



MANUFACTURING PROCESSES AND DEFECTS

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Abstract

A manufacturing process involves turning raw materials into finished products. Nowadays, everyday items undergo careful design and engineering to best fit their purpose. To exploit metals several processes can be chosen by engineers. There are many reasons why researching manufacturing processes is important; each process is unique and can deliver different mechanical and physical properties (dependent on the material). This paper focuses on three key manufacturing processes: drawing, die casting, and welding. The method for this research included: exploring literature, journals, and websites to study what is currently known; using diagrams to illustrate key elements of the manufacturing processes; and investigating applications that serve as examples of the chosen manufacturing processes. These findings support research that justifies why certain processes are chosen. Key factors such as cost, mechanical properties, defects, and product geometry play a large role in choosing a manufacturing process.

Table of Contents

Abstract	1
Table of Contents	2
List of Figures	3
Drawing	4
Process summary	4
Typical application.....	5
Advantages and disadvantages	6
Grain microstructure of low carbon steel after drawing	6
Typical defects	7
Die casting	8
Process summary	8
Typical application.....	10
Advantages and disadvantages	10
Grain microstructure of aluminium alloy die-casted component.....	11
Typical defects	12
Welding	13
Process summary	13
Typical application.....	15
Advantages and disadvantages	15
Grain microstructure of a 304 stainless steel welded joint	16
Typical defects	17
Conclusion	19
References	20

List of Figures

Figure 1: Basic overview of the drawing process	5
Figure 2: Multistrand electrical cable (Science Learning Hub, 2010: Online)	5
Figure 3: Grain structure change during drawing (Portland State University, (no date): Online)	6
Figure 4: Necking in a round bar (Gisforgirard, 2023: Online).....	7
Figure 5: Hot-chamber die-casting diagram	9
Figure 6: Cold-chamber die-casting diagram	9
Figure 7: A die-casted gearbox housing (Precise Cast Co Ltd, (no date): Online) ..	10
Figure 8: Vertical cross-section of an aluminium alloy die casting, showing the micro grain structure (Shercliff, 2012: Online).....	11
Figure 9: Shrink porosity (Weiheng, 2020: Online).....	12
Figure 10: Crack in a die-casted component (Dolin Casting, 2020: Online)	12
Figure 11: Gas metal arc welding diagram	14
Figure 12: Example of a welded joint on an exhaust system.....	15
Figure 13: Cross-section of a butt weld joint (Bhattacharya, (no date): Online)	16
Figure 14: Lack of weld penetration on a welded joint.....	17
Figure 15: Example of a weld burn-through	18

Drawing

Process summary

Although the process of drawing is similar to extrusion, it involves the material being pulled through a die, rather than pushed through. The die, which usually has a tapered inlet, reduces the cross-section of material to obtain the desired profile – as seen in Figure 1. This process introduces high levels of tensile stress as forces are applied to the material in opposing directions, i.e., the force of the material being pulled through on one end and the resistant force of the die. However, compressive stresses are also present due to the squeezing of the material as it is pulled through the die. The majority of drawing operations are performed without heating the material; however, annealing is sometimes required between dies to relieve work hardening.

There are two main categories of drawing, these involve the use of either bar or rod stock material (large diameters) or wire stock material (smaller diameters, as low as 0.03mm). When drawing bar or rod stock, the material is usually formed in a single-draft operation, i.e., the material is pulled through a single die. The drawing of wire stock requires the material to be pulled through multiple dies (usually between 4 and 12); this is known as a continuous drawing operation.

When planning a process that involves drawing, one of the key requirements is calculating the maximum reduction in cross-section that can be achieved in a single pass through a die. The drawing stress must not exceed the yield strength of the material being drawn, otherwise, the material will start to elongate. In single-draft tube/bar drawing, a cross-sectional reduction of ~50% is usually achieved, while in wire drawing, this value is ~30% (P.Groover, 2013).

