injected under high pressure into a mold cavity. The mixture cools to form a molded workpiece that is ejected in the same way as are plastic parts. The molding equipment used is very similar to that used for injection molded plastics. Molds are of hardened tool steel. The molded part is in the "green"



Fig. 2L2-1 A copper electroformed microwave guide (shown on the right) and the aluminum mandrel on which it was formed (shown on the left). The mandrel is dissolved chemically after the plated coating is of the desired thickness. The flanges in the finished part were "welded" to the guide by plating additional metal at the joint after assembly. Electroforming is particularly suitable for complex parts like this, particularly if surface details must be accurately produced. In this example, the interior dimensions are the most critical. (Courtesy A. J. Tuck Company)

state immediately after molding, strong enough for handling in the factory but not for product use. It is then subjected to a treatment that removes the binder material, either by solvent extraction, catalytic action, or by high temperature vaporization, or a combination of these methods. This may take from one to 24 hours, depending on the size of the parts and the method used. Metal density is then typically about 60% and the workpiece is in the "brown" state, still strong enough for handling.

The workpiece is then sintered in a vacuum or hydrogen/nitrogen atmosphere with methods that are similar to those used in conventional PM sintering. (See description in L1d above.) The sintering temperature usually ranges from 2200 to 2500°F (1200 to 1400°C) for a period of 3/4 to 4 hours. Sintering bonds the metal particles together to form a strong, usable part. The parts are 95 to 99% dense but

have shrunk to a size 15% to 25% smaller than the molded dimensions.

The MIM process is carried out with low alloy steels, stainless steels, soft magnetic materials, copper, and other non-ferrous metals. Complex parts can be made with the process to good dimensional tolerances. A final punch press sizing operation may be employed when required tolerances are particularly close. Because of the fine particle size required in the metal powder (less than 20μm in diameter - finer than that used for conventional PM parts), the raw material tends to be expensive. The time-consuming binder removal process is also expensive and must be closely controlled. The process is most applicable for high production quantities of small parts (under golf ball size). Intricate parts, not feasible with conventional PM forming often can be made with the process. Parts produced by the process include pistol, rifle,

and shotgun parts, stepper motor rotors, fuel injector components, and automotive parts.

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Chapter 3 - Machining Processes

A. Lathe and Other Turning Operations

A1. *lathe operations (general description)* - produce, with a cutting action, surfaces of rotation (surfaces having a round or partly-round cross section), both external and internal, in a workpiece. The workpiece is rotated in a lathe, screw machine, or chucking machine. It is held between centers or in a chuck or collet, or fastened to a face plate. The cutting tool is fed into the work or along the work, or both, to produce a part of the desired shape. There are several basic types of lathes and related machines as described below and many varieties of tools that can be fed against the workpiece. These machines are used extensively in the production of parts that contain surfaces of rotation. The basic operations performed on lathes are the following:

A1a. *turning* - is the most prevalent lathe operation. In its most common form, a single-point cutting tool is moved on a precise path with respect to a rotating workpiece. When the tool moves parallel to the axis of rotation, straight turning takes place and the surface machined is cylindrical or part of a cylinder. When the cutting tool moves uniformly closer or farther from the axis of rotation as it moves longitudinally, a tapered surface is generated. (This is often accomplished in engine lathe by moving the tailstock supporting center for the work to an off-center position, out of alignment with the headstock axis of rotation.) Fig. 3A1 shows examples of straight and tapered turning. Engine lathes, turret lathes, screw machines, and chucking machines all

perform turning operations, to produce all kinds of shafts, axles, spindles, pins, etc. with straight or tapered turned surfaces. Parts as small as wristwatch shafts and as large as ocean liner propulsion components are turned on lathes. Producing a turned surface of considerably smaller diameter than that of the original workpiece may involve one or more roughing cuts, usually with a large depth of cut. Finishing cuts to produce greater accuracy or smoother surfaces normally have a small depth of cut.

A1b. *form turning* - occurs when a single-point cutting tool moves longitudinally in a path other than a straight line, or when a cutting tool ground to a particular curved or otherwise irregular edge is fed radially into the rotating workpiece. The profile of the round workpiece then takes the shape of the cutting tool path or the inverse of the form tool edge. The lengths of surfaces produced by form tools on a lathe, shown in Fig. 3A1b, are limited by the width of the tool.

A1c. *tracer turning* - is a process for form turning. The inward and outward motions of the cutter as it moves longitudinally along the length of the part are controlled by the motion of a stylus as it bears against a template or master part. Several passes may be used, after which the part duplicates the shape of the template. A variety of tracing mechanisms are available, powered hydraulically, pneumatically, or electrically. The tracing operation is one of those shown schematically in Fig. 3A1. (The movement may also be controlled electronically

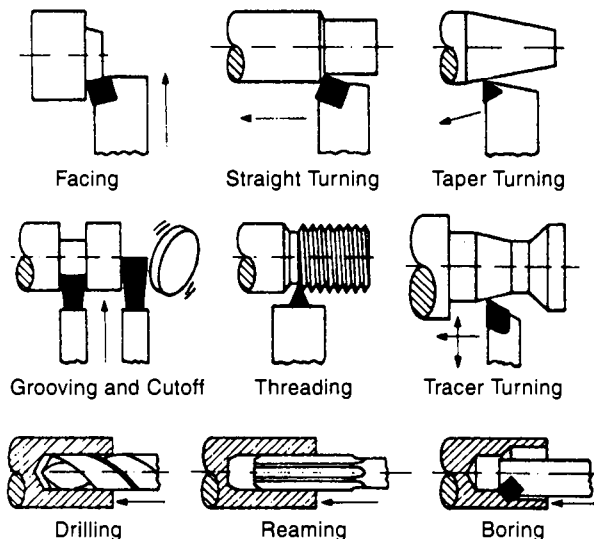


Fig. 3A1 Facing, turning, grooving, thread cutting, drilling, reaming, and boring performed on turning equipment. In facing, the tool moves perpendicularly to the axis of rotation of the spindle and a flat surface is produced. In straight turning, the tool moves parallel to the axis of rotation and a cylindrical surface is generated. In tapered turning, the tool moves at an angle to the axis of rotation and a tapered surface is produced. In tracer turning, the single point cutting tool moves inward and outward as it moves longitudinally, creating a contoured or other shaped surface on the rotating workpiece. The tool's path can be controlled by a template or by computer numerical control (CNC). In grooving, the tool, ground to the width of the groove desired, is plunged, or fed inwardly, creating a groove in the outer surface of the workpiece. Grooving can also take place internally when a cutter inserted in the center hole of a workpiece is fed outwardly. In threading, the cutting tool, shaped to the flank angle of screw threads, moves longitudinally in a fixed relationship with the rotation of the workpiece. (from Bralla, *Design for Manufacturability Handbook*, 1998, McGraw-Hill Companies. Reproduced with permission.)

without tracing, by using numerical or computer-numerical control, CNC). Some tracer lathes have an additional tracer-controlled cross slide at the rear of the work to facilitate the machining of grooves, undercuts, and chamfers.

A1d. **facing** - produces flat surfaces whose plane is at right angles to the axis of rotation of the part.

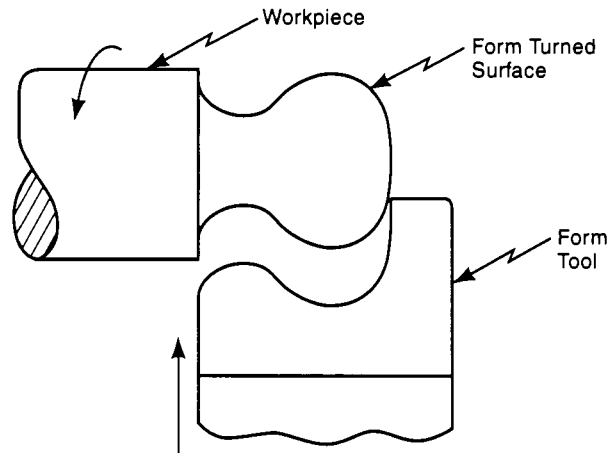


Fig. 3A1b Form turning - The tool is ground to the shape desired and is fed into the workpiece as it rotates, cutting a surface whose shape is the inverse of that of the form tool.

As the part rotates in the lathe, the cutting tool moves radially toward the axis of rotation, removing material as it advances. (It can also move outward from the center, but the other direction is much more common.) The operation is used to produce flat surfaces on castings and other parts that usually also require turning or some other lathe operation. The process is illustrated in Fig. 3A1.

A1e. **grooving** - The cutting tool, usually ground to the width and bottom shape required, is fed into the work, cutting a groove of the desired dimensions. Grooves can be cut into any external or internal surface that such a cutting tool can reach. (Internal grooves are usually called recesses.) Fig. 3A1 includes a view of the grooving operation.

A1f. **knurling** - is not really a machining (cutting) operation because the knurl is formed, not cut, in the workpiece. Knurling is a common lathe or screw machine operation. The hardened knurling tool rolls against the cylindrical surface of the rotating workpiece with high pressure, causing the surface material of the workpiece to flow into peaks and valleys according to the pattern of the knurling tool. The result is a surface in the finished part that is roughened to a particular pattern, useful to improve the grip if the part must be held or rotated by hand when it is used. Several different patterns are possible. Other uses for the operation are for

decoration and to increase the diameter of the part slightly to facilitate a press fit.

A1g. cutting off (parting) - When parts are made in lathes and screw machines from bar stock, the final operation is to sever the part from the remaining bar material. This is accomplished by advancing the cutoff tool, a narrow grooving tool, radially into the work. When the cutting edge advances to the axis of rotation of the part, the part is severed and falls to the bed of the machine. Some machines, which make blanks for further machining or other operations, are designed to perform only cut off operations and other simple ones on bar and tubular stock. The operation is shown schematically along with grooving in Fig. 3A1.

A2. lathes and other turning machines

A2a. engine lathes - are general purpose machines that provide the most basic means of performing turning, facing, grooving, knurling, and threading operations (Fig 3A1). These machines can also drill, ream, and bore holes at the center of rotation. A typical engine lathe has a chuck or collet

to hold the workpiece in a powered rotating spindle, and a bed that normally consists of two ways. A tailstock holds the end of the workpiece opposite the spindle if the workpiece is long enough to require support at the end. A drill, reamer, or other tool can also be mounted in the tailstock so that holes can be machined at the axis of rotation of the workpiece. Other cutting tools (usually single point) are positioned in a compound rest and cross-slide that are mounted on a carriage that can move in an axial direction along the bed of the lathe. The ways of the bed are machined to be smooth and precisely in line with the spindle. Transverse movement of the tool is provided by the cross slide or the compound rest. The compound rest can be placed at an angle for short taper turning or for angle facing cuts. In all cases, the movement of the cutting tool can be precisely controlled with machine screws, mostly with manual crank actuation. Axial movement of the tool carriage, however, can be automatic through rotation of a lead screw. With the lead screw, the movement of the carriage also can be geared to the rotation of the spindle so that screw threads can be machined. Fig. 3A2a illustrates a typical engine



Fig. 3A2a A typical turning operation being performed on an engine lathe. The bar workpiece is held in the three-jaw chuck and is supported by a center in the tailstock. (Photo courtesy Clausing Industrial, Inc.)

lathe. These machines are very versatile and are especially applicable for performing turning and related operations when production quantities are limited.

A2b. turret lathes - differ from engine lathes in that they have a slide carrying a usually hexagonal tool holder, a "turret", in place of the tailstock. The turret can hold cutting tools in each of its sides and can be fed longitudinally and, on some machines, transversely. Turret lathes are, therefore, lathes adapted for production work. They are particularly suited for moderate production levels when automatic screw or chucking machines may not be justifiable, but when the turret lathe's tooling arrangement permits more rapid production than is feasible with engine lathes. Spindles of machines intended for machining of bar stock are equipped with collet chucks. When other components are to be machined, the spindles are fitted with chuck jaws suitable for gripping the workpieces.

A typical ram-type turret lathe is shown in Fig. 3A2b. When the turret lathe is set up for a particular operation, retraction of the turret automatically indexes it and positions the cutting tool required so that it is in place for the next operation. Feeds can be automatic or manually operated to pre-set stops. Turret lathes generally have a four-sided

turret on the cross slide of the machine. Some machines also have a fixed tool at the back of the cross slide. Tools on the cross slide turret can also be indexed and fed in the sequence that the particular workpiece requires. Once the turret lathe has been set up with the required tools, the component to be produced can usually be fully machined without tool changes or adjustments.

Semi-automatic and automatic operation of turret lathes can be achieved by incorporating various modifications including automatic headstock control, power feed to the turrets, and automatic turret indexing. The use of some of these features may enable one operator to tend more than one machine. In the fullest degree of incorporation of these devices, the turret lathe becomes an automatic screw machine or chucking machine as described below. Then an operator is needed only to load and unload, and monitor the operation. Current practice, however, instead uses computer numerical control to achieve automatic operation of turning machines.

A2c. screw machines - are automatic lathes, originally developed for the mass production of screws from bar stock but long since used for a wide variety of parts from bar stock over a broad size range. Once set up, these machines run completely automatically. It is common practice for one operator

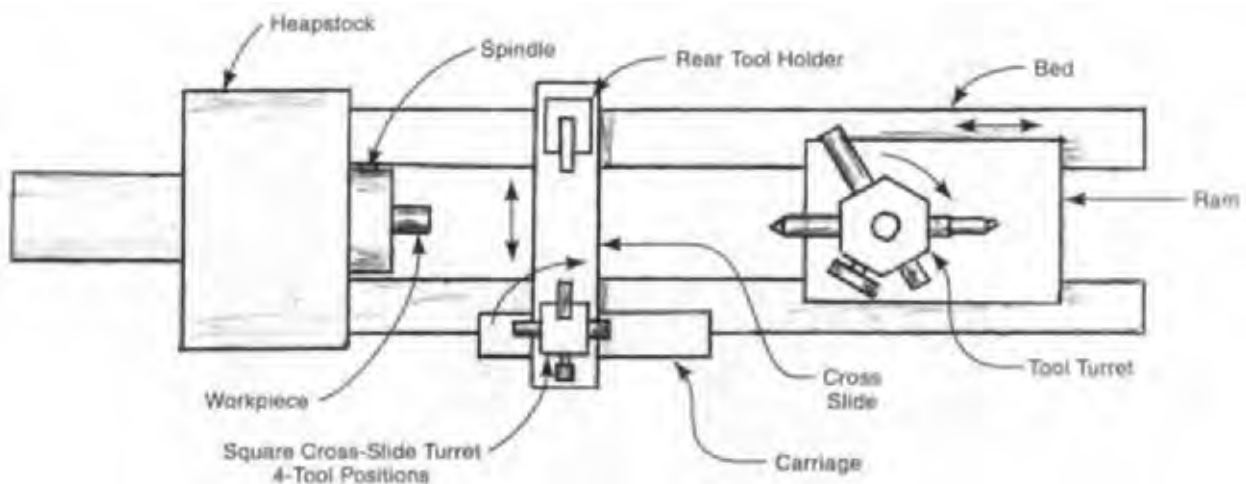


Fig. 3A2b Overhead view of a ram-type turret lathe. The turret on the ram holds up to 6 cutting tools. Four tools can also be held in the turret on the cross slide and an additional one on the rear tool holder.

to run a bank of such machines. Machines are available for producing parts from bar stock as large as 8 in (200 mm) in diameter but most work is performed on machines capable of processing bar of 2 in (50 mm) diameter or less.

A2c1. *single spindle screw machines* -

There are two common varieties of single-spindle screw machines: the Brown and Sharpe or turret type and the Swiss type. The Brown and Sharpe type is essentially an automatic turret lathe. Typically, it has a six-sided turret, mounted vertically on a ram, a cross slide on which two tool-holders can be placed and one or two upper tool slides mounted near the spindle. Cutting tools on these holders are moved to machine the bar as it rotates. The bar is held in a spring collet in the spindle. All motions of these devices are controlled by cams. With the proper cams and set ups, the machine will operate fully automatically. Bar stock is fed automatically through the hollow spindle after each piece is cut off; the operation, therefore, continually repeats. Additional bars can be fed automatically from a magazine attachment. Some machines are equipped with pick-off attachments that grasp the turned part and hold it for secondary operations that require the workpiece to be non-rotating. Screw driver slots, flats, and cross holes can thus be machined with this attachment. Fig. 3A2c1 illustrates

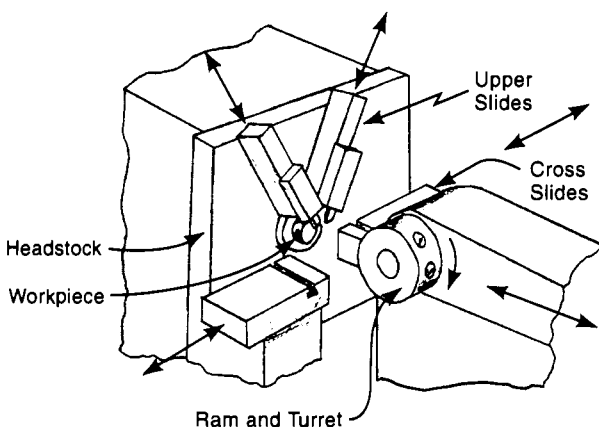


Fig. 3A2c1 A turret-type (Brown and Sharpe type) single spindle screw machine. The two upper slides, the two cross slides and the turret all can hold cutting tools.

the Brown and Sharpe type of machine. These machines are no longer manufactured, having been replaced by machines whose tool and stock movements are actuated by computer numerically controlled servo motors rather than cams. However, very many of these cam-operated machines are still in use throughout the world.

A2c2. *Swiss-type screw machines* -

In the Swiss-type machines, tools are mounted on two cross slides and three upper slides arranged radially around the spindle. The headstock, holding the rotating bar, can slide longitudinally on the machine's ways. Tool movements are controlled by cams. Tools feed radially to the center of rotation of the bar. Rocker arms, driven by cams, provide the approach and infeed motions for the upper tools. Longitudinal feeds are made by shifting the headstock rather than tool slides, again by cam control. Single-point cutting tools are normally used on all slides. Swiss-type machines were originally developed for clock and watch manufacture and are particularly suited for small shafts and other very small parts. Fig. 3A2c2 illustrates the cutting tool and feed arrangements of these machines. Most current designs of Swiss-type screw machines utilize CNC with servo or stepping motors instead of cams to provide tool and headstock motions.

A2c3. *multiple spindle screw machines* -

have 4, 6, or 8 spindles instead of the single spindle of the Brown and Sharpe and Swiss-type machines. The spindles are held in an indexing drum in the headstock of the machine. Each spindle has a collet that holds a separate piece of bar stock. This arrangement permits the cutting action to be divided so that a portion takes place simultaneously on several different workpieces. The spindles all rotate and then index to a new position after each cutting sequence. There is a tool slide in line with each spindle and, often, a cross slide for each spindle position. All spindle and tool slide motions are automatic, controlled by cams or servo motors. Bar stock is fed at one spindle position. Some machines are equipped to stop the rotation of one spindle and to perform milling and transverse drilling operations on the workpiece. The production rate of multiple-spindle machines is considerably faster than that on single-spindle machines because the operations

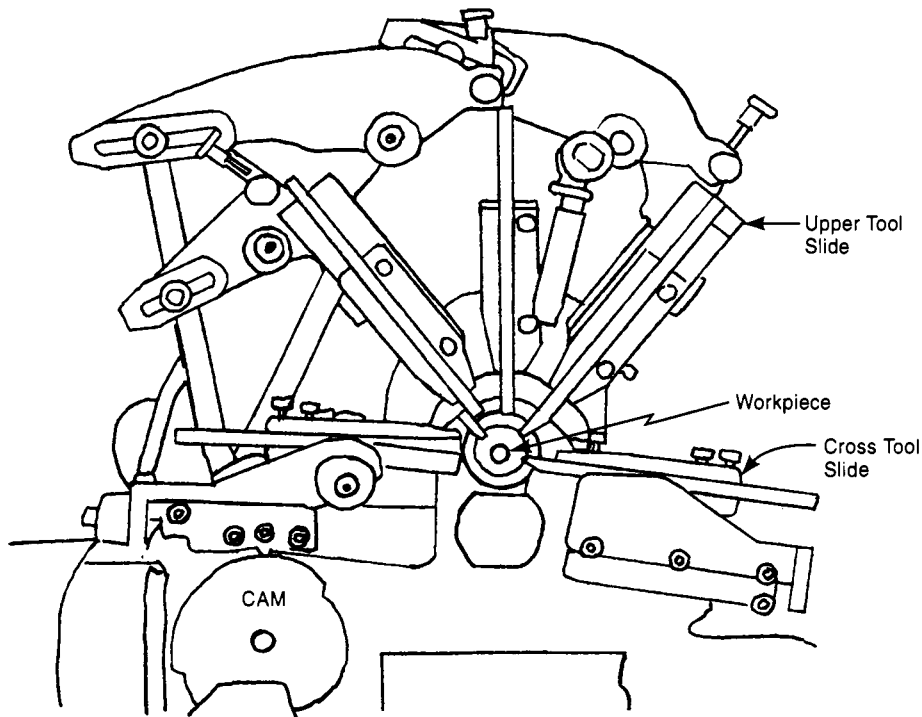


Fig. 3A2c2 Swiss-type screw machine. Cutting tools are arranged radially around the machine spindle. Tool infeed is controlled by cams. Longitudinal feed is provided by moving the spindle head.

are almost all performed simultaneously. Cycle time for a particular part is equivalent to the time required for the longest cutting operation plus the time required to index the spindles. These machines are ideal for high production situations. One operator typically tends a group of such machines. Fig. 3A2c3 illustrates a typical multiple spindle headstock and tool arrangement.

A similar operation can take place with discrete parts instead of bar stock. Each spindle then has chuck jaws made to fit the workpiece. One spindle position is used for loading and unloading workpieces. At each of the other positions, one or more operations are performed on the workpiece. The machines are then designated *multiple-spindle automatic chucking machines*. (See following paragraph.)

A2d. **chucking machines** - are automatic lathes designed for operations on castings, forgings, and other parts, rather than on bar-stock. Mechanisms and other features are similar to those of screw machines except for the bar feeding

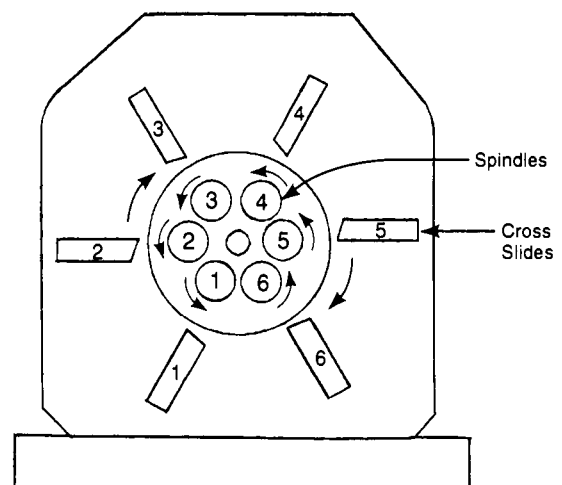


Fig. 3A2c3 The headstock of a typical six-spindle, multiple-spindle screw machine. All six spindles carry bar stock and rotate continuously. Periodically, each spindle is indexed to a new position. Cutting operations at all indexed positions take place simultaneously. There are also as many as six cutting tools located on the tailstock of the machine.

system. Instead, chucking machines have means at the spindle for holding the part to be machined. Special chuck jaws usually must be made to hold the workpiece if its shape is at all irregular. Most chucking machines are single-spindle but multiple-spindle machines also are widely used. Multiple-spindle chucking machines have one or more spindle locations where the spindle rotation stops for loading and unloading workpieces. Chucking machines are made for various sizes of workpieces ranging up to above 50 lb (23 kg) for vertical-spindle machines. Most horizontal-spindle machines are for workpieces under 10 lb (4.5 kg).

A2e. **turning centers** - (See T1.)

B. Round-Hole-Making Methods

B1. **drilling** - The most common tool for drilling, a twist drill, is a rod with helical flutes and two or more cutting edges at the end. It is rotated about its

axis and fed axially into the work. As it advances, it produces or enlarges a round hole in the workpiece. The chips are carried away from the hole by the flutes in the drill. (When drilling an axial hole with a lathe, the workpiece rotates rather than the drill.) There are other types of drills that may not have helical flutes. Others may have only one cutting edge. The drilling process is very common and is used with a wide variety of machines ranging from the most sophisticated computer-controlled or multiple-spindle machines to hand-held electric or crank-driven drills. The most common diameter range for drilled holes is about 1/8 in (3 mm) to 1 1/2 in (38 mm) although diameters from 0.001 (0.025 mm) to 6 in (150 mm) can be drilled with commercially available special drills. Fig. 3A1 includes an illustration of drilling as performed on turning equipment. Fig. 3B1 shows some typical drills.

B2. **counterboring** - enlarges a hole for part of its depth and usually machines a flat bottom in the

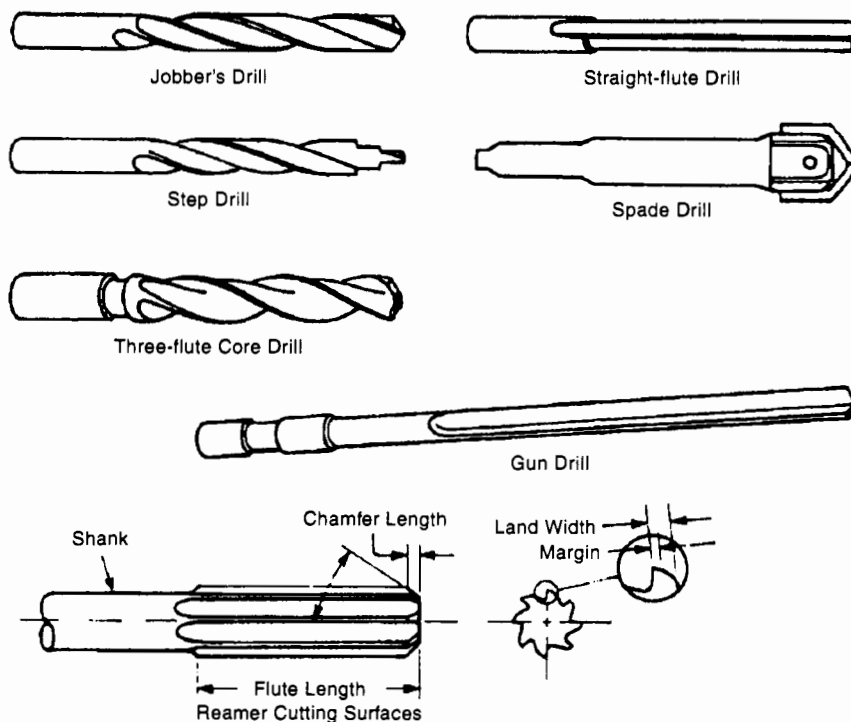


Fig. 3B1 A series of drills and, at the bottom of the group, a typical reamer. (from Bralla, *Design for Manufacturability Handbook*, 1998, McGraw-Hill Companies. Reproduced with permission.)

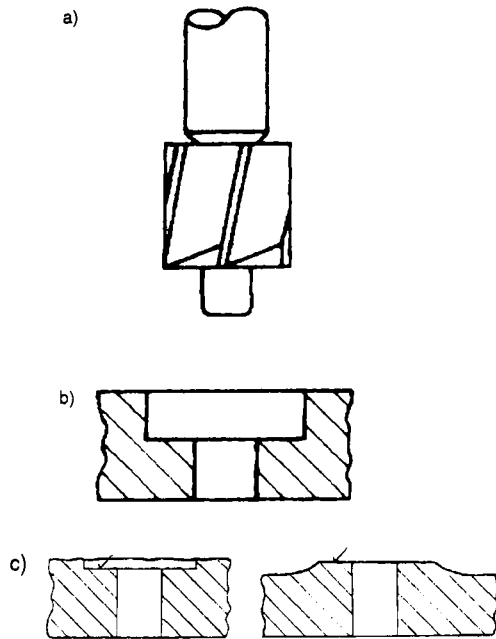


Fig. 3B2 A counterboring/spotfacing tool (view a) and a cross-sectional view of the counterbored hole it produces (view b). View c) shows cross-sections of two slightly different spotfacings produced by the same tool. The purpose of counterboring is to produce a recess of prescribed depth while spotfacing is performed to provide a smooth and perpendicular flat surface for a fastener or other object.

enlarged portion. The operation is most often performed to provide clearance for a bolt head or multi-diameter part. The rotating cutter is guided by a pilot that fits into the existing hole, so that the counterbored surface is concentric with the original hole. A multi-diameter counterboring tool can produce stepped counterbores. Fig. 3B2 illustrates a counterboring tool in view a) and the counterbored hole it produces in view b). (The tool also can be produce spotfacing, as shown in view c).

B3. countersinking - is an operation that adds a chamfer at the entry end of a hole. A rotating cutting tool, with the edge set to the angle of chamfer desired, is fed into the hole and removes material at the edge. The tool is centered by the hole; therefore the chamfer is concentric with the hole's axis. The operation is typically used to remove burrs or a sharp edge at the end of a hole, or to provide space for a tapered screw head or other tapered object.

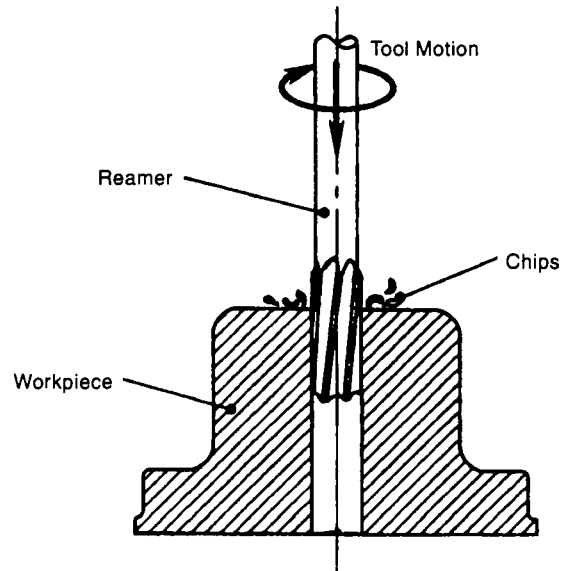


Fig. 3B4 Reaming is used to improve the accuracy, surface finish and straightness of round holes. (from Todd, Allen, and Alting, *Manufacturing Processes Reference Guide*, Industrial Press, 1994.)

B4. reaming - is a secondary machining operation for existing holes. It can provide a more accurate diameter, improved straightness, and a smoother surface finish as it slightly enlarges the hole. A rotating tool, a reamer, is used. The operation can be performed on a drill press or other drilling machine and is sometimes done by hand. Reamers normally remove 0.005 to 0.015 in (0.13 to 0.38 mm) of diameter. Reamers normally float, that is they follow the direction and location of the existing hole, but they can also be guided by bushings to slightly improve the hole's direction or location. The operation is most common with holes from 1/8 to 1 1/4 in (3 to 32 mm) in diameter but both smaller and larger holes can be reamed. A typical reamer is illustrated in Fig. 3B1 and the reaming operation on a lathe is shown schematically in Fig. 3A1 and Fig. 3B4. Taper reamers are used for finishing tapered holes.

B5. boring - is an operation that enlarges and improves the accuracy of an existing hole. Either the work or the cutting tool rotates about the center axis of the hole. The single point tool describes a circle, removing material from the surface of the existing hole as it advances, enlarging the hole, normally increasing the precision of any of a number of

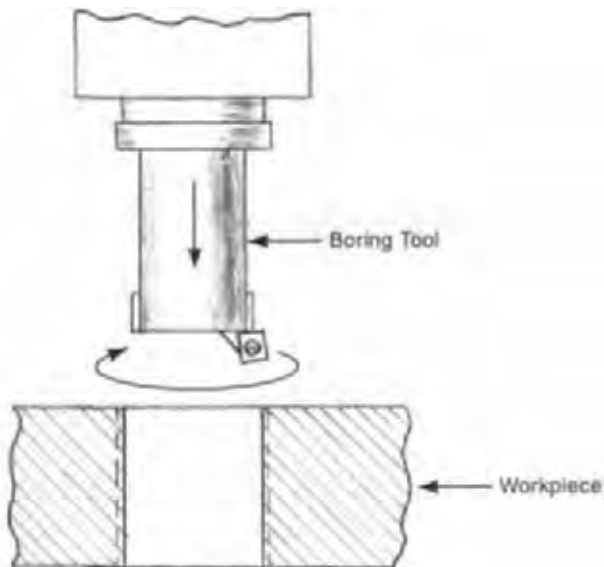


Fig. 3B5 Boring operations slightly enlarge and improve the precision of an existing hole.

factors. They are: its location, diameter, direction, cylindricity, and finish. When this operation is performed on a boring machine, the workpiece is stationary and the cutting tool rotates; when performed on a lathe, the workpiece rotates. On a lathe, the operation can then be considered to be internal turning. The tool spindle and the workpiece holder must be rigid enough to provide the desired accuracy in the bored hole. The operation is performed on holes from about 1/4 in (6 mm) in diameter and larger but is more common on larger holes, especially those too large to be drilled accurately, and for the machining of cast or forged large holes. Fig. 3B5 illustrates the process, and Fig. 3A1 shows it as one of a series of lathe operations.

B5a. jig boring - is performed on jig boring machines, which are vertical boring machines of very high accuracy. The table movement is extremely accurate and the spindle and spindle bearings are very precisely made. The machines are mainly used for making jigs, gages, dies, and fixtures, especially where accurate layout and hole location are essential.

B5b. horizontal boring mills - are basically large horizontal milling machines capable of performing boring, milling, and other machining oper-

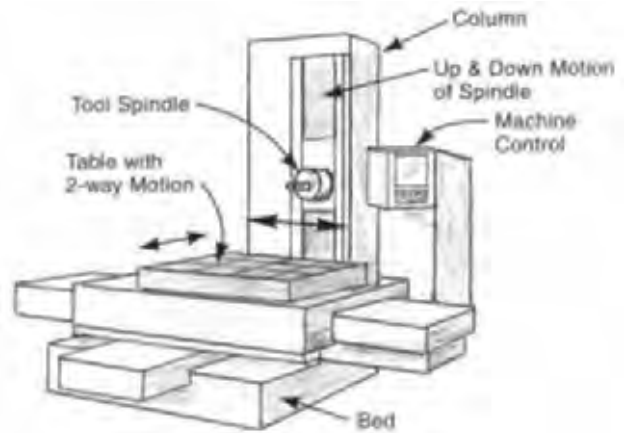


Fig. 3B5b A horizontal boring mill. This machine can perform boring, milling, and drilling operations.

ations on large and often complex parts. These units are sometimes called, horizontal boring and milling machines. The table can move in x and y directions. (Some machines have a table that also swivels.) The headstock that holds the spindle can be raised or lowered. The tool-holding spindle can move inward or outward. These machines are used in the machining of large components that have horizontal holes requiring the precision that boring provides. The machines normally include an end support column, opposite the spindle, for long boring bars. Tolerances with the machines can be as low as one or two ten thousandths of an inch (0.003 to 0.005 mm). Fig. 3B5b illustrates a horizontal boring mill.

B5c. vertical boring mills - are machines with a horizontal table rotating on a vertical axis, and a precision tool head (often two tool heads) capable of movements up and down and side to side (in and out radially). There may be more than one cross slide with tool-holding capability. These machines can be considered to be large lathes turned on end. They are especially suited to boring and other operations on parts too large for a conventional lathe. Workpieces are typically round and heavy with large diameters and shorter lengths. The workpiece is clamped to the rotating table, which can be as large as 40 ft. (12 m) in diameter. Both boring and facing are possible. There is no spindle for milling cutters; all cutting is by single point tools. Fig. 3B5c illustrates a typical vertical boring mill.

