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Materials Selection Report

Engineering Design and Materials (ACHA4001)

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1 Introduction

This report will conduct in-depth research and analysis into the materials and manufacturing processes required to mass produce a 4-Cylinder Petrol Road Car Internal Combustion Engine (ICE) Piston. Initially focusing on the expected environment and application of the piston, such as expected mechanical loads and temperatures. The report will then investigate methods and materials used in industry when producing a piston. Finally determining a suitable option of manufacturing the material into the final piston unit. Each selection of options will lead to a final choice supported and justified by external research to improve the credibility and accuracy of the decisions.

2 Piston Application

During the lifespan of a piston, it will be expected to perform under a various number of thermal and dynamic situations. A gasoline piston and engine's overall objective are to convert the chemical combustion of air, fuel, and a spark into mechanical work. Usually linked with the rest of the engine via a connecting rod, a piston is the direct connection between the compressing and recoil forces of the combustion cylinder and the rotating crankshaft. (Stan and Faitar, 2020)

An Internal Combustion Engine (ICE) piston has numerous applications and physical responsibilities:

1. A piston will experience high temperatures caused by the combustion and frictional forces.
2. The piston will need to have the material strength and integrity to withstand the multiple extreme forces experienced in constant succession.
3. Producing a sealed chamber between the combustion cylinder and piston head is essential to assist with the intake and exhaust gases.
4. Each component of an engine, and specifically the piston, is to produce as much positive kinetic energy and minimise the negative resistive forces.

2.1 Piston Temperatures

The piston face and subsequently the entire piston, through convectional heat transfer, experiences direct extreme heat energy from the combustion process taking place. (Saad Abed Ali and Abudella, 2008) claims that the combustion gases peak up to 4000K within the gas chamber. The limited options for the piston to sufficiently dissipate the heat is through the piston's high thermal conductivity, the piston skirts and cylinder wall, the piston rings and lubricating oil. It is essential that the chosen material for manufacturing doesn't have an adverse effect upon the regular temperature changes. Each aspect of the piston experiences different thermal loads and is an essential characteristic when designing and manufacturing a piston:

Table 1: A table displaying the peak measured Thermal Load of a Road Car Petrol ICE Piston (Sathishkumar and Kannan, 2020)

Piston Component	Thermal Load (K)
Piston Head	573
Piston Rings	493
Piston Skirt	463
Piston Lower Portion	243

Table 2: A table displaying alternative sourced results to support expected Thermal Loads of a 4-cylinder Petrol ICE (Mahle, 2016)

Piston Component	Thermal Load (K)
Piston Crown (Head)	473-673
Piston Skirts	393-453

2.2 Piston Strength and Integrity

The piston travels within the cylinder twice for every rotation of the crankshaft, and when the crankshaft rotates anywhere between 1,000 to 15,000 (in extreme circumstances) revolutions per minute, the piston will be accelerating up to extremely high velocities across a small displacement. (Mishra, 2013) As well as the inertia and supporting forces from the conrod, the gas forces also act directly onto the piston top face. (Mahle, 2016) has measured that the expected mechanical load for a 4-cylinder piston is between 6-9 MPa and is travelling at over 25,000 m/s². It is essential that the piston material has a high Young's Modulus and has a high fatigue resistance at these velocities and pressures. This force can then be dissipated and controlled through a number of factors:

- Solid, accurate construction between components to transfer the kinetic energy into the crankshaft.
- Sufficient wall thickness of the cylinder to withstand any piston slap and focus the forces in a positive direction.
- Utilising a manufacturing process and materials to:
 - o allow for a low mass piston, reducing inertia.
 - o Have a high level of wear resistance and hardness to withstand constant use.

2.3 Piston Gasses

A feature to a piston and its overall design is how the piston is used to support the engine in controlling the air and fuel mixture as well as the exhaust gasses. The piston, along with the skirts and rings, act as the bottom moving side to a sealed chamber in which the compression and combustion takes place.