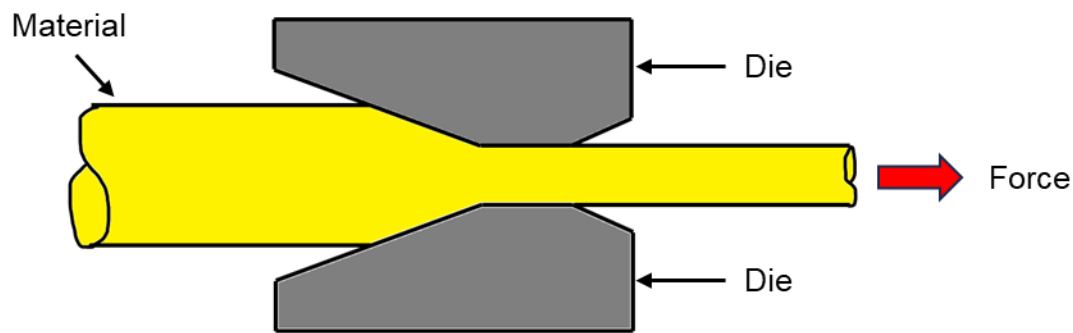


Figure 1: Basic overview of the drawing process.

Typical application

The wire inside electrical cables is formed using the wire drawing process – an example can be seen in Figure 2 (Science Learning Hub, 2010: Online). Copper is the primary material used for electrical cable as it has good ductility and great electrical conductivity.

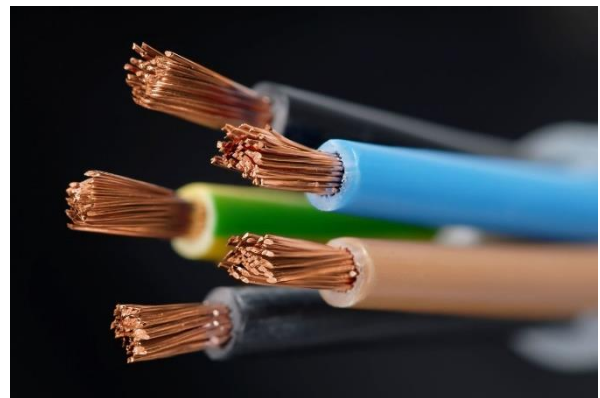


Figure 2: Multistrand electrical cable (Science Learning Hub, 2010: Online).

Advantages and disadvantages

Advantages	Disadvantages
Tight tolerances can be maintained	Materials that can be used are finite – high tensile yield limit and high ductility are required
Mechanical properties, such as strength and hardness, are enhanced	Manufacturing issues can lead to high quantities of scrap due to the fast processing rate of wire drawing
A good level of surface finish	Limited reduction in size from stock material to the finished product
Fast wire drawing processing speeds – as high as 50 m/s	

(P.Groover, 2013)

Grain microstructure of low carbon steel after drawing

Drawing introduces tensile and compressive stresses, which lead to the grains of the material being refined longitudinally – as seen in Figure 3 (Portland State University, (no date): Online). The amount of grain boundaries – per unit volume - is increased, which makes the material more resistant to plastic deformation. All of this equates to an increase in the strength and hardness of the material, albeit at the expense of a decrease in ductility.

Low carbon steel is a commonly used material in bar drawing; the ultimate tensile strength of this material can increase from ~650 MPa to ~900 MPa (Wu, 2020: [online video]).

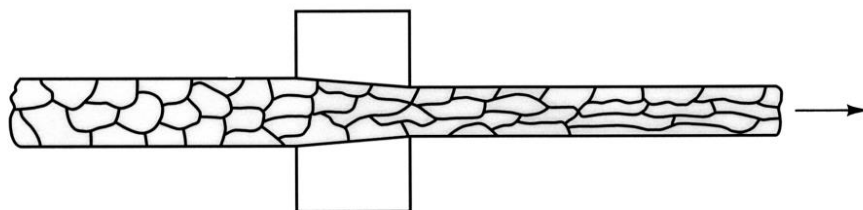


Figure 3: Grain structure change during drawing (Portland State University, (no date): Online).

Typical defects

- 1) **Longitudinal scratches:** These can be caused by a scored die surface, lack of lubrication, or an ingress of foreign contaminants. To prevent this defect from occurring periodic cleaning and inspection (TPM) of the equipment should be introduced.
- 2) **Internal cracking:** This can be caused by excessive friction between the die and the material, an excessive reduction in the cross-section of the die, and a die entry angle that is too steep. Solutions to prevent internal cracking include ensuring sufficient lubrication is being fed into the die and altering the die design (shallower entry angle) (Hodge, 2016).
- 3) **Necking:** This is when the material surpasses its ultimate tensile strength, and the cross-sectional area of a region decreases – as shown in Figure 4 (Gisforgirard, 2023: Online). This defect can be caused by an incorrect die design (material unable to flow smoothly), and an excessive drawing rate. To help mitigate this defect, either the die design needs to be altered and/or the drawing rate needs to be reduced.

