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1 Introduction

Pistons for internal combustion engines have historically been made from cast iron and steel alloys. However, in modern times, aluminium alloys have become the preferred material for pistons due to their superior properties in terms of weight, thermal conductivity, and strength-to-weight ratio.

Steel alloys have higher ultimate strength than aluminium alloys, making them suitable for high-load applications where the piston must withstand significant stresses such as commercial diesel engines. However steel alloys are heavier and have lower thermal conductivity, which makes them less desirable for modern engines that prioritize lightweight and efficient designs.

Aluminium alloys offer a higher specific strength than both cast iron and steel alloys, meaning they can withstand greater mechanical stresses for a given mass. This property makes them ideal for high-performance engines that require fast acceleration, and improved fuel efficiency. Additionally, aluminium alloys have excellent thermal conductivity, which allows for efficient heat transfer and reduced hot spots in the piston, cylinder, and cylinder head.

Overall, while steel alloys have played an important role in the history of piston manufacturing, aluminium alloys have become the preferred material for modern internal combustion engines due to their superior properties in terms of weight, thermal conductivity, and strength-to-weight ratio.

2 Piston Material Properties

High-performance pistons require specific material properties to withstand the extreme conditions and stresses of racing and high-performance driving. These properties include high strength-to-weight ratios, high-temperature capabilities, wear resistance, and good thermal conductivity.

One of the most critical properties of high-performance pistons is their strength-to-weight ratio. Materials with a high strength-to-weight ratio can withstand high mechanical stresses without adding unnecessary weight to the engine. Lightweight materials such as aluminium alloys are preferred for high-performance pistons due to their excellent strength-to-weight ratio. However, it is important to balance strength with durability, as materials that are too brittle can fail under stress.

High-temperature capabilities are essential for high-performance pistons, as they must withstand the extreme temperatures generated by high-performance engines

The average temperature of the cylinder and piston crown during combustion varies depending on engine operating conditions and can range from which ranges from 100 to 250 °C for the cylinder wall (Finlay, 1985) Whereas the piston crown temperature can exceed 300 °C (Yang, 2021).

Combustion temperature can be in the region of 1500°C

For these reasons materials with high melting points and low coefficients of thermal expansion (CTE) are preferred, with the CTE influencing the piston's fit in the cylinder bore, (Smith, 2017)

Finally, good thermal conductivity is critical for high-performance pistons. Materials with high thermal conductivity can dissipate heat more efficiently, which is important for reducing the risk of hot spots and engine damage as mentioned cylinder temperatures can be around 1500°C.

Aluminium alloys are particularly effective in this regard, as they have excellent thermal conductivity, a typical value for aluminium being 237 watts per meter kelvin (W/m K) opposed to a 0.5% carbon steel being 54W/m K (matweb, 2023)

Overall, high-performance pistons require a careful balance of properties to ensure that they can withstand the extreme conditions of racing and high-performance driving. Lightweight materials with high strength-to-weight ratios, high-temperature capabilities, excellent wear resistance, and good thermal conductivity are preferred for high-performance pistons. Material selection depends on the specific requirements of the engine and the type of racing or driving conditions it will be subjected to.

3 Alloy Selection

There are many suitable alloys used in pistons, detailed below are some possible candidates for material selection.

1. 2618 Alloy: This alloy is low in silicon and higher in copper, making it one of the strongest aluminium alloys used in piston production. It has a high fatigue resistance and is commonly used in racing applications. As well as it is less susceptible to cracking at high temperatures due to its low silicon content which aids inductility.
2. 4032 Alloy: This alloy is a high-silicon alloy with low copper content. It has excellent thermal stability allowing tighter cold clearances to be specified. It has a lower fatigue resistance compared to 2618 alloy therefore is more prone to cracking especially at high temperatures.
3. 6061 Alloy: This alloy is widely used in various applications due to its high strength, low weight, and excellent corrosion resistance. However, it is not commonly used in piston production due to its low silicon content, which reduces its thermal stability.
4. 2024 Alloy: This alloy is commonly used in piston production due to its excellent machinability and moderate strength. However, it has a lower fatigue resistance and strength compared to 2618 and 4032 alloys.

The application specified is to be for a Piston in a racing motorcycle, which will be naturally aspirated, be required to perform well for a minimum of one season but not required to last any longer and cost not to be too much of a consideration. For this application either AL 2618 or AL 4032 would be better suited.

Alloy 2618 is an aluminium alloy that contains copper, magnesium, and silicon as its primary alloying elements. It is known for its exceptional strength, ductility, and resistance to fatigue. These properties make it an ideal material for high-performance racing pistons that are subjected to extreme conditions. In contrast, alloy 4032 is an aluminium-silicon alloy that is less ductile and less strong than 2618, making it more suitable for lower performance applications.

