

# University of Wales Trinity Saint David

Wales Institute of Science & Art



## ***Piston Material Selection Report***

***Engineering Design and Materials ACHA4001***

Callum Carter-Davies

Student ID: 2008376

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## 1 Introduction

This report will detail the analysis of materials and manufacturing techniques in order to narrow down the selection to isolate the most suitable materials for use in a piston in a 2.0 litre petrol-powered 4 stroke internal combustion engine seen in cars such as the Mazda 3 (Figure 1). The piston will be optimised for longevity, affordability, and efficiency to maximise reliability as this type of vehicle would generally be used for day to day activities such as transporting people.

The intention of this report is to compare materials that are suitable for use as a piston material, weigh up the benefits and drawbacks of those materials, and detail how the piston can be manufactured from the chosen material or combination of materials.



*Figure 1 - Mazda 3 2.0 Skyactiv-G 2019 (Autocar.co.uk, 2019)*

The combustion process within the cylinders of an engine creates a large amount of pressure and heat. The reciprocation of the pistons, which can exceed 100 cycles per second, generates substantial inertial forces through the piston whilst the piston is operating in temperatures which can exceed 300 °C, dramatically affecting the structural integrity of the piston. The expanding gases as a product of combustion also apply pressure through the piston (Bosch, 2018).

Pistons, like many other engine components, are designed to be a specific shape with specific dimensions at operating temperatures. The piston needs to fit well in the bore of the cylinder and have the piston rings sealing up smaller gaps to maintain the seal of the combustion chamber and ensure proper clearance. The piston will be manufactured with the goal of being the correct dimensions at the operating temperature after undergoing thermal expansion (Chitthaarth M R and Manivannan, 2015).

## 2 Material Properties

The piston must be made of a material with a particular set of properties which ensure the piston can achieve effective performance whilst subjected to the harsh conditions in the combustion chamber throughout its entire lifespan, and to extend the lifespan of the piston by as much as possible (Dev, Aherwar and Patnaik, 2019).

The piston should be designed with fatigue strength as a priority as a major cause of piston failure is from high-cycle fatigue (Najafi *et al.*, 2019). The material used should have a high fatigue strength for it to endure higher loads or more cycles before suffering from fatigue failure, as the use case of the piston is one in which the piston will be reciprocating very frequently with a predictable amount of force acting upon it varying with engine speed.

The material should also be chosen with the density of the material as a priority, as this correlates with the mass of the piston. The mass of the piston is of particular importance as it determines the magnitude of the inertia of the piston, with an increased mass increasing the force acting upon the piston and the components connected to the piston. It also has a significant effect on the efficiency of the engine (Spangenberg *et al.*, 2006).

### 3 Material Selection

A material analysis was conducted to narrow down the selection of materials using the material properties database included in the Granta EduPack (Ansys, 2021) software. The first analysis plotted the materials on a graph of fatigue strength against density, providing an easy way to compare the materials against each other by the factors identified as being most important in the previous section.

