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Material Selection for Piston Investigation

Engineering Design and Materials – ACHA4001

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1 Introduction

This report is an investigation into the material properties required for a piston for use in an internal combustion engine (ICE). The aim of the report is to select a suitable material for the piston for use in a mass-produced petrol-powered ICE passenger vehicle designed for everyday use.

As explored by David *et al.*, (2019) the auto industry contributes 40% of total greenhouse gas emissions and the effect that ICE powered vehicles have on the environment is an increasing concern to customers.

As such this type of vehicle has a focus on efficiency and wear resistance of components as the customer will expect a good fuel efficiency, a long product life and a good value product. To remain economically viable the production costs of the vehicle must be minimised without sacrificing quality. These factors will be considered when deciding on material selection.

2 Material Properties

In order to understand what materials properties are required for the piston, the environment in which it functions must first be understood.

As described by Kumari, singh and kasera, (2021) pistons under go cyclic loadings over long periods of time from gas pressures in the cylinder as well as high inertia forces created from rapid acceleration and deceleration as the piston as it moves in the cylinder. As a result, pistons need to have a high wear resistance and a high specific strength to resist these repeated loads over years of operation. Specific strength is a measure of a materials strength to weight ratio and is calculated by dividing ultimate tensile strength by density. Therefore, it is important that the material selected has a high ultimate tensile strength as well as a relatively low density.

To put these inertia forces into perspective Woodthorpe *et al.*, (2019) describes these inertia forces as regularly exceeding 2000 times the force of gravity (9.81m/s^2). As well as expressing how a reduced piston mass results in a reduced thermal inertia and better thermal expansion leading to a quicker warm up phase after a cold start improving efficiency and reducing emissions by minimising blowby.

Blowby describes the leakage of combustion gases out of the cylinder into the crank case through the gap left between the piston and the cylinder wall. This is an important consideration for minimising emissions as Dhariwal, (1997) states that blowby contributes 15-35% to the total un-burnt hydrocarbon emissions of a vehicle.

Therefore, reducing the density of the material and therefore the mass of the piston is essential in creating a long-lasting product as this reduces the load on the piston significantly in addition to reducing the emissions of the vehicle.

In order to minimise wear the material selected will need to have a high specific stiffness in order to resist the forces placed on it during operation without deforming and causing additional wear to the cylinder. In addition to this a high ductility is required to resist permanent deformation of the material. Specific stiffness is a measure of a materials ability to withstand deformation compared against its density as is calculated by dividing a materials modulus of elasticity by density, as such it is important that the material selected has a high modulus of elasticity and a relatively low density.

Reducing wear is an important design consideration because as described by Johansson *et al.*, (2008) increased cylinder wear will lead to an increase in emissions due to the cylinder wall losing its oil retaining capabilities as a result the oil consumption of the engine will increase.

The ability to withstand temperature is a key consideration for a piston as temperatures can reach up to 350°C at the piston head (Singh *et al.*, 2019). However this is the hottest spot on the piston as described by Carvalheira and Gonçalves, (2006) the average temperature of the piston wall is 150°C. Therefore, it is important for the material selected for the piston to maintain a high yield strength above 150°C and have a melting point above 350°C. A high thermal conductivity is also important in order to minimise the occurrence of hotspots on the piston.

Shown below (table 1) is a range of expected values the piston will need to meet based on 2618 T61 Aluminium. Chue, (2009) expresses that 2618 T61 Aluminium is a common choice of material used in the production of forged pistons for high performance applications. As such these values are likely higher than what is needed for a passenger vehicle.

Modulus of Elasticity (GPa)	73.8
Modulus of Rigidity (GPa)	28.3
Yield Strength (GPa)	0.29
Ultimate Tensile Strength (GPa)	0.379
Density (g/cm ³)	2.7
Melting Point (°C)	510
Specific Stiffness (GPa cm ³ /g)	27.33
Specific Strength (GPa cm ³ /g)	0.14

Table 1 - Material Properties of Aluminium 2618 T61 Alloy (Engineering ToolBox, 2008)

To ensure a long product life the material used must be corrosion/oxidation resistant. Ease of manufacture and machineability are also key considerations in ensuring that the piston remain economically viable for mass market production as this keeps production and labour costs down enabling a more competitive market value for the product as well as a better value for the customer.