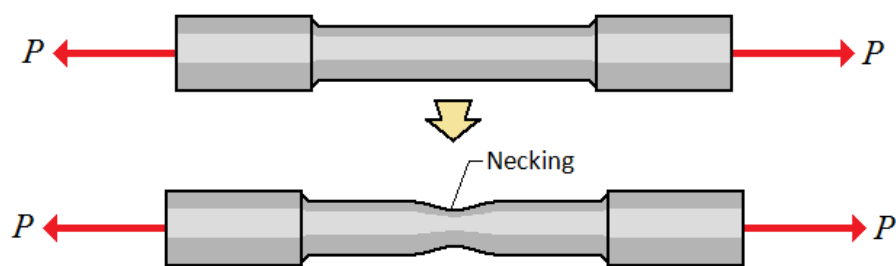


Figure 4: Necking in a round bar (Gisforgirard, 2023: Online).

Die casting

Process summary

Die casting is a permanent-mould casting process, meaning that the mould (die) is re-used multiple times, unlike sand and investment casting. The basic concept of this process involves injecting molten metal into the mould cavity at a very high pressure (7 – 350Mpa); the high-pressure element is what separates this process from other permanent-mould casting processes. The appropriate pressure is sustained until the material has solidified. Once the material has solidified, one half of the die is separated from the die which is fixed, and then ejector pins are actuated, forcing the cast product out of the die. The die halves are coated with lubricant and the process is repeated. Production output rates of up to 500 parts per hour are common in die casting.

Die casting is split into two main categories, hot-chamber and cold-chamber. In hot-chamber die casting, the raw material is melted in a pot that is directly connected to the mould cavity via a nozzle. Once the material is molten, a plunger is used to force the material through the gooseneck and into the mould – a summary of this process can be seen in Figure 5. This process is only suitable for low-melting point alloy metals (lead, zinc, tin) due to the nozzle and gooseneck not being able to cope with the higher-temperature molten metals. The main characteristic that differentiates cold-chamber from hot-chamber die casting is the fact the material is melted offline in a separate furnace; a ladle is then used to transfer the molten material into the shot chamber. Following this, a ram is used to force the molten metal into the mould cavity - a summary of this process can be seen in Figure 6. This process is primarily used for high-melting point alloys, such as aluminium, brass and magnesium alloys (however, it will still work with low-melting point alloys) (P.Groover, 2013).