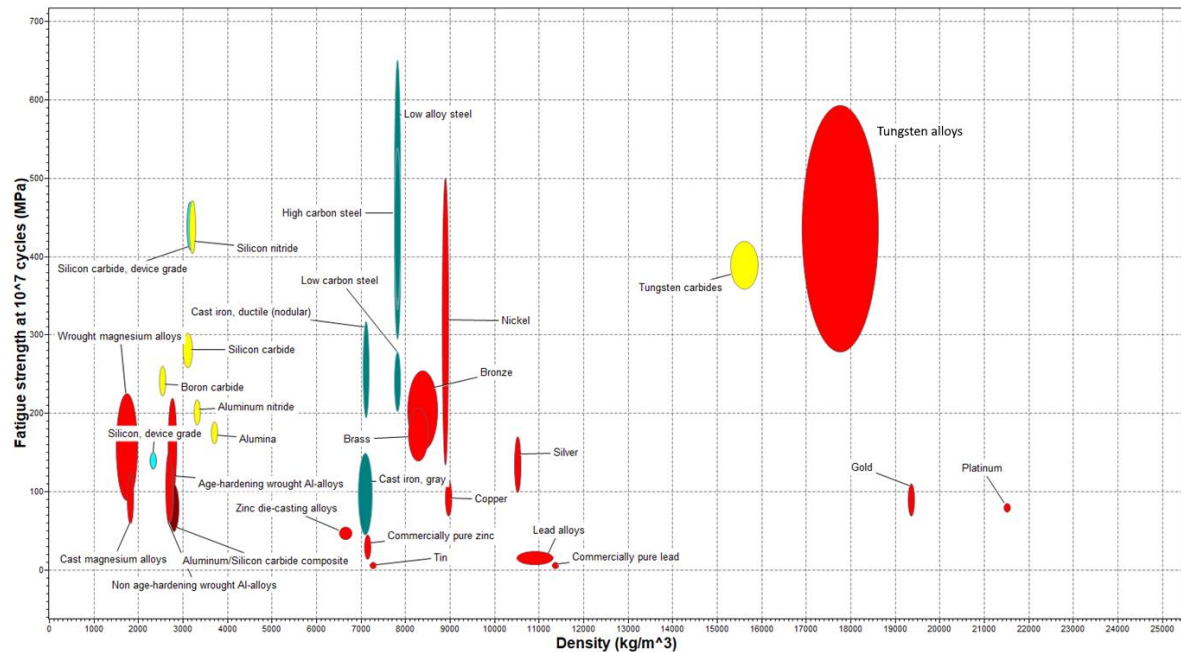


Figure 2 - Graph of material fatigue strength plotted against density (Ansys, 2021)

Under the assumption that the volume of material used to construct the piston will be constant independent of the material, the most ideal materials are all under a density of  $8000 \text{ kg/m}^3$  and have a fatigue strength above  $150 \text{ MPa}$  at 10 million cycles. The materials of particular interest are the carbides and nitrides, as well as magnesium alloys, aluminium alloys, steel alloys (Ansys, 2021).

Aluminium alloys are the most widely used material for manufacturing pistons due to their mechanical properties. Aluminium based alloys have improved fatigue strength allowing them to withstand more cycles of the same load before failure. They also have a low co-efficient of thermal expansion which is ideal for use in the combustion chamber as the piston will be in an environment where it can be operating at around  $300^\circ\text{C}$  but can also have to function well at ambient temperature on engine start up. Reinforcing the aluminium alloy with ceramic materials improves heat resistance, toughness, and wear resistance without a significant increase in mass (Dev, Aherwar and Patnaik, 2019).

A large benefit of ceramics is that they conduct heat less than aluminium alloy meaning the thermal efficiency of the engine is increased when using a piston with a ceramic coating. This increases the

temperature of the air-fuel mixture in the crevice and crown regions which leads to a reduction in carbon monoxide emissions and an increase in performance and efficiency (Silambarasan et al., 2015).

The magnesium alloys appear to be more suitable than aluminium alloys as they have a similar fatigue strength with a lower density which would be beneficial for reducing inertia and increasing longevity. Further research into magnesium alloys suggests that they would actually be worse as a piston due to them being worse at handling thermal load, which causes the piston to weaken and fail. The volume of the piston material could be increased to account for this but it would increase mass (Amal and Ramesh, 2018).

Pistons can also be manufactured from steel alloys despite the steel alloys having a much greater density of approximately 2.5 times more than aluminium. A steel alloy piston would be able to achieve higher mechanical and thermal loads, enabling the piston to operate under higher compression ratios and improve efficiency, particularly in small turbocharged engines (Saverio et al., 2018).

For the use case identified in the Introduction section, the most suitable material identified is an aluminium alloy reinforced with ceramic material as it has a good balance between fatigue strength and density.