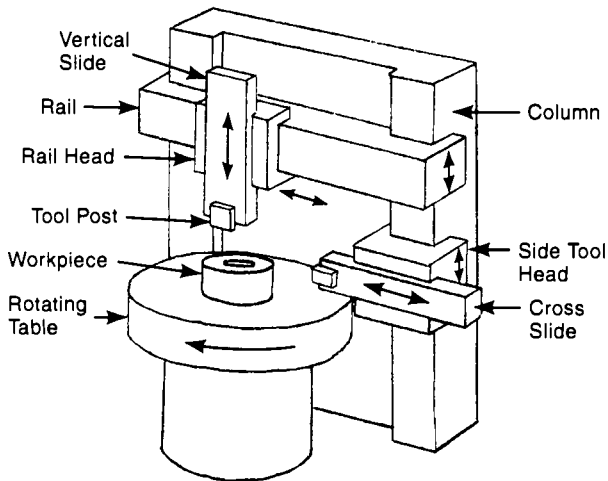


Fig. 3B5c A vertical boring mill. (vertical boring and turning machine.)

B6. **gun drilling** - is shown in Fig. 3B6. A rotating single-flute drill, normally carbide-tipped, is guided by a bushing at the start of the drilled hole and is self-guided thereafter by a bearing surface opposite the cutting edge. A hole through the whole length

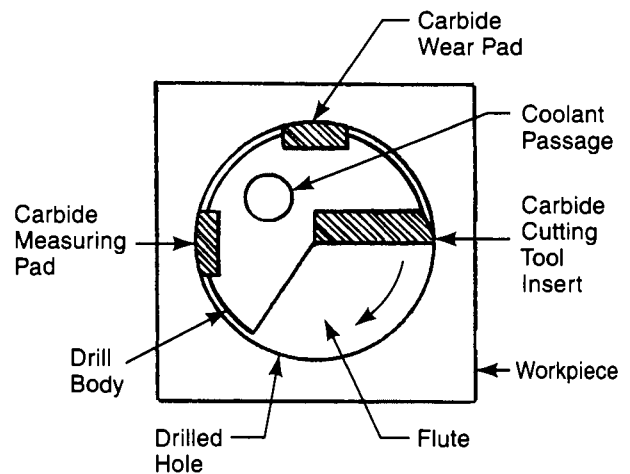


Fig. 3B6 A typical gun drill, viewed from the cutting end.

of the drill provides a means for oil coolant to flow at high pressure to the cutting edge and to flush chips from the hole. Deep, straight, holes are possible with the process which was originally developed for manufacture of gun barrels. Hole depths of over 250 times diameter are possible. Fig. 3B6-1 shows

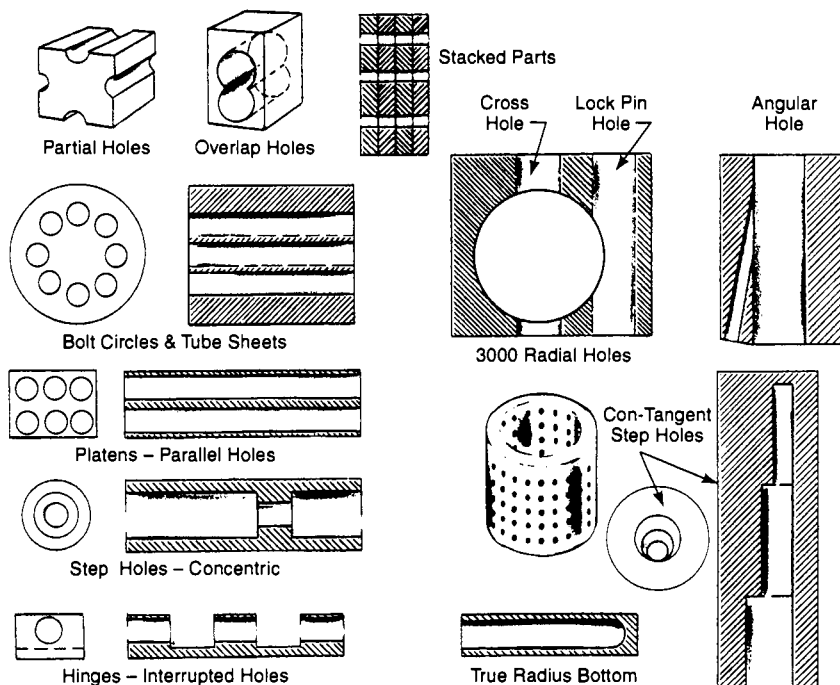


Fig. 3B6-1 The range of hole drilling applications, in addition to gun barrels, for which gun drills are used. (Courtesy Eldorado PCC Specialty Products)

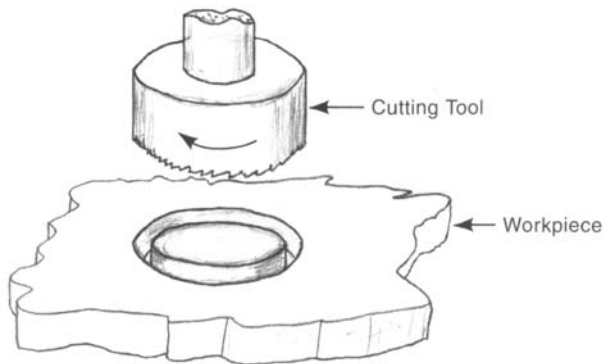


Fig. 3B7 Trepanning. In this example, a hole saw type of milling cutter is being used.

various applications of gun drilling. Also see *guns* and Fig. G9.

B7. *trepanning* - makes a circular groove in a workpiece through the use of one or more cutters or cutting teeth rotating about a central axis. If the grooves are cut all the way through the workpiece, a hole is created and a circular center piece (called a *slug*) is produced. The process is used primarily for large, shallow holes. It is also used to machine round disks from flat stock and is illustrated in Fig. 3B7.

Deep-hole trepanning is similar to gun drilling in that forced lubrication is used, the drill is self-piloting, and special drilling machines are employed. It differs in that a center slug is produced.

B8. *multiple-spindle drilling* - When production quantities are sufficiently large, it may be justifiable to construct a drilling head with a number of drills, all of which are driven from the same power source and make contact with the workpiece at the same time, drilling a number of holes simultaneously. There are three basic types of multiple-spindle drill heads: adjustable, geared, and gearless. The adjustable variety uses universal joints so that the drill positions can be varied, and are desirable for moderate size lots. For higher production and greater precision of hole location, the geared variety are preferable. The gearless type allows close spacing of the drilled holes. Fig. 3B8 shows a typical multiple-spindle, adjustable drilling head.



Fig. 3B8 A typical multiple spindle drilling head with provision for adjustment of the position of individual drills. (Courtesy RMT Technology, Bellwood, IL.)

C. Grinding and Abrasive Machining

At the point where the cutting takes place, grinding is very similar to other machining operations, the difference being that the workpiece is cut by the sharp edges of small pieces of abrasive material, rather than the edge of a hardened steel or carbide cutting tool. The irregularly-shaped abrasive particles may be bonded to a wheel or coated belt, or may be used loose. The particles commonly consist of aluminum oxide, silicon carbide, cubic boron nitride, diamond, or other hard materials. The individual abrasive grains are each smaller than a conventional metalworking cutting tool, and the grains on a typical wheel make a multitude of minute cuts. Fig. 3C illustrates the grinding process schematically.

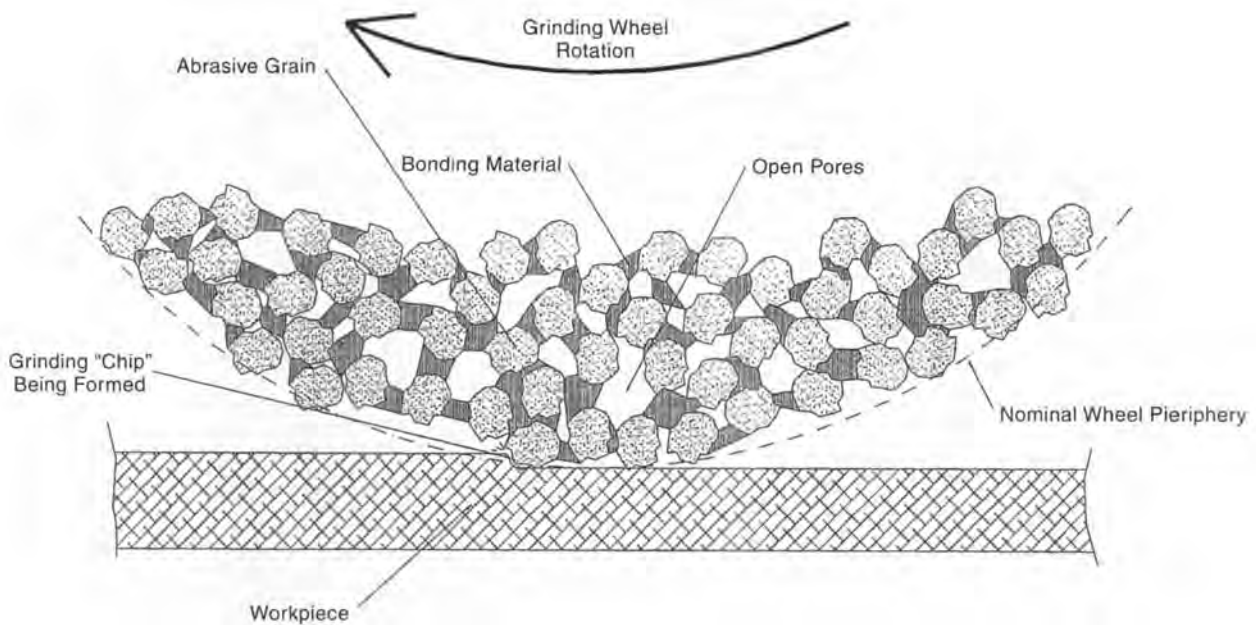


Fig. 3C The grinding process. Sharp edges of individual abrasive grains act as minute cutting tools, removing small amounts of material from the workpiece. (Courtesy J. R. Casey Bralla)

(Some grains, depending on their shape, do not cut but instead rub or slightly deform the surface of the workpiece.) Cutting speeds are high but the depth of cut from each grain is shallow. A water or water-oil emulsion is often sprayed on the wheel and workpiece to control the dust that otherwise arises and to overcome the heating effect of the operation. Grinding wheels are often porous, especially those designed for use with softer materials.

As the wheel cuts, it wears, causing some abrasive particles to become smooth but causing others to fracture, exposing new sharp edges. New wheels, and those that have become worn, are dressed with a diamond tool that removes some of the abrasive material and bonding agent, exposing sharp edges of new abrasive grains and providing a straighter, more uniform, cutting surface. Grinding is most commonly a finish-machining operation to provide a smoother surface or greater dimensional accuracy, particularly with hardened materials. When used as the primary metal removal method, the term, *abrasive machining* is often used.

C1. cylindrical grinding - is used to produce external cylindrical surfaces by removing material,

creating smoother surfaces, and providing more precise dimensions. In all such operations, both the grinding wheel and the work rotate. The grinding wheel moves toward the workpiece to contact it and away from the work after the grinding is completed. However, in many cases, the wheel also traverses the work or vice versa. There are two basic methods for grinding the surfaces of components such as shafts, axles, cylinders, and rolls: center-type grinding and centerless grinding.

C1a. center-type cylindrical grinding - is performed on lathe-like machines. The workpiece is usually held at each end on pointed centers and is rotated about these centers. (It may also be held by a chuck or other holding device.) The grinding wheel normally rotates on an axis parallel to the axis of the workpiece. The wheel and the workpiece contra-rotate so that the contacting surfaces move in opposite directions. After the wheel and the work have made contact, there usually is axial motion between the wheel and the work for the full length of the surface to be ground, plus some overrun. The wheel may also be fed only transversely into the workpiece as it rotates. In this case, the wheel has either

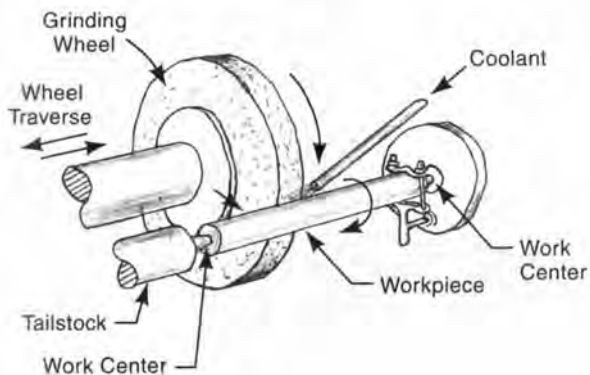


Fig. 3C1a Center-type grinding. Note that the grinding wheel rotates, has transverse motion across the whole length to be ground, and is fed into the workpiece as material is removed. The workpiece, held in centers, rotates against the grinding wheel.

a flat face or have a form dressed into it. The ground surface of the workpiece, then, can have contours, grooves, or whatever shape is dressed into the face of the wheel. If tapered surfaces are desired, the machine is set so that the axes of rotation of the work and the wheel are not parallel. Long, slender parts, and others subject to deflection or vibration during grinding may be supported by a steady rest. Fig. 3C1a illustrates the process.

C1b. centerless grinding - is a process for machining cylindrical surfaces wherein the workpiece is not held between centers or in a chuck. Instead, the work is supported by a work-rest blade at the correct height and contained between two wheels, as shown in Fig. 3C1b. One wheel is the grinding wheel; the other is a regulating wheel. The regulating wheel does not grind; it rotates the workpiece at a constant rate of speed. The process produces accurate diameters and roundness, with smooth surfaces in parts such as pins, shafts, and rings. Both throughfeed and infeed methods can be used, and production can be quite rapid. The method is normally not applicable if there are flats, keyways, or other interruptions in the workpiece's cylindrical surface. Conventional centerless grinders can accommodate solid parts up to about 7 in (18 cm) in diameter and rings and tubing up to about 10 in (25 cm) in diameter.

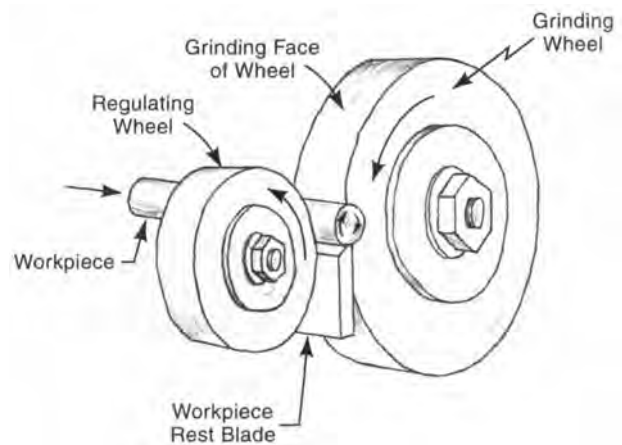


Fig. 3C1b Through-feed centerless grinding.

Larger sizes are too heavy for smooth operation and require special equipment.

C1b1. through-feed centerless grinding - In this method, the regulating wheel is canted slightly, as shown in Fig. 3C1b1, causing the work-

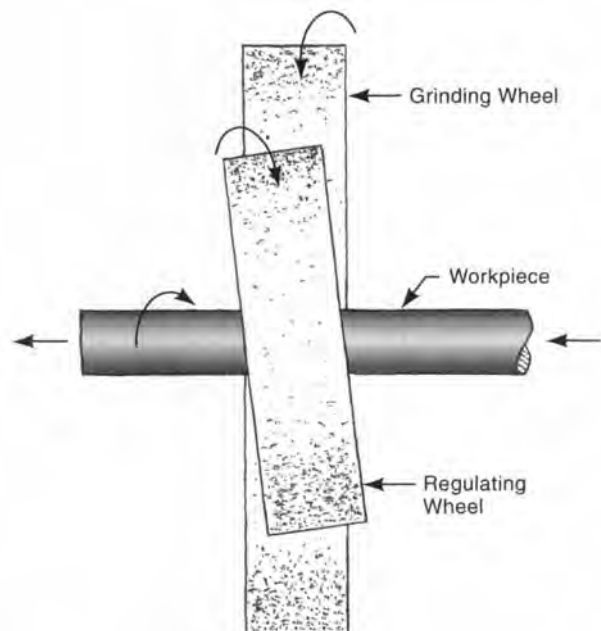


Fig. 3C1b1 In through-feed centerless grinding, the inclination of the regulating wheel induces a sideways thrust on the workpiece.

piece to move axially across the grinding wheel as the grinding takes place. This arrangement provides a rapid operation that can be made automatic if production quantities are sufficient to justify the use of an automatic feed for workpieces to be ground, feeding them end-to-end. The process is used for grinding pins, shafts, and similar parts of constant diameter. Piston pin grinding is a notable application. Parts that have heads, projections, or shoulders that would block the movement of the workpiece through the machine, cannot be through-feed centerless ground.

C1b2. infeed centerless grinding - differs from the through-feed process in that the part does not move axially. Stops in the machine prevent axial movement until the part is ejected. Instead, the grinding wheel is fed into the work once the workpiece is positioned. After grinding, the wheel retracts, the part is removed or ejected, and another is inserted. If the grinding wheel is dressed with a form, that form is ground into the workpiece. Tapers, multiple diameters, grooves, and other irregular shapes can be ground so long as the grinding wheel is appropriately dressed. The process is also useful when a portion of the workpiece is larger than the surface to be ground. It is illustrated schematically in Fig. 3C1b2. The process is fast but not quite as rapid as the through-feed method since workpieces must be inserted and removed individually. The process is used in the manufacture of ball bearings and parts not having a uniform diameter.

C1b3. end-feed centerless grinding - is used for tapered parts. Either the regulating wheel or the grinding wheel, or both, are dressed to provide the desired taper angle. The two wheels and the workrest blade are set in fixed relationship to each other. There is a stop to control the position of the workpiece, which is fed and removed axially. Fig. 3C1b3 shows the process.

C2. internal grinding - is a process for finish machining existing round holes. It normally is performed on a lathe-like machine. The workpiece is held in a chuck or faceplate holding fixture and

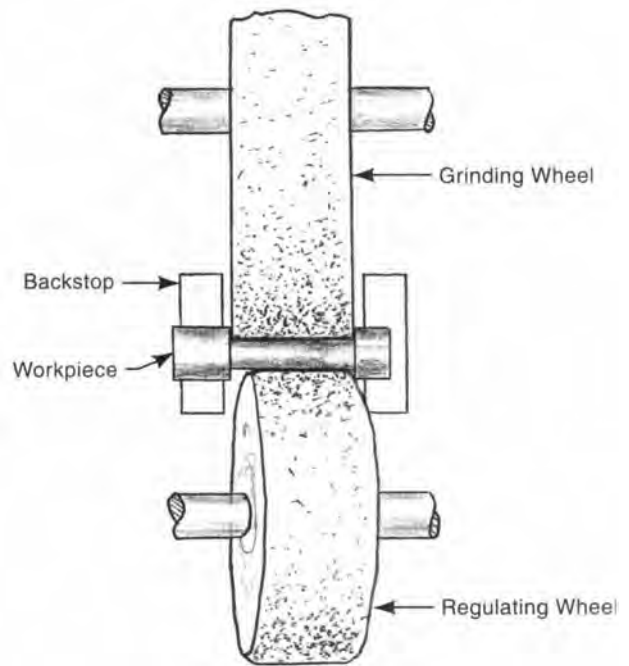


Fig. 3C1b2 Infeed centerless grinding. The method is used when a portion of the workpiece is larger than the ground surface. The workpiece is placed in position; the grinding wheel is fed into the work; the wheel retracts after grinding and the workpiece is removed or ejected.

rotated about the axis of the hole to be ground. The rotating spindle carrying the small grinding wheel is inserted into the hole and then fed radially to contact the surface. The wheel can be cylindrical or dressed with a form. If the internal surface to be ground is cylindrical, the wheel is also traversed axially. Diameter control can be maintained by dressing the grinding wheel with a diamond tool in a fixed position with respect to the axis of the hole. Internal grinding is most commonly used to finish machine precision holes in hardened workpieces. Large, heavy parts are internally ground on vertical spindle machines since loading and positioning such parts is easier if the rotary surface is horizontal. If the large workpiece is too bulky or unbalanced to rotate, it is held in a fixed position and the grinding wheel is moved in a planetary motion around the hole's axis, as in jig boring.

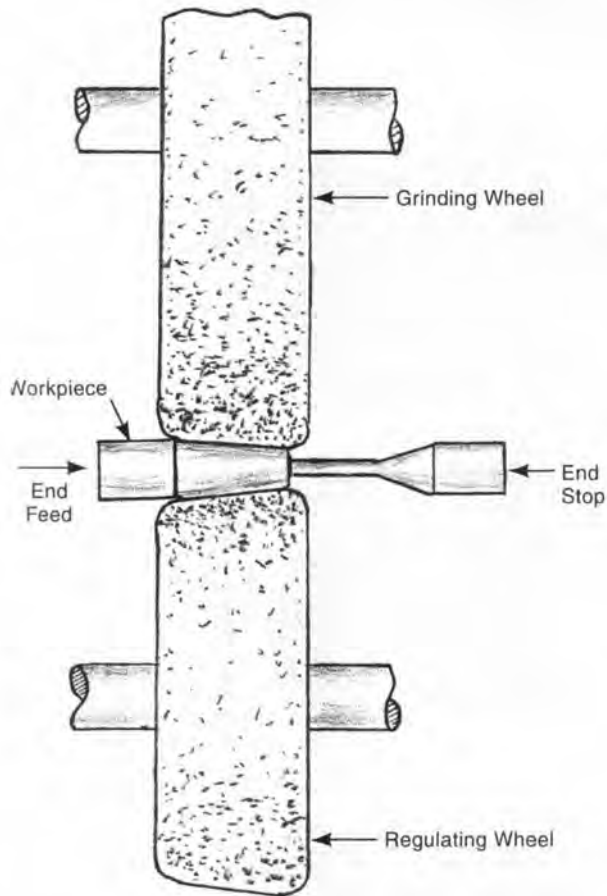


Fig. 3C1b3 End feed centerless grinding is useful when the surface to be ground is tapered. The workpiece is positioned and removed axially.

C2a. internal centerless grinding - can be used to finish machine sleeves, rings, and similar parts. As illustrated in Fig. 3C2a, the workpiece is held between three rolls, which locate it and provide rotation. The grinding wheel is inserted into the center hole and fed radially to contact the inner surface of the hole as in regular internal grinding. The process insures concentricity between the outer diameter of the part and its center hole. It is suited to mass production situations because the part does not have to be placed in a chuck, and handling is simplified. The grinding of bearing raceways is a common application. Sleeves and cylinder liners are also ground by this method. Tapered holes can

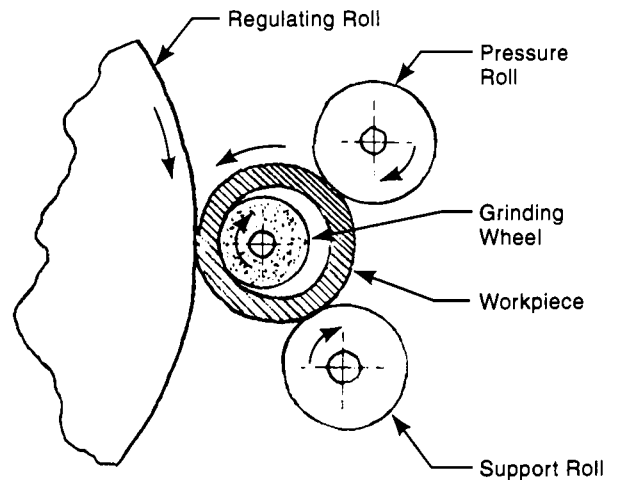


Fig. 3C2a Internal centerless grinding.

be ground on some machines that allow the axis of the grinding wheel to be set at an angle to the axis of rotation of the workpiece.

C3. surface grinding - moves the workpiece in a horizontal plane so that it passes under a revolving grinding wheel which contacts it and removes surface material. The result is a part with a flat, smooth surface and an accurate thickness or height. Various arrangements of grinding wheels and various table movement methods can be used. Major arrangements are shown in Fig. 3C3. The table movement is most often reciprocating but rotary tables are also common. The wheel spindle may be horizontal or vertical. The latter requires a cup-shaped or segmented wheel, which cuts on its face.

The most common method for holding the workpiece is with a magnetic chuck, although holding fixtures and other methods may also be used. Surface grinding is also used to sharpen cutting tools. For some applications, especially when heavier metal removal rates are appropriate, the operation may be carried out with an abrasive belt (passing over a roller at the point of contact) rather than a bonded wheel. When the wheel is dressed with a form, the workpiece surface can be ground with that shape instead of a flat surface.

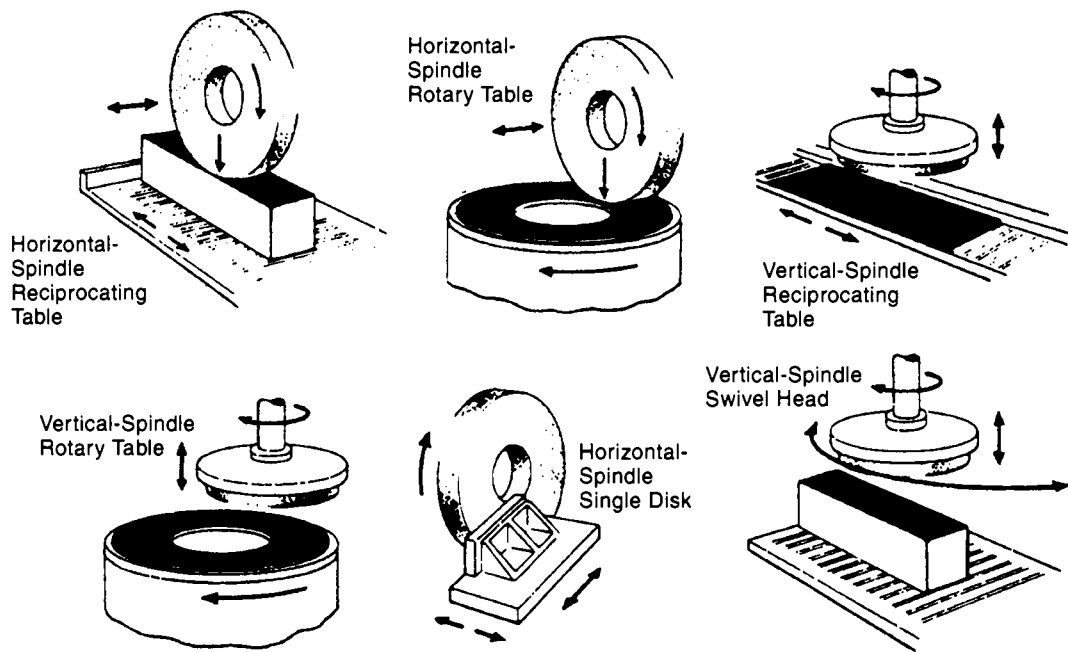


Fig. 3C3 Various equipment arrangements for grinding flat surfaces. (Courtesy American Machinist, Penton Media, Inc.)

C3a. horizontal spindle surface grinding - is surface grinding with a horizontal grinding wheel spindle. The wheel cuts on its periphery. The table may be either circular with a rotational motion or, more commonly, rectangular with a reciprocating motion. In both arrangements, the wheel advances perpendicularly to the basic direction of motion with each cycle of table movement, and thus generates a flat surface. See Fig. 3C3. This approach is used extensively in tool shops to make and recondition dies and to produce machine surfaces on which there are moving parts. With a reciprocating table, horizontal-spindle surface grinding can be used to machine slots in hardened workpieces. By dressing a form on the grinding wheel, the ground surface can be given a form rather than a flat surface.

C3b. vertical spindle surface grinding - uses a grinding wheel mounted on a vertical spindle with either a rotary or reciprocating table. Various methods are used to move the wheel across the work, as shown in Fig. 3C3. The cup-shaped, segmented, or

cylindrical wheel covers a larger area than the side of the wheel does in a horizontal spindle arrangement, so cross feed of the worktable or wheel may not be necessary. These machines are typically used in production applications, while horizontal-spindle machines are more common in toolroom or jobbing work. Vertical spindle machines are used in the manufacture of cylinder head surfaces, gear and pulley faces, and other moving parts that require flat, smooth, surfaces. Weldments, castings, and forgings are ground on these machines. These parts usually have somewhat liberal tolerances for dimensions and surface finish; however, vertical spindle machines have the capability of producing the fine finishes and close tolerances typical of toolroom work. Some machines have more than one spindle and thus can do rough and finish grinding in one pass, or can grind several surfaces of the workpiece simultaneously.

C3c. creep-feed grinding - is an abrasive machining process capable of heavy stock removal.

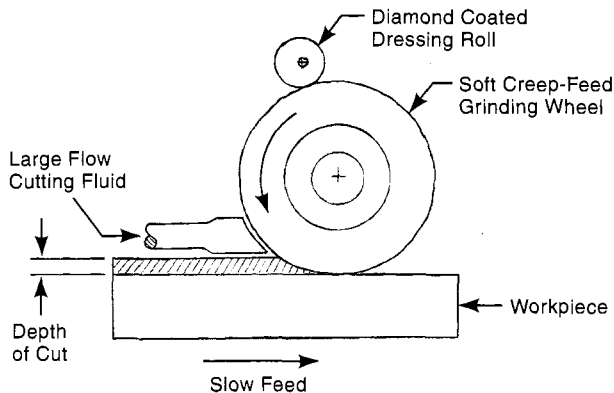


Fig. 3C3c Creep feed grinding. Note the slow feed, large depth of cut, soft wheel, and heavy flow of cutting fluid.

It is particularly applicable to hard materials that would be difficult or unfeasible to machine with a milling cutter. The depth of cut normally ranges from 0.20 to 2 in (5 to 50 mm), much more than in conventional grinding, but the table speed is low, 0.4 to 20 in (1 to 50 cm) per minute. The process thus resembles milling, but the grinding wheel takes the place of the milling cutter. The grinding wheel is soft and made with a very open porous structure to provide space for flow of cutting fluid. The wheel spindle is lowered gradually as the wheel wears. Continuous crush-dressing is normally used, and wheels can be dressed with a form if desired. Cutting forces are high and the machine must be rigid and capable of closely-controlled table speeds; otherwise wheel breakage would occur. Fig. 3C3c illustrates the process. Note the “climb milling” direction of the grinding wheel rotation.

C4. jig grinding - A jig grinder is a precision vertical-spindle machine, similar to a jig borer. It is used for internal grinding. It has a horizontal table that can be moved and located very accurately. The spindle head contains a high-speed grinding head that rotates the grinding wheel about its axis but that axis can also revolve in a planetary motion. The head can also move vertically with reciprocating motion. Thus, holes can be ground to very accurate

locations and diameters and, as the head reciprocates vertically, to high levels of cylindricity. The machine is used for finish grinding of hardened dies, molds, jigs, and fixtures.

C4a. tool post grinding - involves the mounting of a power-driven grinding wheel for either external or internal grinding on the tool post of a lathe. The wheel then performs conventional grinding operations on parts held in the lathe. This method is a useful means to provide cylindrical grinding in shops not equipped with the conventional cylindrical grinding machines. Care must be taken to avoid damage to the lathe components from trapped grinding dust from the operation.

C5. low-stress grinding - is a variation of conventional grinding in which the objective is to minimize stresses developed in the workpiece by the grinding operation. It differs from conventional grinding in that very low wheel infeed or downfeed rates, frequently dressed coarse, softer, open-grain wheels, and liberal flow of coolant are used. Wheel speed also may be low. Abrasive grains in the grinding wheel should be sharp, and wheels should not be allowed to become loaded. The process is applicable when the part to be ground is subject to high stresses in use or is susceptible to damage from heat. Parts made from some materials such as high-strength steels, cobalt alloys, titanium alloys and high-temperature nickel alloys that are particularly sensitive to surface cracking and residual stresses from conventional grinding, can be finish-ground with this approach².

C6. plunge grinding - is simply a center-type grinding operation where there is no transverse feed of the grinding wheel. Instead, the wheel is fed directly into the work. If the wheel is dressed with a form, that form is ground into the workpiece. If the width of ground area is no more than the width of the wheel, the operation can be referred to as plunge grinding. The term “in-feed grinding” is also used.

C7. disc grinding - is a means for producing flat surfaces. The workpiece is held against the flat

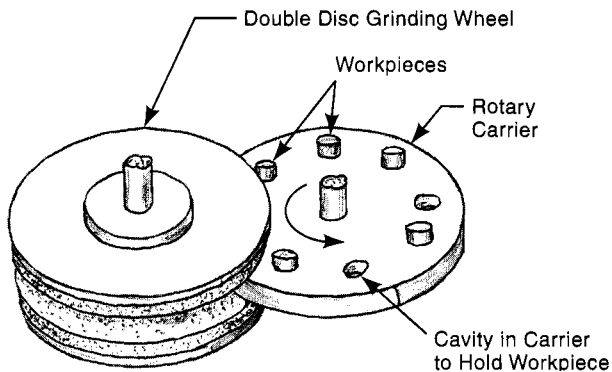


Fig. 3C7 Double disc grinding. Both the top and bottom surfaces of the workpiece are ground at the same time.

side (face) of a large rotating abrasive disc. (See Fig. 3C3.) The operation can be performed manually when dimensional requirements for the part are not severe. In production situations, *double disc grinding*, as illustrated in Fig. 3C7, is sometimes employed. The workpiece is fed between two abrasive discs which grind the opposite surfaces of the workpiece at the same time, thus controlling flatness, thickness, and parallelism in the same operation. Parallelism and flatness of surfaces is particularly good with these machines because there is no magnetic chuck to pull down non-flat parts, only to have them spring back to a non-flat condition after the operation. Double-disc grinders are used in the production of automotive connecting rods, disc brake rotors, compressor vanes, and cast-iron rocker arms.

C8. abrasive belt grinding - uses an abrasive-coated cloth belt to remove metal. The endless belt runs between a drive wheel and a contact wheel, and the workpiece bears against the belt at the contact wheel. The abrasive grains on the belt are arranged with orientation and spacing to optimize metal removal rates. The process can provide faster metal removal than grinding with a wheel and is then often referred to as *abrasive belt machining*. Metal-removal rates of 30 in³/min/in (193 cm³/min/cm) of belt width are feasible with standard belts.⁴ This rate is faster than those attainable with milling machines, even under the fastest metal removal conditions. Belts as wide as 10 ft (3 m)

allow the entire surface to be ground in one pass. The process can provide lower heat levels than grinding with an abrasive wheel because the belt carries away heat effectively. Lubricants may be used to facilitate the operation. The approach is used for rough metal removal from castings, forgings, and other shapes, especially when the workpiece is large. Surface, cylindrical, and centerless grinding can be performed with abrasive belts. Abrasive belts can also be used for hand grinding and polishing.