One of the critical properties that make 2618 a popular choice in racing piston design is its high strength. This alloy has a higher ultimate tensile strength and yield strength compared to 4032. For example, the ultimate tensile strength of 2618 is typically around 441 MPa@24°C., while that of 4032 is around 380 MPa @ 25°C (matweb, 2023). This means that pistons made from 2618 can withstand greater stress and load without deforming or breaking.

Another significant advantage of 2618 is its high ductility. Ductility is the ability of a material to undergo plastic deformation without breaking. Additionally, 2618 has excellent fatigue resistance, which is crucial in high stress racing applications. Fatigue resistance refers to the ability of a material to withstand cyclic loading without developing cracks or failures. The fatigue strength of 2618 is typically around 124 MPa, while that of 4032 is around 114 MPa both @24°C and the same cycle number (matweb, 2023). This means that pistons made from 2618 can withstand more cycles of stress without failure than those made from 4032.

Despite the advantages of 2618, it is more expensive than 4032. This is due to the additional alloying elements and manufacturing processes required to produce it. However, the cost is often justified by the superior performance and reliability of 2618 pistons, which can ultimately save money in the long run by reducing engine failures and maintenance costs.

The issues of higher wear, especially in the areas of the piston skirt and ring grooves can be mitigated with processes such as hard anodized coatings, however this is again an additional cost.

In conclusion, 2618 is the superior choice for racing piston design due to its exceptional strength, ductility, and fatigue resistance. While it may be more expensive than 4032, the benefits of using 2618 can ultimately outweigh the cost in terms of performance, reliability, and long-term cost savings.

4 Manufacturing Process

In the manufacturing of a piston the first decision to be made is whether it should be forged, CNC machined from billet or cast.

In this application forged or billet pistons are both advantageous over cast pistons owed to their higher strength. This is typically due to the grain structure of castings being more randomised than that of forging or billet. In many cases silicone is also added during casting which decreases the ductility of the alloy which as mentioned before has its drawbacks in performance orientated pistons. Forging compared to billet pistons are the stronger piston, again owing to a more uniform grain structure. However a billet piston is more cost effective for small production runs and prototyping due to the fact dies do not need to be produced, therefore you can go from design to product much faster.

As cost is less of a factor a forged piston would be the ideal choice.

The machining process used to make forged pistons involves several steps. First, the raw material is heated to soften it and make it easier to shape. The material is then shaped into a rough shape through forging, using a hydraulic press and a die.

Next, the rough shape is subjected to several machining processes to create the final shape and dimensions of the piston. The exact process depends greatly on the machine tools capabilities and the tooling available as well as the design of the piston, for example a perfectly cylindrical piston is not ideal due to the change in dimensions due to thermal expansion affecting the diameter of the piston differently at different points around the circumference as well as increasing losses due to friction caused by the skirt and cylinder wall, Baehtel, 2017. This can be achieved on a conventional lathe with the use of a cam attachment, or alternatively can be ground or CNC machined.

A variety of drillings are made, for oil passageways and to rough out the bore for the wristpin before reaming to final size with greater precision

Conventional turning for the ring grooves is generally acceptable as well as filling un-wanted material from the forging to remove weight.

Then the piston is subjected to heat treatment to harden the metal and improve its strength and durability, typically for 2618 a T61 temper is used. The T61 temper process involves heating the aluminium alloy to 160-180°C for 2-4 hours, followed by hot water quenching in order to reduce residual stresses.

Finally with 2618 being less wear resistant, hard coatings, such as anodizing with PTFE, can be applied to the piston skirt to improve wear resistance and reduce friction. Anodizing with PTFE involves immersing the piston in an electrolytic bath containing sulfuric acid and applying an electric current to produce a hard and porous oxide layer on the surface of the aluminium. The PTFE is then impregnated into the surface of the anodized layer to provide a low-friction surface. This process improves the performance and durability of the piston, allowing it to withstand high-temperature and high-pressure conditions.

Other options are available however it is very dependent on the application and material selection with products from JE reducing wear and friction but also reducing noise on cold start caused by the larger cold clearances required when using 2618 (Smith, 2017)

5 Conclusion

Piston material is a complicated topic and there is always a level of compromise when choosing a material, in this application 2618 may be the best choice however it comes with its drawbacks, in the way of cost and longevity.

This is also the case in the manufacturing process, if cost was more of an issue or timescale for manufacturing then CNC machining may be preferred, however with the tooling made the option to make more of the same piston is always available.

There are also many variables which dictate how a company may manufacture a piston, whether it is being outsourced to a 3rd party, experience levels in certain processes and design requirements.

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