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Material Selection Report

Engineering Design & Materials (ACHA4001)

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1 Introduction

The topic of this technical report will be to investigate the material selection and manufacturing process for a piston within an Internal Combustion Engine (ICE). A piston is perhaps the most vital component of any vehicle containing an ICE as it is responsible for compressing a ratio of air/fuel into a gas that transfers energy into a crankshaft allowing the vehicle to propel. The aim of the report will be to decide on the most suitable material and process when manufacturing a piston, based on specific characteristics and properties and the specifications required for road application.

The piston in an automotive application consists of a hollow cylinder with several segments making up the whole component as follows:

- 1) Piston Crown
- 2) Ring Belt
 - a) Compression Rings
 - b) Oil ring
- 3) Skirt
- 4) Pin Boss

Figure 1 below shows us where each section is on a piston.

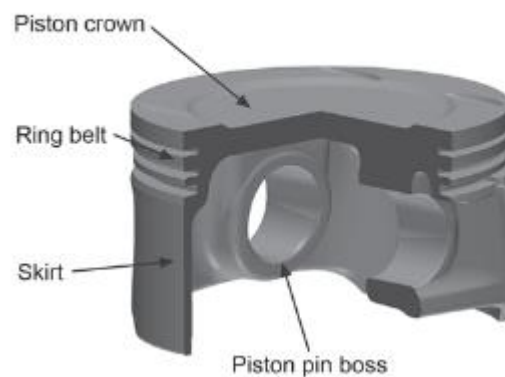


Figure 1 – Annotated piston (GmbH, 2016)

2 Material Properties

When selecting a specific material for a component, the properties of that material must be considered as they will dictate whether the component will be able to perform the task or result in failure. Components all require different properties depending on their requirement, when deciding on properties we can split them into 6 groups which will allow us to narrow down the choice of material.

The 6 groups are as follows:

1. Engineering Properties
2. Chemical Properties
3. Manufacturing Properties
4. Thermal Properties
5. Magnetic Properties
6. Electrical Properties

The working environment of a piston means that it will be subject to high pressure created by the gas inside the cylinder, high temperature due to combustion, friction caused by the sliding of the piston up and down the cylinder and inertia caused by the mass of the piston as the crankshaft rotates. (Singh et al., 2020)

When taking the above factors into account, we can decide that the most important properties of a piston can be considered as follows:

1) Engineering Properties

- a) Relative Density
- b) Tensile strength
- c) Hardness
- d) Frictional Wear

2) Chemical Properties

- a) Resistance to Oxidation
- b) Resistance to degradation

3) Manufacturing Properties

- a) Melting point
- b) Malleability
- c) Machinability

4) Thermal Properties

- a) Heat dissipation

When considering the above properties, not all metals will contain the properties required for the application, this is when alloys should be considered. An alloy is a mixture of a base metal having chemical compounds or other metals added to them to increase characteristics of the material. A modern automotive piston will consist of an aluminium alloy such as aluminium with a silicon additive. The most common material in automotive pistons consists of an Aluminium Alloy consisting of around 12% silicone due to its better formability during manufacturing, machineability and improved corrosion resistance. Due to the nature of the environment of the piston, the improved hardness and impact strength in this elevated temperature environment will reduce fatigue on the component. (Akhtar *et al.*, 2018)

Table 1 - Material Properties of Aluminium & Titanium alloy (<https://www.slideserve.com/amos-roberts/aluminum-titanium-comparison>)

Aluminum/Titanium Comparison

	Aluminum alloy	Aluminum alloy	Titanium Alloy	
Property	7075-T6 (ww-T-700)	7075-T6; 7075-T651	Grade 5 Ti6Al4V	% Different
Source	Casing.xls	Matweb	Matweb	
Yield Strength (Mpa)	455	503	1103	219.28%
Ultimate Strength (Mpa)	531	572	1172	204.90%
E (Gpa)	71.76	71.76	113.85	158.65%
n	0.33	0.33	0.33	
Density (g/cc)		2.81	4.43	157.65%
Melting Temp (°C)		477	1600	335.43%
Thermal Conductivity (W/m-K)		130	6.7	5.15%
Specific Heat (J/g-K)		0.96	0.5263	54.82%

Table 1 above gives us a comparison of material properties between specific aluminium alloys and titanium alloys. It shows us the ultimate yield strength in both alloys, which is the upper limit of force that can be applied without permanently deforming the component, an important factor in determining a piston material. It also shows us the thermal conductivity of both materials, which will tell us how effective they are at conducting heat both into and out of the material. If the piston were unable to transfer heat, thermal efficiency of the engine would decrease, and the lifespan of the component would be reduced. (RSalunkhe *et al.*, 2019)

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3 Material Selection

When manufacturing any component, careful consideration and thought must be put into the process of designating a material. Many factors must be evaluated to ensure that the material selected can perform the task required of it.