C9. abrasive jet machining - provides cutting action from the effect of finely-powdered abrasive in a high-velocity stream of gas. With the gas carrier, the abrasive and gas are raised to a pressure between 30 and 120 lbf/in² (200 and 830 kPa). The stream is passed through a nozzle of 0.005 to 0.032 in (0.13 to 0.81 mm), and reaches a velocity of 500 to 1000 ft/s (150 to 300 m/s). The stream is directed at the desired place on the workpiece. This can be done by hand for rough cuts, stripping, or deburring. However, precision cuts require the nozzle to be mounted on suitable equipment. Masks of rubber, glass, or copper may be used to help limit the abrasive action. The process can be used for drilling, cutting, etching, trimming, cleaning, and deburring operations on a variety of metals and non-metals, especially hard and fragile materials. (The process is less suitable for softer materials that may trap the abrasive.) Ceramics, glass, silicon, and mica are machined with this method. Sheets of these materials can be cut and drilled, and abrasive jet can produce intricate holes that would not be easily made by other methods. Other applications are marking identification on workpieces, trimming, and cleaning electronic components, and removing surface coatings including plating. The process is illustrated schematically in Fig. 3C9. Cutting rates are slower than those achieved with more conventional processes but there is no heat damage to the workpiece.

C10. abrasive flow machining (AFM) - uses a viscous, putty-like abrasive medium which is pumped so that it flows against the workpiece. The abrasive particles in the medium rub against the workpiece, gently removing surface material.

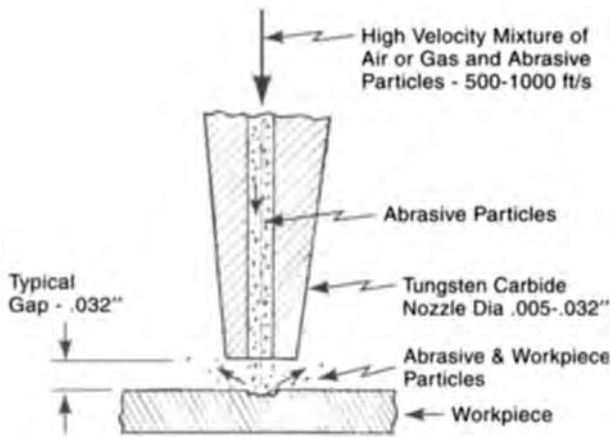


Fig. 3C9 Abrasive jet machining - A high velocity stream of air or gas and abrasive particles impinge on the workpiece and remove workpiece material. The process is particularly useful in drilling, cutting, or engraving hard, brittle materials including non-metallic materials. (Courtesy Omax Corporation.)

The process is used to round sharp corners, finish edges, remove recast layers from EDM or laser machining, polish surfaces, and remove burrs (See K1.) AFM is particularly useful when the area to be machined is not accessible for other methods. In practice, two cylinders on opposite sides of the workpiece are used to contain and pump the medium, which flows back and forth repeatedly (through as many as one hundred cycles) until sufficient material is removed from the workpiece.

C11. ultrasonic machining - utilizes an abrasive in a water slurry and a shaped tool. With the abrasive between the tool and the workpiece, the tool is vibrated at ultrasonic frequency. The vibration of the tool drives the abrasive particles against the workpiece, cutting a cavity that has the same shape as the tool. The frequency of vibration is usually between 19,000 and 25,000 Hz with a low amplitude - 0.0005 to 0.0025 in (0.013 to 0.063 mm). The abrasive slurry is pumped through the gap between the tool and the work. The gap ranges from 0.001 to 0.004 in (0.025 to 0.1 mm). The stainless or carbon steel tool is attached to an ultrasonic generator through a "horn", usually of Monel metal. Fig. 3C11

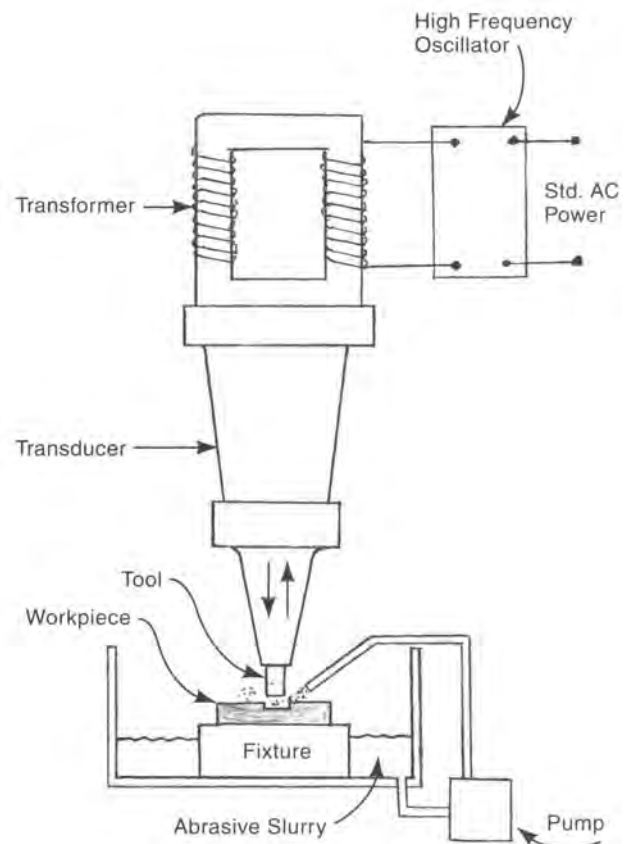


Fig. 3C11 A schematic view of a typical arrangement for ultrasonic machining.

illustrates the process schematically. It is most advantageous for shallow cuts in hard, brittle, non-conductive materials that are difficult or unfeasible to cut by other methods. Slots, holes, and cavities of various shapes can be produced in ceramics, glass, carbide, tool steels, honeycomb material, and gem stones. Holes and cavities can be non-round and curved. Material removal rates are low, but there are no heat effects, no burrs, and surface stresses are low. Holes have some inherent sidewall taper.

C11a. rotary ultrasonic machining - uses a rotating tool, coated with diamond abrasive and ultrasonically vibrated, to machine hard and brittle materials. There is no abrasive slurry but a liquid coolant, usually water, is used. Milling, drilling, and threading operations can be performed, but

drilling is the primary application. Non-metals: glass, alumina, ceramic, quartz, sapphire, and composite materials are normally processed.

D. Milling

Milling is a means of creating a desired surface with a rotating multi-toothed cutter. Each tooth of the cutter removes material as the workpiece advances against it. The axis of rotation of the cutter may be either horizontal or vertical. The cutter can provide cutting action on its side or at its end (face), or both. The cutter rotates rather rapidly and its position is normally stationary; the work moves past the cutter with a suitable depth of cut at a relatively slow feed rate. Milling is the most common machining operation for producing flat surfaces, but slots, and contoured or stepped surfaces and screw threads can also be produced. A variety of milling operations and the cutters used are illustrated in Fig. 3D. (Also see *machining centers*, T.)

D1. *face milling* - shown in Fig. 3D1, produces a flat surface at a right angle to the axis of rotation of the cutter. Depending on the depth of cut, some machining also takes place on the periphery of the cutter. For flat surfaces, face milling is generally preferable to peripheral milling from the standpoints of tool economy, simplicity of set-up, and cutter rigidity. However, the operation is limited to flat surfaces.

D2. *peripheral milling* - The milled surface, if flat, is parallel to the axis of rotation of the cutter, and is produced by cutting teeth located on the periphery of the cutter body. The operation is usually performed on horizontal-spindle machines. The milling cutter or cutters are mounted on an arbor that has outboard support. The surface may be flat or contoured, depending on the profile of the cutter. Flat and contoured surfaces, slots, and key-ways, are machined by this method. (Fig. 3D, in views a), b), f), and g), shows peripheral milling. Views c), d), and e) show both peripheral and face milling.)

D3. *end milling* - uses a cutter, commonly of smaller diameter, with teeth on both the end (face) and periphery. Fig. 3D, in views n) and o), illustrates the operation. The approach is versatile in that slots, recesses and profiles can be machined. Machining can also be carried out in areas not accessible to other types of cutters. However, the length-to-diameter ratio of end mills is high and they can be supported only at one end, so they are less rigid than cutters for other milling methods. Lighter feeds may be required to reduce cutter deflection. Material removal rates are less than with other milling methods and accuracy may not be as great.

D4. *slab milling* - is peripheral milling with cutters that produce a flat surface over a wide area. The axis of rotation of the cutter is parallel to the machined surface. The cutter often removes large amounts of material. Sometimes, two or more cutters are used per arbor with opposing helixes to balance cutting forces. See view b) of Fig. 3D.

D5. *form milling* - When the peripheral cutting edges of the milling cutter are ground with a form rather than in a straight line, that form is transferred to the workpiece as the milling operation proceeds. The operation is called form milling and is illustrated schematically in Fig. 3D, views i), k), l) and m). Milling of gear teeth is a common application of this approach.

D6. *gang milling* - is simply milling with more than one cutter on the arbor of the milling machine. This produces multiple surfaces on the workpiece with one pass of the cutters. Also see straddle milling, as follows.

D7. *straddle milling* - involves the use of two cutters on one arbor with a space between them. Two surfaces are cut in one pass, but the area between them is not machined, as illustrated in Fig. 3D, view Q).

D8. *fly cutter milling* - involves the use of a single-point cutter rather than a multiple-tooth cutter to perform a milling operation. It is face milling with only one cutting tooth. The method is useful for producing

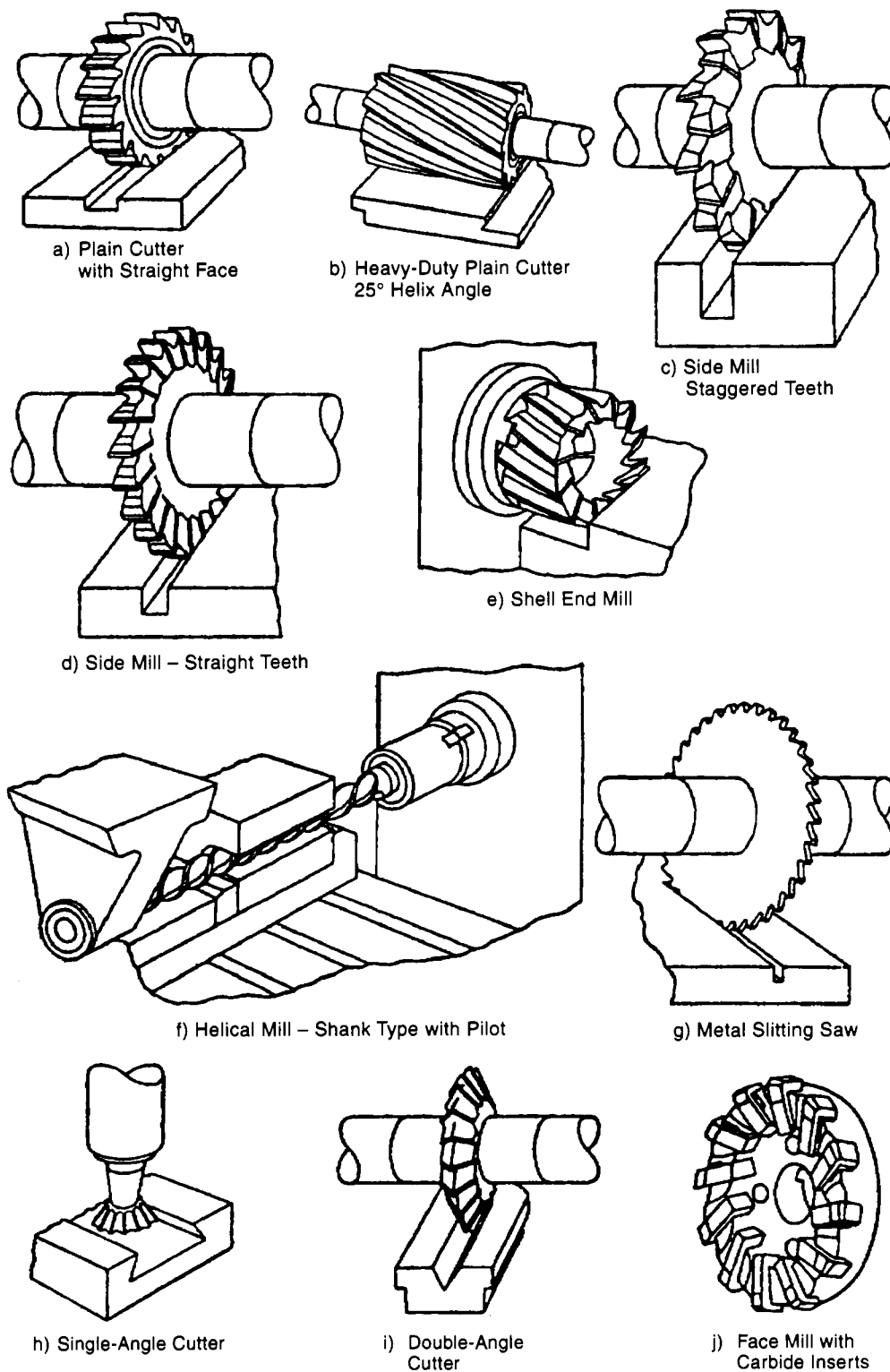


Fig. 3D A collection of milling cutters and the operations that they perform. (from LeGrand, *American Machinist's Handbook*, 1955, McGraw-Hill Companies.)

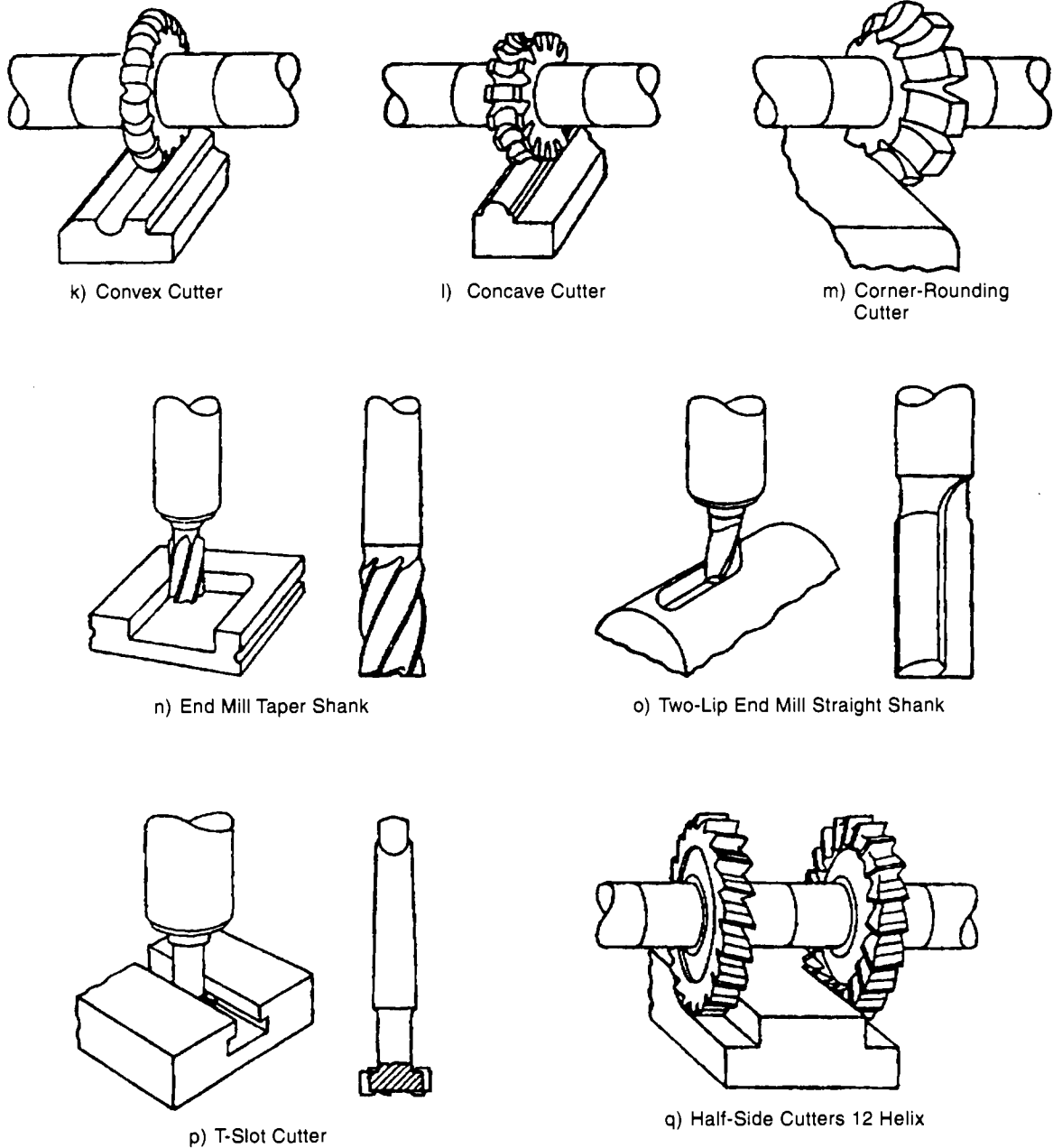


Fig. 3D (Continued).

flat surfaces in a tool room situation where the optimum multiple-toothed cutter may not be available. Obviously, cutting feed rates are much less than with face mills but may be satisfactory when flycutters are the only tools available and requirements are for only one piece or a small quantity.

D9. **pin routing** - involves the use of a template to guide the movement of a high speed routing cutter (small diameter end mill). Typically, the process is used to blank flat stock of sheet metal or other materials. Stacks of thin material can be cut by this method, to produce multiple parts.

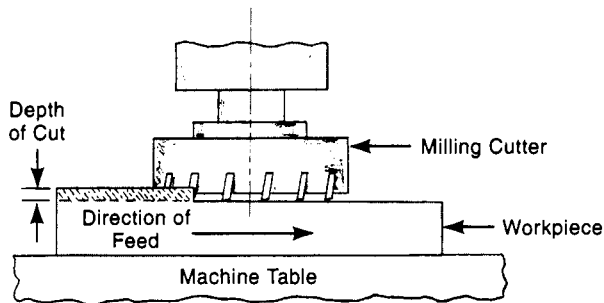


Fig. 3D1 Face milling.

D10. **spotfacing** - is a simple operation, shown in Fig. 3B2 view c) that is normally used to provide a small flat bearing surface, perpendicular to the axis of a hole, for a bolt head or nut. An end-cutting rotating tool is fed into the workpiece along the axis of the bolt hole, often with a drill press rather than a milling machine. Depth of cut is often not critical as long as the surface machined is flat and perpendicular to the axis of the bolt hole. The operation is the same as counter-boring except that the depth of cut is shallow, only enough to create a flat machined surface. It is most commonly performed on castings and forgings where the surface prior to the operation has some irregularity.

E. Screw Threads

Screw threads are made with a large number of different methods involving both machining (cutting) and forming processes. Cutting methods include the use of hand-operated taps and dies for internal and external threading, and machines for single-point screw-thread cutting, thread-cutting die heads, thread milling, and thread grinding. Forming methods include rolling of external threads and cold-forming of internal threads.

E1. **hand-die external threading** - A typical external hand-threading die is illustrated in Fig. 3E1. These are called button or acorn dies and are useful for cutting screw threads in prototype and limited-quantity production. The die is placed on the end of the screw blank and is rotated with a wrench-like

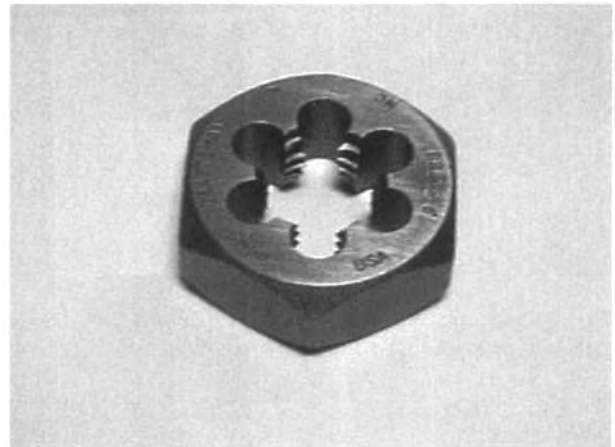


Fig. 3E1 A hand die for cutting external threads.

tool. It feeds itself forward at the lead rate of the screw as it cuts the threads.

E2. **internal thread tapping** - utilizes taps such as that shown in Fig. 3E2. The tap is rotated like a drill or reamer and is self-fed axially into the hole in the workpiece to create an internal thread. Taps can be positioned and fed manually, and rotated with a hand tool, or can be used with a drill press, lathe, automatic screw machine with a tapping attachment, or a special tapping machine. Tapping machines and attachments have the capability of reversing the rotation of the tap to remove it from the work after the thread cutting is

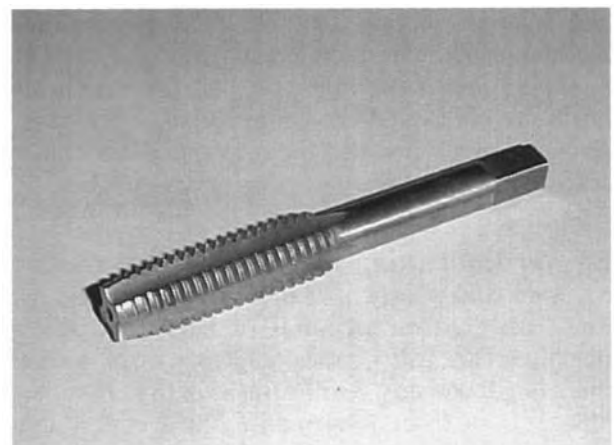


Fig. 3E2 A solid tap for machining internal screw threads.



Fig. 3E2-1 A collapsible tap. (Courtesy Landis Threading Systems.)

completed. These solid taps are used for internal threads of 0.050 in (1.2 mm) to 6 in (150 mm) diameter⁵.

Collapsible taps automatically retract the cutters to clear the new threads and do not have to be reversed for removal, but are not available for diameters less than about 1 1/4 in (32 mm). They are usable for diameters up to about 24 in (600 mm)⁵. See Fig. 3E2-1.

E3. single-point screw-thread cutting - is a lathe operation. A form cutting tool that has a profile corresponding to that of the space or spaces between the required screw threads makes repeated passes along the workpiece. The cutter is attached to the lathe carriage and is moved longitudinally along the bed by the lathe's lead screw, which is geared to provide the rotational rate needed to produce a screw of the proper pitch. Both external and internal threads can be generated by this method, as shown schematically in Fig. 3E3. The method is used for large screws, for which die heads are not available or impractical, when quantities are small, or when the material is difficult to machine.

E4. thread cutting die heads - are efficient, accurate, and widely used in production threading. They are used on all kinds of lathes and screw machines, on drill presses, and as part of special threading machines. As illustrated in Fig. 3E4, they have sets of insertable multi-toothed cutters that are changeable when different pitches of threads are to be machined or when the cutters need re-sharpening. Like button dies, die heads are

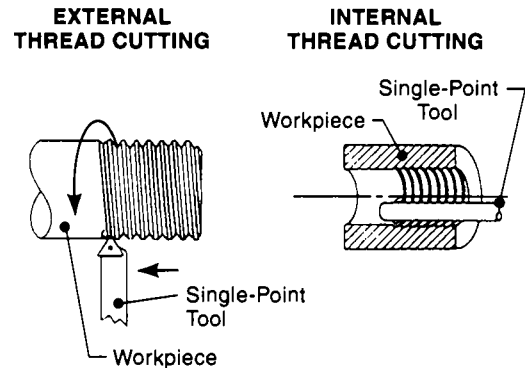


Fig. 3E3 Single point machining of external and internal screw threads. (from *Manufacturing Processes Reference Guide*, R.H. Todd, D. K. Allen, and L. Alting, Industrial Press, New York, 1994.)

self-feeding at the lead rate of the thread. At the end of the cut, the cutters retract automatically for rapid withdrawal. Perhaps the largest single application is pipe threading, on special small machines that can be transported to building construction sites.

E5. thread milling⁵ - utilizes a form-milling cutter. Both the workpiece and cutter rotate. Most cutters are the multiple-rib type shown in Fig. 3E5, but single-rib cutters are also used, though cutting one thread at a time requires more time. The method is applicable to both internal and external threads. (In internal thread milling, the cutter diameter should not exceed 1/3 of the hole diameter.) Thread



Fig. 3E4 A die head for external threads with inserted multi-toothed cutters. (Courtesy Landis Threading Systems.)

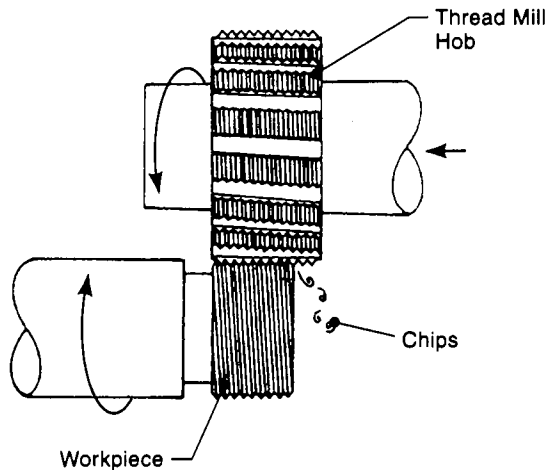


Fig. 3E5 Thread milling of external threads. (from *Manufacturing Processes Reference Guide*, R.H. Todd, D. K. Allen, and L. Altng, Industrial Press, New York, 1994.)

milling is used in situations where die-head cutting or tapping is difficult, for example, in difficult-to-machine materials, long threaded lengths, high helix-angle threads, or large, coarse-pitch threads. However, milling is not suitable for square threads or others with a flank angle nearly 90 degrees from the axis.

E6. thread grinding⁶ - is used when particular accuracy and surface smoothness are required, when heat-treated workpieces are threaded, or when the material is otherwise difficult to machine. Threads are ground in stainless and tool steels and in sintered iron components, particularly when they have been heat treated for hardness or are used in precision applications such as adjustment screws and feed screws. Both center-type (3C1a) and centerless cylindrical grinding machines (3C1b) are used. The wheels may be dressed to grind multiple ribs or a single rib. In either mode, the workpiece moves axially across the wheel as it rotates.

With center-type grinding, several passes are usually required. Center-type grinding can be used on short runs, but is not limited to small-quantity production.

With centerless grinding, the wheel is always dressed for multiple-rib grinding. The workpiece is

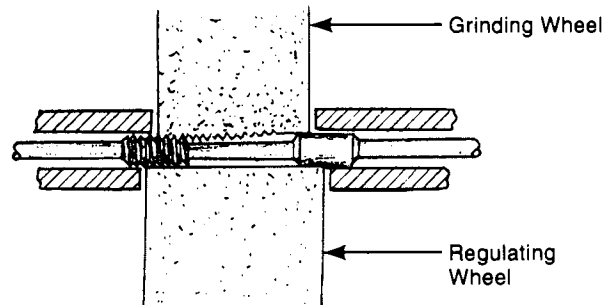


Fig. 3E6 Centerless thread grinding of headless screws.

first ground to the correct diameter and then the threads are made as the work passes across the wheel. Centerless thread grinding is more of a high production method, used when quantities are 10 or 15 thousand per lot or more. Process times are very short but setups require more time. Fig. 3E6 shows centerless thread grinding.

E7. thread rolling - is a cold-forming method for making external screw threads. The blank workpiece is rolled between opposing dies which have a negative screw thread profile. The dies may be flat or cylindrical. Die heads, somewhat similar in appearance to cutting die heads, are often used, but these units have hardened rolling tools in place of the cutters. A third method allows several blanks to be run at one time between a cylindrical die and a concave die in planetary fashion. With all these process variations, the screw thread produced is of high quality with an accurate thread and smooth surface finish. No material is wasted and there are strength advantages because of the cold-working of the workpiece material. However, the diameter of the blank to be threaded must be accurate for the finished part to have the correct pitch diameter. The operation is rapid and is particularly suited to mass production of threaded fasteners. The flat-die method is illustrated in Fig. 3E7.

E8. cold-form tapping of internal threads - differs from tapping with cutting taps as described above, in that the workpiece metal flows rather than being cut and removed to form the threads. Both kinds of taps are used in essentially the same

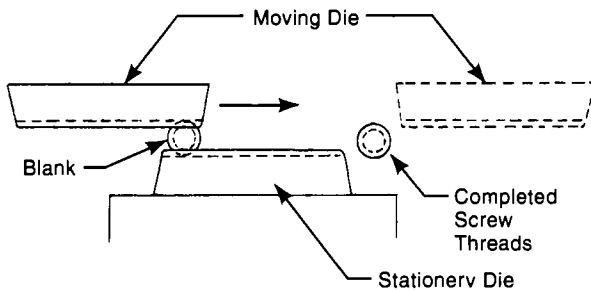


Fig. 3E7 Thread rolling with flat dies.

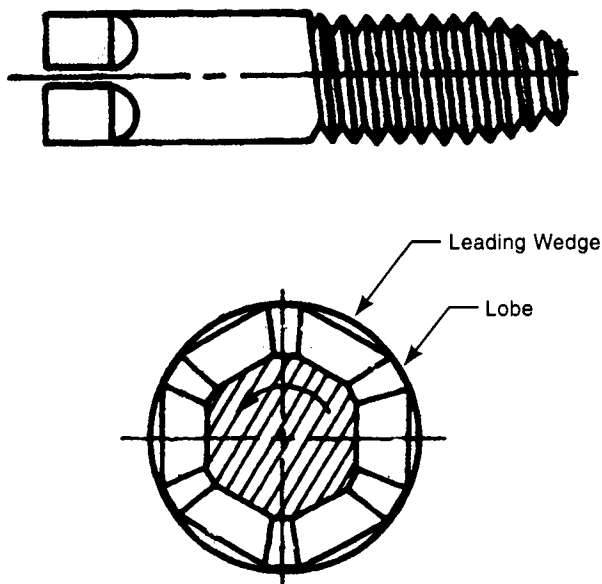


Fig. 3E8 A typical thread forming tap.

way and they look somewhat similar. A cold-forming tap is illustrated in Fig. 3E8. Cold-forming taps produce strong screw threads but the threads formed fill only 65 percent or less of the space of full threads. Soft and ductile materials must be used. Tapping speeds are higher than with cutting taps.

F. Broaching

Broaching is a high-production machining operation that involves the one-way movement of a broach, a cutting tool with a series of progressively-stepped teeth. The teeth move parallel to the surface

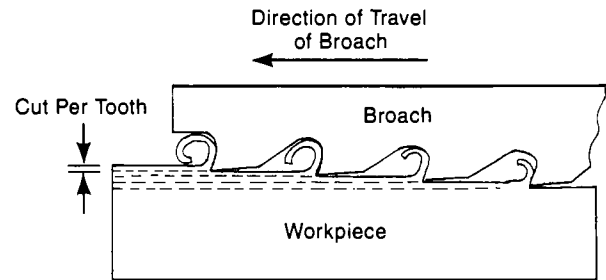


Fig. 3F The cutting action of a broach. (Drawing courtesy J. R. Casey Bralla.)

being machined and each one removes a precise amount of material. The action is similar to that of a saw except that each tooth is set slightly higher than the one that precedes it and is wide enough to machine the entire surface. As with a saw, the spaces between the teeth hold the chips until the teeth pass from the workpiece. One pass of the broach results in the completion of the operation. The broach can be pulled or pushed across the work. Fig. 3F illustrates the cutting action schematically. Broaching is used to machine holes, (particularly non-round holes), flat surfaces, splines and slots. One common application is the machining of keyways in pulleys and gears, as shown in Fig. 3F1. The initial teeth to contact the workpiece are often designed to provide a roughing cut, while the final teeth provide finishing to the dimension desired. In that way, the operation can provide both high

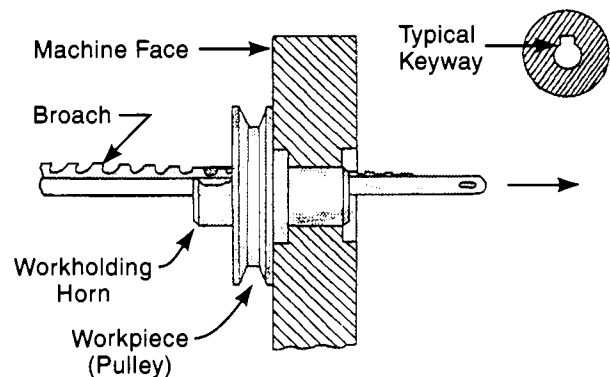


Fig. 3F1 Internal broaching of a keyway in a pulley and the cross-section of a typical broached keyway. The pitch of broach teeth is exaggerated to illustrate the process.

accuracy and excellent surface finish. The operation is rapid and particularly suited to mass production conditions. Operator skill requirements are not high because the needed precision is incorporated into the broaching tool. However, broaches are expensive and this is why broaching is chiefly found in mass production situations where the tooling cost can be amortized. However, some internal shapes are not practical to machine by other methods and that is why broaching is commonly used for keyways, splined-shaped holes, dovetail slots, and “fir tree” shaped slots for turbine blades. The equipment required for broaching ranges from simple arbor presses for keyway broaching, to huge special machines used in the automotive industry for surface-machining engine blocks and other large components. Holes as small as 0.050 in (1.3 mm) and surfaces as large as 20 in (0.5 m) wide, have been machined with this method.⁴

F1. internal broaching - is machining by broaching the inside surface of a hole or other opening in the workpiece. The most common broaching operations produce keyways, key slot openings in locks, spline-shaped openings, and other non-round enlargements of holes in pulleys, gears, or other parts that are to be fastened to shafts. There must be an initial hole or opening in the workpiece to provide room for entry of the broach. Helical surfaces can be cut with helical broaches if the workpiece is rotated as the broach advances. Fig. 3F1 illustrates internal broaching of a keyway.

F2. external broaching - takes place when the broaching tool machines an outside surface of a workpiece. Examples are the machining of flat surfaces, cam surfaces, and gear or ratchet teeth.

F3. pot broaching - uses a ring- or tubular-shaped broaching tool with the cutting teeth on the inside. Normally, the workpiece is pushed through the tool with hydraulic force. The tool cuts the entire workpiece periphery in one pass. Machining of gear teeth is a typical application.

G. Sawing

Sawing is the parting of material through the use of a narrow cutter, a saw, which contains a series of cutting edges that pass against the work

in a continuous or reciprocating motion. As the cutter is advanced into the work, material is removed by each tooth, and a slot is formed, eventually extending through the entire thickness of the workpiece, and severing it into two pieces. The chip produced by each tooth is carried in the space between the teeth until the teeth exit the workpiece. The cutter can be in disk, band, or reciprocating blade form. Cutting teeth are typically set, i.e., offset slightly and alternately from both sides of the saw blade to provide a slightly wider cut (kerf) than the thickness of the blade so that there is room for its passage. The operation is used to cut billets, extrusions, castings, forgings, and various other shapes into blanks for further operations. Bars of various cross sections, rods, angles, and various other structural sections are cut to length by sawing.

G1. circular sawing - uses a saw in the form of a circular disk, with cutting teeth on the periphery. As the circular saw rotates, it is fed against the workpiece, machining a narrow slot in the workpiece and eventually severing it. Circular saws for metal cutting are sometimes called *cold saws* because they don't significantly heat the workpiece as friction saws do. They often have inserted cutter teeth of carbide rather than teeth formed of the blade material, or have cutter segments fastened to a center disc. Blades are sometimes large in diameter to permit the sawing of bulky workpieces. Kerfs are considerably wider than those on band or hack-saws because the circular blade must be thick enough to provide rigidity. Accurate and smooth cut surfaces are feasible with this method. The circular saw process is used to make blanks for subsequent operations or to cut structural members to the desired length. Fig. 3G1 illustrates a circular cut-off saw (coldsaw).

G2. band sawing - is most commonly a cut-off operation. Instead of a circular disk, the saw is an endless steel band with cutting teeth on one edge. The blade moves as it cuts in one direction. Cutting is continuous and blade wear is uniform over the whole length of the blade. Since the blade is normally thin, little material is lost to chip waste and power requirements are modest. The workpiece or the blade can be fed manually or mechanically.