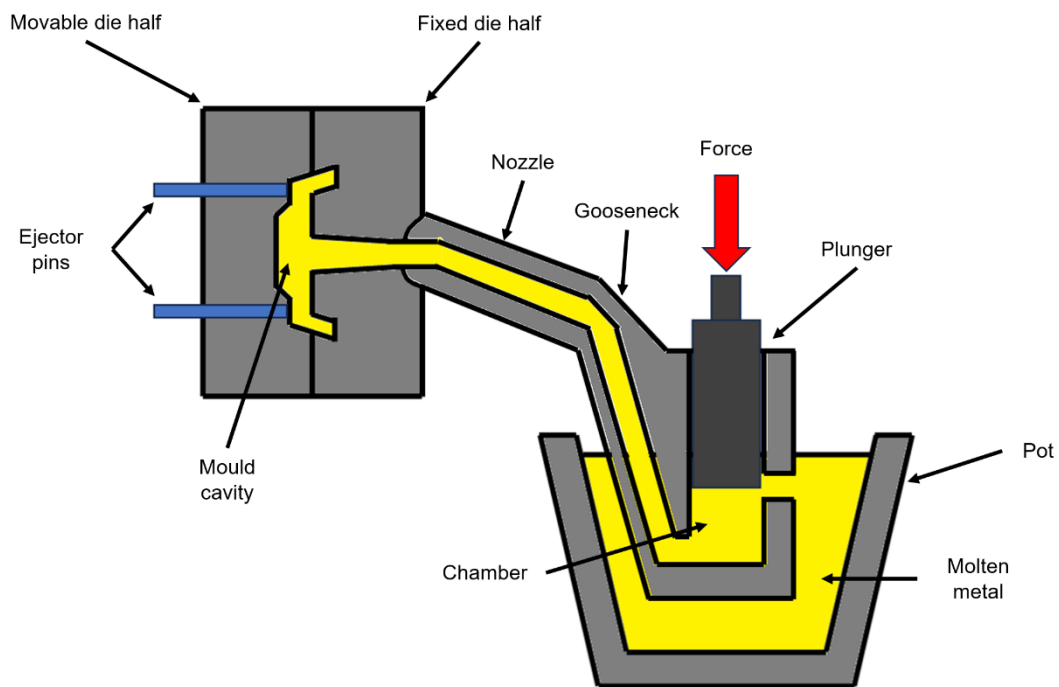


Figure 5: Hot-chamber die-casting diagram.

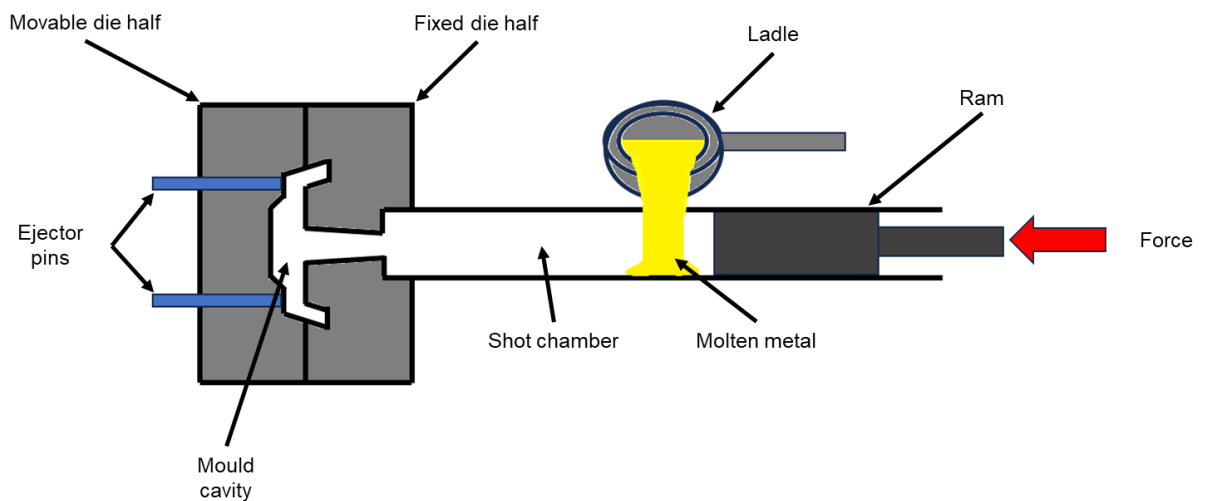


Figure 6: Cold-chamber die-casting diagram.

Typical application

Die casted components are heavily used throughout the automotive industry, gearbox housings being one of the most common products – as seen in Figure 7 (Precise Cast Co Ltd, (no date): Online). This process is used because it offers good dimensional accuracy, high strength properties and can produce intricate design geometries.

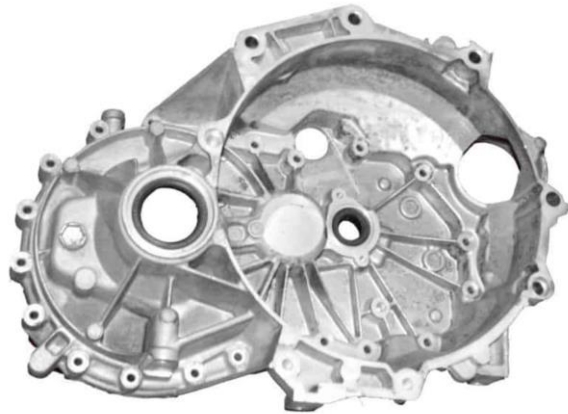


Figure 7: A die-casted gearbox housing (Precise Cast Co Ltd, (no date): Online).