3 Material Selection

3.1 Material Criteria

As discussed in the previous section, the criteria for the material and target values are as follows:

- Good Wear Resistance
- High Specific Strength - $0.14\text{GPa cm}^3/\text{g}$
- High Specific Stiffness - $27.33\text{GPa cm}^3/\text{g}$
- High Ductility
- Low Density - 2.7g/cm^3
- Low Thermal Inertia
- Melting Point Above 400°C
- Corrosion/Oxidation Resistant
- Low-Cost Manufacture
- Good Machinability
- Low Thermal Expansion

3.2 Possible Materials

Initial selection of possible materials is easier visualised with the use of a splodge chart (Figure 1).

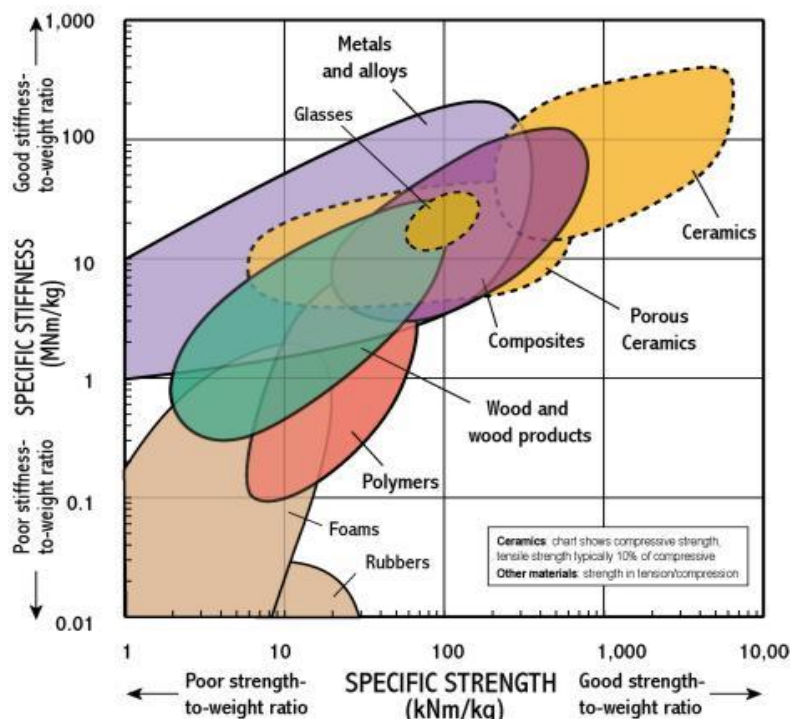


Figure 1 - Material Properties Splodge Chart (University of Cambridge - Materials Group, 2011)

Figure 1 shows various material families and gives a good understanding of their capabilities. The further to the top right of the chart the material is then the higher the ratio of combined stiffness and strength to weight. From the chart it can be observed that Metals/Alloys are a good choice for this use for their relatively high specific strength and specific stiffness, their high melting points and as described by Schreer *et al.*, (2014) alloy pistons have had a long proven use in road vehicles, mainly steel and aluminium.

Ceramics and composites may also be considered for their high specific strength and high specific stiffness however the production and use of ceramic and composite pistons is unproven and would require a large amount research and development making this unsuitable for this application. Wood, Polymers, Foams and Rubbers are unsuitable for this application as they have relatively low melting and combustion points.

3.3 Material analysis

3.3.1 Aluminium

The benefits of aluminium alloys include:

- Low density – 2.7 g/cm^3 (Engineering ToolBox, 2008)
- High specific strength
- Good machinability
- Low thermal inertia
- High thermal conductivity
- Good castability
- Good forgeability
- Many alloys available
- Good availability
- Low Cost
- Good resistance to oxidation/corrosion

The downsides of aluminium alloys include:

- Not as strong as comparable materials (Steel)
- Lower melting point than comparable materials (Steel)

Modern aluminium pistons are hypereutectic this denotes that the alloy used contain more than 12% silicone (Si) (Al-helal, 2013). As discussed by Ahmed *et al.*, (2016) the Al-Si alloy commonly used increases the hardness of the material leading to a higher specific stiffness as well as increasing the ductility of the material. This is further supported by Wang *et al.*, (2004) who describe this materials as having better wear resistance, a higher thermal conductivity and a lower coefficient of thermal expansion when compared to aluminium alloys of less silicone content. These properties are possible as this alloy creates a structure known as a Metal Matrix Composite (MMC). As described by Jorstad and Apelian, (2009) the Al-Si alloy forms an MMC when silicone crystals are formed during solidification and are distributed throughout the material in an eutectic matrix. Hypereutectic pistons also have a lower density as Silicone has a lower density then aluminium, $\rho_{Si} = 2.33 \text{ g/cm}^3$