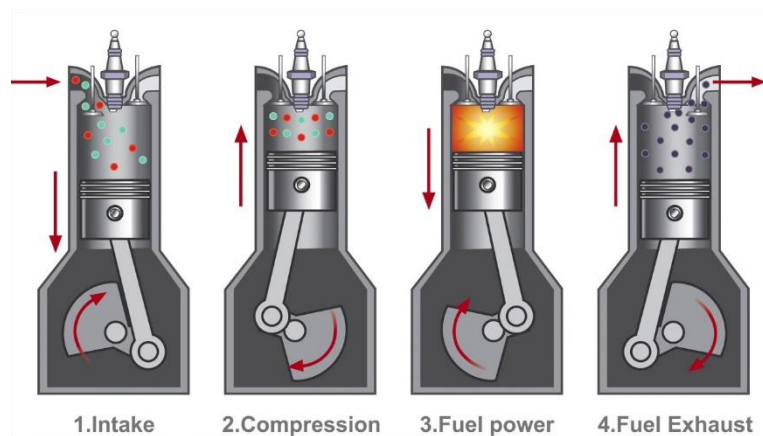


Figure 1: a computer-generated image showing how the movement of a piston is used to change the volumetric size of the combustion chamber (Toyota of Orlando, 2017, 00:59)

The top crown face of the piston has endured a wide array of design alterations to optimise the efficiency and combustion within the chamber. (Lee, Z R., Ku, P X., 2021) conducted basic simulations on SolidWorks to compare 4 variants of piston crowns. The exaggerated variants used were a 'Flat Top', 'Bowl', 'Square Bowl' and 'Dome' design. It was established that the 'Bowl' crown had the best efficiency performance during combustion as the air and fuel mixture was sufficiently used up the fastest. This is beneficial because the fuel can be running 'leaner', as none is wasted out the exhaust, providing the customer with a better miles per gallon on fuel, and ultimately lower running costs.

It is vital that when the piston is subjected to the chemical combustion of atmospheric air and fuel, the materials chemical properties:

- can prevent oxidation, reactivity and flammability.
- have little to no toxicity during the lifespan (including sourcing and disposing) of the piston.
- have high chemical stability and has no possible chemical bonds with the combustion gasses.

2.4 Piston Efficiency

The design of an ICE is a symphony of multiple moving components working closely in unison. The piston, at the heart of the engine, needs to be manufactured to a high tolerance so that it has the tight fit required, yet operate under the least amount of resistance manageable. If the piston diameter is manufactured too small or the piston head and skirts experience thermal expansion, a phenomenon of piston slap could occur. 'Piston slap' is where the piston head doesn't run in concentric with the cylinder wall and 'knocks' or 'slaps' repetitively. This induces an unwanted lateral movement and uncontrolled wear across the piston and chamber cylinder. In extreme circumstances, if unmanaged this wear can lead to unrepairable damage and ultimately component failure. (Geng, Z., Chen, J. 2005)

3 Material Properties

With the piston being designed and manufactured to achieve the expected piston applications, it is essential that the material selected can fulfil the criteria. The use of a Material bar chart or graph can help to eliminate a selection of materials.

Material Bar Chart or Graphs are commonly used in industry to quickly and visually understand what resources are available to the manufacturer to achieve the desired outcome. Shown below in figures 2, 3 and 4 are:

-Strength (MPa) vs Maximum Service Temperature ($^{\circ}\text{C}$) these are two essential criteria for the piston application.

- Strength (MPa) vs Toughness (KJ/m^2) to see if the piston can withstand the potential shock or impact loads.

-Elasticity (Young's Modulus GPa) vs Cost (£/kg) these are two essential criteria for the piston application.