Advantages and disadvantages

Advantages	Disadvantages
High production output rates	Geometry of products is limited due to the die design limitations
Practical for large production volumes	Not economical for low production volumes due to high tooling cost
Tight tolerances can be achieved	
Can produce products with wall thicknesses as low as 0.5mm	
Due to the small grain sizes, good strength properties are achieved	

(P.Groover, 2013)

Grain microstructure of an aluminium alloy die-casted component

The outer region of an aluminium alloy die-casted component consists of small, randomly arranged grains due to rapid heat transfer into the mould walls – this is known as the chill zone. Next, nuclei that are perpendicular to the surface propagate from the chill zone to form a columnar zone. The central portion of the casting is called the equiaxed zone, which forms due to the segregation of the various alloying elements. Figure 8 shows a typical grain structure of an aluminium alloy die casting (Shercliff, 2012: Online).

The ultimate tensile strength of aluminium alloy die castings ranges between 295 MPa and 325 MPa (Dynacast, (no date): Online).

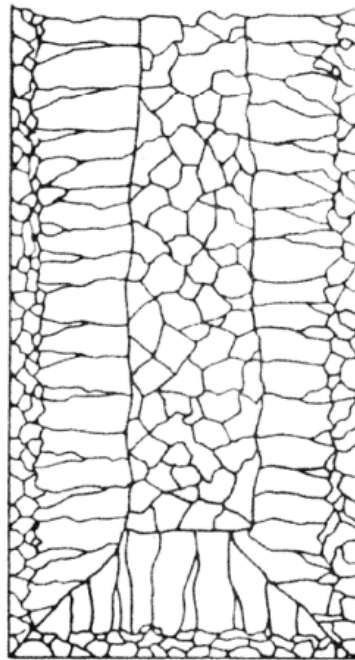


Figure 8: Vertical cross-section of an aluminium alloy die casting, showing the micro grain structure (Shercliff, 2012: Online).

Typical defects

1) **Gas porosity:** This is when voids or holes appear in the die casting. It occurs when air pockets are contained within the mould cavity. Gas porosity can be reduced by ensuring there is sufficient mould ventilation, and by improving the design of the die and runners (Dynacast, no date).

2) **Shrink porosity:** This takes place during the solidification of the molten metal, at which point voids/hollow sections form – as shown in Figure 9 (Weiheng, 2020: Online). The main cause of this defect is component design (substantial wall thickness variation and sharp transitions between features). Shrink porosity can be kept to a minimum by enhancing the design of the component geometry and ensuring sufficient temperature management is employed (Dynacast, no date).

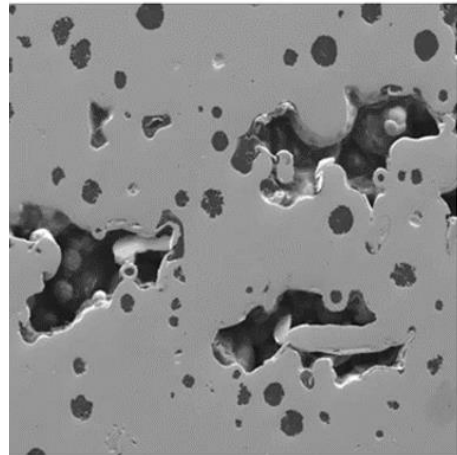


Figure 9: Shrink porosity (Weiheng, 2020: Online)

3) **Cracks:** These are fractures that appear on the surface of the die casting because of the casting being cooled too quickly and/or different regions cooling at different rates – an example can be seen in Figure 10 (Dolin Casting, 2020: Online). The risk of cracks can be mitigated by optimising the design of the die to allow the casting to cool evenly (Dynacast, no date).



Figure 10: Crack in a die-casted component (Dolin Casting, 2020: Online)

Welding

Process summary

Welding is the process of permanently joining two or more parts together. The base metal and parent metal are fused at the points at which their faces meet each other, by the application of heat and/or pressure. The use of a filler material is sometimes used, depending on the welding process and application. An assembly which has been fused by welding is termed a weldment. While welding is predominantly affiliated with the joining of metals, plastics are also sometimes joined together using this process – this summary concentrates on the welding of metals. When welding metal, two materials of the metal specification/group are usually welded together, however dissimilar metals can be joined.

