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Materials Selection Report

ACHA 4001

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2106621

March 2023

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1 Introduction

Pistons are a critical component of an internal combustion engine (ICE), This technical report will look at a piston from a 4-stroke gasoline fuelled engine. They must withstand extreme temperatures, pressure and mechanical stress without failure or deformation. Therefore, the selection of materials is crucial to the success of the piston, having a direct impact on the performance, longevity, and efficiency of the engine.

This report aims to explore different material options which are commonly used in the production of pistons within the automotive industry. It will look at their properties, such as thermal expansion, wear resistance and strength, and how this material selection impacts the piston performance. A comparison will be made of these different materials, highlighting their strengths and weaknesses before deciding which material is best suited for the application.

Lastly, a detailed analysis of the production steps involved in manufacturing a piston. The manufacturing process of casting and forging will be considered, as well as an examination of the prerequisites required for both manufacturing processes.

2 An Insight into a Piston

The piston must operate in a dynamic, thermal, and mechanical environment. The piston is responsible for converting energy generated from the combustion of fuel and air, into mechanical motion. This energy is then transferred to the crankshaft through the connecting rod. Most commonly, a piston is typically a cylindrical component with varying profiles, depending on the needs of the engine (*Stojanovic, Glisovic, 2016*).

2.1 Requirements of a Piston

- Withstand high temperatures and pressures created by the combustion process.
- The ability of the material to maintain its shape even when faced with extreme pressure and temperature.
- Designed with the correct choice of profile to ensure it is the most efficient for power output and combustion.
- Be of a tight enough fit to not allow leaks and maintain compression, while having the lowest friction losses achievable.

2.2 Temperature

Within a 4-stroke gasoline engine, the piston and surrounding parts all reach different working temperatures, below is an example of the range of temperatures under normal operating conditions:

- Piston Face: 301°C
- Cylinder Wall: 190°C
- Spark Plug: 593°C
- Intake Valve: 246°C
- Exhaust Valve: 649°C

(*VEHQ, 2023*)

Hayes et al (*1994*) found that the amount of throttle can affect the heat generated within the combustion chamber. A temperature of 129°C was observed with very little throttle and 246°C when the throttle is fully open. The efficiency of the cooling system can further affect the temperature range. Meaning that piston material selection, in terms of heat tolerance, is critical to its success.

2.3 Pressure

For a four-stroke gasoline engine, pressures between 6.0 MPa and 9.0 MPa are to be expected from a naturally aspirated engine. With the addition of a turbocharger, these gas forces will increase, leaving figures between 14.0 MPa to 24.00 MPa (*Mahle, 2016*).

2.4 Common Problems

When it comes to fit and clearance, too tight of a fit can cause an increase in friction, The piston system accounts for around 40% of the frictional force of the engine, with approximately 70% of that frictional force being that of the piston rings (*Summerfield, 2020*), the result of this increase is a loss of power. If the clearance is too much, and the gap between the piston and the cylinder wall is too great, there is a risk of piston slap, a phenomenon which causes the piston to shake on the downward power stroke, as the engine warms, the reduction in clearance can eliminate this problem (*Carbiketech, 2023*).

3 Desirable Material Properties for use in a Piston

This section will look at the key material properties to help narrow down material choices, looking into various properties which need to be considered for a piston to be successful in its hostile environment.

3.1 Engineering Properties

Table 1 - Material Properties (Tudor, 2023)

Material Property	Corresponding Definition
Brittleness	Property of a material which enables it to withstand permanent deformation
Creep	Is a slow and progressive deformation of a material
Corrosion Resistance	Material's ability to withstand the deterioration and chemical breakdown of a material when exposed to certain environments
Ductility	Property of a material which enables it to be drawn out into a thin wire
Elasticity	The ability of a material to resume its normal shape after being stretched or compressed
Electrical Conductivity	The degree to which a material will conduct electricity
Fatigue	The long effect of repeated straining action which causes the strain or break of the material
Hardness	Resistance of a material to force penetration or bending
Impact Strength	The ability of a material to resist suddenly applied loads
Malleability	Property of a material which permits it to be hammered or rolled into sheets of other sizes or shapes
Plasticity	Material's ability to undergo some permanent deformation without rupture(brittle)
Strength	Mechanical properties that enable a material to resist deformation under the actions of an external load
Stiffness	Is the resistance of a material to elastic deformation or deflection
Thermal Conductivity	The rate at which heat passes through a specified material
Toughness	Property of a material which enables it to withstand shock or impact

3.2 Chemical Properties

Whether cast iron, steel or aluminium, the piston meets fluids and gases during the combustion process. The piston will also encounter oil from below the piston rings. The piston top will be in contact with fuel, gasoline in this case, when this is combusted, can reach temperatures of up to 300-350°C (Singh *et al*, 2020). This will then influence the surface properties of the piston.

3.3 Thermal Properties

Thermal conductivity is a property which describes the ability of a material to conduct heat. A material with high thermal conductivity can transfer heat efficiently, while a material with a lower thermal conductivity transfers heat slowly (*Hsin-ni, 2017*).