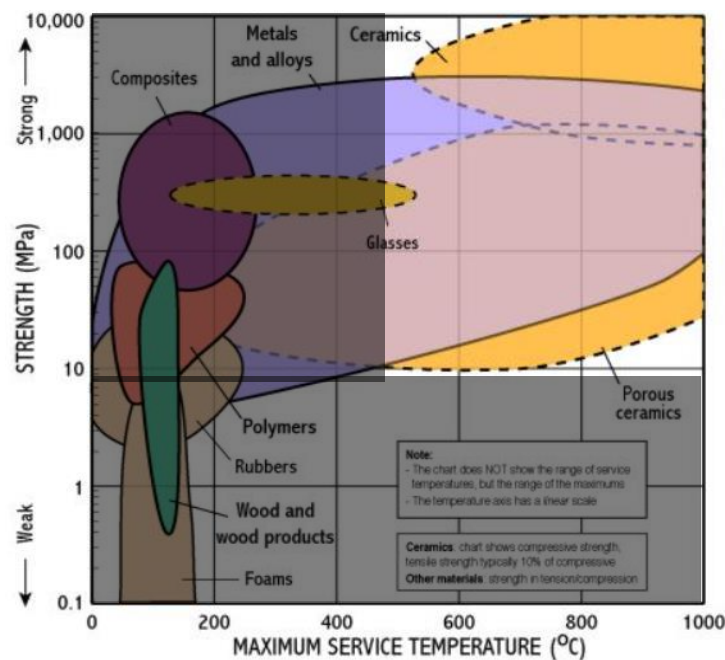


Figure 2: A Strength vs Maximum Service Temperature Materials Graph to show the Material groups that can withstand the high loads and temperatures expected. (University of Cambridge Department of Engineering, 2002)

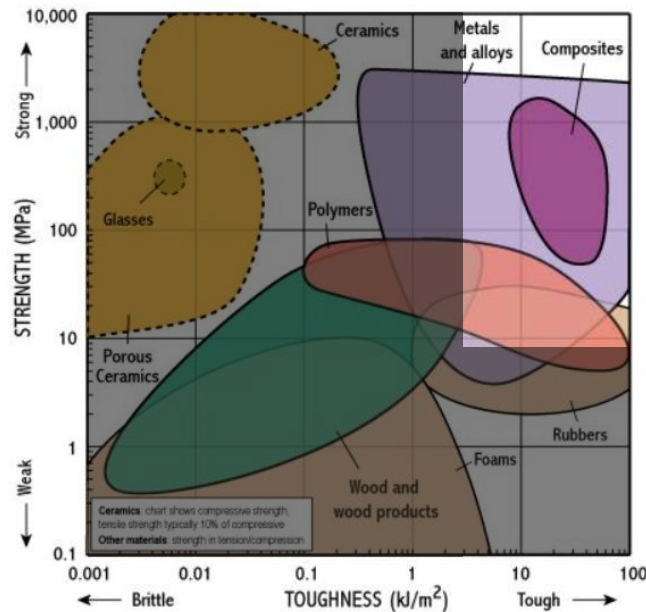


Figure 3: A Strength vs Toughness Materials Graph to show the Material groups that can withstand the shock and potential impact loads as well as the high loads. (University of Cambridge Department of Engineering, 2002)

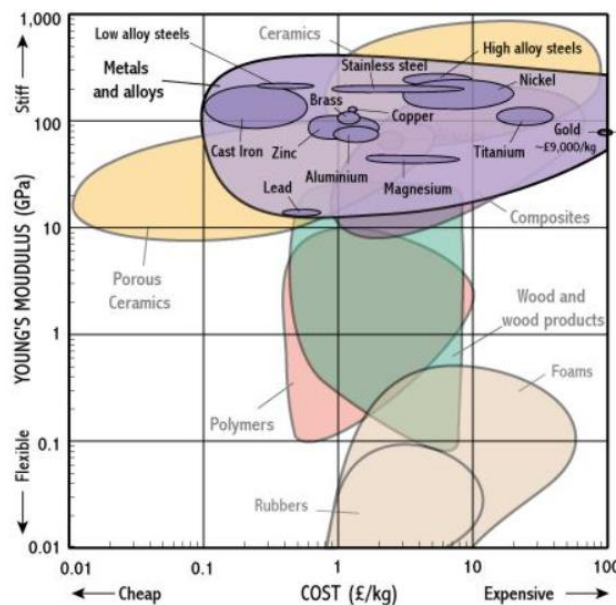


Figure 4: A Young's Modulus vs Cost Graph to show the spread of 'Metals and Alloys' materials. (University of Cambridge Department of Engineering, 2002)

Using the material graphs in figures 2, 3 and 4, show that the material group ideal for manufacturing is metals and alloys. From here further analysis into the specific material properties can be completed to make a final selection.