The process of welding is split into two main categories: fusion welding and solid-state welding. Fusion welding involves the melting of the two base metals by the application of heat. On the other hand, solid-state welding involves the use of either pressure, or heat and pressure combined.

An example of a frequently used fusion welding technique is gas metal arc welding (MIG welding). During MIG welding an electric current flows through an electrode, which in this case is also the filler material (bare wire). Once the weld torch trigger is enabled, the energized wire is fed continuously until it reaches the workpiece and initiates an electric arc – a sufficient gap must be maintained between the tip of the wire (electrode) and the workpiece to ensure a plasma arc is sustained (~5500°C). A shielding gas is injected through a nozzle and into the weld zone; this prevents elements in the atmosphere, such as oxygen, nitrogen and hydrogen, from reacting with the molten metal. Since no slag is deposited onto the weld bead – unlike other fusion welding processes – no further grinding or cleaning is required, making this one of the more productive welding techniques. The diagram in Figure 11 summarises the basic elements of gas metal arc welding (P.Groover, 2013).

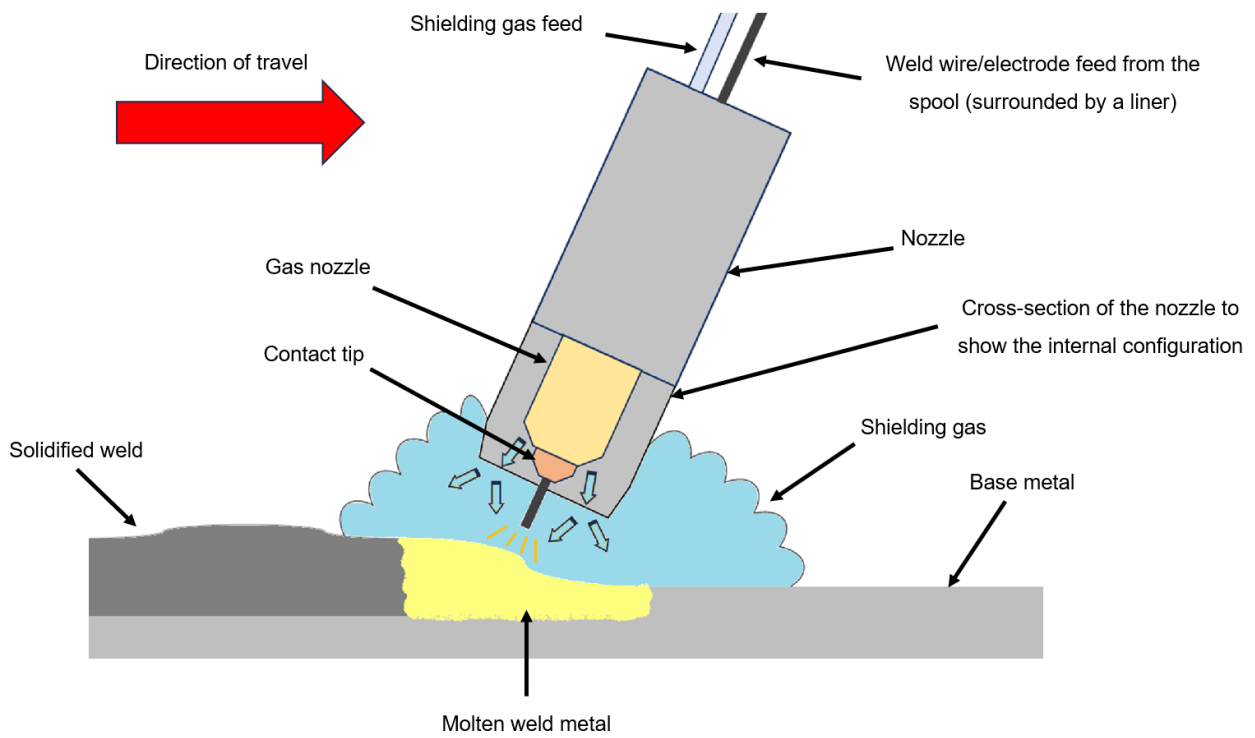


Figure 11: Gas metal arc welding diagram.