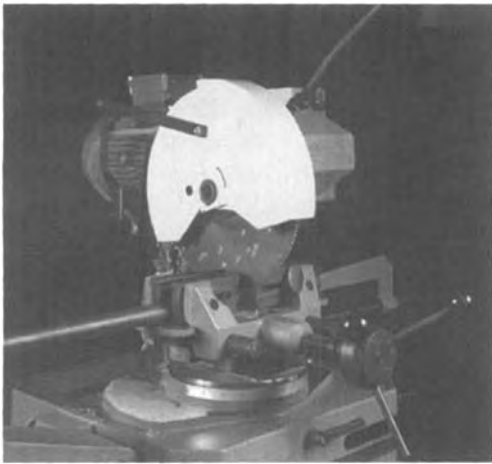


Fig. 3G1 A circular cutoff saw. (cold saw).
(Courtesy Clausing Industrial, Inc.)

For cutting off, the blade is normally horizontal and is fed mechanically or by gravity. Band saws are also used for contour sawing. (See G3 below.) Band sawing is suitable for thin-walled tubing and other somewhat fragile parts because cutting forces are lower than with other sawing processes.

G3. contour sawing - uses a band saw. The powered band normally moves vertically downward and the workpiece, resting on a horizontal table, is fed into the moving blade either manually, with or without power assist, or automatically, into the moving blade. The cut can be in a straight line or a curved path, depending on the shape of the part to be produced. Contour work is not uncommon in tool shops for templates, cams, dies, and fixtures. Flat stock is the most common shape cut by this method but material of other shapes is also processed. A quantity of parts of thinner material can be cut in one operation by stacking a number of blank sheets. Views of some typical applications of contour sawing are shown in Fig. 3G3.

G4. hacksawing - uses a reciprocating saw, either manually or mechanically operated, to perform a cut-off operation. Cutting takes place only on the forward stroke. Feed of the blade is commonly by gravity but hydraulic and other mechanical feeds

are often used on production hacksaws. Production hacksaws also incorporate a rapid return stroke to minimize the cutting time. The short, straight blade is less expensive than a bandsaw or circular saw blade but the cutting is less rapid. Once loaded, power hacksaw machines complete the operation automatically, stopping when a limit switch is tripped. Blades and equipment are less costly than those used with other sawing methods.

G5. abrasive sawing - uses a circular, band, or reciprocating saw blade, with a cutting edge that consists of abrasive particles rather than teeth formed in the edge of the metal blade itself. Thin, circular, cutters of bonded abrasive are most common. Surface speeds are much higher than with conventional sawing. Abrasive sawing is used when the workpiece material is hard or otherwise difficult to cut with metal cutting teeth. Hot metal billets are cut with this method. Cutting is quite rapid with large-wheel, high-horsepower machines. Coolant may be used to improve the finish of the cut surface, reduce burrs, and minimize heat effects. Smaller machines are usually operated manually. Equipment costs are low for this approach but the wheel cost is high compared with other sawing methods.

G6. diamond-edge sawing - is a kind of abrasive sawing that uses diamond abrasive particles because of particular hardness of the workpiece material. Cutting of ceramics, glass, stone, carbide, hardened die steel, nickel, and cobalt alloys are typical applications. Sufficient coolant and accurate feed control are necessary.

G7. friction sawing - uses an extremely high speed saw blade that softens or melts the workpiece material with frictional heat. The cutting teeth then remove the softened material with a cutting action. Either a bandsaw or large circular saw is used. The movement of the blade prevents it from overheating since any one part of it is in contact with the hot work for only an instant. However, the blade may also be water cooled. The blade is heavier and not necessarily as sharp as conventional blades. The process is suitable for hardened

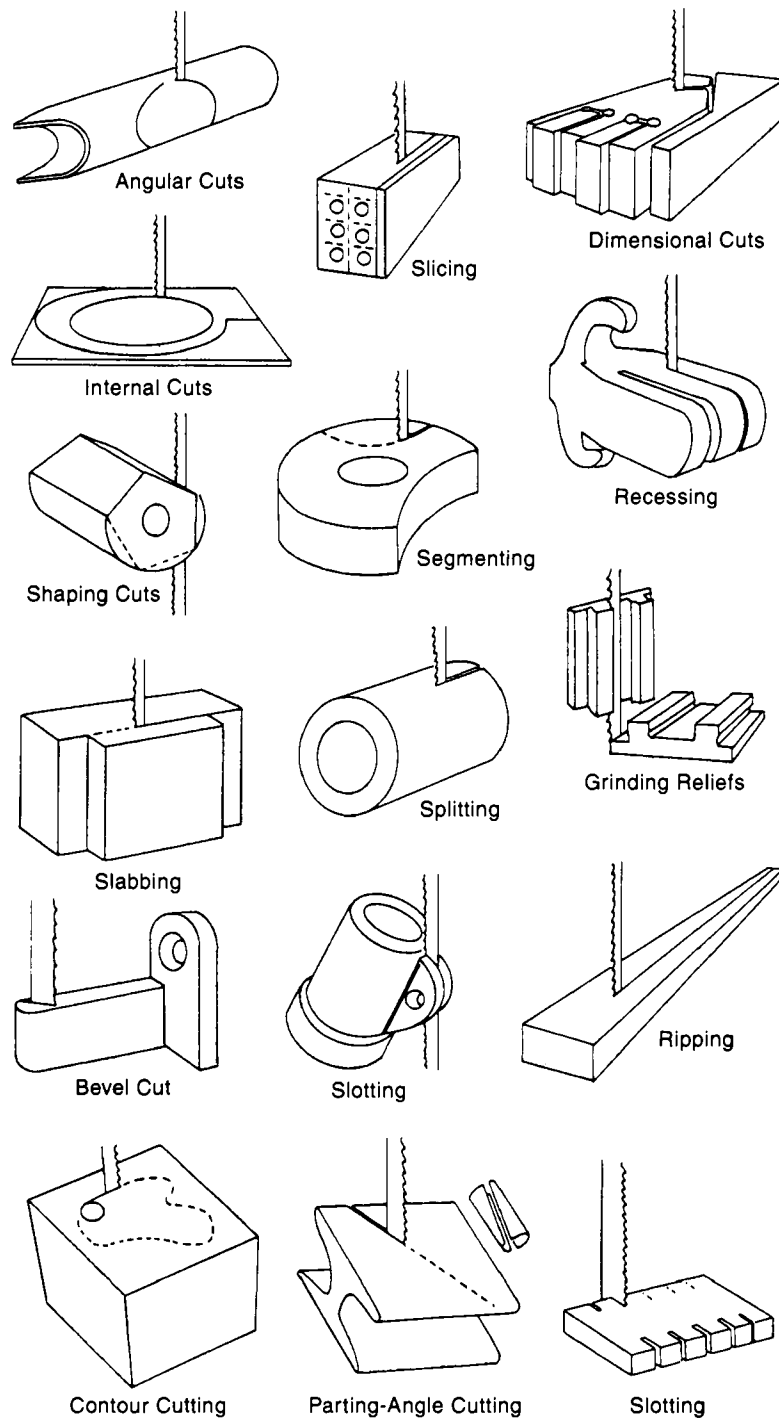


Fig. 3G3 Various contour sawing operations (Courtesy DoAll Company).

materials (Rockwell C 42 or more) which can not be cut well with conventional sawing. Material adjacent to the kerf is heat-affected. The method is slightly less accurate and has a poorer surface finish than that produced by other sawing methods. Copper, aluminum, and cast iron are not suitable for the process.

H. Flame Cutting (Thermal Cutting)

Flame cutting involves one of two underlying processes: 1) the severing or cutting of metal pieces by melting a narrow slit. 2) severing or cutting by chemical action wherein the metal oxidizes at high heat. The variety of methods used is discussed below. Flame cutting is most widely used for cutting heavy plate - as thick as 30 in (75 cm) - and structural shapes and sheet where tolerances are not so strict. The cutting torch is often manually guided, especially in field work or when tolerances can be liberal. However, flame cutting machines guide the torch more accurately along straight lines or curved paths. Template tracing, optical tracing of part drawings, numerical- or computer-numerical control are methods used to guide the torch tip along whatever path is required to cut the desired workpiece from the stock to be cut. The process is most often used to cut parts from flat stock. However workpieces of many other shapes can be cut with the process. It is also commonly used in dismantling various structures or equipment. Most flame cutting torches can be portable, so field dismantling is quite feasible.

H1. oxy-fuel gas cutting (OFC) - uses acetylene, natural gas, propane, or hydrogen in combination with oxygen to fuel the process. With ferrous metals, a small area of the workpiece to be cut is first brought to a temperature of about 1600°F (870°C) with a flame of pure gas or a gas/oxygen mixture. When the metal reaches the proper temperature, oxygen is added to the fuel mixture and the workpiece metal in a narrow section is oxidized (burned) with the aid of the oxygen. Iron oxide, in liquid form, is generated and is blown away from the workpiece by the force of the gas stream exiting the torch nozzle. As the torch moves, a narrow slit is made in the workpiece. With non-ferrous metals,

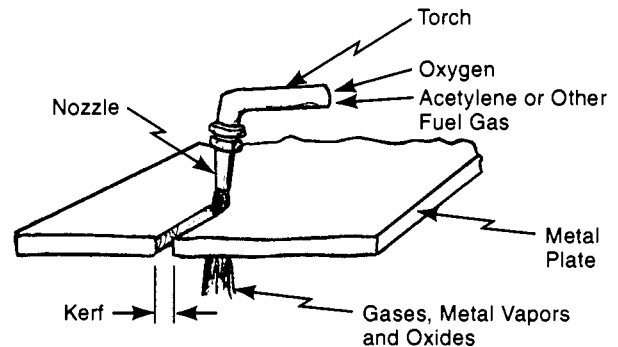


Fig. 3H1 Schematic view of oxy-fuel gas cutting (OFC).

oxidizing may not take place, and the metal is removed by simple melting. The torch is commonly held and controlled manually, particularly for work not requiring great dimensional accuracy, but mechanically-held torches controlled by templates, optical tracing, or computer numerical control are also used. The process works best with carbon and low alloy steels. A typical cutting speed for 1 in (25 mm) thick steel plate is 18 in (0.46 m) per minute. When cutting stainless steels, metal powders or chemical additives are incorporated in the stream to improve the cutting action. Some machines have multiple torches and can cut a number of parts from one piece of sheet or plate material at the same time.

Parts are most commonly cut from flat plate. Material from 1/8 to 60 inches in thickness can be cut. Ship building, construction, tank, pressure vessel, and heavy equipment manufacture, are industries that use the process. It is illustrated in Fig. 3H1. Straight or beveled cuts can be made, and welding is a common subsequent operation. There is a heat-affected zone adjacent to the cut, and this can have adverse effects with some materials and applications.

H2. metal powder cutting (POC) - is a method applicable to metals that do not flame cut very easily. Preheated iron powder is injected into the flame to raise the cutting temperature. Oxidation of the iron provides an aid to cutting metals that are highly resistant to oxidation. Chromium-nickel stainless steels, high-alloy steels, and cast iron are cut with

this method. It is also used to remove gates and risers from iron and stainless steel castings, and to cut stacked sheets or plates more easily.

H3. chemical flux cutting (FOC) - adds flux to the cutting gases to make the metal oxide more fluid and more easily removed from the gap of the cut. Powdered chemicals such as sodium carbonate, and other salts of sodium are used. The process is sometimes called *flux injection*. Its use is relatively minor.

H4. arc cutting - involves a group of processes that use the heat of an arc to melt a metal workpiece to sever it or remove metal. All common arc welding processes (See chapter 7.) can be adapted to metal cutting as well as metal fusion. When arc processes are used to cut steel and other easily oxidized metals, oxygen may be used in conjunction with the arc to support the oxidation. In metals that do not oxidize, the cutting action is mainly from pure melting and air or a shielding gas is used to provide the force needed to help expel the molten metal from the gap. The most significant processes in this group are plasma arc cutting, air carbon arc cutting, and oxygen arc cutting (oxygen lance cutting). Gas metal arc cutting, gas tungsten arc cutting, shielded metal arc cutting, and carbon arc cutting, are other arc cutting processes that are not widely used in industrial production situations.

H4a. plasma-arc cutting (PAC) - uses the extremely high temperature (20,000 to 50,000°F (11,000 to 28,000°C) of the plasma arc to melt the workpiece metal. Severing is a result of melting rather than oxidation. A direct current arc between a tungsten electrode and the torch body creates the required high temperature, and partially ionizes a stream of nitrogen, hydrogen, argon, air or a mixture thereof. (Partially ionized gases are a mixture of positively-charged ions, free electrons, and neutral atoms.) As the stream of gas leaves the nozzle, the separated electrons recombine with the gas atoms and release additional energy. The constricting effect of the nozzle further increases the arc temperature, and quickly heats and melts the workpiece metal. A shielding gas is often used to protect the ionized stream, and sometimes a

surrounding stream of water is also used to help confine the stream so that the melting takes place in only a narrow kerf. The force of the stream, the shielding gas, and water, all expel the melted metal from the cut.

The process provides very high cutting speeds, 4 to 5 times higher than those achievable with standard oxy-fuel cutting. It works equally well with metals that do not oxidize because melting rather than oxidation is the means by which the metal is removed. There is a heat-affected zone but it is narrower than that resulting from oxy-fuel-gas cutting. Stainless steel and aluminum are major applications of the process, although mild and alloy steel, titanium, bronze, copper, and magnesium are also processed. Smooth cuts in plates up to about 6 in (150 mm) thick are feasible². Ductwork, over-the-road tanks of aluminum or stainless steel, food and chemical processing equipment, ships and barges, are all manufactured with the use of this process. Fig. 3H4a illustrates plasma cutting.

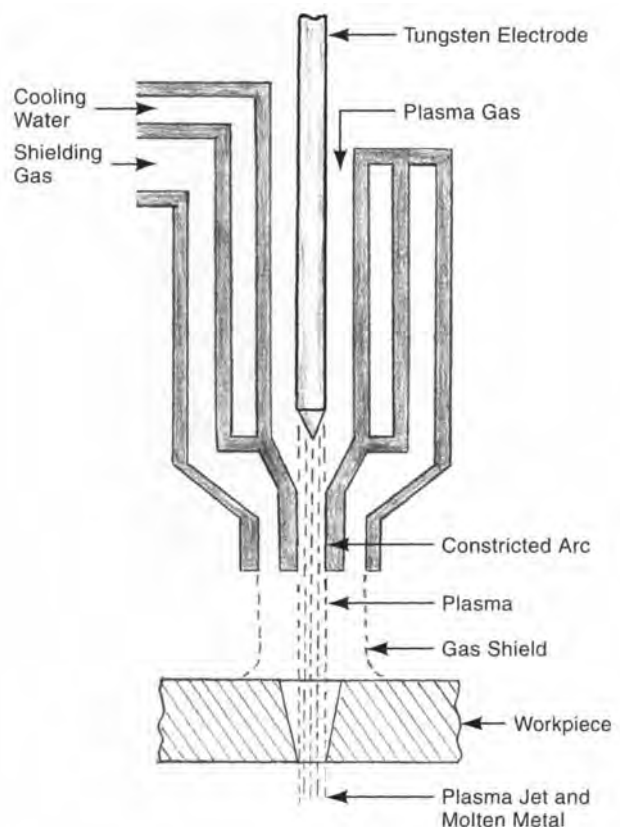


Fig. 3H4a The principles of plasma arc cutting.

H4b. *air-carbon arc cutting and grooving* -

In this process, intense heat from an electric arc between the tip of a carbon electrode and the metal workpiece melts workpiece material. A high-velocity air stream passing through the arc blows the molten metal away from the area of the cut. Though it can be used for through-cutting, the method is commonly used for gouging, an application not feasible with oxy-fuel gas cutting. When used for gouging, it leaves a clean groove. One common application is the preparation of square-edged plate for welding. Another is to remove defective welds so that the joint can be reworked. The process is also used to remove sprues, runners, risers, and fins from castings. Cast iron, steel, stainless steel, ductile and malleable iron, nickel, aluminum, copper alloys, and other non-ferrous metals have been processed with this method. Equipment is simple, but the operation is noisy and the scattering of molten metal may be a problem.

H4c. *oxygen lance cutting (LOC)* also known as *oxygen arc cutting* - is used in steel mills to sever material that is already hot from the steel-making process. A small pipe (lance) carries oxygen to the workpiece, which is hot enough to start the oxidizing reaction without the need for further heating by fuel. The heat generated by the oxidation, combined with the oxygen flow from the pipe, are sufficient to continue the oxidizing reaction and oxide removal until cutting is complete. The lance is usually a simple length of pipe or tubing with a diameter of 1/8 to 1/4 inch (3 to 6 mm) coated with non-conductive mineral material and connected to a valve and oxygen supply hose. The lance is consumed as the operation proceeds. When cool workpieces are to be cut, the surface of the metal is heated with a separate torch to a temperature high enough to start the oxidation reaction with the oxygen lance. The operation can be performed under water.

In some process variations, aluminum or magnesium wire in the lance develops additional heat of oxidation enabling the lance to cut concrete, bricks, and other non-metal objects.

H4d. *gas metal arc cutting* - is the metal cutting version of GTAW, gas metal arc welding. In both

processes, the heat is provided by an electric arc between the workpiece and a continuously-fed metal wire, shrouded by the flow of an inert shielding gas. In the case of metal arc cutting, the purpose of the operation is to sever parts of the workpiece rather than to fuse it to another part. The molten metal is evacuated from the area of the cut by a combination of the force of the shielding gas, the arc, and vapor pressure from materials vaporized by the arc. This method is not highly significant in industrial production situations.

H4e. *gas tungsten arc cutting* - is the cutting variation of GTAW, gas tungsten arc welding. For cutting, higher amperages and increased shielding gas flow are employed. The arc melts workpiece metal, which is forced out of the cut by gas pressure from the shielding gas and the effects of the arc. Gas tungsten-arc cutting is used for cutting stainless steels and various non-ferrous metals including aluminum, copper, nickel, magnesium, silicon-bronze, and copper nickel. An argon-hydrogen gas mixture is commonly used. As with gas metal cutting, this method is not widely used in production situations.

H4f. *shielded metal arc cutting* - is similar to "stick" welding when that method is used to cut the workpiece rather than to fuse it to another member. A metal electrode in rod form, coated with flux, is used without any gas jet or blanket. The heat of the arc of high current density melts the workpiece, and gravity is used to carry away the molten metal. This method is limited to situations where it is inconvenient to use more effective flame cutting methods.

H4g. *carbon arc cutting* - is not a significant industrial process but is found in small shops that lack more-sophisticated equipment. The arc between a carbon-graphite electrode and the workpiece melts the workpiece where the arc contacts it. Gravity and pressure of the arc, rather than the air jet used with air-carbon-arc cutting, removes the molten metal.

H5. *laser cutting* - is an alternative process for cutting plate and sheet materials. See O below.

I. Electrical Machining Processes

11. electrical discharge machining or EDM - is sometimes called, *spark erosion machining*. It uses a series of fine, electrical discharges or sparks to erode the workpiece material. The discharges pass from the tool (cathode) to the workpiece (anode) at a rate greater than 20,000 times per second. The workpiece material, which must be electrically conductive, melts or vaporizes at the point where it is touched by the spark. A dielectric fluid, usually kerosene, circulates between the electrode and the work. The fluid confines the spark, cools and solidifies molten material, and carries away the residue. The process is advantageous for hard, conductive material including hardened steel and carbide. There is no significant cutting force, so delicate shapes can be produced.

The gap between the anode and the work is only about 0.002 in (0.05 mm) and is servo controlled. There is an overcut equivalent to the length of the spark from the electrode to the work. The cutting

rate is slow compared with conventional machining but is still advantageous for materials too hard or otherwise not easily machined. The rate of cutting and surface finish are controllable by varying the frequency, voltage, and current in the electrical pulses. Higher energy levels in the pulses produce faster erosion of the workpiece but a rougher surface finish. Typically, the rate of cutting is reduced toward the end of the operation, in order to provide smoother surfaces. Spark erosion produces small craters in the workpiece and these craters are manifested as a matte finish on the workpiece. The tool also is eroded since some spark action is in the reverse direction. Additionally, some secondary operations may be required to remove a hard, thin, re-cast surface layer, or fine surface cracks caused by thermal stresses, depending on the material used and the function of the part produced.

11a. ram EDM - is sometimes called "die-sinker" EDM, and the principle is illustrated in Fig. 311a. The electrode is shaped to fit the desired

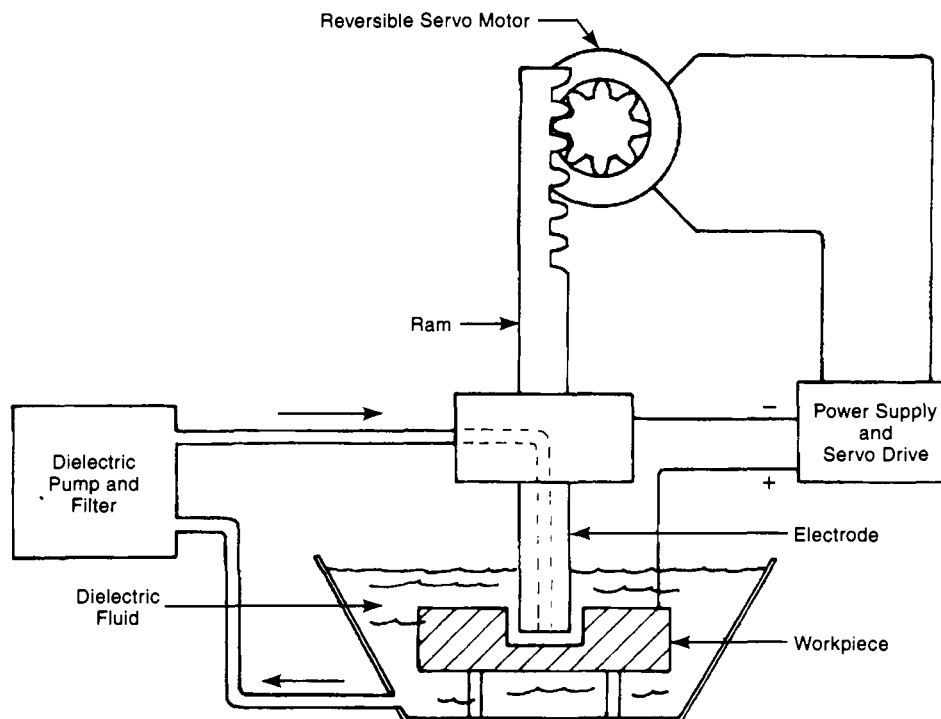


Fig. 311a Ram EDM. A series of fine, rapidly repeating electrical sparks from the electrode to the workpiece erode a cavity in the workpiece. The cavity matches the shape of the electrode. (Courtesy American Machinist, Penton Media, Inc.)

cavity and is fed into the workpiece, which is eroded to match the electrode shape. The electrode is made undersize to allow for the expected overcut, commonly 0.0005 to 0.020 in (0.013 to 0.5 mm). Feed is downward into the work, but CNC controls can also provide transverse movement of the electrode to produce special shapes in the cavity. Since the tool also erodes and becomes tapered, extra tools are often made. Graphite is a common electrode material, but copper, brass, aluminum, copper-tungsten, zinc-tin, and other alloys are also used. The process is mainly used to machine cavities in hardened steel dies and molds. It is also used in machining carbide, and in salvaging hardened parts or tools such as broken taps. Slots, non-round holes, small deep holes, and the machining of honeycomb and other fragile parts, are additional applications.

11b. wire EDM - uses a constantly-moving wire instead of a shaped electrode. The wire, of 0.001 to 0.013 in (0.025 to 0.33 mm) diameter, passes through the work, with a vertical axis, (though it may be set at an angle when required when cutting apertures for stamping tools.) Tungsten, copper, and brass are common wire materials. The wire or the work, is fed horizontally as the cut progresses, to cut a slit or shaped through-hole in the workpiece. Different wire material is constantly exposed to the spark, so wear of the wire is widely distributed and is not a problem. The process, shown in Fig. 311b, is often used to cut die openings in hardened stock to produce dies and die components. A high level of accuracy and fine detail can be achieved.

11c electrical discharge grinding (EDG) - is similar to electrical discharge machining (See 11), except that the electrode is a rotating wheel instead of an electrode that is stationary except for its downfeed. The workpiece and wheel are immersed in dielectric fluid, and metal is removed by the same kind of spark erosion as that which occurs with EDM. The wiping action of the wheel produces better surface finishes than with ram-type EDM. The graphite wheel is dressed as necessary to compensate for its wear in the process. The volume of material lost by the wheel from wear averages about 1/3 of that removed from the workpiece but

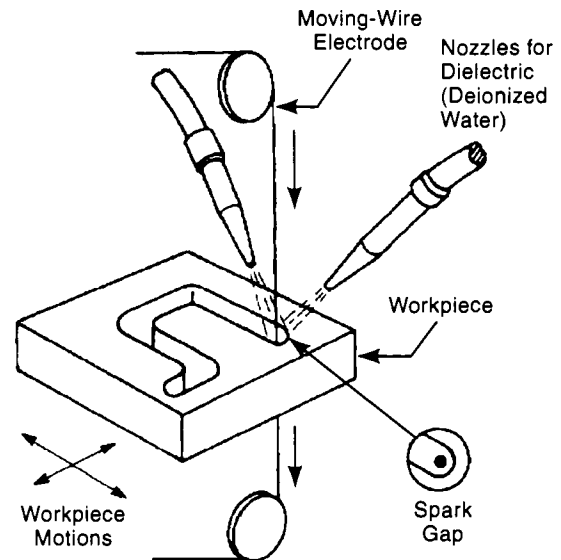


Fig. 311b Wire EDM. Electrical sparks from the wire to the workpiece cut a contoured slit in the workpiece as the wire advances. (Courtesy American Machinist, Penton Media, Inc.)

is considerably less in many instances. Since the wheel wear is spread over its circumference, the amount of reduction of wheel diameter from dressing is normally small. The process is used in shaping carbide form tools and in grinding fragile or brittle materials. Material to be ground by EDG must be electrically conductive. There is a thin heat-affected layer from the process. The layer varies from 0.0001 to 0.0015 in (0.0025 to 0.038 mm) in depth. Fig. 311c illustrates the process.

12. electrochemical machining (ECM) - removes metal by a reverse electroplating process. The workpiece becomes the anode and the tool is the cathode of the electrolytic process. A highly conductive electrolytic fluid is pumped into the space between the workpiece and the tool, and high-amperage current removes workpiece material by anodic dissolution. The workpiece takes a mirror-image shape of the tool. The gap between the electrode (tool) and workpiece is as small as 0.001 in (0.025 mm) and pressure of the electrolyte must be high to insure adequate flow. Temperature control

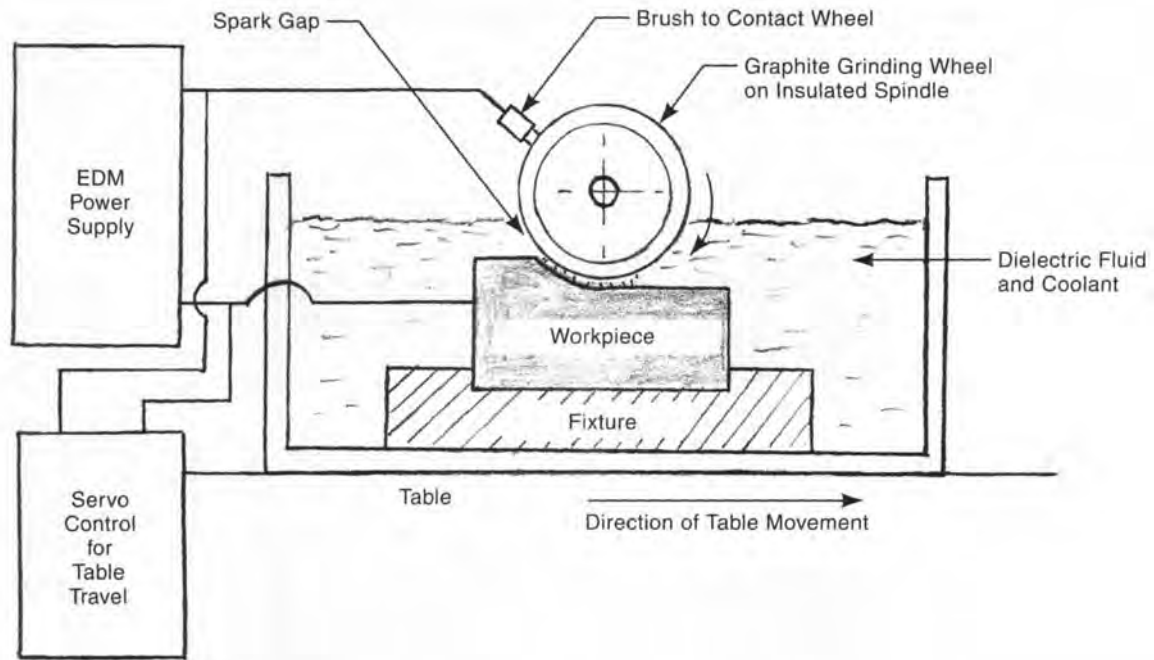


Fig. 311c Electrical discharge grinding (EDG) - is EDM with a rotating wheel electrode. Electric sparks from the electrode erode the workpiece. The shape of the periphery of the wheel is transferred to the ground surface of the workpiece.

of the electrolyte, control of the gap and feed rate of the tool and maintenance of electrolyte cleanliness are important elements in the process. The electrolyte is circulated through equipment that removes the operational debris from the fluid. The process is particularly suited to hard materials and others that are difficult to machine by conventional methods. Workpiece hardness does not affect its machinability by the process, but the workpiece material must be electrically conductive. The tool does not wear and no stresses are induced in the workpiece by the operation. Common tool materials are copper, brass, bronze, stainless steel, and copper-tungsten. Metal removal rates are good compared to a number of other non-traditional machining processes, and average 1 in^3 (16 cm^3) per minute per 10,000 amperes of current. The process is used for die sinking, manufacture of jet engine parts, cam profiling, and the machining of small, deep holes. ECM is most advantageous for materials that are difficult to machine by conventional methods. A typical electrochemical machining set up is illustrated in Fig. 312.

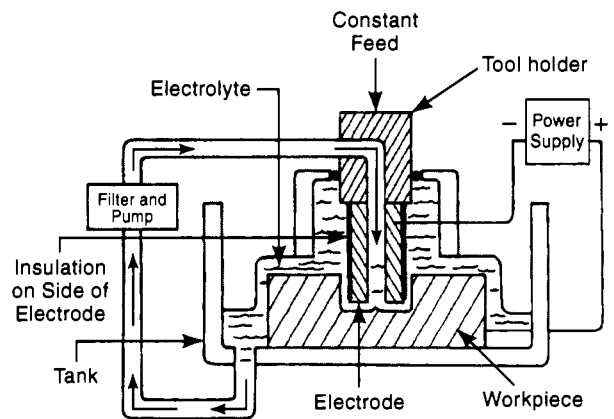


Fig. 312 Electrochemical machining (ECM). Heavy electrical current passing through the electrolyte between the electrode and the workpiece causes anodic dissolution of the workpiece material. (from Bralla, *Design for Manufacturability Handbook*, 1998, McGraw-Hill Companies. Reproduced with permission.)

I2a. electrochemical grinding (ECG) - is similar to electrochemical machining but replaces the relatively stationary tool with a rotating conductive grinding wheel. The wheel normally consists of aluminum oxide abrasive bonded to a metal wheel, which acts as the cathode of the electrolytic circuit. Electrolytic fluid circulates in the area where the abrasive contacts the work. A combination of electrolytic and mechanical action removes material from the workpiece but the electrolytic action predominates, accounting for about 90 percent of metal removal. Anodic dissolution of the workpiece metal leaves surface metal oxides. In conventional ECM, the flushing action of the electrolyte removes these oxides. In electrochemical grinding, the abrasive mainly functions to remove the oxide film, exposing a new metal surface to the electrolyte. The abrasive also separates the metal wheel from the work, preserving a fine (0.001 in or 0.025 mm) gap between the two. It also carries the electrolyte solution to the gap.

The process has the advantage of relatively high metal removal rates for hard metals, freedom from heat damage to the workpiece, and the ability to grind fragile parts. Plunge, surface, cylindrical, and internal grinding are all feasible with the process. However, capital costs are high and the electrolyte

can be corrosive to the equipment and workpiece. The process is commonly used in sharpening carbide cutting tools, avoiding the high wear rates of expensive diamond-abrasive wheels that would otherwise be required. It is also used for grinding surgical needles, honeycomb structures, and other fragile parts. ECG is illustrated by Fig. 3I2a.

I2b. electrochemical turning (ECT) - is another application of electrochemical machining. The workpiece rotates as in conventional turning but the cutting tool is replaced by an electrode. Electrolytic fluid is directed to the gap between the tool and the work, and material is removed by electrolytic action between the workpiece (anode) and the electrode (cathode). Facing and turning cuts can be made. Disc forgings and bearing races are machined by the process.

I3. electrochemical discharge grinding (ECDG) - is sometimes called, electrochemical discharge machining. It is a combination of electrochemical grinding (ECG) (See I2a) and electrical discharge grinding (EDG) (See I1c). Stock removal is primarily by ECG but oxides from ECG are then removed by intermittent spark discharges instead of

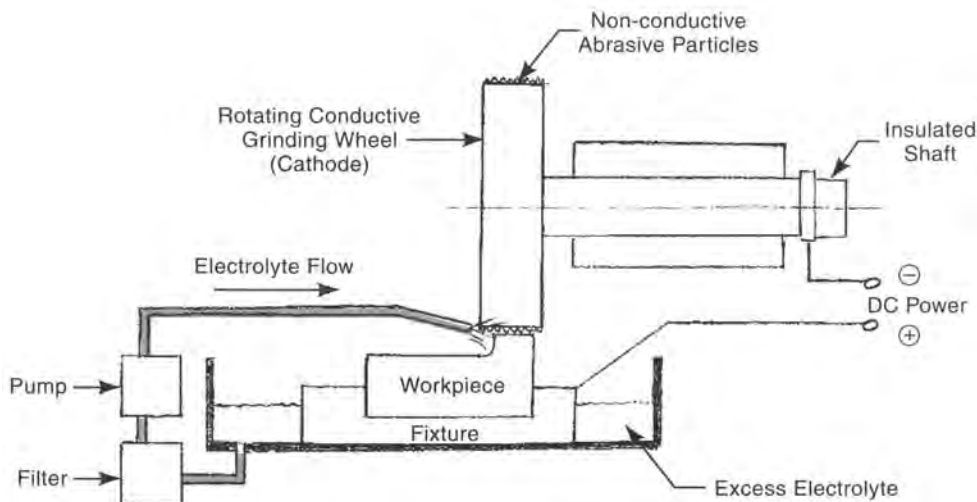


Fig. 3I2a Electrochemical grinding. Most of the metal removal results from electrolytic dissolution of the workpiece caused by flow of electrical current in the electrolyte between the conductive grinding wheel and the workpiece. Abrasive grains on the wheel remove surface oxides and expose more metal to the electrolyte.

by abrasive particles. The wheel is conductive (normally made of graphite) and has no added abrasive. The fluid used is a highly-conductive electrolyte in contrast with EDG, which uses a dielectric fluid. The wheel rotates rapidly (4000 to 6000 ft/min - 1200 to 1800 m/min), bringing fresh electrolyte between the workpiece (the anode) and the wheel (the cathode). Spark discharges occur randomly when the breakdown voltage of the oxide film is exceeded. Alternating current or pulsating direct current are used. Current densities are less than in ECG (to avoid cratering of the workpiece and wheel), and metal-removal rates are considerably slower. However, the wheel cost for the graphite-only wheels is less than that required for abrasive wheels used with ECG. The process is used in the grinding of carbide cutters. It can also be used with hardened tool steels, nickel alloys, and parts that are heat-sensitive or fragile. Honeycomb and other fragile parts are advantageous because they are finished free from burrs and stresses. Form grinding can be used if the wheel has a profile.