3.3.2 Steel

The benefits of steel alloys include:

- High specific stiffness
- High melting point
- High yield strength
- High ultimate tensile strength
- Good castability
- Good availability
- Low Cost
- Good forgeability
- Low thermal expansion
- Low thermal conductivity

The downside of steel alloys include:

- High density – 7.85 g/cm^3 (Engineering ToolBox, 2008)
- Relatively high thermal inertia
- Not a machinable as aluminium

Papaioannou, Leach and Davy, (2019) describe the benefits of steel pistons stating that the lower expansion rate of steel, when compared to aluminium, reduce the frictional losses of the engines as the clearance between the piston and cylinder wall can be smaller additionally this reduces blowby. As such an increase in fuel efficiency and a reduction in emissions can be observed. The higher yield strength of steel also allows for a greater compression ratio and as described by López *et al.*, (2020) maintain an optimal compression ratio is a key consideration in modern downsized vehicles.

3.3.3 Magnesium

The benefits of magnesium alloys include:

- Very low density – 1.74 g/cm^3 (Lee *et al.*, 2013)
- Good castability
- High specific stiffness
- Good thermal conductivity

The downsides of magnesium alloys include:

- Poor corrosion resistance (Lin *et al.*, 2008)
- Poor wear resistance
- Asymmetrical tensile and compressive strengths (Sukedai and Yokoyama, 2010)
- High cost
- Low availability

Magnesium based MMC's offer significant benefits, as Karuppusamy *et al.*, (2021) explains pistons made from this material can offer up to 35% reduction in component mass. However, the raw material and manufacturing costs of magnesium alloys is far above that of steel and aluminium.

3.4 Material Choice

The material selected is aluminium for its low cost, widespread availability, ease of manufacture (cast or forged), good machinability as well as its proven use in petrol passenger vehicles makes it the best candidate for a mass market everyday use vehicle. Its low density and low thermal inertia make it a good choice for an efficient engine. A good resistance to corrosion also ensures a long product life. Steel was not selected as its strength benefits over aluminium were unnecessary in a petrol power

vehicle in addition its high density makes it unsuitable for this use. Although magnesium offers significant benefits over aluminium its high cost and low availability make it unsuitable for a mass-produced vehicle. Additionally, its poor corrosion and wear resistance mean this material does not have the longevity required for everyday use.

The alloy of aluminium that will be used is AlSi-16 which consists of 16.48% Silicone, 1.28% Copper, 1.07% Nickle, 0.79% Magnesium, 0.38% Iron and 0.14% Manganese and exhibits the previously discussed properties of hypereutectic alloys (Rajnovic and Sidjanin, 2007).

4 Manufacturing processes

As described by Barbieri *et al.*, (2017) in the manufacturing of aluminium pistons there are two main methods used, forging and casting.

4.1 Forging

The forging process uses a large die that is first heated then a billet of the selected alloy is forced into the die by a hydraulic press, this process creates a tight grains structure in the alloy and as Jensrud and Pedersen, (1998) explains this gives the piston improved strength and ductility. However, these benefits come at the cost of an increase density as a result the piston expands more when heated and as such a bigger clearance needs to be left between the piston and cylinder wall resulting in fuel efficiency losses and emissions increase due to blowby as well as an increase in frictional losses. Due to their higher density forged pistons have a higher thermal inertia and as such have a longer warm-up phase leading to further losses from blowby as well the potential for piston slap, where the clearance of the piston allows to move in the cylinder contacting the piston wall, increasing wear.

The forging process only forms the rough shape of the piston additional machining and drilling are required to form the finished product as a result forged pistons are more labour intensive and take longer to complete than casting resulting in a higher cost.

4.2 Casting

Gravity casting is the most widespread method of producing pistons. The gravity casting process entail creating a mould of the part out of ceramic and pouring the molten alloy into it and relying on the force of gravity the form the part as a result this leads to a looser grain structure than forged pistons. However, the losses in strength and rigidity can be mitigated using hypereutectic MMCs mentioned in the previous section. This process requires very little machining to finish the product as well as the ability to quickly produce the product in mass quantities once the initial mould has been produced.

4.3 Manufacturing process selection

The process that has been selected is gravity casting as after the initial investment in the mould the process is low cost and well suited to mass production. Forged was not chosen as it increased warm up phase, lower fuel efficiency and higher emissions as such it is not well suited for everyday use.

5 Conclusion

As discussed for the application of a petrol passenger vehicle the selected alloy (AlSi-16) and gravity casting process fits the selected criteria of a low cost and good quality product as well as enabling cost effective mass production.

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