Typical application

An exhaust system is heavily reliant on the process of welding. The process of MIG welding is commonly used for joining exhaust components together – an example of a welded joint on an exhaust system can be seen in Figure 12. The key benefits of welding in this application are that it allows good design flexibility and ensures a near-leak-free joint, which is important for adhering to strict emissions standards.

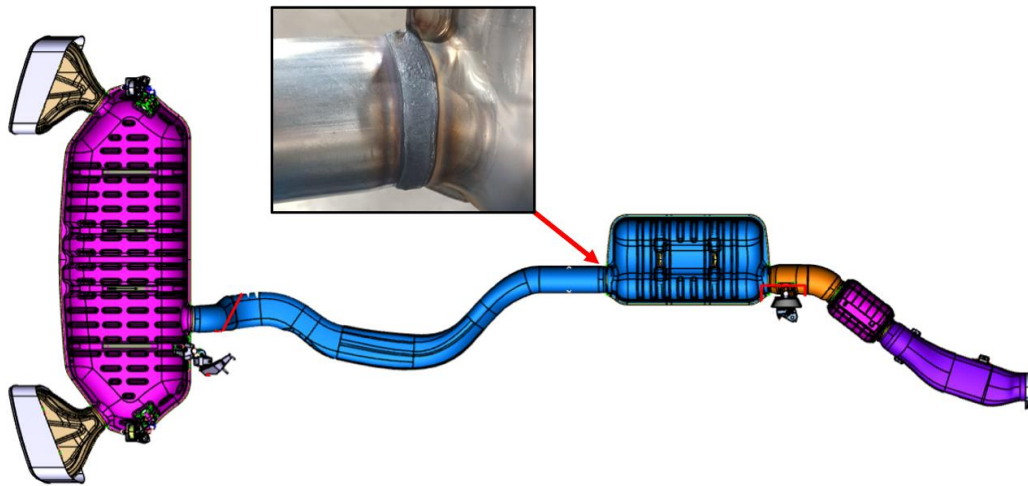


Figure 12: Example of a welded joint on an exhaust system.

Advantages and disadvantages

Advantages	Disadvantages
Flexible, in terms of where this process can be conducted	Many welding applications are manual and require the use of highly skilled, and expensive, tradesmen
Economical when compared to mechanical fastening techniques	Some welding defects are not easily detected, i.e., lack of penetration
Welded joints can be stronger than the base material	The form of the base/parent metals can distort

(P.Groover, 2013)

Grain microstructure of a 304 stainless steel welded joint

There are four main microstructure zones in a welded joint: fusion zone, weld interface, heat-affected zone and unaffected base metal zone – as seen in Figure 13 (Bhattacharya, (no date): Online). In the fusion zone, the grains align into a columnar arrangement, perpendicular to the weld interface zone. The weld interface zone comprises a narrow base metal layer that has melted and resolidified without mixing with the fusion zone. Next is the heat-affected zone (HAZ) which is the base metal region that has been subjected to temperatures (below its melting point) that alter the microstructure; this usually has a detrimental effect on the mechanical properties of the material due to the increased grain structure size. Finally, the unaffected base metal zone is a region that's too far from the hot fusion zone to not alter the material's microstructure (P.Groover, 2013).

The ultimate tensile strength of this commonly used material (304 stainless steel) is 515 MPa (Metals4U, no date: Online).