I4. *electrochemical honing (ECH)* - is electrolytic action added to conventional honing (J1), and is quite similar to electrochemical grinding. Material is removed from the workpiece by a combination of electrolytic action and mechanical abrasion. The electrolytic action removes most of the material, and the abrasive action of the honing stones removes the oxides produced by the electrolytic action. The equipment provides both reciprocating and rotational movement of the honing stones, as in conventional honing. However, electrolytic fluid handling is added. The tool that holds the honing stones is hollow and fluid passes from the tool into the gap between the stones and the workpiece. The gap between the tool and the work is approximately 0.003 to 0.005 in (0.08 to 0.13 mm) at the start of the operation, increasing to about 0.020 in (0.5 mm) at the conclusion, but the stones remain in contact with the workpiece, normally the surface of a machined hole. (The wedging action of a conical piece in the tool forces the stones outward as the honing takes place.) The operation provides metal removal three to five times as fast as regular honing, while the wear of the honing stones is considerably less. Deburring action is also superior and the work is more apt to be free from stress-induced or heat damage. However, the

operation requires more complex equipment due to the need for control of the electrolytic action and the corrosiveness of the electrolyte. Therefore it is not necessarily more economical than conventional honing. The process is used to refine the bores of hardened parts such as gears and pump components, particularly when production quantities are large.

I5. *electro etching* - is a method for marking workpieces that are electrically conductive. A stencil is placed on the workpiece and a pad containing an electrolyte is placed or dabbed on the stencil. The workpiece and the pad are connected to sources of direct electrical current. The current removes workpiece material electrolytically in the areas corresponding to openings in the stencil. The method is useful for placing identification markings on metal parts with fairly smooth surfaces. Electro etching is normally performed manually and is a suitable method when production quantities are modest.

J. Finish Machining Operations

J1. *honing* - is a low-velocity abrasive machining process. One or more bonded abrasive stones or "sticks" are put in area contact with the surface to be machined (in contrast with grinding processes where the abrasive and the work are in contact essentially on a line). Slow movement of the sticks in several directions abrades the high spots on the workpiece surface and makes the surface smoother and more true (i.e., with greater dimensional and geometric accuracy). Because of the slow movement, there are no heat effects to the metal surface. The process, illustrated in Fig. 3J1, removes only a small amount of material - less than 0.005 in (0.13 mm)² - but improves the dimensional accuracy and surface finish of the surface being honed. The operation can be performed by hand but, for production situations, machines that impart reciprocating motion in several directions, or a combined reciprocating and rotary motion, are used. Cutting fluids are normally employed. The most common application is the finish machining of bored holes to remove tool marks, waviness or taper. The stones are allowed to "float" and follow

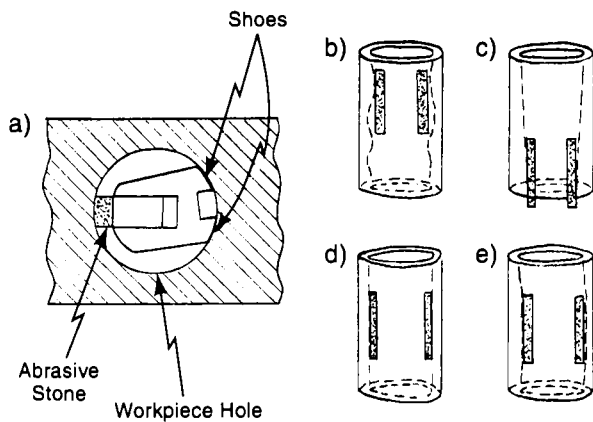


Fig. 3J1 Honing. a) end section view of typical single-stone abrasive honing tool in a hole. Views b) through e) show, greatly exaggerated, hole discrepancies that are improved by honing: b) waviness, c) taper, d) out-of-roundness, e) bowed shape.

the direction of the hole's axis. The cylinder walls of internal combustion engines are typically finished by honing. Gear teeth and bearing races are also honed.

J2. lapping - is another low-velocity abrasive machining process. It utilizes a fine abrasive in paste or powder form, which is contained between the workpiece and the lapping tool. The lapping tool is made of material softer than the workpiece and is shaped to mate with the surface being machined. It has the function of holding the abrasive. A random, reciprocating motion of the lap and the abrasive, with light pressure applied, refines the dimensions and smoothness of the workpiece surface to a close tolerance. Unlike honing, the motion is not necessarily in more than one direction. Very little material is removed, seldom as much as 0.001 in (0.025 mm)². The purpose is to remove fine scratch marks or to create very flat or otherwise smooth and precise surfaces. The process is also used to provide a very close fit between mating surfaces. Flat, cylindrical, or spherical surfaces, or those of special shape can be processed with this method. The operation can be performed by hand or with machines designed for the purpose. In some cases, abrasive coated paper, bonded abrasives, or cloth

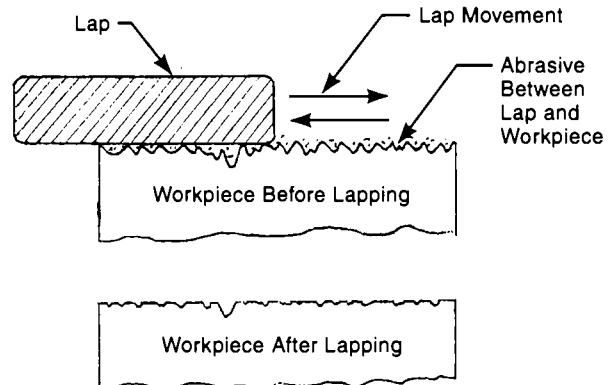


Fig. 3J2 Lapping. The abrasive particles held in place by the soft lap, remove peaks from the workpiece surface. Note: Peaks and valleys in the workpiece are shown greatly exaggerated.

laps are used. The relative motion between the lap and the workpiece is always slow. Typical applications are finishing of gage blocks, plug gages, ball bearing races, valve seats, roller bearings, and optical parts. Parts requiring metal-to-metal sealing surfaces are frequently lapped. The process is illustrated in Fig. 3J2.

J3. superfinishing - is a third low-velocity surface-refinement process. A solid abrasive is used, but it is loosely bonded so that it wears to the shape of the workpiece surface. Thus, a large surface area is in contact with the abrasive at all times during the operation. A controlled, bidirectional movement of the workpiece and the abrasive under light pressure removes high spots and smooths the surface, removing surface material that has been smeared or distorted by prior grinding or machining. Typical speeds of movement between the work and the abrasive are 12 to 50 ft (4 to 15 m) per min at a pressure of 10 to 40 lbf/in² (70 to 275 kPa). A liberal amount of oil-based cutting fluid normally accompanies the operation. Typically, from 0.0002 to 0.001 in (0.005 to 0.025 mm) of material is removed. Mirror-like surface finishes can be produced. Fig. 3J3 illustrates the process which is used to smooth flat, curved, or spherical bearing surfaces. Automotive crankshafts, camshaft bearings, brake drums, and distributor shafts are typical superfinished parts.

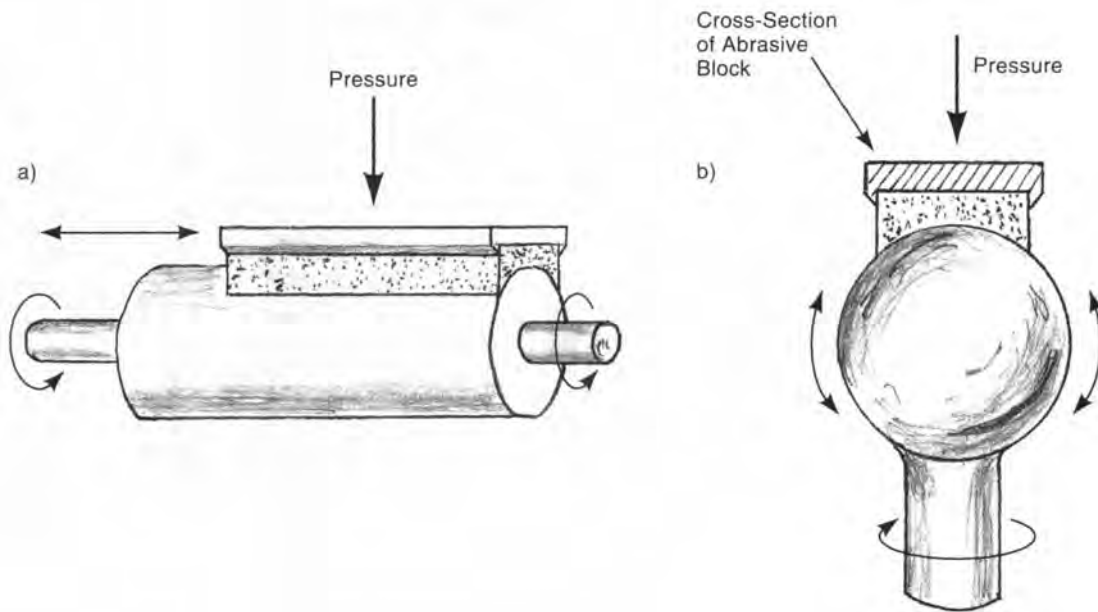


Fig. 3J3 Superfinishing. a) a cylindrical surface. The workpiece revolves while the abrasive block is moved back and forth along the axis. b) a spherical surface. The abrasive block moves around the spherical workpiece as it rotates. In all applications, the abrasive conforms to the shape of the workpiece.

J4. burnishing - is a means of smoothing machined or other surfaces by rubbing a smooth hard object against the surface with considerable pressure. Burnishing is not a machining operation - no workpiece material is removed - but instead deforms and presses down localized high spots from cutting tools, and thereby smooths rough areas.

J5. roller burnishing - refines the surface of a workpiece by pressure rolling rather than by removing metal. The burnishing tool incorporates one or more hardened, finely polished rollers, which bear against the workpiece at high pressure. Each roller achieves the desired effect by deforming the surface material of the workpiece as it rolls against it, compressing the minute peaks of surface roughness into the valleys. The force applied to the burnishing tool depends on the amount of pressure required to exceed the yield point of the workpiece material. Multiple rollers may be used, depending on the shape of the surface being roller-burnished. Gear-tooth finishing is one common burnishing operation, performed by rolling the gear workpiece against three smooth, hardened, burnishing

gears. Fig. 3J5 shows the principles of the operation and Fig. 3J5a, b, and c illustrates typical configurations that are roller burnished and the burnishing tool that is used. Compressive stresses, left in the surface after the operation, and surface work

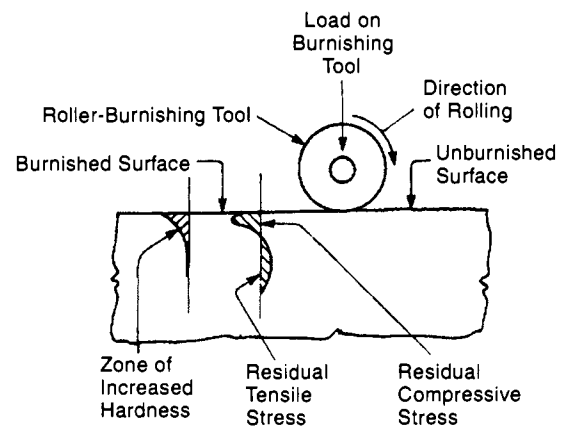


Fig. 3J5 Schematic illustration of the roller burnishing process. (from Bralla, *Design for Manufacturability Handbook*, 1998, McGraw-Hill Companies. Reproduced with permission.)

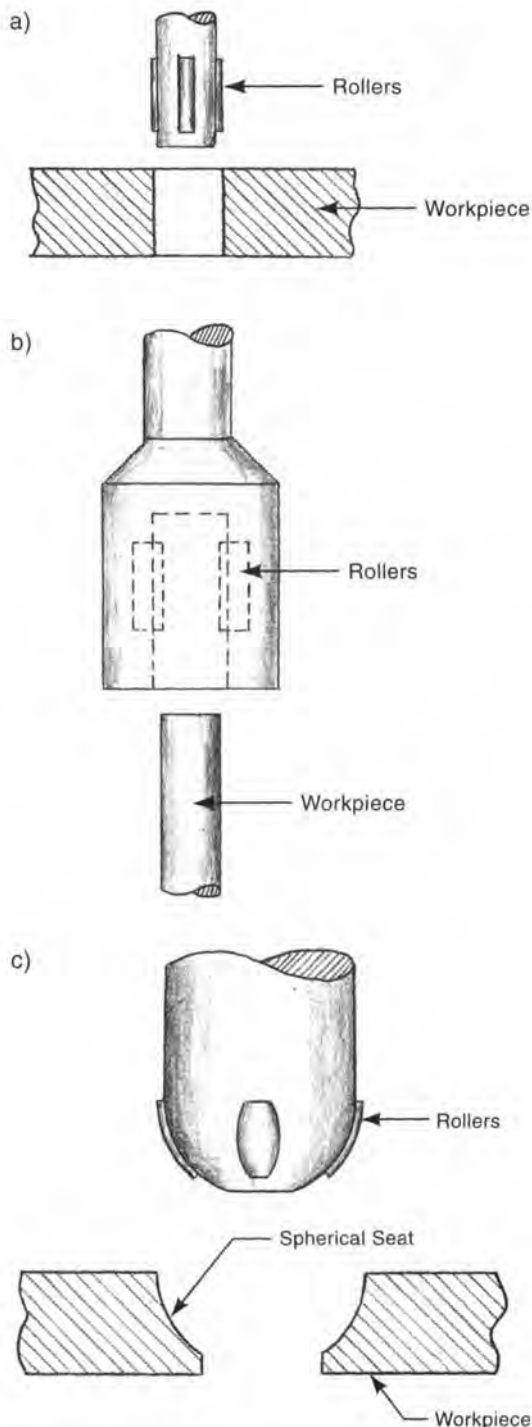


Fig. 3J5a Typical surfaces that can be roller burnished and the burnishing tools used. (from Bralla, *Design for Manufacturability Handbook*, 1998, McGraw-Hill Companies. Reproduced with permission.)

hardening improve resistance to wear and fatigue failure. The process is limited to workpieces up to about Rockwell 40C in hardness and with walls thick enough to withstand the forces involved. Roller burnishing of holes can be a substitute for, or a supplement to, reaming and boring. Typical parts that undergo the operation are cylinder bores, valve stems, piston rods, turbine shafts, pump plungers, and rolls for the plastics and paper industries.

K. Deburring

The thin, sharp, ragged metal edge that forms whenever a metal part is machined or stamped, normally must be removed for reasons of safety, accuracy of dimensions, fit of mating parts, and appearance. Typical burrs are illustrated in Fig. 3K. Burrs form on edges and corners of surfaces, holes, and slots. Similarly, flash, the thin edges of metal (or whatever material is used) that often accompany casting, forging and molding operations, must be removed or controlled. The following is a summary of the many methods that can be employed to remove burrs and flash.

K1. abrasive flow deburring - is an application of abrasive flow machining. (See C10.) A putty-like material containing abrasive is flowed by hydraulic pressure over the workpiece edges that have burrs. The force of the material helps break off the burrs and the abrasive particles provide cutting action that smooths the edges. The process is

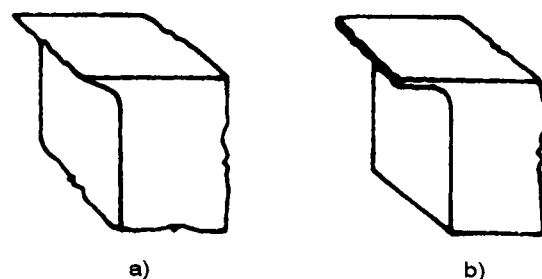


Fig. 3K Typical burrs. View (a) shows the typical shape of the most common burrs. View (b) illustrates a more pronounced burr. (From Bralla, *Design for Manufacturability Handbook*, McGraw-Hill, NY.)

repeated back and forth for a number of cycles until the desired results are achieved. It is particularly applicable to removing burrs in places that are not accessible to more conventional deburring methods. Surfaces can also be refined by this method. Ultrasonic motion from a graphite tool is sometimes used to provide more aggressive abrasive action. An orbiting tool may provide similar benefits. Abrasive flow deburring is illustrated in Fig. 3K1.

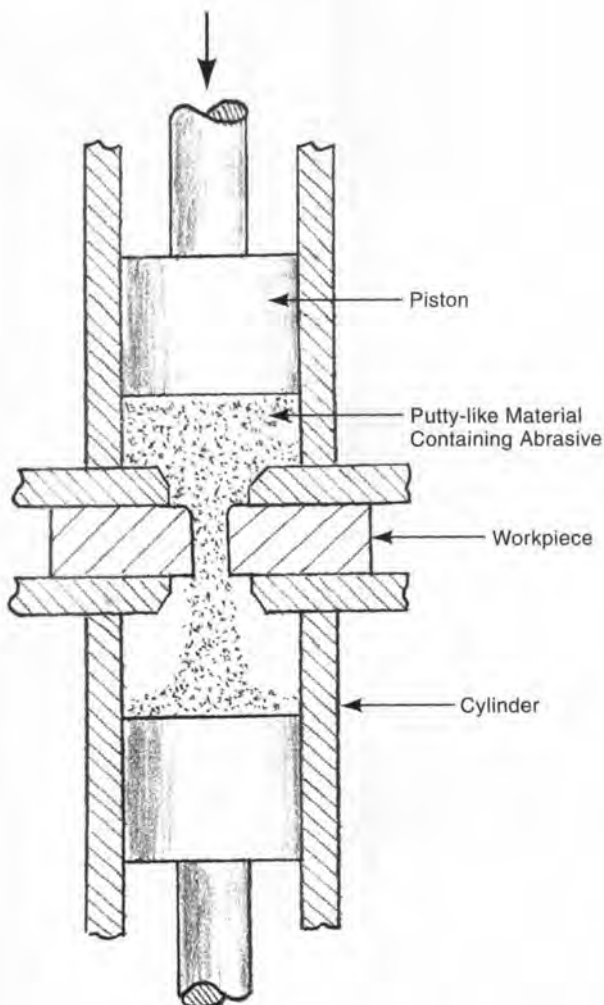


Fig. 3K1 Abrasive flow deburring. Reciprocating movement of the pistons forces the putty-like material containing abrasive particles, back and forth against the workpiece, removing burrs and smoothing the surface.

K2. abrasive jet deburring - uses a high-velocity stream of abrasive particles or glass beads that are directed against the burrs. The burrs are either broken off, peened over by the force of the abrasive stream, or are worn away. The abrasive particles can be carried by a gas stream, or mechanically thrown against the workpiece. Plastic and rubber workpieces may be cryogenically cooled just prior to the operation. The low temperature makes these materials more brittle and facilitates the fracture of the burrs. (See C9.)

K3. barrel tumbling - A group of parts to be deburred is placed in a rotating barrel that contains abrasive powder, small, pebble-size stones, and water. As the barrel rotates, the mixture continually slides to the lowest point. During this sliding, the breaking and peening action of the stones, combined with the cutting action of the abrasive, removes the burrs. (Also see 8B2.) This method is economical since workpieces do not have to be handled individually and little operator attention is required during the operation. Fig. 3K3 illustrates the process. Barrels rotating on a horizontal axis are most suitable for deburring. Machined parts, stampings, small sand-mold castings, die castings, forgings, and powder metal parts are all deburred with this approach. Plastic, glass, and rubber parts

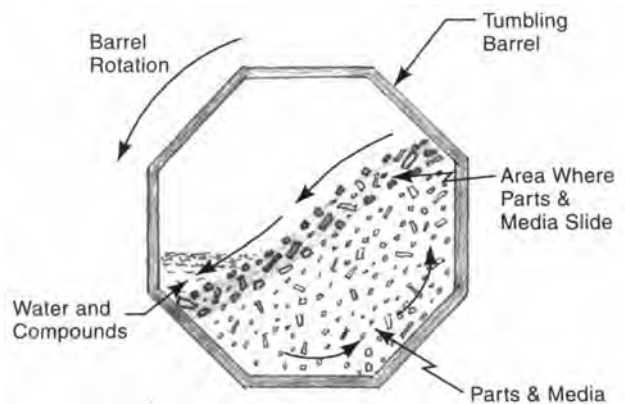


Fig. 3K3 barrel tumbling - As the barrel rotates, about 25 percent of the mixture of parts and media form a layer that slides downward, providing abrasion that breaks off and wears down burrs. The operation is slow but labor costs are low because a number of barrels can run at the same time with almost no operator attention.

can also be processed. After tumbling, the parts and media are separated by screening.

K4. *chemical deburring* - uses the same process as that used in chemical machining (See S.). A buffered-acid solution dissolves workpiece material including, and especially, burrs. Large groups of parts can be deburred simultaneously by immersion in the chemical solution, making the method economical. However, since the chemical solution acts on all surfaces of the workpieces immersed in it, critical-dimension surfaces may have to be masked. The process can be used for both ferrous and non-ferrous metals. Stampings and machined parts are commonly processed.

K5. *electropolish deburring* - is an application of electropolishing (8B3). Electrolytic action removes stock from all surfaces, especially the burrs, which are more prominent and draw a more dense electric current. Machined parts and stampings, including stamped gears, are deburred by electropolishing. Thin or fragile sections can be processed since there are no forces exerted on the workpiece by the operation. Excellent surface finishes can result from the process. It is limited to electrically-conductive workpiece materials.

K6. *electrochemical deburring* - is similar to electropolish deburring except that shaped electrodes are used. As such, the process is a special application of electrochemical machining (See I2.). The electrodes are positioned to concentrate the electrolytic action at the burrs. Surface residue is removed after the operation. The method is particularly suitable for removing burrs from inside surfaces that are not accessible for other methods. As long as an electrode can be positioned near the burr, the electrochemical dissolution will take place.

K7. *liquid hone deburring* - uses an abrasive (typically 60 grit) suspended in water. The mixture is then forced over the burred edges of the workpiece. The method is applicable to very fine burrs and very little edge radius takes place.

K8. *manual deburring* - is hand deburring with any of a variety of tools such as scrapers, knives, files, and emery cloth, to cut burrs from the workpiece. Powered rotary files or burrs, belt sanders, or other powered hand tools may be used. These methods are appropriate for small-quantity production where it does not pay to establish a more automatic approach, for burrs inaccessible to automatic devices, for burrs of variable size, and for fragile parts.

K9. *thermal energy deburring* - involves placing the workpiece in a closed container into which a charge of natural gas is introduced. The gas is ignited and the high temperature wavefront thus generated burns off and vaporizes the burrs. The workpiece is not significantly heated but the thin, prominent burrs are subjected to an instant of very high temperature. Surfaces of the workpiece are not dimensionally changed, or otherwise affected by the operation, though the material where the burrs were located may have a heat-affected zone. The method is applicable to ferrous, nonferrous and some plastic workpieces. Plastic moldings can have thin flashing removed by this process. One common application is the deflashing of zinc die-cast carburetor bodies.

K10. *ultrasonic deburring* - is used to remove minute burrs such as those developed during honing operations. A mixture of buffered acid and fine abrasive powder in a tank is agitated by ultrasonic vibration. This causes the burr to be both abraded and chemically dissolved. (The process is actually closer to ultrasonic cleaning - described in section 8A2b - than the ultrasonic machining described above, because the vibration is over a wide area in the tank instead of immediately below a particular tool.) A delicate balance must be achieved between three factors: burr size, acid, and abrasive, if the process is to give best results.

K11. *vibratory deburring* - shown in Fig. 3K11, is similar to barrel tumbling except that the agitation is produced by mechanical vibration rather than tumbling action, and the vibrations provide a somewhat more aggressive cutting action. (See 8B2.) Large quantities of parts can be processed at one

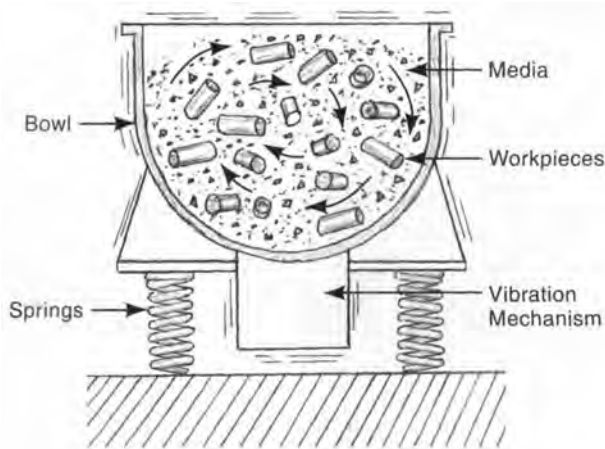


Fig. 3K11 Vibratory deburring. An eccentrically-mounted weight on a rotating shaft provides the vibration.

time. The method is faster than conventional barrel tumbling but not necessarily more economical since both processes proceed automatically once the parts are loaded.

K12. *water-jet deburring* - The force of a jet of water of high velocity is used to break burrs from the workpiece. The process can be used for all metals, with higher pressures used for harder metals. For hard steel, deburring pressures in the area of 40,000 psi (275 MPa) are used. (See M, hydrodynamic machining.) The process is also useful for removing loose chips and dirt from machined parts, and some CNC milling machines are equipped with water jets for that purpose.

K13. *centrifugal barrel tumbling* - is similar to barrel tumbling except that centrifugal force is used to increase the cutting and breaking forces. In this process, the tumbling barrel is placed at the end of a rotating arm. The rotation provides centrifugal force that may be as much as 25 times the force of gravity, greatly accelerating the deburring action.

K14. *spindle finishing* - is a variation of barrel tumbling. Instead of being placed loosely in the barrel along with the media and other parts, the part

to be finished is clamped to a spindle and is then immersed in the moving media where it is rotated. Deburring action on the part then be quite rapid, although only one part is normally deburred at a time. By a suitable design of the holding fixture for the workpiece, the abrasive action can be concentrated where it is needed and other areas can be protected. The process can provide improved surface finishes. Although the operation is effective, labor costs may be higher than with other methods unless loading and unloading are automated. The operation is frequently used for finishing cylindrical automotive and appliance parts.

K15. *powered brush deburring* - uses the force of a powered, rotating wire brush to break off and remove burrs from the workpiece. Machined gears are often deburred with this method, which, with the proper brushes, can also round sharp corners. Cleaning, descaling, and surface finish improvement can also be accomplished. Splines, tubing, screw threads, and stampings are also deburred by this method. It is also used with nylon-abrasive brushes. These are brushes of nylon filaments that are impregnated with abrasive grits, and are useful for removing small burrs, for radiusing corners, and improving surface finish.

K16. *abrasive belt sanding* - is a manually-controlled operation aided with belt sanders or flap wheels. For a manual operation, high output rates are possible. The workpiece is held in such a way that the abrasive action of the belt is directed against the burr to be removed. The process can remove sizable burrs but can also produce a very small burr itself. Flashing from castings, forgings, and cold heading can be removed. Flap wheels provide flexibility needed to reach depressed areas. De-scaling and cleaning are also accomplished with these wheels.

K17. *laser deburring* - utilizes laser energy, directed by CNC equipment, to remove burrs. (See O.)

K18. *plasma glow deburring* - is a method used on plastics. Heat from a low-temperature argon-oxygen plasma removes flashing and thin burrs.

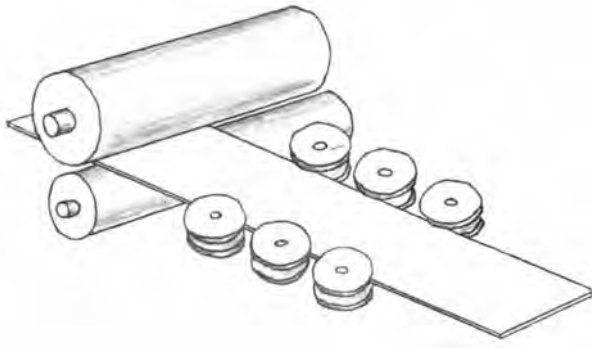


Fig. 3K20 Edge rolling uses pressure rollers at the edges of a strip of sheet metal to force burrs down against the sheet after slitting or shearing operations.

K19. skiving - is used when sheet metal is slit. A cutting tool is set to scrape off burrs as the strip passes the tool. The operation is thus automatic and does not affect other workpiece surfaces.

K20. edge rolling - is another method used when sheet metal is slit. Instead of scraping off the burr, it is pressed down against the sheet by the force of metal rollers, which are set to bear against the slit edge. The method is illustrated in Fig. 3K20.

K21. burnish deburring - is similar to edge rolling except that the slit edge is run against a smooth metal surface instead of a roller. The burr is broken off or pressed down, and the edge is smoothed.

K22. edge coining - is used with stamped sheet metal parts. Press tooling, designed to fit the part, coins the burred edges, forcing the burr into the base metal.

K23. robotic deburring - is an automatic, robotic version of manual deburring. The deburring tool, a file, rotating brush, or other tool, is manipulated by a robotic arm that is programmed to maintain the tool in contact with the burr-containing edge. If the tool used is compliant, as a brush, exact location of the tool is not critical and robotic control is

relatively easy. Sometimes the robot is programmed to handle the workpiece rather than the deburring tool, picking up and moving the workpiece against a brush, bur, or abrasive tool.

K24. CNC machining center deburring - Tool-changing machining centers can be programmed and equipped to use a rotating wire brush instead of a rotating cutting tool. The machined moves the brush along the burred edges of the part.

K25. cryogenic deflashing - Plastic and rubber workpieces can have molding flash removed by tumbling them in either a rotating barrel or vibratory equipment at cryogenic temperatures. {The temperature used depends on the workpiece material but ranges from about -210 to -300°F (-135 to -180°C .)} Liquid nitrogen is introduced to the tumbling chamber to provide the required low temperature. The entire workpiece tends to be chilled to the cryogenic temperature but the thin flash, made brittle at the low temperature, is more vulnerable and it tends to break off from the workpiece. Flash formed at the junction of the mold halves, from gates, and from mold cores or ejector pins, are all removed by this method. Suitable media: steel balls, ceramic cylinders, walnut shells, nails, etc. and, sometimes, only the workpieces themselves, provide the striking force that breaks the flash. In another approach, the workpieces can be cryogenically cooled and placed in an abrasive stream that breaks off and abrades the burrs.

L. Filing

Filing involves the removal of material from a workpiece with a file, a tool that has cutting teeth arranged in succession along a surface. A file is somewhat like a saw that is very wide, wide enough to cut a surface rather than a slit. The cutting teeth of files are typically quite small, providing slow and easily-controlled cutting action. A variety of cutting tooth arrangements are available, the choice of which depends on the use to which the file will be put. Files are usually used to remove only a small amount of material from workpieces. Filing is most often a completely manual operation with

the motion and force of the file provided by hand. However, filing machines are available that provide either a reciprocation motion like that of a jig saw, a continuous motion similar to that of a band saw, or a continuous motion provided by a rotating disc-shaped file. With these machines, the workpiece is still manually held and controlled. Filing is performed for many purposes including burr or flash removal, size and shape adjustments, and surface smoothing. A skilled machinist can make accurate parts by filing in conjunction with other machining operations, though such an approach involves high labor costs.

L1. *burring (rotary filing)* - Burrs and rotary files are small filing tools of round cross-section that are power-rotated. They are normally utilized with hand control of portable electric, pneumatic, or flexible-shaft-driven tools. They are used for such operations

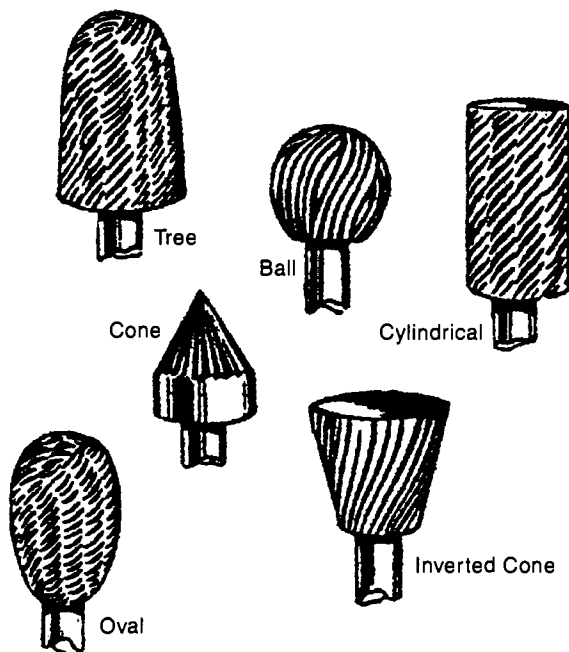


Fig. 3L1 Typical head shapes of burrs and rotary files. (Both rotary files and burrs have cutting teeth. The teeth of rotary files are made by upsetting the tool surface with sharp forming tools; the teeth on burrs are made by grinding.) (from LeGrand, *American Machinists Handbook*, 1955, McGraw-Hill Companies. Reproduced with permission.)

as burr and flash removal, chamfering corners, elongating holes and slots, and making other minor shape changes in workpieces. Fig. 3L1 illustrates several typical burrs and rotary files.

M. Water Jet Machining (Hydrodynamic Machining)

This process uses a narrow, high-velocity jet of liquid as a cutting agent. The jet travels at a speed of up to 3000 ft/s (900 m/s) and is from 0.002 to 0.040 in (0.05 to 1.0 mm) wide. The liquid is primarily water, but polyethylene oxide or other polymers may be added to keep the stream coherent. Cutting occurs where the jet strikes the work material. Although thin soft metals can be cut with the process, it is best adapted to non-metallic materials such as wood, rubber, plastics, fabric, gypsum board, leather, acoustic tile, paperboard, and various food products. The process is mostly used to cut out parts from materials in sheet form or to slit web materials. Cutting disposable diapers is a significant application, as are gasket, shoe sole, and carpet cutting. Water jet is also used for wire stripping, cutting of foods, separating printed circuit boards, paint stripping, and cleaning. Noise from the jet is a disadvantage of the process which is illustrated in Fig. 3M.

M1. *abrasive water jet machining (AWJ)* - adds abrasive particles to the water jet to aid the cutting action. The abrasive is added after the stream has left the orifice. This enables the process to be used for cutting of a wide range of ferrous and non-ferrous metals and non-metallics. Because the process is sensitive to variations in process parameters such as the type and amount of abrasive, water pressure and flow rates, tool traverse rate, and material thickness, automatic computer control is vital. Cutting is normally carried out under water, which eliminates objectionable noise that would otherwise accompany the process. Many but not all composite materials can be cut with the process without delamination of the material. The process is also used to blank parts from sheet and plate materials. Materials from 1/16 to 3 in (1.6 to 75 mm) thick are

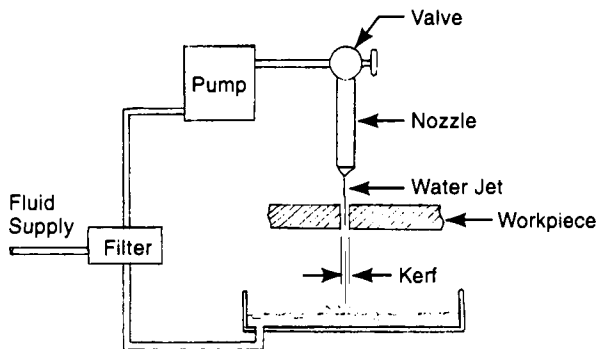


Fig. 3M A schematic illustration of water jet (hydrodynamic) machining.

commonly cut. Removal of sprues, risers, and gates from castings, other trimming of castings, forgings, and other parts and beveling of edges prior to welding are other applications. The process is slower but more accurate than plasma cutting and much faster but not as accurate as wire-EDM cutting. There is no heat affected zone and the cut edge is smooth. Fig. 3M1 illustrates the process. Some plastics that give off toxic fumes when heated, can be cut with this method without ill-effects. Aluminum, which can give problems with laser cutting because of its reflective surface, can also be cut advantageously. Stainless steel, tool steel, Inconel, brass, titanium, glass, ceramics, marble, and carbon fiber reinforced materials are also cut with abrasive water jet.