Table 3: An Excel generated table based upon table 4 to rank each potential material at meeting the set criteria

Material	Ranked Melting Point	Ranked Fatigue Endurance	Ranked Elasticity	Ranked Density	Ranked Cost (£ per kg)	Recyclable	Average Rank
Cast Iron	3	1	3	4	1	yes	2.4
Aluminium 2618A	6	3	6	2	2	yes	3.8
Aluminium 4032	5	4	5	1	4	yes	3.8
Carbon Steel	2	2	1	5	5	yes	3
Titanium	1	5	2	3	3	yes	2.8
Gold	4	6	4	6	6	yes	5.2

Table 4: An Excel generated table based upon figures sourced from external references (Smiths High Performance, 2021) (JE Pistons 2017) (The Engineering ToolBox, 2003) (MatWeb, 2023) (Engineering Fundamentals, 2023) (Trading Economics, 2023) (Borui Llaoning Borui Machinery Co., 2023) (Cohenusa, 2023) (Roane Metals Group LLC, 2020) (European Investment Bank, 2018)

Material	Melting Point Temperature (K)	Fatigue Endurance (Mpa)	Elasticity (Mpa)	Density (kg/m3)	Cost (£/kg)
Cast Iron	1400	350	200000	7340	1.25
Aluminium 2618A	785	124	75000	2770	6.00
Aluminium 4032	800	110	79000	2680	8.00
Carbon Steel	1700	300	180000	7860	10.00
Titanium	2000	103	116000	4500	7.00
Gold	1300	32	75000	19320	50000.00

4 Material Selection

The overall criteria and application of the piston has determined that Iron is all round most suitable material for the road going ICE 4-cylinder petrol engine. Iron has a high enough melting point along with a set of thermal, stress and strain characteristics that would provide an acceptable level of reliability. It is not essential for this piston to have the lightest density as the criteria is added value as opposed to performance. Furthermore, the availability and cost of the material ranked best (cheapest) so that overall cost doesn't impact the profit revenue of the piston, engine, and car.

5 Manufacturing Processes

For a car manufacture aiming to produce a mass amount of vehicles, the important purposes of investing into materials, machines, people and infrastructure, is profit. Take raw materials and time as cheaply as possible, add value and sell on for an overall profit. Many different factors such as brand perception and target audience, to name a few, somewhat stem from the manufacturing process. The ever-present points of the efficiency, price, reliability, and environmental impact are key drivers in what customers consider when purchasing a new car. Each component needs to achieve what the customer is expecting at the least amount of cost to the manufacturer (Tudor, 2023). With a 4-cylinder piston engine, the piston is a component that needs no adjustment to design between each unit and requires mass manufacturing. A few options available to manufactures converting the raw material into a final product is Casting, Forging and Metal Powder Sintering (Sinha, 2012).

5.1 Casting

Casting has a large number of variations in process options depending on the final thermal, integral and visual properties required.