Due to the fact that there are several suitable choices in material when manufacturing an automotive piston, when the material properties have been narrowed down for the required application, the following must be considered:

- The lifespan of the material within its application
- Method of manufacturing
- Cost of the material and the manufacturing process chosen.

In the modern era of the automotive industry, car manufacturers are using various types of aluminium alloys for piston manufacturing due to the above-mentioned properties which is further improved by introducing other compounds. Although aluminium is a more expensive option than other metals that were used for pistons such as cast-iron, the gains through a lower mass, increased strength, lower friction and higher strength makes it a cost-effective choice for most applications (Bhutto *et al.*, 2016). Aluminium alloys are also easier to manufacture than compared to more specialist metals such as Titanium which requires additives to improve characteristics due to its poor wear resistance and difficulties in machining which would increase costs.

Table I. Cost of Titanium Compared to Competing Automobile Materials^{1,6,7}

Item	Material (\$ per Pound Contained)			
	Steel	Aluminum	Magnesium	Titanium
Ore	0.02	0.10	0.01	0.30
Metal	0.10	0.68	0.54	2.00
Ingot	0.15	0.70	0.60	4.5
Sheet	0.30–0.60	1.00–5.00	4.00–9.00*	8.00–50.00

* Magnesium sheet is not commonly used. Castings are \$2.50–\$10.00 per pound.

Table II. Standard Components Manufactured from Titanium

Year	Component	Material*	Manufacturer	Model
1992	Connecting rods	Ti-3Al-2V-rare earth	Honda	Acura NSX
1994	Connecting rods	Ti-6Al-4V	Ferrari	All 12-cyl.
1996	Wheel rim screws	Ti-6Al-4V	Porsche	Sport wheel option
1998	Brake pad guide pins	Ti grade 2	Daimler	S-Class
1998	Brake sealing washers	Ti grade 1s	Volkswagen	All
1998	Gearshift knob	Ti grade 1	Honda	S2000 Roadster
1999	Connecting rods	Ti-6Al-4V	Porsche	GT3
1999	Valves	Ti-6Al-4V & P/M-Ti	Toyota	Altezza 6-cyl.
1999	Turbo charger wheel	Ti-6Al-4V	Daimler	Truck diesel
2000	Suspension springs	Timetal LCB	Volkswagen	Lupo FSI
2000	Wheel rim screws	Ti-6Al-4V	BMW	M-Techn. option
2000	Valve spring retainers	β-titanium alloys	Mitsubishi	All 1.8 l-4-cyl.
2000	Turbo charger wheel	γ-TiAl	Mitsubishi	Lancer
2001	Exhaust system	Ti grade 2	General Motors	Corvette Z06
2001	Wheel rim screws	Ti-6Al-4V	Volkswagen	Sport package GTI
2002	Valves	Ti-6Al-4V & P/M-Ti	Nissan	Infiniti Q45
2003	Suspension springs	Timetal LCB	Ferrari	360 Stradale

* P/M = powder metallurgy; LCB = Low-Cost Beta

Figure 2 - Metal price comparison 2004 ((Froes et al., 2004)

Figure 2 above shows us a price comparison between different materials, although the reference information is from 2004 it shows how expensive titanium is compared to that of Steel or Aluminium when deciding on what material to use.

4 Manufacturing Processes

When deciding on the material that will be used to manufacture a piston, the manufacturing process must also be considered due to the cost of production and the different qualities that the final product may possess. Low production volumes of a component means that the initial tooling and manufacturing cost would be relatively high compared to that of large volume which may be the deciding factor when choosing a method of production and tooling required (Poli, 2001). Different materials will require different methods of manufacturing to obtain the characteristics required for application, the main manufacturing processes for a piston are die-casting or forging.

The die-casting process consists of a molten metal being poured into a mould usually made of cast iron due to its higher melting point compared to that of most materials used in component manufacturing. Table 1 below shows us the melting point of the most common metals used in either the mould or the piston itself.

Table 2 - Metal densities & Melting points (Densities from <https://theengineeringmindset.com/density-of-metals/>)

Metal	Symbol	Density (kg/m³)	Melting Point (C)
Aluminium	Al	2,705	660
Cast Iron	Fe	7300	1127-1204
Mild Steel		7,850	1425-1540
Titanium	Ti	4,520	1670
Silicon	Si	2,328	1411

The most common methods of die casting pistons are pressure casting or gravity. Figure 2 below shows us the process of pressure casting, where a molten metal is forced into a die via a plunger. Once the casting cools into a solid state, the pattern is retracted, and the cast is then pushed out of the mould where it will then go through a treatment cycle.