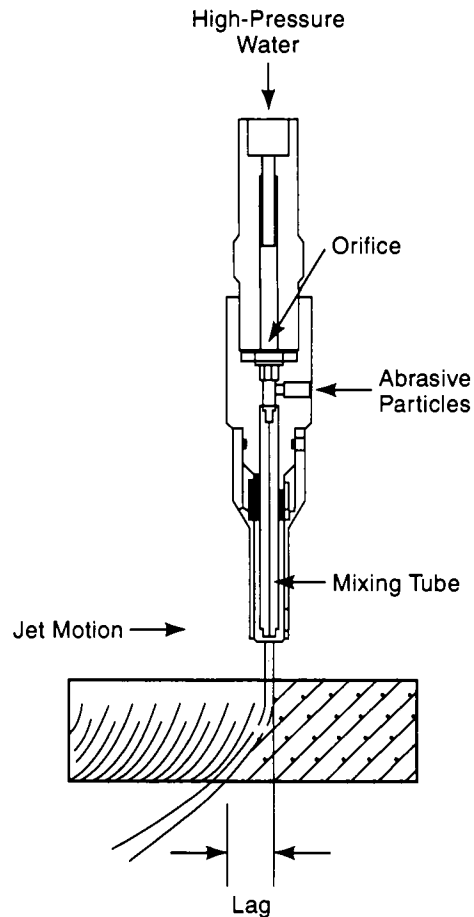


Fig. 3M1 Schematic view of abrasive water jet machining. (Courtesy Omax Corporation.)

N. Electron Beam Machining (EBM)

EBM is essentially the same process as the more common electron beam welding, except that the beam is used to cut instead of to fuse. The beam size, power, and dwell time are set to provide a cutting action. Magnetic coils focus and direct the high-energy electron beam. The electrons striking the workpiece melt and vaporize the workpiece material. Any material can be processed. Very narrow slits and small holes can be machined, as narrow as 0.0005 to 0.001 in (0.013 to 0.025 mm). Depth-to-diameter ratios of 100 to 1 are possible. Holes can be drilled in steel

up to about 0.3 in (7.5 mm) thick. When holes and slits are machined, a backing material is placed under the workpiece. When the beam penetrates the workpiece, this backing material vaporizes, expelling the molten workpiece material from the hole. The process takes place in a vacuum of 10^{-5} mm/Hg.² The machining part of the operation is very rapid but the part must be placed in a sealed chamber and a vacuum must be drawn. The size of the workpiece that can be machined is limited by the size of the chamber. Equipment costs for this process are high and there must be protection against the x-rays that are generated when the electron beam strikes the workpiece. The operation

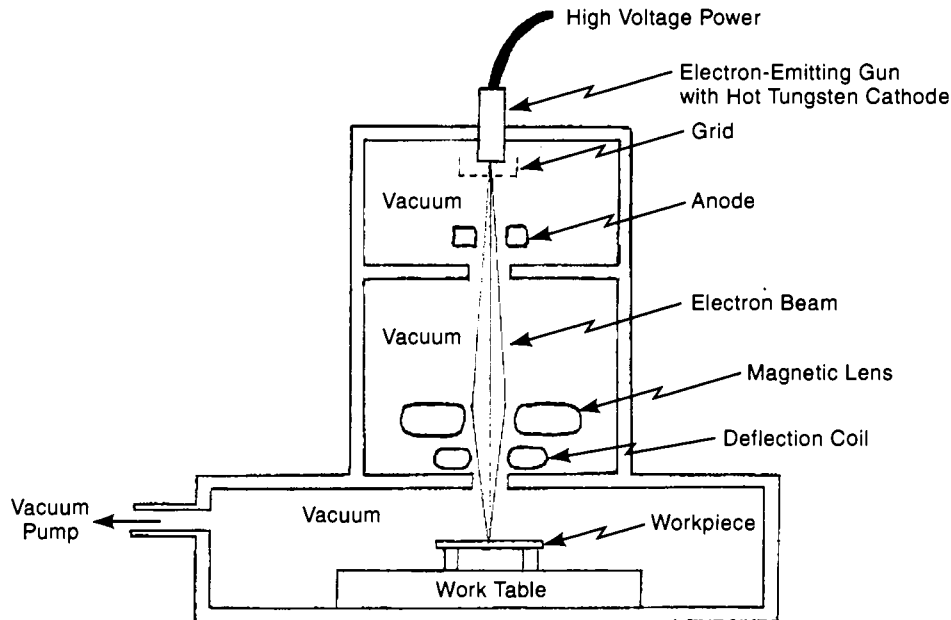


Fig. 3N Schematic illustration of electron beam machining. A high speed stream of electrons, emitted from a cathode, is accelerated and focused. It strikes the workpiece and heats and vaporizes the material at the point of contact. A vacuum chamber is necessary to generate and focus the beam and the workpiece is normally also in a vacuum. The workpiece table is controlled to be movable in two directions.

is normally computer controlled. There is a small heat-affected zone and a thin recast layer at the cut. Machining of semiconductors and sapphire bearings are two commercial applications. Filters and screens are made by drilling multiple holes in sheet material.

O. Laser Beam Machining

The laser beam, used for welding, is also adaptable to machining (cutting) operations. The heat generated by a powerful beam of coherent light, melts and vaporizes workpiece material. The process is best suited for drilling very small [0.005 in (0.13mm)] holes, but is also used increasingly for cutting flat stock. Depth-to-diameter ratios of 10 are feasible in laser-machined holes.² The process works best with materials less than 0.2 in (5 mm) thick but can be used with greatly reduced

cutting speeds with metals up to about 0.5 in (13 mm) in thickness and non-metals up to about 1 in (25 mm) thick. With thin materials, the process is faster than mechanical cutting. Holes can also be drilled rapidly.

CO₂ or another gas may be blown from the nozzle to assist in removal of melted material from the cut. There is a thin recast layer and zone of heat effect where the cut takes place. The surface of the cut can be irregular, and there tends to be some taper in it. The depth of cut in blind holes and grooves is difficult to control. Typical applications of laser cutting are the machining of carbides and diamond drawing dies. Scribing, engraving, perforating, slitting, trimming and deburring are other operations. Turning, threading and milling of difficult-to-machine materials are feasible. Machining silicon wafers and other electronics components is a common application.

The process has grown as a desirable method for cutting out sheet material components, particularly

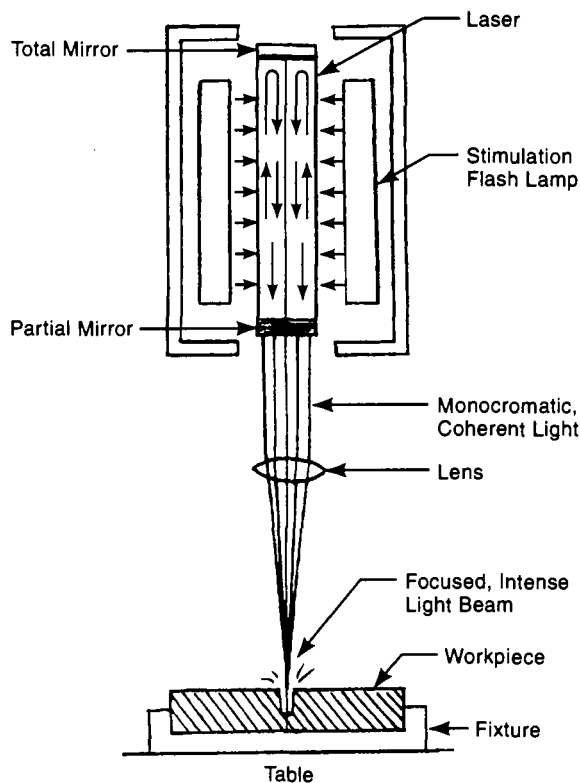


Fig. 3O Laser beam machining. The focused beam of coherent monochromatic light provides intense energy that melts and vaporizes workpiece material in a very small spot. By moving the beam and/or the workpiece, grooving, slitting, engraving, and other machining operations can be performed.

when quantities are too low to justify the expense of blanking dies. Steel, Inconel, Hastalloy, titanium, and stainless steel, and various plastics and other non-metallic materials are cut with the process. The degree of light reflectance of the material affects the type of laser that is best to use. Reflective metals such as copper, aluminum, gold, and silver do not work as well. Fig. 3O illustrates the process.

O1. laser-assisted hot machining (LAM) - uses laser processing combined with milling or turning to machine materials that may not be easy to machine by normal methods. The laser and cutter work together; laser energy heats the workpiece

material locally at the point of cutting, softening the material and facilitating the cutting action. Tool wear is reduced substantially, cutting forces are lessened, and higher speeds can be used. Titanium, cast iron, steel, and silicon carbide ceramic have been cut experimentally with this approach.⁷

P. Shaping

Shaping is no longer a common machining operation, having been largely replaced by milling. Shaping produces flat or contoured surfaces by the reciprocating action of a single-point cutting tool that moves in a straight line. The stroke of the tool is normally horizontal. (Vertical shapers are called *slotters*. See section R below.) (Also see *gear shaping*.) The tool is hinged so that it doesn't affect the workpiece on the return stroke. The only movement of the workpiece is its gradual feed across the path of the cutter between strokes. The reciprocation motion and feed are automatic. If the vertical position of the tool is changed between strokes, slots, contours, gear teeth, or other shaped surfaces can be produced. Shapers are versatile machines, simple to set up, and use inexpensive cutting tools. They are still useful for toolroom and maintenance machining. Fig. 3P illustrates a typical horizontal shaper.

Q. Planing

Planing is similar to shaping except that the workpiece rather than the cutting tool has the reciprocating motion. The workpiece is clamped to a table that moves back and forth in a straight line against a single-point cutting tool. Planing is used for parts that are too large for it to be practical to machine them with a shaper. Machining ways of machine tools is an example. The tool is fed across the path of the work between strokes. Multiple tools can be used at one time and can be fed in different directions to produce several machined surfaces on the part at one time. Some planers have been equipped with milling cutters in place of the single point cutting tools in order to increase their

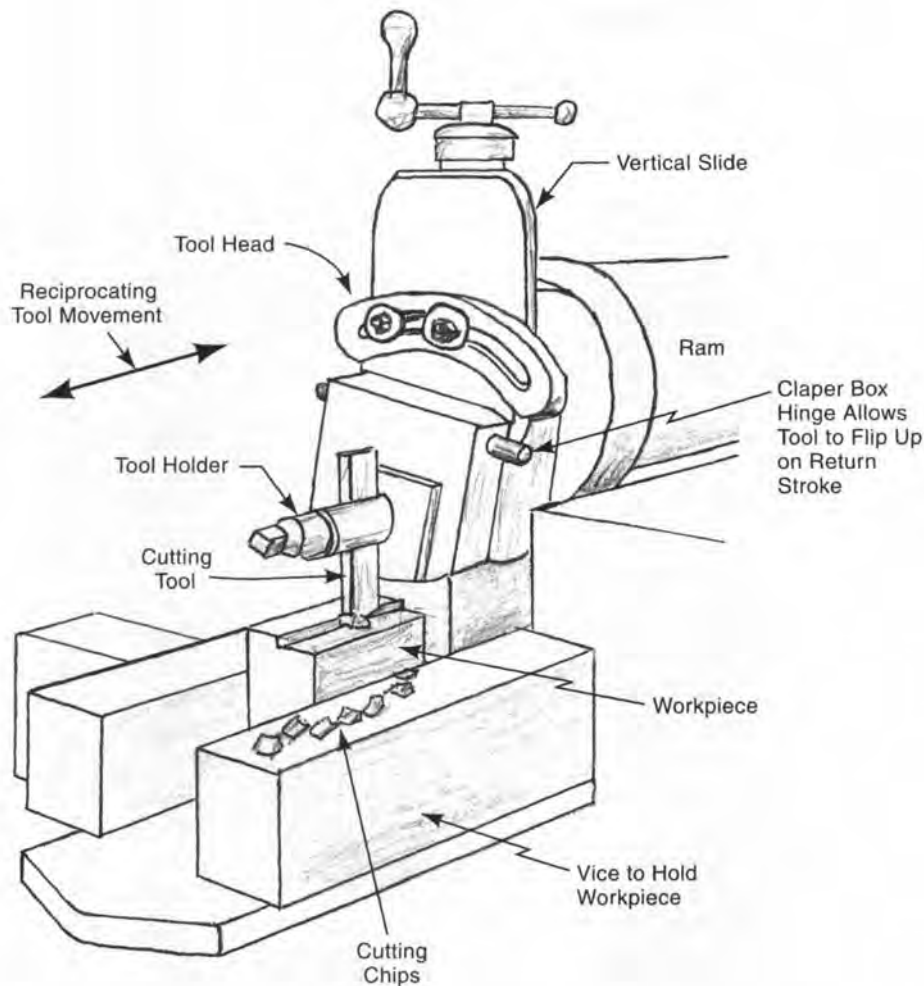


Fig. 3P A shaper makes repeated straight cutting strokes with a single point cutting tool to generate surfaces, slots, and other shapes in a workpiece.

metal removal rates, and are then called planomilling machines or planer-mills.

R. Slotting

This process is essentially the same as shaping except that the movement of the cutter is most often vertical, and the process is usually used to make a keyway or other slot in the part, rather than a flat or contoured surface. Gear shapers are special machines similar to slotters, used for machining spur and helical gears.

S. Chemical Machining

In all chemical machining processes, metal is removed by the etching action of an alkaline or acid solution that is in contact with exposed surfaces of the workpiece or blank material. There is no external electrical circuit. There are several steps in the process: 1) Metals to be processed are cleaned of oil, dirt, scale, and other contaminants that will interfere with the exposure of the surface to the etching solution. Alkaline cleaning, solvent wiping, and vapor degreasing are the most common cleaning methods. 2) Areas not to be chemically

machined may be masked to prevent exposure to the chemical agent. 3) The workpiece is etched (machined) by contact with the chemical solution, usually by immersion. Circulation of the solution or agitation of the workpiece are necessary to ensure uniform metal removal rates. 4) The mask is removed, the workpiece is cleaned of the etching solution, rinsed, and dried.

Aluminum, steel, titanium, and magnesium are the most common materials chemically machined but the process is applicable to almost any metal. Honeycomb structures and other delicate parts can be processed because there are no cutting forces. The process has also been used to salvage oversize parts. It creates no residual stresses in the workpiece. Equipment costs are lower than for conventional machining.

S1. *chemical milling* - is the term used to designate chemical machining when the purpose of the operation is to change the shape or some dimensions of the part, or to remove a significant amount of material. Maskants are normally used to control the location of the stock removal. Usually the entire workpiece is covered by the maskant by spraying or dipping. The maskant is then removed from the areas to be machined. Machining takes place when the workpiece is immersed in the chemical solution. Agitation of the solution ensures that it makes equal contact with all surfaces of the workpiece. The depth of cut is controlled by regulating the immersion time in the solution. The process is most suitable for shallow cuts, which can take place over large areas. One common area of application is to machine pockets or cavities in aerospace parts for weight reduction. Other applications are tapering, removal of undesirable surfaces, and overall size reduction of workpieces. Aluminum is the material most commonly chemically milled. Advantages of the process are the fact that it can be applied to hardened or difficult-to-machine metals, and difficult-to-machine shapes, and no burrs or internal stresses are produced. About 0.5 in (13 mm) is about the maximum depth of cut. Weld joints and other non-homogeneous material structures may yield satisfactory results.

S2. *chemical engraving* - is the process name used when the purpose of the operation is to make patterned surface depressions in the workpiece so as to produce lettering, other nomenclature, figures,

or decorations. The pattern can be either depressed or raised. Masks are applied either as a photoresist or by screen printing. A variety of metals can be processed including stainless steels. Brass, aluminum, and copper are also commonly treated. Chemical engraving of printing plates is one of the earliest applications of chemical machining. The making of nameplates and instrument panels are other applications. Depressed patterns may be filled with contrasting paint for improved readability. The process is more suitable than pantograph machine engraving when fine detail is required.

S3. *chemical blanking* - uses chemical machining to create blanks from sheet material. It is most often used to make parts from thin stock using the photochemical method for configuring the maskant. Manual methods of scribing and stripping the maskant from around the desired part, are also feasible for larger, simpler parts, and those requiring less stringent dimensional accuracy. Manual methods can also be used when a photoresist mask may not have adequate chemical resistance to the solution used, especially when quantities are low and the cost of making a blanking die is not economically justifiable. The mask can be applied by screen printing or offset printing. It is normally duplicated on both sides of the sheet in accurate register so that machining can take place from both sides at the same time.

Etching takes place either by immersing the workpiece in the chemical solution or by spraying the solution on the workpiece. Typical components produced by chemical blanking include electric motor laminations, templates, magnetic recording heads, disk springs, and gaskets.

S4. *photochemical blanking* - is illustrated step-by-step in Fig. 3S4. This process uses a photosensitive resist, which is a light-sensitive material, as the maskant in chemical machining. The resist material is applied by dipping, spraying, roller coating, or flow-coating. The material is hardened in the areas wanted by exposing it to light through a photographic negative whose image corresponds to the shape of the part to be produced. This photo negative is prepared in advance of the operation.

The usual procedure is to draw the blanked part, greatly enlarged, photograph it, and create a negative the same size as the part to be produced.

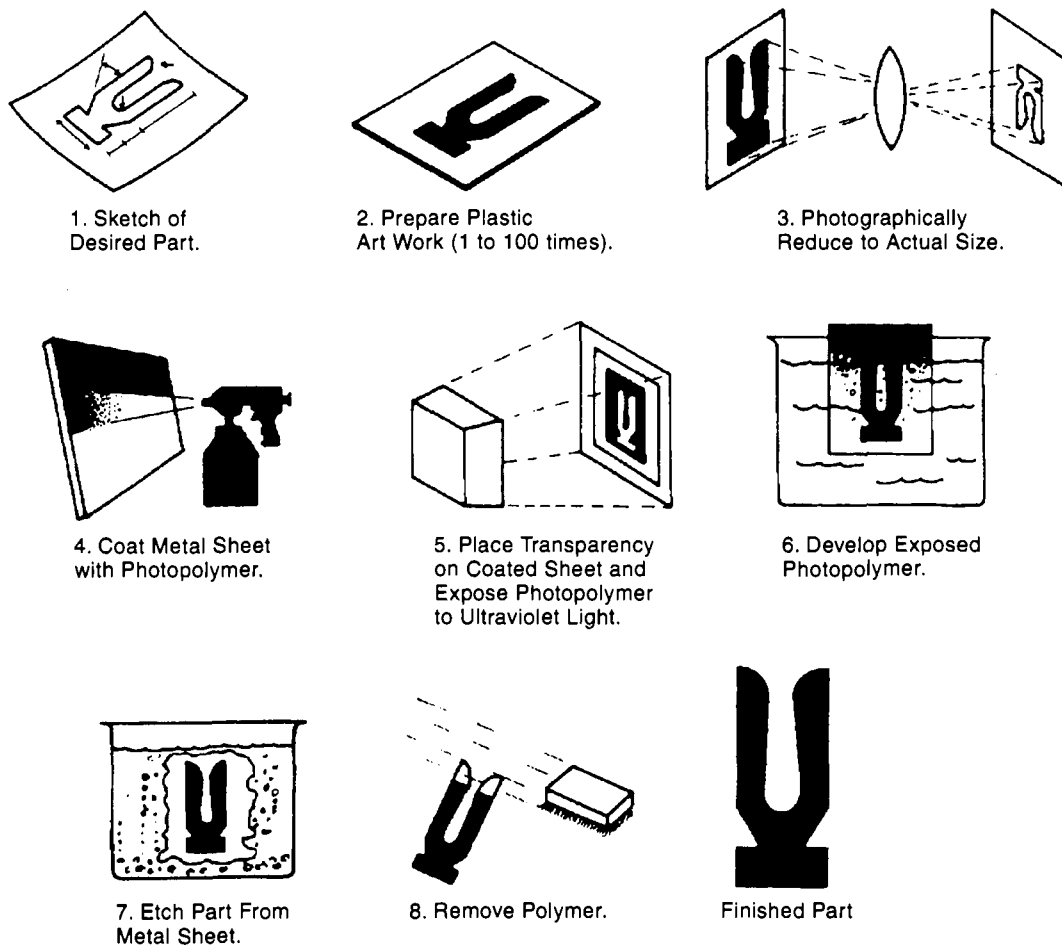


Fig. 3S4 Major steps of photochemical blanking. (Courtesy Mechanical Engineering.)

The negative is attached to the workpiece after the workpiece has been coated with the masking material and it has dried. Normally, for blanking, a similar negative is attached to the workpiece on the opposite side but in precise registration with the first one. Blue light shone through the negatives hardens (polymerizes) the resist material in the areas exposed to the light. The negatives are removed and the workpiece is processed to remove the unhardened portions of the maskant. The workpiece is then immersed in the chemical reagent, that removes the workpiece material that is not masked. The process is particularly adapted to small, complex, and precise parts, made from very thin materials that are not suitable or feasible for conventional blanking. Photochemically blanked

parts are burr free. The electronics industry is an extensive user of photochemical blanking and machining in the production of integrated circuits, circuit boards, and other components. Shadow masks for television sets and screens for various purposes are made with the process.

T. Machining Centers

Machining centers are machines that can perform varied machining operations in sequence, automatically, under computer numerical control and in only one set-up. Milling (including contour milling), drilling, boring, reaming, and tapping are common operations performed by such centers, which are

outgrowths of the conventional milling machine. The keys to their operation are twofold; 1) The machines can be programmed for operation by computer numerical control (See below.) to make whatever cuts the workpiece requires with pre-selected feeds and speeds. 2) They include automatic tool changers that permit the use of a wide variety of cutters, each suited to the operation they perform. The tool changers store whatever tools are needed for the complete series of operations on the part and insert and remove them from the machine spindle as needed. Fig. 3T illustrates a well-equipped horizontal machining center.

Horizontal-spindle machines are most common, but vertical-spindle machines are also available. Machines designed for larger parts may have a traveling spindle column instead of a traveling table. Current state-of-the-art machines have five or more axes and five kinds of controlled movement of either the workpiece or tool position and the feed. The axes controlled may vary with the machine's purpose and design, but can include table movement in and out and side to side, table rotation, spindle head movement up, down, and rotative, and

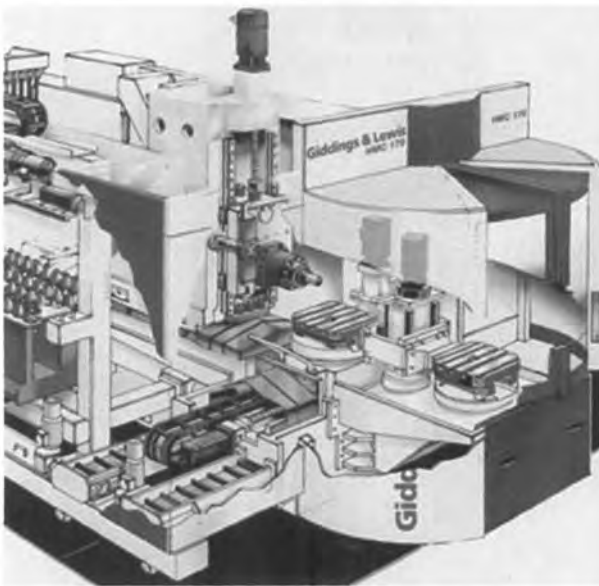


Fig. 3T A horizontal machining center. This CNC machine has a large-capacity tool changer and dual work tables so that one workpiece can be machined while another is unloaded or loaded. (Courtesy Giddings and Lewis Machine Tools.)

axial movement of the spindle. Fig. 3U illustrates one example of 5-axis control. Tool rotational speed, tool feed, tool dimensional offsets, coolant flow and tool changing can all also be performed under the computer control. For example, table and tool movements can be at the slow speeds needed for feeding the cut, or can involve rapid traverse to new cutting positions; the spindle can stop, start, and change speeds, as appropriate for the operation; and cutting fluid can be turned on and off, as needed. Operations can be performed on different sides of the workpiece in sequence, because the table can move or rotate to present a new surface to the cutters. All these operations are automatic. The machines are engineered to provide precise, close-tolerance positioning of the cutters and workpiece. They are particularly applicable to low- and moderate quantity production that otherwise would require a sizable number of separate machining operations on single-purpose equipment. Since machining centers operate automatically and don't require nearly as much operator skill as is needed to operate traditional single-purpose equipment, labor costs are low. However, programming requires special skills, and the investment required for the equipment is sizable.

Some machines are equipped with multiple work-positioning pallets and mechanisms to transfer the pallets to and from the machine table. The pallets and table are designed so that, when assembled, they are in a fixed relationship with one another. Given sufficient memory in the CNC system, as many as 20 or more pallets can be loaded with workpieces, that may or may not be identical. The workpieces are then processed automatically by the machining center, which loads each pallet, machines its workpiece in accordance with the program, and then discharges the pallet and workpiece. The machine then repeats the process, assembling another pallet to the table, machining its workpiece, discharging it, and so on. In this way, machines can be run on a night shift or at weekends, unattended, when power costs are usually lower. Machining centers equipped for this type of operation have sensors included that can detect tool wear, tool breakage, or some other problem that would render the machined part defective. When such a problem is encountered, an alarm may be sounded and the machine stopped automatically.

The types of parts most advantageously processed on machining centers are those that are machined on several surfaces and those with a large number of operations, particularly those made in smaller quantities, where special-purpose equipment is not justifiable economically.

T1. *turning centers* - While the typical machining center was based on earlier boring mills or milling machines, the turning center has its roots in the turret lathe. Turning centers differ from turret lathes in having automatic tool changers that can remove and install cutting tools in the machine's turret, in having the tailstock replaced by a live powered spindle and chuck, and in having NC or CNC control. These machines provide the same benefits and have similar applications to those of machining centers but deal primarily with parts that have surfaces of revolution.

T2. *multiple operation machines* - are part of a trend to provide more complex CNC machines that can perform the operations of both the turning center and the machining center. By adding additional cutter spindles and feeds, and additional tool changing capacity, both turning and milling as well as drilling, tapping, boring, and other capability, more operations can be performed on a workpiece without moving it to another machine. This capability can provide greater dimensional precision from cut to cut, less possibility of marring the workpiece during handling and storage between operations, and faster throughput times. As this trend continues, the distinction between milling, turning, and other operations on separate machines becomes more blurred. Such developments are made possible by the development of the controls and machine-element positioning devices that are part of CNC machining.

U. Numerical and Computer Control

These controls provide a means for operating machine tools and other equipment automatically. They represent a difference from earlier automation in that the machine elements are controlled by electronic pulses rather than mechanical devices. The pulses activate drive motors and other devices of the machine tool. Setting up a machine for a particular

operation involves the entry of coded numerical data rather than the fabrication and installation of cams or other mechanical apparatus. The coded data are in the form of numbers, letters, and special symbols. The complete set of such data for any operation is called the *part program*. Data are stored on various magnetic media: magnetic tape, computer storage disks, etc. Perforated paper or "Mylar" plastic tape, widely used for data storage in earlier numerical control systems, is seldom seen any longer. The part program is stored on a CD-ROM or hard drive. When the program is read by the control unit, it is converted to a series of electrical pulses sent to the machine's motors. These electrical pulses provide the power to move the machine's spindle, tool slides, worktable, and other elements. They control the amount, direction, and speed of each moving machine element, as needed to carry out the operation.

There are three elements to a numerical control system: 1) the part program - a planned sequence of commands acted upon by the machine controller and then by the machine itself. 2) the controller - the numerical control system, computer-numerical control system, or programmable controller that reads the program and directs the machine tool, and 3) the machine tool, equipped with precise electrical power drives (servo motors or stepper motors) for the machine movements to be controlled. This approach provides great flexibility and ease of changeover so that automatic operation is economically feasible, even with one-of-a-kind or other limited production. There are various degrees of sophistication of this approach. They reflect developments as electronic devices and computers have become more powerful and more affordable. The development of numerical control has coincided with and has been an essential factor in the development of machining centers. The advantage of numerical control is that it enables the machine to run automatically in accordance with an optimized program; a machine operator is not needed to manipulate handwheels, levers, or other mechanical devices. If a number of parts are to be produced, all are made with a consistent machine sequence. With NC and CNC, automatic operation is affordable even with limited production quantities.

The simplest arrangement may have only two axes of movement and position to control, the longest table slide (usually the X-axis), and the machine

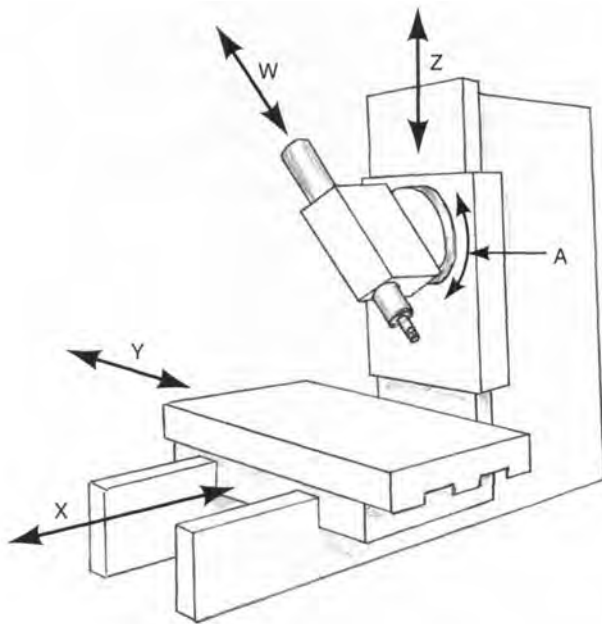


Fig. 3U A representation of the machine motions of a 5-axis milling machine.

table slide at right angles to it (usually the Y-axis). To these can be added the advance, feed and retraction of the machine spindle (the Z-axis) and the arrangement then would constitute three-axis control. In more elaborate systems, up and down movement of the worktable or machine head, rotation of the machine table, and the movement of the spindle mounting may all be added. Fig. 3U illustrates movements on a typical machine with 5-axis control.

Several degrees of sophistication of machine movement can be offered by the control system: *Point-to-point* positioning controls the position of the table but not necessarily its path from one location to another. This facility may be useful for hole-making operations, turret punching, and spot welding. Straight line control adds the control of the tool or table movement from one position to another so that straight milling cuts can be made. With earlier equipment, movement was usually only along the X or Y axis. Straight line motion where more than one axis is involved is typically called, *linear interpolation*. *Contouring* or *continuous-path* control, also called *circular interpolation*, allows curved surfaces to be machined, controlling both the direction and velocity of motion of machine elements.

Another important aspect is the degree to which information is fed back to the controller or computer during the operation. *Open-loop systems* do not have any feed back. The machine simply follows the instructions specified by the controller. This arrangement may be quite acceptable for simple two- or three-axis situations where tolerances are less stringent. *Closed loop systems* include sensors that transmit information back to the computer about the instantaneous location of the machine elements and the computer then may adjust the position of the machine element in accordance with that information. In more sophisticated installations, sensors may detect whether the tool has broken. They may measure the changing dimensions of the workpiece and adjust the cutting tool position accordingly, and may measure torque or actual cutting speeds. Compensations can be made to adjust for material variations, or dulling or wear of the cutters. This approach is sometimes referred to as *automatic adaptive control (AAC)*. Fig. 3U-1 illustrates both closed-loop and open-loop systems schematically.

U1. NC, numerical control - is an earlier term for electronic control of machine tools. In the system, tool movements are instigated and controlled from numerical data that has been entered and stored. The numerical data are in the form of numbers, letters, and special symbols. The complete set of such data for any operation is called the *part program*. In the earliest systems, numerical data were stored in the form of holes punched in paper or Mylar plastic tape. The program was read by a tape reader/controller which then fed electrical pulses to the NC machine. Numerical processing power and sophistication were very limited. The term *numerical control* is still widely used to designate control systems that may be more sophisticated than earlier systems, but the more proper term for almost all current systems is *computer-numerical control, CNC*. Fig. 3U1 illustrates a typical traditional NC system.

U2. computer numerical control (CNC) - introduced in the 1970's, uses a computer in addition to a controller (and, more recently, in place of most of the functions of the machine control unit) as the heart of the system. Earlier NC systems used hard-wired controllers with a fixed logic. CNC,

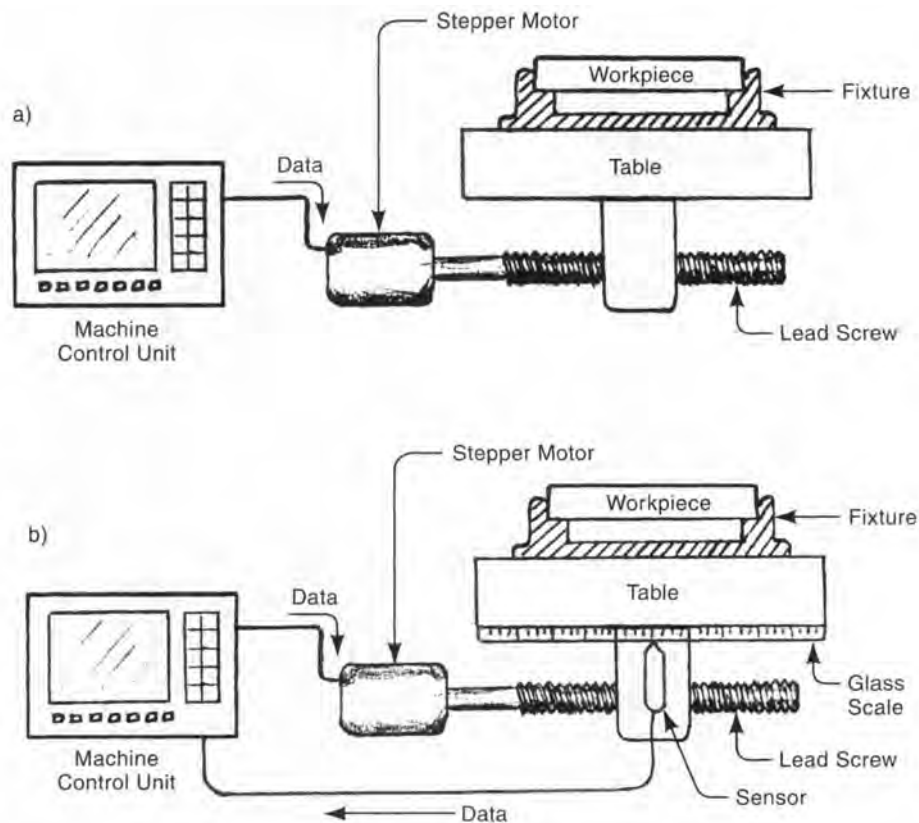


Fig. 3U-1 Open and closed loop control systems. An open-loop system in view a) shows data being transmitted to one of the machine tool's stepper motors causing it to move the machine table a stipulated amount. There is no feed back to verify the table's position. In view b) sensors detect the table's position with respect to a glass scale and this information is fed back to the machine control unit, which may send further signals to the stepper motor to adjust the position of the table. In some closed-loop systems, additional sensors may similarly transmit data of other conditions back to the machine control unit.

with a "soft" wired computer as part of the machine control unit (MCU), provides much greater flexibility and vastly increased functions in the control system. The MCU embodies circuitry that translates computer signals into movements of the machine elements. The computer simplifies the tasks of modifying and storing instructions for particular parts since the computer's data storage system rather than perforated tape can be used for this function. An alphanumeric keyboard provides a means of entering the program manually, and a visual monitor screen displays the program or an illustration of the movement path of the tooling on the workpiece. The addition of a computer to the system also increases the ability of the system to process feed-back information from sensors.