## 4 Manufacturing Processes

Pistons for petrol engines are typically created from an aluminium alloy through a casting process. Cast pistons can be manufactured through a casting process known as Gravity Die Casting which involves pouring the molten material into a mould and waiting for it to set, then extracting it from the mould. It typically results in between 10-40% of the material being wasted however this material can be melted down and reused (Swift and Booker, 2013).

Forged pistons are created by striking the heated material into a die using a press or a hammer causing the material to undergo plastic deformation and be formed into the appropriate shape (Swift and Booker, 2013). Forged pistons are stronger than cast pistons made from the same alloy and have increased resistance to heat and pressure which enables them to be stable at higher compression ratios. The increase in strength allows for a reduction in mass from the structure as the forged pistons can have thinner walls and withstand equal forces to cast pistons. Forged pistons also have a higher fatigue resistance than the cast counterparts. However, forged pistons are more expensive to produce as the manufacturing process is more complex than casting (Spangenberg *et al.*, 2006)

A ceramic coating can be applied to the piston's surface through a method called plasma spraying, this increases the hardness of the surface. An increase in surface hardness has been found to decrease the friction coefficient of the surface, reducing wear, which could be useful to reduce the wear on the skirts of the piston. A downside of ceramic coating is the brittle nature of ceramic materials stemming from their hardness which could result in the coating shattering, and another negative of ceramic coating is the potential for a loss of adhesion to the surface of the piston (Rahim *et al.*, 2009). Ceramic coating also adds cost to the manufacturing process so may not be suitable in cases where cost is being prioritised however it reduces wear thereby increasing the longevity of the component.

The automobile manufacturer Porsche, in collaboration with MAHLE, have developed a technique to produce high performance pistons through 3D printing. This takes an aluminium alloy powder and melts it into the piston shape over more than 1000 layers through a process called laser metal fusion. The resulting piston has 80% of the mass of the forged equivalent but has increased rigidity in comparison. The 3D printing technique optimises the design by avoiding the inclusion of unnecessary mass of the piston which would typically be impossible or not worthwhile to remove. The major downside of this technique is the time required to manufacture a single piston being

approximately 12 hours and the cost of the technology due to it being a fairly new technology (MAHLE Group, 2020).

For the purpose of this report, forging is the manufacturing process chosen to be used in the production of the piston. This would add extra durability to the piston, extending the life cycle of the component.

## 5 Conclusions

In this report, a range of materials have been identified as suitable for use as the material for a piston in a reciprocating internal combustion engine through the use of the Granta Edupack (Ansys, 2021) software to collect and graph material data. Identifying the mechanical properties required for successful piston operation in the combustion chamber allowed for the collected data to be assessed for suitability of materials to that environment and for further research to be carried out to determine which materials would be appropriate for use as a piston.

It was also noted that a combination of materials could be used in the manufacturing of the piston to further improve the capability of the piston, for example a piston cast from an aluminium alloy could have a ceramic coating applied to the crown in order to increase hardness and improve the thermal efficiency of the system. Applying ceramic coating to the skirt of the piston could reduce wear from friction (Rahim *et al.*, 2009).

This report also assessed the manufacturing techniques used in the creation of pistons. Casting the piston from an aluminium alloy combined with the application of ceramic coating by plasma spraying was chosen as the most suitable option in order to increase hardness and reduce wear, increasing the number of cycles the piston could be subjected to hence achieving the objective of longevity and efficiency without increasing cost significantly.

Forging the piston was opted against due to the cost and potential for additional mass. The Porsche/MAHLE 3D-Printing technique was disregarded due to the cost of the process and the potential for being unable to access proprietary materials and equipment.

Due to potential for failure from thermal load, the magnesium alloy was also excluded as an option for the piston material despite having a better fatigue strength for its density (Amal and Ramesh, 2018). A steel alloy was also considered as it has a high fatigue strength however the high density of the steel alloy ruled it out as an option (Figure 2).

To conclude, the piston material chosen was an aluminium alloy with a ceramic coating on the skirt due to the low density and relatively good performance of fatigue strength with the benefit of the reduction in wear.

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