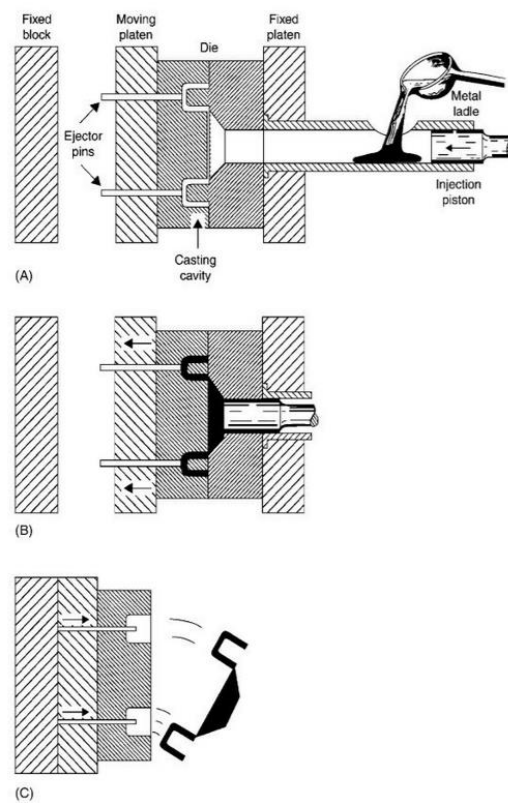


Figure 3 - Pressure Casting (Higgins and Bolton, 2010)

In the process of gravity die-casting, a similar process is followed as to the pressure casting where a molten metal is poured, however in this method the molten metal is poured into a vertical mould so that gravity can force the molten liquid to take up the shape of the mould. Once the cast has cooled, it then goes through a treatment cycle. Figure 3 below shows us a gravity die cast.

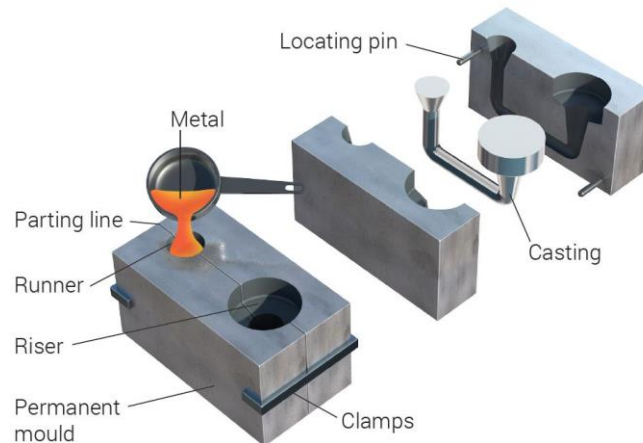


Figure 4 - Gravity die cast (<https://www.engineeringclicks.com/die-casting/>)

The forging process is becoming one of the most used manufacturing processes when making components due to its efficiency. In the process of forging, a cool or heated metal is compressed by a hydraulic press or hammer blow with enormous force to force the metal into the shape of a die (Cleary *et al.*, 2012).

After the casting or forging process, alloys may also receive heat treatments to further improve properties of the alloy. This is known as precipitation hardening which increases the materials yield strength and hardness which is an important characteristic of a piston (Bolton and Higgins, 2020).

5 Conclusion

In conclusion we can see that there are multiple parameters to consider when deciding what material and manufacturing process to use when producing a piston. The main properties to consider when deciding on a material consists of thermal efficiency, yield strength and the overall mass of the component to reduce the forces of inertia, improving efficiency. In the automotive industry alloys are being used increasingly due to the improvements of wear resistance, lower thermal expansion and improved strength and heat transfer. The addition of cheap elements to create aluminium alloys significantly reduces the overall cost making them more affordable for mass production. (Skryabin and Kuklin, 2020)

As the field of additive manufacturing continues to evolve and the technology improves, we may see a shift towards that becoming the industry standard. Additive manufacturing for example is where a three dimensional (3D) component is build by adding material in a series of layers guided by a digital model of the component. This new process also allows more intricate parts to be created as opposed to the process of casting or forging, this is also becoming more popular with metal powders being used to manufacture components in 3D orientations which can result in significant cost reductions.(T. DebRoy, 2017)

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