This can greatly improve the accuracy and efficiency of the operation. With sophisticated programs involving feed-back and, increasingly, fuzzy logic and artificial intelligence, the computer can optimize the operation, achieving maximum cutting speeds and feeds and responding to problems revealed by sensors on the machine. Almost all CNC systems also provide the more usable contouring/continuous-path machining.

The sequence of steps in programming and operating a CNC machine are shown in Fig. 3U2 and are as follows: 1) The part specification, with any essential manufacturing notes, is prepared. 2) A NC part program for performing one operation (or several combined operations necessary to make the part) on a particular machine tool is prepared from

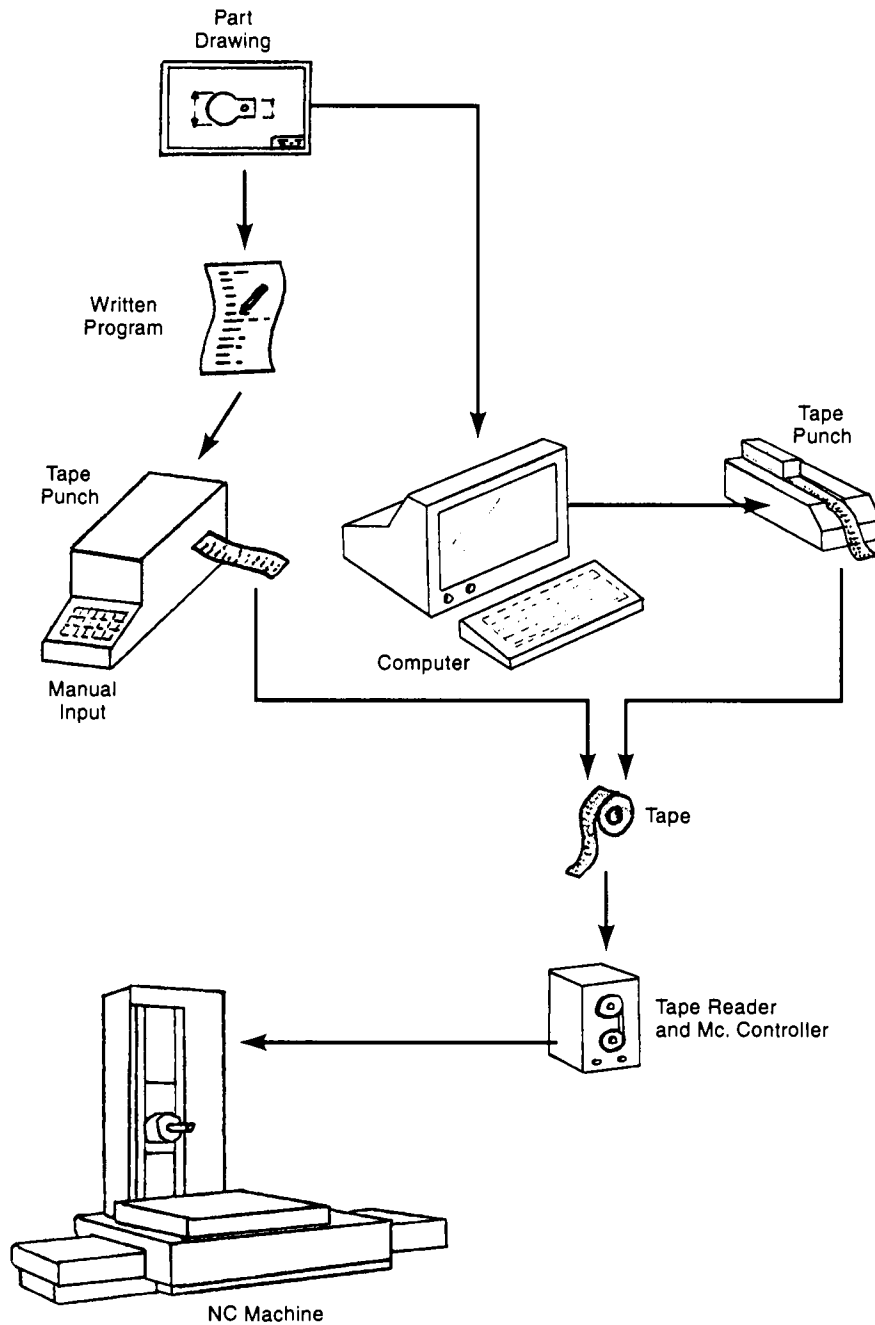


Fig. 3U1 The elements of a typical earlier NC system. The NC machine is controlled by perforated tape, which is punched with either a manual punch or a device connected to a personal computer.

the part specification. This work is typically done on a computer that can send the processing program for the part to the machine control unit (MCU) by one of a number of methods: a) directly

by wire, b) in older systems, by means of a tape punching device connected to the computer and then a tape reader connected to the MCU, c) by magnetic tape which is then fed to the MCU, d) by

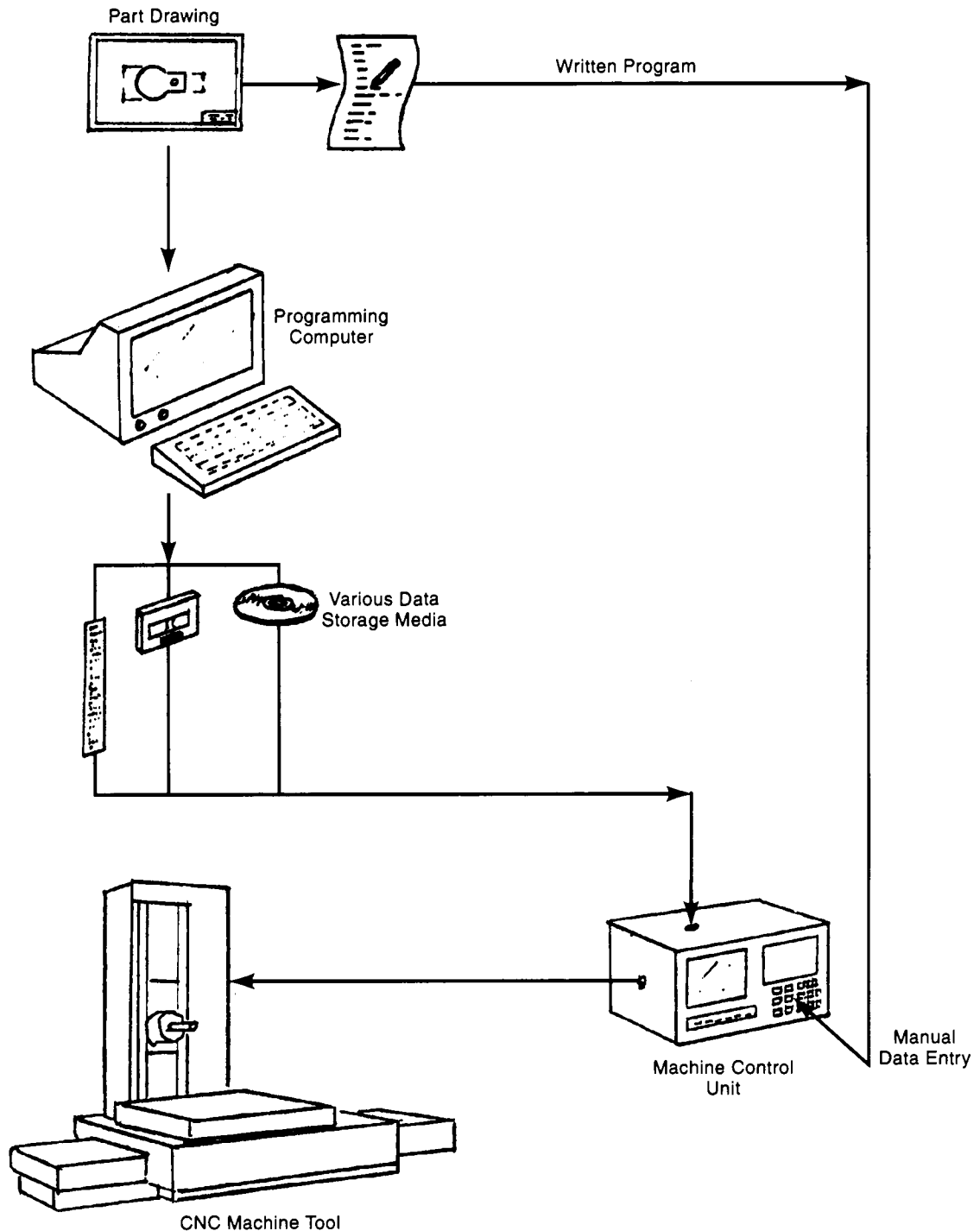


Fig. 3U2 A typical CNC system. The machine control unit (MCU) responds to a program entered on perforated tape, on one of a variety of magnetic storage media, or from a program manually entered directly into the MCU.

a computer disc or disc pack, which is inserted in a reader in the MCU. 3) The MCU reads the program and sends electrical pulses to the NC machine which, following the electrical pulses, performs the operational steps required.

U2a. **DNC (direct numerical control)** - is an earlier term for *computer numerical control, CNC*. It was used when the numerical program was fed to the controller directly from a computer rather than from punched tape. Direct numerical control now refers to the situation in which one central computer controls a number of machines at the same time, downloading the NC data as it is needed by each machine. *DNC* now also refers to *distributive numerical control*, a more complex and larger arrangement where one central host computer feeds programs to several satellite *DNC* computers, which, in turn, feed the programs to *CNC* units they control. Each of The machine tools each have a microprocessor that processes data from the central computer. The whole program may be downloaded at one time into the memory unit of each machine's controller or may be downloaded piecemeal as needed to keep ahead of the operation. The latter approach is referred to as "drip feed". The programs may reside in the central computer's memory system or may be loaded into the central computer from a floppy disc, punched tape, or other data storage device. Machines connected to a central computer in this way are part of a *local area network (LAN)*.

U3. **programmable controllers** - This term dates from the advent of numerical control. The earliest programmable controllers were devices that were very simple, by present day standards, and were first used primarily in process equipment such as mixers, providing time and speed control for a number of steps of automatic operation. The term *programmable logic controller (PLC)* was also used. The terms then referred to machine tool controllers that were hard wired for the particular machine functions they would control. They accepted numerical data from punched tape but also had capability for program modification or entry from a keyboard. The term is still used to designate the electronic device at the machine tool that can perform the entire *CNC* function but which is now more commonly referred to as the *machine control unit (MCU)*.

As computers have replaced the hard-wired circuits, and computer power has become more economical, these units have been developed to perform more and more functions. Now, in addition to providing the basic program, programmable controllers include capability for closed loop control and adaptive control, utilizing feed-back from various sensors on the machine. Panel displays, machine interlocks, and other auxiliary control functions are incorporated. The basic program can come from the unit's own permanent storage, from a disc reader in the unit, or from a central computer.

U4. **CAD-CAM - Computer Aided Design - Computer Aided Manufacturing** - involve the creation of a part's design in digital form and then the translation of that design into a program for *CNC* operation of a machine tool. In the *CAD* phase, the designer develops the part's design by computer instead of by making a drawing on paper or film. *CAD* equipment includes a personal computer or workstation, a design program, and storage media for the completed design. The designer enters coordinates and dimensions with the computer keyboard, mouse, or light pen. The design is pictorially displayed on the computer monitor and can be printed, if desired. In the ideal situation, not yet realized, it would be possible to feed the computerized design automatically to a *CAM* computer or computer circuits, that would transform it into a control program for a machine tool. The program could then be fed to the machine tool to produce the part just designed. Thus, the task of programming the *CNC* system to make the part would be performed by the computer, and no human intervention would be required. Differences in machine control systems and between design objectives and manufacturing objectives make the complete achievement of this ideal quite difficult. Existing *CAD-CAM* systems simplify but do not eliminate the need for human participation in the programming of the machine tool except in some very simple 2-axis applications. In present practice, the production engineer operates a *CAM* computer, enters design data and specifies the sequence of operations, starting and ending points, intermediate dimensions, and process parameters such as feeds and speeds. The *CAM* program puts all these data in a form that can be read by the machine control unit. The *CAM* computer also may display tool movements,

and the appearance of the workpiece at various stages of the operation. (A complete CAM system also may provide various administrative control information to monitor such items as work-in-process, cycle time, inventory, machine and labor efficiencies, and schedule compliance, etc.)

U5. *digital readouts in machining* - These are electronic devices that display for the machine operator the precise position of the machine table or other machine elements. As such, they are an aid to the manual operation of machine tools, simplifying for the operator the task of moving machine tables and cutters to the correct position for machining or other operations.

U6. *automatic tracing* - is used in some machining operations to control the position and movement of a cutting tool so that the operation can be performed automatically. Various devices are used. Tracing attachments for lathes and milling machines typically follow a fabricated template using electrical, pneumatic, or hydraulic systems. Contoured surfaces can thus be machined. These devices improve the productivity and versatility of some machine tools, because tracing often permits the machining of surfaces that would be difficult or impracticable to machine manually. The approach is common in the machining of injection molds and die casting dies. When parts are to be blanked from flat stock by flame cutting, routing, water jet, and abrasive water jet machining, optical tracing is sometimes employed. With this method, the cutter duplicates the path of lines on a drawing of the part's outline.

U7. *robots and robotic operations* - See chapter 14 of this handbook.

V. Trimming

Many manufacturing processes for shaping parts leave some unwanted material that must be removed from around the desired shape. Deep drawing, die casting, forging, plastic sheet molding, compression molding, reaction injection molding, and rotational molding are examples of processes

that may leave flash or other excess material that must be removed. Various processes are used for such an operation, including the following: die cutting with dies like blanking dies but with suitable clearances for the part to be trimmed, pin routing (vertical milling), laser beam machining, abrasive jet machining, hydrodynamic (water jet) machining, and abrasive water jet machining.

W. High-Speed Machining

High speed machining is most common in milling operations but is also used in drilling and boring. The procedure is characterized by very high spindle speeds which, with normal feed rates per revolution, provide very high feed rates per minute. Surface cutting speeds may also be faster than normal. The method is heavily used in the aircraft industry to machine aluminum structural parts. Aluminum is the predominant material machined by high speed methods, although steel is also processed. One particularly attractive field of application is called *unitization*, the machining of a large, complex single part from a large material plate or block instead of assembling a series of small parts. The method requires careful balancing of tools and tool holders, CNC control of the operation, and more expensive machine tools with less-massive but high-powered spindles. Adaptive control systems are advisable. Spindle speed maximums range from 8000 to 40,000 rpm. Feed rates are as high as 800 ipm.

Another application of this approach is to the machining of dies and molds from tool steels. Small cutters are used, rotating at high rpm's but with normal surface speeds. The higher speeds permit more close passes to be made without time penalty, providing better precision and smoother contours, and greatly reducing the need for hand finishing benchwork, thereby significantly reducing cycle time and finishing costs.

X. Special Purpose Machines

When production quantities are very large, it is often advantageous to design and build machine tools that are dedicated to the production of specific parts. Such machines can provide both labor and

quality advantages because the necessary precision can be built in, and the machines can incorporate spindles and tooling to perform several machining operations on the part simultaneously. Handling of the part is greatly reduced. Advantages of specialization can be gained and machines do not need apparatus and structure for a variety of parts. Examples of special purpose machines are those built to drill, bore, ream, or tap a number of holes simultaneously, to drill holes from more than one side, or to mill or broach one surface while performing another operation on another surface. Another method for accomplishing the same objectives is to construct a machine having an indexing table. The table rotates a fixed amount on a timed sequence and its position is accurately located after each movement. Several different machining heads can be located in fixed positions next to the table. The workpieces are positioned in fixtures on the table. After each operation, the table indexes to move each workpiece to the next station, with one station used for loading and unloading. Each time the machine indexes, one part is completed through a series of operations.

Y. Transfer Lines

Transfer lines move the workpieces automatically from one machine to another. In such arrangements, a whole series of machine tools are dedicated to the production of one part, or sometimes a family of similar parts. The workpieces are held on fixtured pallets and the transfer mechanism moves the pallets from machine to machine between operations. Devices on each machine automatically position and clamp the pallet and fixture to the precise location for the

necessary operations. The machine tools at each station are automatic and are usually dedicated to specific operations on each part. Automotive engine block manufacturing is typically carried out on transfer machining lines with automatic equipment at each station.

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Chapter 4 - Processes for Plastics

A. How Plastics Are Made

A1. definition - Plastics are organic chemical compounds of high molecular weight that have a structure resulting from the repeated linking together of small molecules, called monomers. The resulting long-chain molecules are polymers. Plastics are one type of polymer; elastomers (rubber-like materials) are another. Polymers can be either natural or synthetic. The molecular weight of the polymer is a multiple of the molecular weight of the monomer. Usually, at least 100 monomer molecules and up to many thousands of monomer molecules may be incorporated in one molecule of a polymer or elastomer.

There are two basic types of plastics, *thermo-plastics*, which soften and melt when heated (melting takes place over a wide temperature range) and *thermosetting* plastics, whose long molecules are crosslinked together. Thermosetting plastics do not melt upon heating but remain rigid until they reach the charring or burning temperature.

A2. polymerization reactions - are the chemical reactions in which the individual, relatively small, monomer molecules link together into very long chains, called polymers. The two basic polymerization reactions are *addition polymerization* and *condensation polymerization*.

A2a. addition polymerization - is a simple combination of molecules without the release of any by-products. In one addition polymerization reaction, a chemical activation of the molecules

with the aid of an initiator (a chemical catalyst or other substance), causes the atoms of the monomer molecules to bond together, creating chains of molecules. These chains may have as many as several hundred thousand repeating molecular units and have a molecular weight from tens of thousands to several million. In another process variation, the atoms within the molecules are rearranged. This causes the molecules to link. In still a third addition polymerization method, monomer molecules are composed of rings of atoms. A suitable catalyst causes the rings to open up and connect with the rings of other similar molecules. The reaction is exothermic; heat generated must be removed from the reactor. Polyethylene, polystyrene, polypropylene, and polytetrafluorethylene ("Teflon") are made by addition polymerization. Fig. 4A2a shows the addition polymerization reaction for polyethylene.

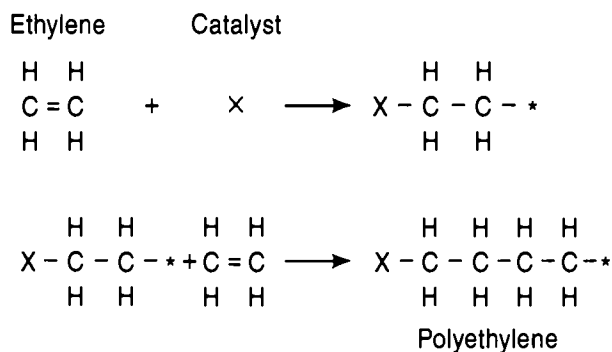


Fig. 4A2a The addition polymerization reaction for polyethylene.

A2b. condensation polymerization - differs from addition polymerization in that the monomer molecules are modified to cause the linking process to take place. A polymer is formed by a reaction between two functional groups attached to a monomer core. The modification also creates atoms, which form small molecules of condensation, most commonly of water, which is removed from the mixture. The repeating unit of the condensation polymer is different from the monomer because of the elimination of the condensation molecules. The condensation compound must be removed immediately. Otherwise it would interfere with further polymerization and could constitute undesirable contamination of the finished polymer. The condensation reaction requires the addition of heat. Some nylons, phenolics, and polyester pre-polymers, are made by condensation polymerization. Fig. 4A2b illustrates the condensation polymerization reaction involved in the production of phenolic plastics.

A3. polymerization methods - There are a number of approaches for effecting the polymerization: bulk, solution, suspension, emulsion, and gas-phase methods.

A3a. bulk polymerization - is a widely used approach. It takes place with the monomers and reactants in the reaction vessel but with no other

materials present except initiators. The monomer is a solvent of the polymerized material. As polymerization proceeds, the polymerized plastic dissolves in the monomer, increasing the viscosity of the mixture. Polymerization continues until all the monomer has been polymerized. Exothermic heat must be removed to keep the reaction under control and prevent it from becoming explosive or developing local hot spots. These may result in degradation and discoloration of the polymer. Heat removal is critical because the reaction is accelerated at higher temperatures. The mixture must also be agitated, even though this can become difficult as the viscosity rises. One method of preventing overheating is to carry out the polymerization reaction in two steps, with special arrangements in the second step to aid in the dissipation of heat. The special arrangements include using thin layers of reacting material, finishing the polymerization in small-diameter tubing or in a free fall in open space or along the walls of the container. In another method, the final step is deferred until the monomer-polymer mixture is cast in molds into rods, bars, tubes, or other useful components. Cast acrylic shapes are made with this method.

In another procedure, the polymer is not soluble in the monomer but separates from it as polymerization proceeds. Nevertheless, plastics of very high molecular weight are produced with this procedure.

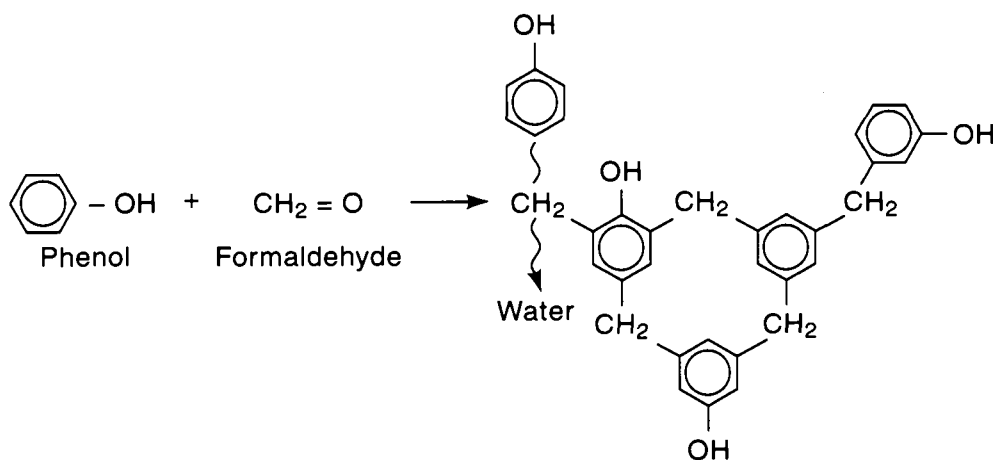


Fig. 4A2b The condensation polymerization reaction, which combines phenol and formaldehyde to produce polymers of phenolic thermosetting plastic.

Bulk polymerization is used in the production of most step-growth polymers and many chain-growth polymers.

A3b. solution polymerization - In this procedure, used when the monomer is not a solvent for the polymerized material, a separate inert solvent is used. This solvent may dissolve the monomer and the polymer as well as the initiator. However, it may dissolve the monomer without dissolving the polymer or may dissolve the polymer only partially, depending on the materials involved. The technique used varies with the solubility of the solvent as does the rate of polymerization and the molecular weight of the finished product. The solvent has the function of absorbing and conducting away exothermic heat and making the mixture easier to stir. It also reduces the rate of polymerization. These effects all virtually eliminate the problem of heat removal that is inherent in bulk polymerization. A solvent is chosen that does not react with other compounds in the reactor, although complete inertness to the reaction is not always possible.

Solvent removal after polymerization may be difficult. For this reason, the solution method is well adapted to the production of polymers that are used in liquid form as adhesives, coatings, impregnating fluids, and laminating resins. The method is also useful when the monomers are gaseous.

A3c. suspension polymerization - In this approach, the initiator is dissolved in the monomer and the monomer is dispersed in a liquid in which it is insoluble, usually water. The polymerized material is also insoluble in this liquid. A dispersing agent is incorporated in the mixture to stabilize this suspension of the monomer and polymer. The polymerized material and the monomer from which it is formed remain dispersed in the non-solvent liquid as small beads or "pearls" of 0.004 to 0.040 in (0.1 to 1.0 mm) diameter. The polymerization proceeds in each individual bead in a manner similar to that of bulk polymerization. However, the water or other liquid is valuable in conducting away the exothermic heat of the reaction and in other respects aiding in the control of the process. Other advantages are the lower cost of water compared to organic solvents and the fact that it does not react with other compounds in the reactor. Another benefit of suspension polymerization is that the finished

plastic exits the process in smaller-size chunks, eliminating the need for later pelletization. The small chunks are easily washed, filtered, and dried for later molding.

A3d. emulsion polymerization - has similarities to suspension polymerization. It uses water, soap (an emulsifier) and a water-soluble free-radical initiator to carry out addition polymerization of the monomer. The monomer, which is insoluble or only slightly soluble in water, is dispersed in an aqueous continuous phase. The reaction tends to take place within small hollow spheres formed by the soap molecules. The monomer diffuses into these spheres. The reaction starts when the initiator reacts with the monomer in the small spheres. The control of the conditions that form the spheres also controls the polymerization reaction. A colloidal dispersion of the polymer, a latex, results. The polymerization is much faster than with other procedures including bulk and solution methods and the polymers produced can have very high molecular weights. The process is widely used. Polystyrene, acrylics, polyvinyl chloride (PVC), polyvinyl acetate, and ABS plastics are made with this method. Synthetic rubbers are also made by emulsion polymerization.

A3e. gas-phase polymerization - is a process in which a gaseous monomer such as ethylene, vinyl chloride or tetrafluoroethylene is polymerized. The gas-phase monomer is introduced under pressure into a reactor along with a catalyst. A reaction takes place that results in the formation of a solid polymer in granular form. Polymer particles can be removed from the reactor and it is not necessary to separate the catalyst. For polyethylene, the reaction takes place at low temperatures [170 to 212°F (75 to 100°C)] and a low pressure of 290 psi (20 bar). Some processes use a fluidized bed of the polymerized material and the solid powder catalyst; others use a stirred bed. Linear low-density polyethylene, high-density polyethylene, and polypropylene are commonly polymerized by a gas-phase process.

A4. compounding plastics - The typical plastic molding material contains a number of ingredients in addition to a plastic resin. Depending on the application and the resin involved, the molding compound may contain any of the following: fillers, reinforcements, colorants, stabilizers,

antioxidants, ultraviolet light absorbers, antistatic agents, flame retardants, blowing agents, lubricants, fragrances, mold release agents, smoke suppressants, antifogging agents, antimicrobials, and plasticizers. Properly blending these ingredients involves a thorough mixing operation. The objective is that any unit of volume of the material has the same distribution of components as that of any other sample and of the entire lot. Mixing methods currently in use are described in the following paragraphs.

A4a. *mixing by tumbling* - Tumbling barrels are effective for mixing dry, solid materials. The barrel is rotated about a central axis and the material it contains falls from the top to the bottom, gradually dispersing additives in the base material. Intake of ingredients and discharge of the mixture after tumbling take place through an opening in the barrel. Several different shapes of barrel are used. The V-shaped barrel, shown in Fig. 4A4a, is common. When the "V" is upright, the materials in each side fall together; when the "V" is inverted, the

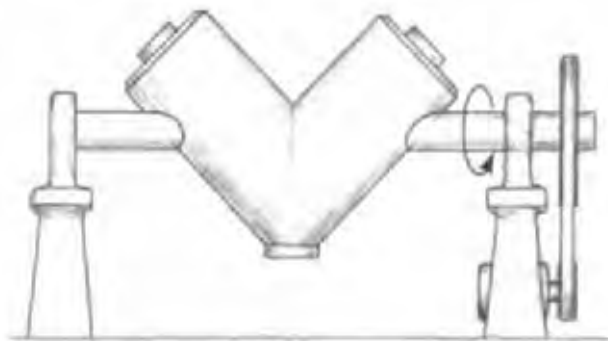


Fig. 4A4a Mixing by tumbling in a V-shaped barrel.

materials fall into each side approximately equally. The repeated combining and dividing in half as the barrel rotates, gradually disperses each material until a uniform mixture is obtained. Granules, crystalline materials, and dry and partly-dry powders can be processed.

A4b. *intensive dry mixing* - involves a container such as that in Fig. 4A4b, with a high speed

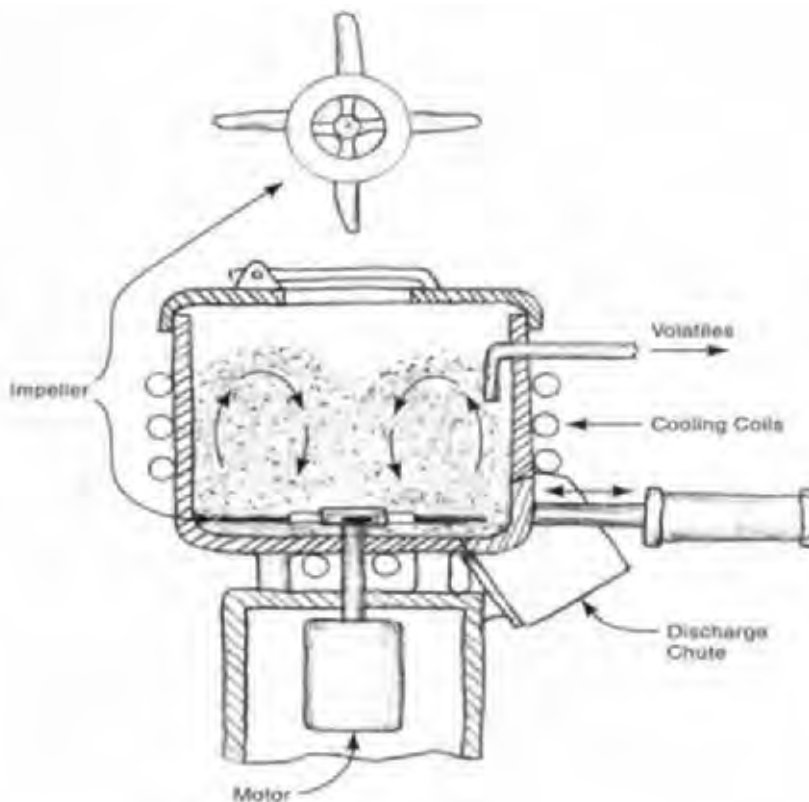


Fig. 4A4b Intensive dry mixing - propeller type.

rotating propeller-like blade at the bottom. It is used for blending powdered resins with various additives. PVC, blended with plasticizer and other additives, is a common application. This type of mixer is equipped with cooling apparatus to remove frictional heat. Volatilized moisture is also drawn off to a vortex and vented.

A4c. internal intensive batch mixing - utilizes mixers of the Banbury type, illustrated in Fig. 4A4c. They normally consist of two horizontal cylindrical chambers, side by side, each with a shaft centered on the cylindrical axis. Each shaft holds rotors of various shapes. The rotor blades move near but do not touch the cylindrical walls of the chambers, producing a strong shearing action. The blades rotate in opposite directions and interact with each other. Some blades are also helical and impart an axial movement to the material being mixed. There are other blade varieties, elliptical or fishtail in shape. The effect of all these shapes is to severely fold, shear, and mix the material in the mixer. The rotors and chambers contain channels

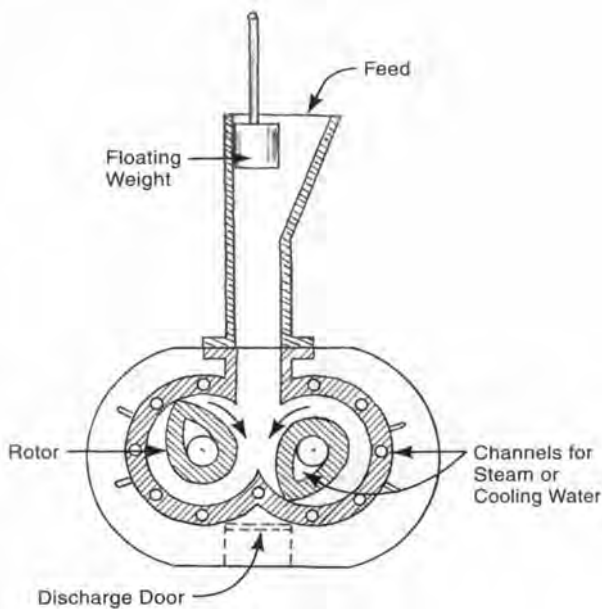


Fig. 4A4c Cross section of a Banbury mixer. Rotors within the two parallel cylindrical chambers knead, fold, shear, and mix the material thoroughly. A weighted piston holds the material in the chambers. Rotors can be of several shapes that may vary along their lengths.

for cooling or heating liquids so that the proper mixing temperature for the particular polymer involved can be maintained. High power levels may be required but mixing of the batch normally can be completed in 2 to 4 minutes and a highly homogeneous mixture results. This equipment is used in the mixing of polyolefins, vinyls, ABS, polystyrene, ureas, and melamines.

A4d. continuous mixing - is quite similar to the internal intensive batch mixer (Banbury mixer) except that it is designed for continuous rather than batch operation. Like the batch-type Banbury mixer, there are two overlapping cylindrical chambers, each with a rotating mixer. There is a feed hopper at one end and a discharge chute at the other end. Near the feed end, the mixers are shaped like screw conveyors to move the material to the more aggressive mixing portion of the chambers. This mixing portion, near the discharge end, contains rotor shapes that shear and knead the material, and interchange it between the rotors. The machines are designed to provide high-quality mixing over a wide range of throughput rates. Even when operating well below maximum capacity, a homogenous mixture results. Fig. 4A4d illustrates this kind of mixer.

A4e. single screw extruders - Standard single screw extruders, as shown in Fig. 4I, have the capability of mixing plastic materials fed through them. Mixing is a desirable function during an extruding operation although it is not the prime function of the machine. Although these machines do not have the blending power of continuous mixing equipment or other dedicated mixing machines, they have proven useful for modest mixing tasks. Common operations are the mixing involved when fillers, antioxidants, stabilizers, color concentrates, or other ingredients are added to the resin compound to be extruded. These machines are also capable of blending reground scrap material. The back pressure of an extrusion die develops some back flow in the material in the barrel, further adding to the mixing. In all such machines, the added ingredient must be metered properly into the feed hopper.

A4f. compounder-extruder mixing - uses a machine similar to a single-screw extruder, but whose prime purpose is mixing rather than extruding.