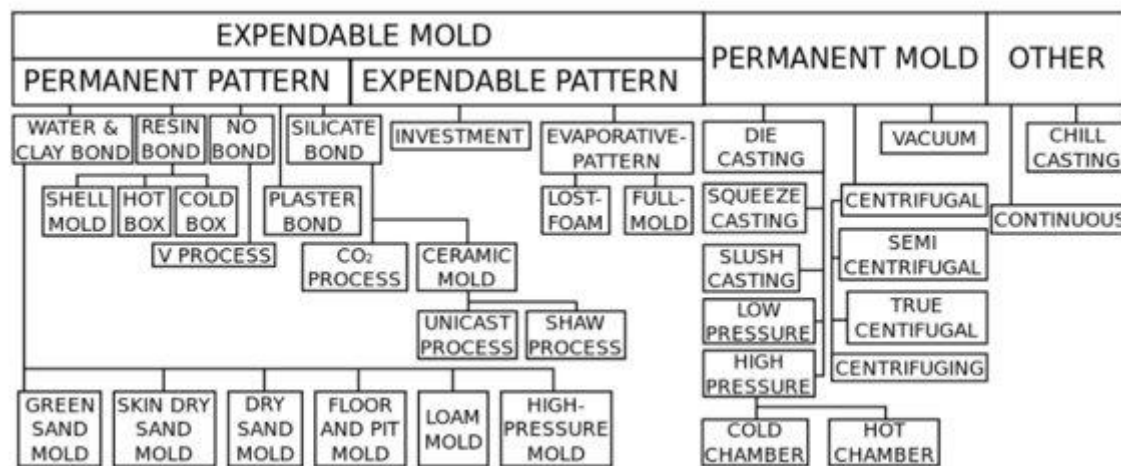


Figure 5: A flow chart displaying the variety of casting options (Tudor, 2023)

A commonly used form of casting is known as 'Die Casting'. Die Casting isn't an option for every material but works well with molten metals and alloys, such as aluminium, zinc, copper, magnesium, etc. (Rapid Direct, 2022)

Die Casting:

- + Provides high production efficiency. Once the molds and machines are set up, the repeatability of mass production spreads initial costs across each unit.
- + Provides a good surface finish meaning little to no further machining and cost is spent on secondary operation costs.
- + Provides a high level of tolerance control. Once produced the parts maintain their intended dimensional accuracy even under high pressure and temperature loads.
- Initial set costs are expensive.
- Doesn't work too well with materials that have high melting points. (Rapid Direct, 2022)

Sand Casting is another form of casting. Sand casting has been historically known for being the first form of casting process when humans first discovered the use of metals. Sand casting works very similar to die casting but uses sand molds instead of high temperature treated metals. Sand casting allows for very complex cored shapes to be produced; however, this does come with a few issues. It is common for sand casting mold to produce imperfections, either minor or major, which will require further machining or a complete restart. Additionally, sand casting cannot make tight tolerances in respect to the other available manufacturing processes (Tudor, 2023). This is not ideal when a mass amount of units it to be produced for as little cost as possible.

5.2 Forging

Forging uses compressive forces to shape a metal billet into the desired part. Forging uses either an open or closed pre-machined die from steel. The billet is then heated to a pre-set temperature and then compressed into the mold.

Forging:

- + Provides a high level of structural mechanical strength due to naturally occurring grain structure.
- + Has minimal cut-offs/scrap wasted, lowering costs.
- + Ensures no internal cavities so quality control can be completed quicker.
- + High repeatability allowing for mass production.
- Hard to ensure consistency and tight tolerances.
- Requires further secondary processing to complete unit.
- Doesn't allow for complex or intricate designs. (Deeco Metals, 2021)

6 Manufacturing Selection

After analysing two of the most common manufacturing processes used in mass production of a piston the selected option for this report is die casting. This decision has been made based on the purpose and application of the piston. Based on (Lee, Z R., Ku, P X. 2021) work the design of the piston will be considerably simple and won't require a complex manufacturing process. It is also expected that many the simple designed pistons will be produced to spread the costs of infrastructure investment and faulty unit wastage, across the sale of good units. Forging would also provide similar results however the lack of secondary process and the smooth clean finish to die casting also allows for units to be produced quicker.

7 Conclusion

Upon completion of in-depth research and analysis, this report has determined that cast iron pistons would be a suitable option for a manufacturer producing 4-cylinder petrol road cars. The choice of metal along with manufacturing process ensures that the piston would be capable of withstanding all expected temperature, chemical and mechanical loads for a relatively reliable amount of time. The objective of this piston is to ensure that, when assembled along with the other componentry, a great amount of added value is provided and the manufacturer can cover any costs with great revenue and invest further into infrastructure, R&D, etc.

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