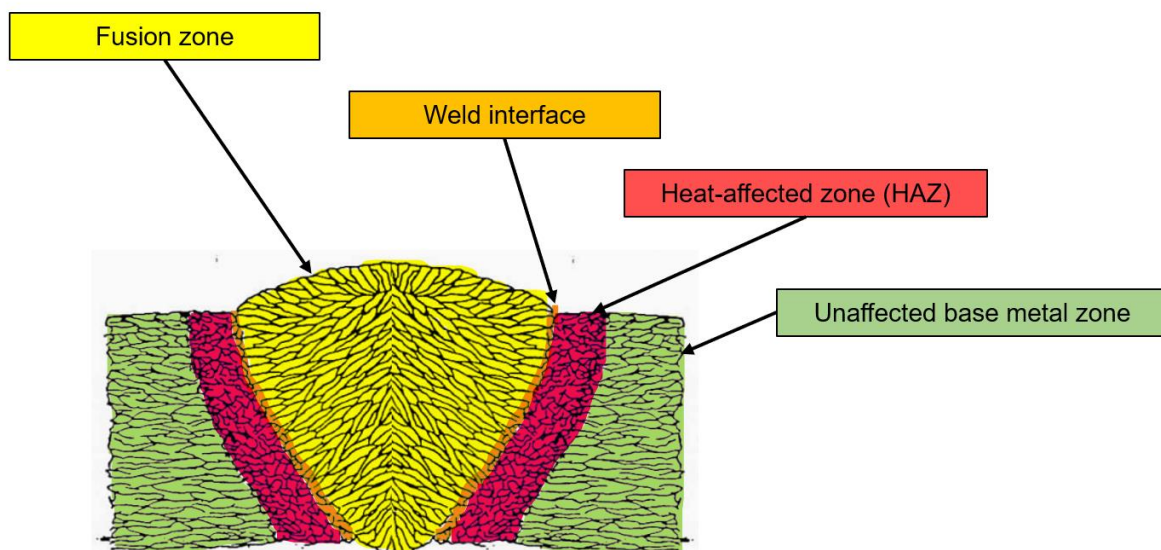


Figure 13: Cross-section of a butt weld joint (Bhattacharya, (no date): Online).

Typical defects

1) **Lack of penetration:** This is a joint that has an insufficient amount of fusion between the parent and base metals. Figure 14 shows a macro etch of a tailpipe weld whereby there is minimal weld penetration into the base metal. There are many potential causes of insufficient penetration, such as:

- Inadequate welding torch position and/or angle
- Incorrect welding torch travel speed
- Incorrect wire feed speed
- Insufficient electric current

To mitigate the risk of this failure occurring, the parameters mentioned above should be altered to suit the type of weld joint being processed.

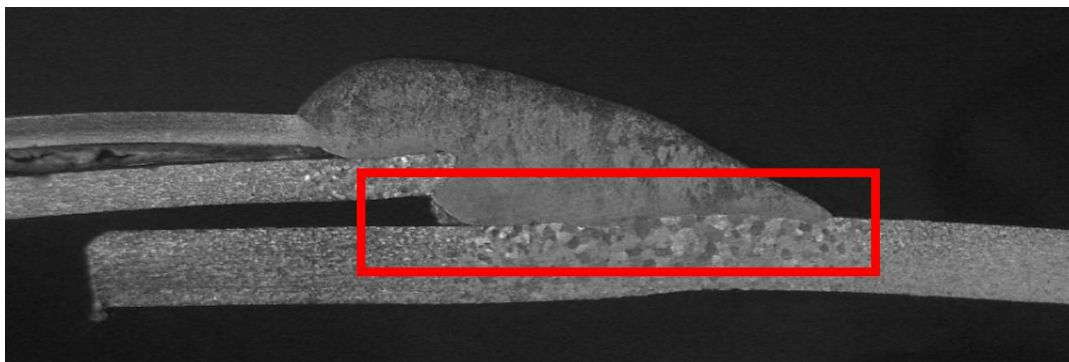


Figure 14: Lack of weld penetration on a welded joint

2) **Cracks:** These are fractures that form in either the base metal or the actual weld bead. This failure can emerge due to a rigid joint that is unable to allow the material to expand and contract; inadequate joint design is also one of the causes. Weld cracks can be prevented by implementing preheating of the metals and controlled cooling of the weld joint. The weld joint design should also be suitable for the application (P.Groover, 2013).

- 3) **Burn-throughs:** This involves the molten metal weld pool burning through the entire thickness of the base metal – as seen in Figure 15. Common causes of this defect include excessive welding current, insufficient base metal thickness and an excessive gap between the base and parent metals. To reduce the likelihood of burn-throughs occurring, appropriate weld parameters for the weld joint need to be applied and proper gap control must be maintained.



Figure 15: Example of a weld burn-through

Conclusion

The manufacturing processes researched in this paper each have their limitations. The mechanical properties of the end products have a strong correlation with the microstructure of the material. In some cases, multiple processes can accommodate the necessary product design requirements; in these cases, cost is usually one of the major factors in determining which process will be chosen. There are opportunities for multiple defects to occur during each process. Therefore, it is key to effectively design the product, and choose a process that accommodates the remedial measures, thereby helping to mitigate the chance of defects arising.

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