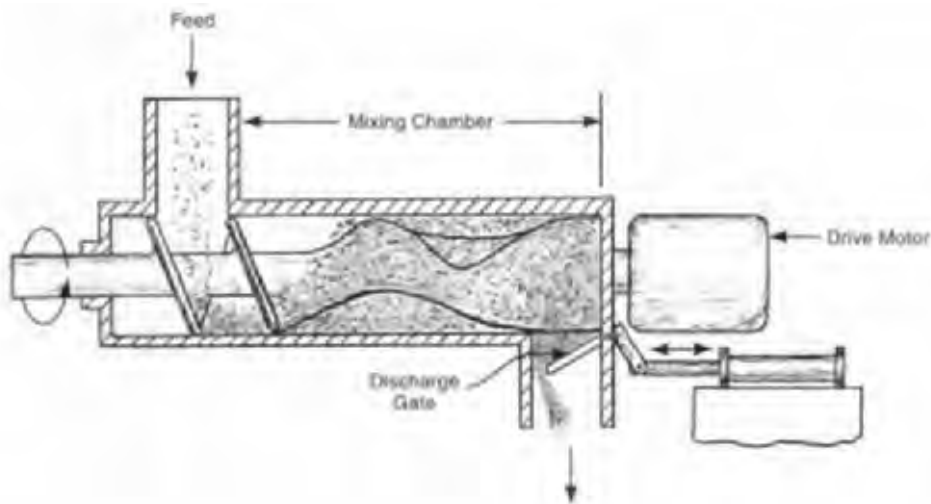


Fig. 4A4d Continuous mixing with a mixer similar to a Banbury type.

The barrel of the machine contains a series of stators outside the flutes of the extruder screw. The stators are opposite handed from the screw and are of alternately different heights. Torpedo and screw modifications are also made in the machine. These involve varied pitch and diameter of the screw and spiral grooves in the barrel. The screw is configured to provide an extensive mixing section and a high intensity variable-shear section. In the central area, the screw and barrel are shaped to permit the escape of trapped air and volatile materials. A vacuum pump draws them off.

A4g. twin screw extruder mixing - is performed on machines with two feed screws side-by-side in a double barrel. The screw flights usually overlap and intermesh. The screws usually rotate in the same direction, which means that there is a wiping and shearing action in the area of overlap. The material follows a figure-8 path as it moves through the machine and is thoroughly mixed. Fig. 4A4g shows the cross-section on one twin-screw mixer.

A5. pelletizing and dicing of plastics - Commercial plastics intended for molding and extruding operations are most often supplied in pellet form. The advantage of pellets is that they can be easily handled, accurately weighed, and conveniently stored. Machines to create pellets from compounded material are of two basic types:

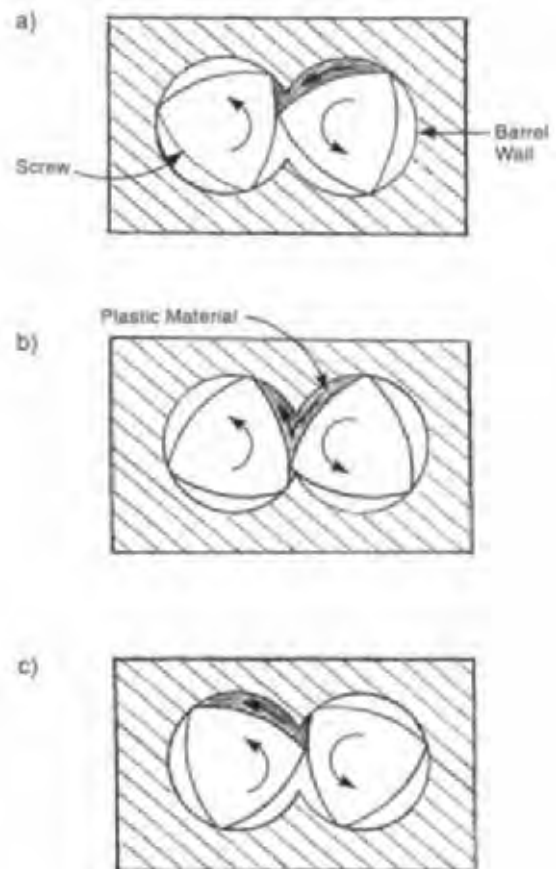


Fig. 4A4g The cross-section of a twin screw mixer showing how the material is mixed as it is transferred from one screw to the other.

1) rolls that mix the material and convert it to a sheet that is slit and diced and, 2) strand pelletizers, or extruders with attachments at the outlet end to cut extruded rod-like shapes into small pieces. The final pelletizing may be carried out with the material either cold and solid or still hot as it emerges from a die.

A5a. *mixing and dicing with two-roll mills* - Two-roll mills can be used as a final mixing step to introduce and blend plasticizers and fine particles of solid additives. Typically, the horizontally-shafted rolls rotate in opposite directions and they pull and nip the material through the space between them, providing good shearing action. The exiting material is slit by strip cutters into ribbons that are fed

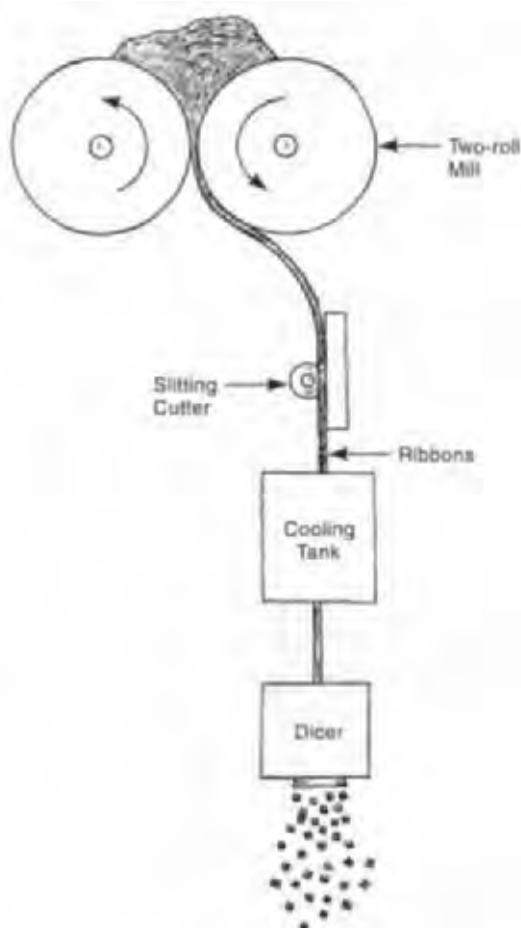


Fig. 4A5a Schematic view of two-roll mixing followed by slitting and dicing.

to a cooling tank and then to a dicer. Fig. 4A5a illustrates the two-roll mixing action.

A5b. *strand pelletizers* - each consist of a screw or gear-pump extruder and die, and a rotating cutter that works against stationary blades. Each machine also has provision for cooling: by air, air-vacuum, or water, either before or after cutting. The machines include a drying system if water is used, and a means to collect the pellets. Hot-face cutters cut the extruded strands into pellets while they are still soft. Cold-cutting systems cut the strands after they have cooled. With cold-cutting systems, the strands may be drawn and pulled through a water bath before cutting. With hot-face cutting systems the cutters act upon the strands before they are cooled by air, fluidized bed, water spray, and/or water stream. The method chosen depends on the properties of the plastic, particularly its melt strength and sensitivity to temperature and its ability to withstand a residence period at a high temperature.

A5c. *underwater pelletizing* - Material exiting from a mixer-extruder flows through heated multiple-opening extrusion dies into a water chamber where the strands are sheared into pellets by a rotating, multi-bladed cutter moving across the die face. Water circulated through the chamber cools the material and conveys the pellets through a discharge port, away from the cutting area, and to a dryer. Water provides a convenient handling medium. The dryer then removes the water from the plastic pellets by centrifugal force. Polyethylene, polypropylene, PET, polystyrene, ABS, SAN, and thermoplastic elastomers are pelletized with this method.

B. Compression and Transfer Molding

B1. *compression molding* - Fig. 4B1 illustrates the process. In the most common approach, a pre-heated preform or tablet, normally of thermosetting plastic, is placed in an open, heated, mold half that is held in a molding press, which usually operates vertically. The press ram descends with the force half of the mold, compressing the preform, so that the material flows to fill the entire mold cavity.

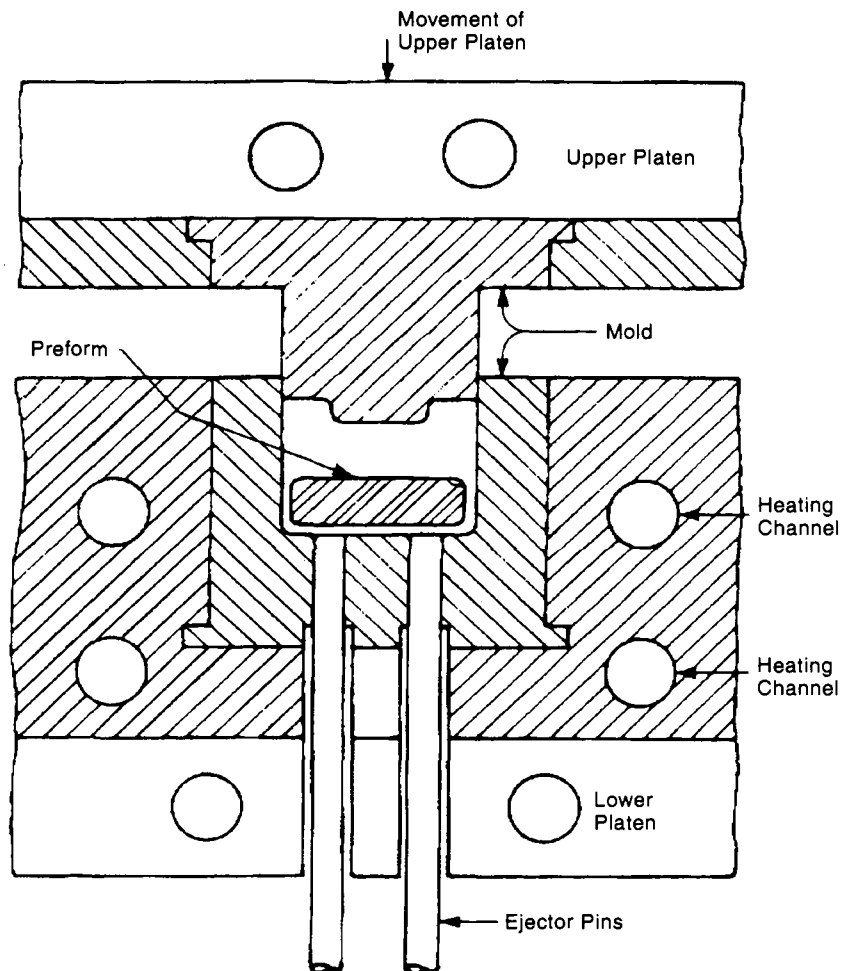


Fig. 4B1 Schematic illustration of compression molding. A preform of thermosetting plastic material is placed in a mold cavity. Heat softens the preform and the ram pressure forces the material into all portions of the mold cavity where it takes the shape of the cavity. The material then sets into a solid part that is ejected from the mold. (from Bralla, *Design for Manufacturability Handbook*⁶.)

The heat of the mold, and that added by the friction of the molding process causes the thermosetting material to polymerize, changing from a somewhat pasty state to a strong, solid state. The mold can be opened and the part removed. There are no sprues or runners in compression molding but the process often produces flash on the molded part at the parting line of the mold halves. This flash is removed manually with a knife, by tumbling (See 3K3.) or, in some cases, with a press containing a trimming die that fits the contour of the part. The use of a preform of developed size minimizes the amount of flash. Preforms are made by compressing granules

of plastic material in a die of suitable size. Instead of preforms, the molding compound may be in the form of powder, paste, or paper or various fibers impregnated with plastic material. Ejector pins are provided in the mold to ease removal of parts. Typical compression molded parts are automobile distributor caps, kitchen utensil handles, and various rubber items.

The use of fillers and reinforcing materials is common with compression-molded thermosetting plastic parts. Section G below describes methods particularly applicable to reinforced plastics molding.

B1a. automatic compression molding - is simply the automation of the otherwise manual compression molding process. Automatic compression molding equipment usually provides: storage of the molding material, metering of the charge of material to be deposited in the mold, transfer of this quantity of material to the mold cavities, operation of the compression molding press, ejection or removal of the molded workpiece from the die cavity, and removal of any extraneous molding material that may remain in the mold cavities after the operation is completed. Although injection molding of thermoset materials is now quite common, automation of the traditional compression-molding operation is often a viable alternative as a labor-saving approach.

B2. transfer molding - This process is a cross between injection and compression molding. It normally applies only to thermosetting materials. The material is first heated in a transfer chamber, which usually forms part of the mold. When the mold closes, the material is forced by a plunger, which is also part of the mold, through sprues and a gate into the heated mold cavity. More than one mold cavity can be fed from a central chamber or "pot". The material polymerizes in the mold cavity, and a solid part is removed or ejected. Usually a preheated preform or measured amount of material is placed in the transfer chamber at the start of each molding cycle. Transfer molding permits the production of more intricate parts with thinner sections than are possible with the compression-molding process. Fig. 4B2 illustrates pot-or sprue-type transfer molding. This process is economical for molding thermosetting plastic parts when the quantities involved are somewhat higher than are economical for regular compression molding.

B2a. plunger molding - is a variety of transfer molding. Instead of using a fixed element of the mold to force the material from the pot into the mold cavity, force is supplied by an auxiliary ram, after the mold is closed. This arrangement allows the speed and pressure of the transfer to be independent of the mold-clamping operation, thereby providing better control. Fig 4B2a illustrates a typical plunger mold.

B2b. screw transfer molding - is a further refinement of the transfer molding process. The

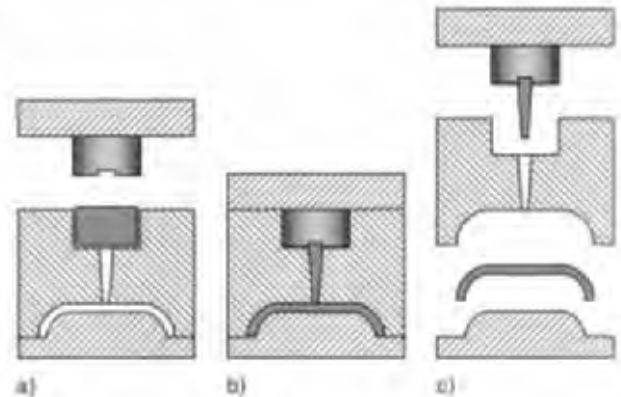


Fig. 4B2 Simplified sectional view of transfer molding. a) A heated preform of thermosetting material is placed in the transfer pot. b) The mold closes, forcing the material into the sprue channel, through the gate, and into the mold cavity. c) After the material is cured, the mold opens, pulling the sprue away from the part, and the part is ejected from the cavity.

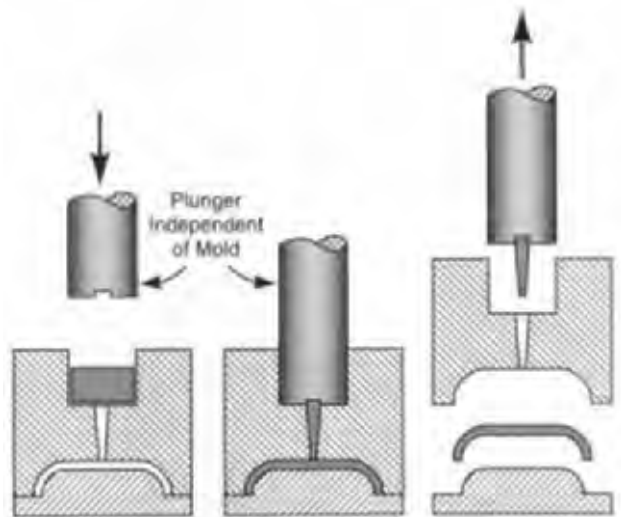


Fig. 4B2a Simplified section view of plunger molding. The process is a variation of transfer molding. It differs in that the plunger is not part of the mold but can be advanced and retracted independently.

material is heated and mixed with a plasticizing screw in the molding machine and is dropped in the pot of the mold. A plunger then forces the material into the mold cavity. Fig. 4B2b illustrates the process, which is useful when the molding material is difficult to preform.

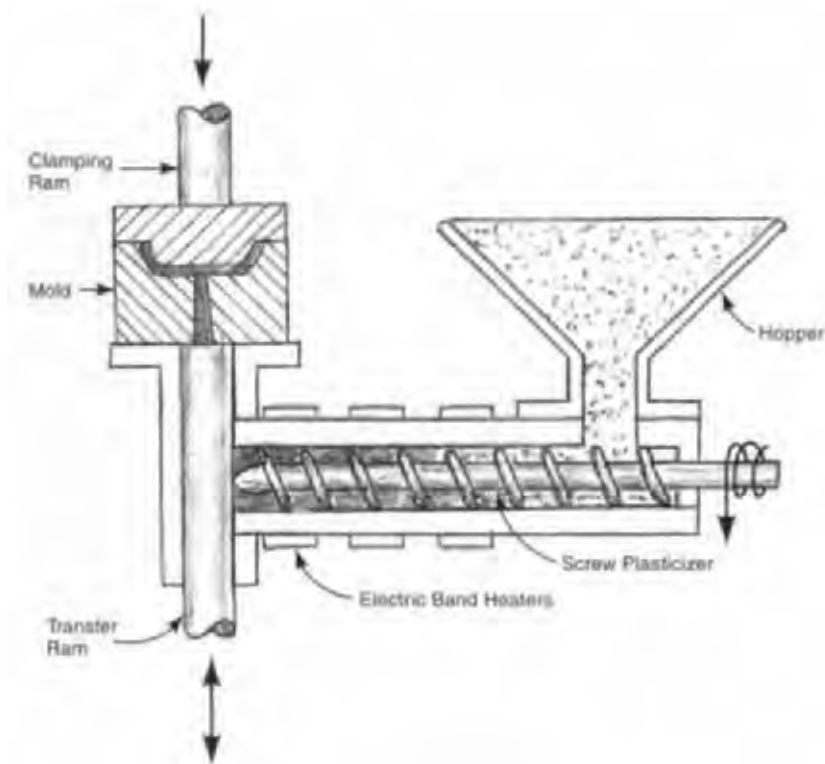


Fig. 4B2b Screw transfer molding.

B3. *cold molding* - is regular compression molding with no use of heat during the compression phase. The thermosetting material, including binders, is pressed to shape in the mold, then removed, and cured in a separate oven. The pressing operation is thus quicker than with hot molding, and the full molding sequence is more economical. However, the dimensional accuracy and surface finish of the molded part are usually inferior to that achieved with conventional compression molding. A number of parts can be cured simultaneously in the oven. The process can be useful for limited quantity production. The term *cold molding* is also used to identify the molding of reinforced thermosetting plastics that have been formulated to polymerize and cross-link at room temperature.

C. Injection Molding

C1. *conventional injection molding* - Injection molded parts begin with a plastic material in granular

form, most commonly a thermoplastic. The granulated material passes from a hopper to a heated cylinder, where it changes from the heat into a pasty mass. (Most plastics, when heated, do not melt into a full liquid, but change into a mass with a consistency similar to that of peanut butter.) The pasty mass is moved forward with a screw feed, by plunger, or both, and, under pressure, is injected into a mold. (Rotation of the screw mixes the material and provides frictional heating; axial movement of the screw forces the material into the mold.) The mold is normally a steel cavity, made from at least two pieces, tightly clamped together. The cavity has the same shape as that of the final part. Multiple cavities per mold are very common. With thermoplastics, the mold is cooler than the cylinder from which the plastic was injected, cool enough so that the plastic, after it enters and fills the mold, cools and solidifies. A typical temperature of the material in the machine cylinder is 400°F. (200°C) and, in the mold, 180°F (80°C). The machine cylinder is heated electrically and the

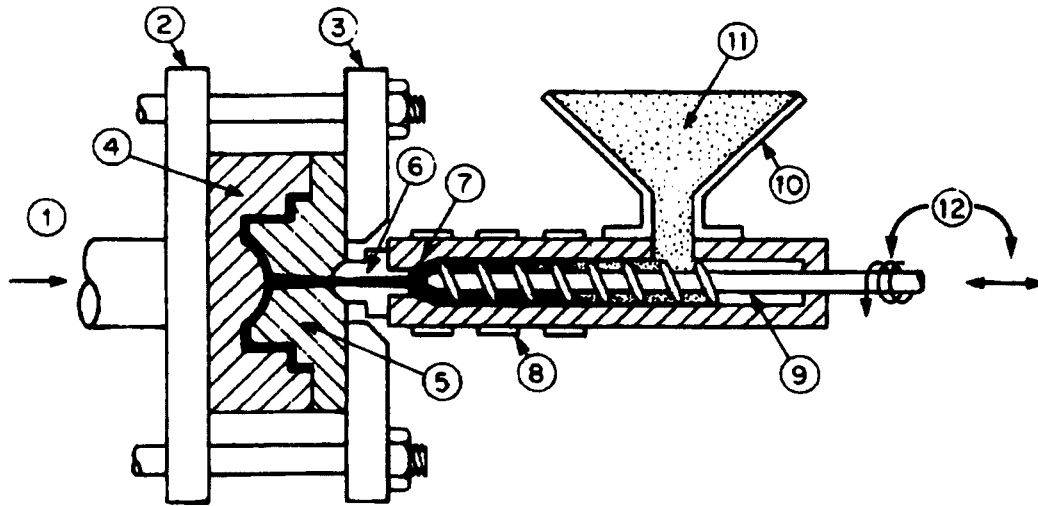


Fig. 4C1 Schematic illustration of injection molding. (1) Mold clamping force. (2) Movable mold platen. (3) Fixed platen. (4) Cavity half of mold. (5) Force half of mold. (6) Nozzle. (7) Cylinder. (8) Electric band heaters. (9) Reciprocating screw. (10) Hopper. (11) Granulated-plastic material. (12) Rotary and reciprocating motion of screw. (from Bralla, *Design of Manufacturability Handbook*⁶.)

mold temperature is regulated with circulating water. The process is normally fully automatic. Cycle times range most commonly from about 15 to 45 seconds, the time being dependent on the wall thickness and size of the part and many other process factors. Figure 4C1 illustrates the injection molding process.

Injection molding is by far the most common process used in the manufacture of parts from plastics. It is almost an ideal mass production method. Parts can be complex and can have color and surface texture molded in (with no need for costly secondary operations). They can have such features as hinges, springs, screw threads, and bearings incorporated fairly easily. Many companies that have made significant DFM (Design for Manufacturability) improvements in their products have done so by combining a number of separate parts and fasteners in a fewer number of injection-molded plastic parts that snap together without external fasteners.

Some typical injection molded parts are the following: housings for various products such as computers, home entertainment products, telephones, caps for containers, pails, handles, laundry baskets, toys, and parts for automobiles and refrigerators.

C1a. hot runner molding (heated runner-less molding) - Injection molds have channels that convey the molten plastic from the molding machine nozzle to the gate of each mold cavity. Normally, the material in these channels cools and solidifies along with the part, forming runners, which are ejected from the mold with the part. The runners are cut from the part, usually by the molding machine operator during the next machine cycle. Although the runner material, usually can be reground and used, it is advisable to avoid the need for these steps by the use of hot runner molds. These molds incorporate electrical units to heat the runners so that the material in them remains in the molten state between shots and is not ejected from the mold with the part. Trimming of the runners from the part is eliminated, as is the need for scraping or regrinding and reprocessing the runner material. Less material needs to be heated for each shot; material is not subjected to repeated heating, which may degrade it, and it is kept at a more uniform temperature as it enters the mold. Another advantage is that the molding cycle is often speeded up because thin-walled parts do not have to wait for the thicker sprues and runners to solidify, and less material needs to be heated for each cycle. Some plastics have a narrow range of processing

temperatures and are better used in a hot runner system that does not force them to be heated to counteract a cooling environment before they reach the mold cavity.

C2. injection molding of thermosetting plastics - This process is very similar to the injection molding of thermoplastic materials. A major difference, however, is that the mold is heated rather than cooled. Another difference is that the injection nozzle may be alternately heated and cooled - heated during injection to facilitate polymerization, but cooled between shots to retard the polymerization of material not yet injected. The thermosetting material is preheated in the cylinder of the machine, but the temperature is not high enough to cause polymerization to take place during the limited time the material is in the machine barrel. Heating reduces the viscosity of the material, however, which facilitates injection and mold filling. Polymerization does take place after the material is subjected to the heated nozzle, the frictional heat of injection, and the heat of the mold. After polymerization, a solid piece can be removed from the mold. Injection pressure is up to about 28,000 lbf/in² (190 MPa). The cycle is normally longer than that required for thermoplastic materials but shorter than that required for compression or transfer molding. The process is sometimes called, automatic transfer molding.

C3. structural foam molding processes - provide parts with a wall structure that includes a solid skin and a core that is cellular. The cellular core comes from the expansion, during molding, of a blowing agent, either an injected gas, usually nitrogen, or a chemical that decomposes into a gas at the molding temperature. A nucleating agent, a fine dry powder, is also added to the resin to control the size of the cells. Structural foam components have a high degree of stiffness in comparison to their weight. Large parts like containers, pallets, and housings, are molded by this method because it provides a means to maintain stiffness without using excessive material or slowing the molding process unduly. The process can also be used with flexible materials to produce components with cushioning or sealing properties.

C3a. low-pressure injection molding of structural foam plastics - In this process, the amount of material injected into the mold is carefully controlled and is less than that required to fill the mold. A blowing agent in the plastic material causes it to expand and fill the mold cavity. The portion of the material that contacts the cool surface of the mold cavity forms a dense skin, while the interior portion becomes cellular. Since the mold is not packed with plastic material, pressures are much lower than with conventional injection molding. Mold costs are low because the molds do not have to withstand high pressures. Large parts - up to about 120 lb (55 Kg) - can be molded with the process. Typical applications are containers, pallets, lawn furniture, outdoor equipment components, and shutters.

C3b. reaction injection molding - This process involves the injection, into a mold, of highly-reactive liquid components, usually of thermosetting material. The components (Polyurethane plastic is most common.), are fed to a mixing chamber just prior to injection. Heating is not required. The materials react, polymerize, and foam in the mold, forming a part with a somewhat smooth and dense skin and a cellular core. Pressures are high in the mixing chamber but low (50 lbf/in² or 340 KPa) in the mold to allow foaming to take place. This permits the use of lighter, lower-cost molds. After molding, parts are post-cured at about 250°F (120°C) for up to 1 hour. The process is suitable for large parts, including appliance components, doors, furniture frames, and vehicle body parts, as well as smaller parts such as gears, wheels, rollers, and sporting goods. Both rigid and flexible material formulations can be used. Fabric and strand reinforcement may be mixed in to provide added strength and stiffness. Epoxy, nylon, and polyester are also molded with this method. See Fig. 4C3b for an illustration of the process. With flexible formulations of urethane, reaction injection molding is used to produce furniture cushions and mattresses.

C3c. high-pressure injection molding of structural foam plastics - In this process, normal injection-molding action and pressure, fill a mold completely with a mixture of a polymer and a chemical blowing agent. The size of the mold cavity

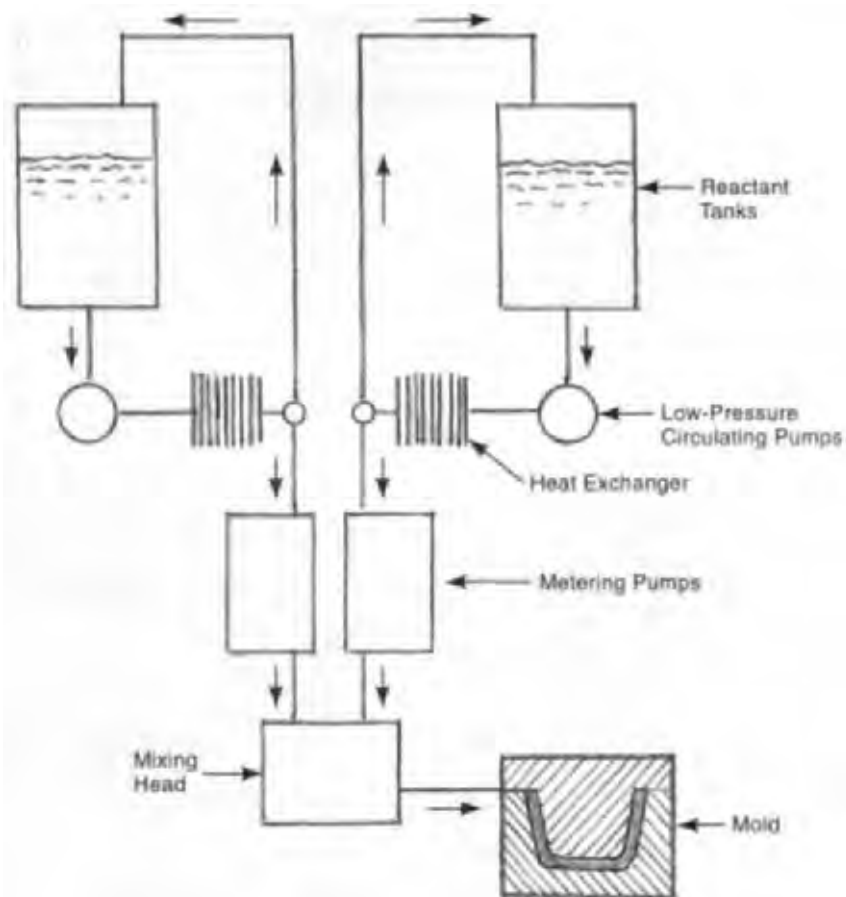


Fig. 4C3b Reaction injection molding.

is then increased by opening the mold platens or by retracting a core element. The material in the mold then foams and fills the expanded space. The high-pressure process uses more expensive and complex tooling but provides a smoother part surface than that obtained with low-pressure injection molding or by reaction injection-molding of structural foam. This process is used for items such as business machine housings where the swirled appearance of the surface of low pressure molded parts may not be acceptable.

C3d. gas counterpressure molding - The principle of this process is to delay the foaming until after a solid skin has formed on the plastic entering the mold, insuring that the molded part has a smooth surface. This is accomplished by pressurizing the mold with nitrogen just prior to injection.

The pressure is slightly above the expansion pressure of the blowing agent in the injected plastic. At the proper instant, before the mold is completely filled, the pressure is released and the foaming action commences. However, foam does not break through the surface of the injected material. Therefore, no swirling pattern appears on the part's surface.

C3e. co-injection or sandwich molding - Two materials are injected in sequence and partly simultaneously into the mold through a special valve. One material forms the skin of the part and the other forms the core. The core material contains a blowing agent to provide foaming action. Two different plastics can be used. The core material can consist of a lower cost material or even recycled plastics. Surface details can be produced accurately

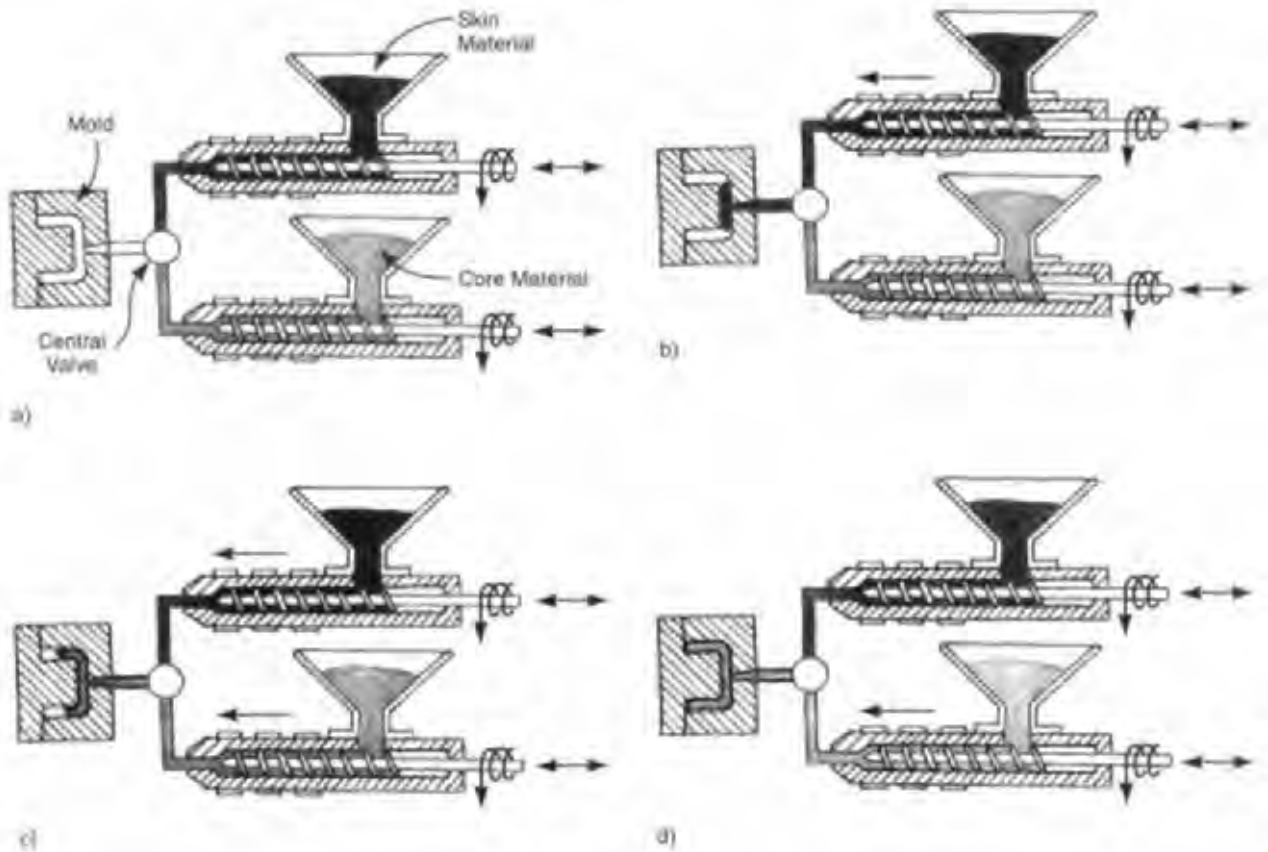


Fig. 4C3e Co-injection or sandwich molding: a) The machine arrangement. b) The skin material (shown in black) is injected first and a thin layer solidifies as it meets the cool walls of the mold. c) Both materials are then injected until all mold walls are contacted by the skin material. d) Filling of the mold is completed with further injection of the core material (shown in gray).

and there is no swirl pattern on the surface. See Fig. 4C3e for an illustration of the process.

C3f. gas-assisted injection molding - Parts made with this process do not have a foam core but instead have a hollow interior due to the injection of nitrogen into the plastic charge as it enters the mold. The gas does not break through the surface of the plastic but does form channels in the hotter, less-viscous material in the interior of the charge. The result, when the mold is filled, is a part with a smooth surface that matches the shape and finish of the mold, but is not solid. Less material is used and the part has similar stiffness advantages, per unit of weight, as a structural foam part. Fig. 4C3f provides a schematic illustration of the process.

C3g. casting of structural foam plastics - is described under *casting of plastics*. See H2.

C3h. extrusion of structural foam plastics - Extruded profiles can be made with a solid skin

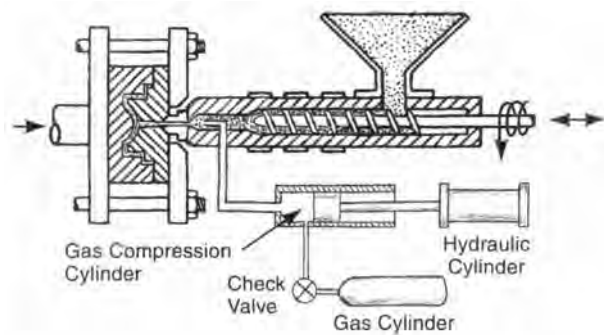


Fig. 4C3f Gas-assisted injection molding creates a part with properties similar to those of a part molded with structural foam.