Table 2 - List of metals and their melting points (*Chakravarthy et al, 2012*)

Metal	Melting Point	
	(°C)	(°F)
Beryllium	1285	2345
Cast Iron, gray	1175 – 1290	2150 - 2360
Chromium	1860	3380
Cobalt	1495	2723
Copper	1084	1983
Cupronickel	1170 – 1240	2140 - 2260
Gold	1063	1945
Hastelloy C	1320 – 1350	2410 - 2460
Inconel	1390 – 1425	2540 - 2600
Incoloy	1390 - 1425	2540 - 2600
Iridium	2450	4440
Iron	1536	2797
Manganese	1244	2271
Molybdenum	2620	4750
Monel	1300 - 1350	2370 - 2460
Nickel	1453	2647
Niobium (Columbium)	2470	4473
Osmium	3025	5477
Platinum	1770	3220
Rhodium	1965	3569
Silicon	1411	2572
Carbon Steel	1425 - 1540	2600 - 2800
Stainless Steel	1510	2750

When a material is heated or cooled, the size and volume can change by an amount proportional to the length and the temperature change, this is known as thermal expansion. A low thermal expansion is a desirable characteristic a piston should possess (enginerringtoolbox.com, 2023).

3.4 Manufacturing Properties

The first manufacturing property to consider is machinability, a term which covers the ease with which materials are machined, it considers the speed at which material can be cut, how it can affect the life of the tools being used and the quality of finish expected. Material properties which can affect machinability are, not being too high ductility, not too abrasive and not too high strain hardening (*Aran, 2007*).

The castability of a material is used to describe the best in which a material can be molded without defects. The material properties which can affect castability are, the material's melting point. A lower melting point is more desirable, as it will take less energy to melt the material, and a high melting point can cause an increase in costs for manufacturing of parts (*Aran, 2007*).

Table 3 - Machinability rating of common metals (Aran, 2007)

Material	Hardness	Machinability Rating
B1112 Steel	160 BHN	100%
6061-T 7075-T Aluminum Alloys	-	190%
Aluminum	-	120%
416 Stainless Steel	200 BHN	90%
1120 Steel	160 BHN	80%
1020 Steel	148 BHN	65%
8620 Steel	194 BHN	60%
304 Stainless Steel	160 BHN	40%

4 Material Selection

Due to the forces and temperatures a piston faces within a cylinder, the material choice can be the difference between a piston that can last the engine's lifetime, and a piston that needs replacing after a certain period, or hard use, such as low cubic capacity (CC) high rpm engines. This section will look at materials considered for the manufacturing of a piston.

4.1 Aluminium

More commonly seen in gasoline engines, aluminium is a lightweight metal that has a low density, allowing it to be lighter than cast iron or steel. Due to the higher engine speeds seen in gasoline engines, this lightweight property is considered desirable, by reducing the reciprocating mass, it allows the engine to accelerate faster, thus improving performance.

When considering the strength of the material, Aluminium used in pistons is designed to have high stiffness and strength. As seen in section 2.4, the piston must withstand high mechanical stress, so the piston must maintain its shape under these conditions. While considering strength, it is important to also consider the ductility of the material, fortunately aluminium is a relatively ductile material and can deform under higher pressures without fracturing. This can help prevent a catastrophic failure of the piston when met with extreme conditions (*Gabrian, 2023*).

Due to the various contaminants the piston will encounter, corrosion resistance must be high enough to protect against corrosion. Aluminium oxidation tends to happen faster than that of steel, due to its affinity for oxygen (*Wiley, 2022*), this can be resolved by applying a protective coating. The application of a thermal barrier coating (TBC) has been shown to improve both performance and emission characteristics in gasoline engines. With a ceramic-coated piston, a decrease of up to 43.2% was found in hydrocarbon emissions compared to the same engine without coated pistons (*Yao et al., 2019*).

To deal with high temperatures, thermal conductivity and thermal expansion must be considered. With the high thermal conductivity of aluminium, the piston is less likely to overheat, this is achieved by allowing the heat to transfer to other nearby components, improving the engine's efficiency.

4.2 Steel

Firstly, looking at the strength and stiffness, steel is a high-strength metal that is denser than aluminium and three times stronger (*Tingwall, 2014*), making it resilient to high temperatures and pressures with little increase in weight. Steel also has a high toughness, which is critical in preventing fatigue failure and fractures to the piston, this can be witnessed in commercial vehicles, where peak pressure in the cylinder can reach 70 bar (*Baskar et al, 2018*).

In terms of corrosion resistance, steel can be prone to oxidation, this can be cured with specialist coatings, other coatings could be used to increase the hardness of steel, and it is common to see the material coated or bonded with other materials (*Mallick, 2020*).

Steel has a moderate coefficient of thermal expansion, lower than that of aluminium. Steel expands around 25% less than aluminium would in the same environment. This reduces the gap between the piston as far as the first piston ring, and the cylinder wall. The main benefit of this is a reduction in emissions and pollutants (*Vasilash, 2014*).

4.3 Chosen Material for Manufacturing

Overall, steel is a strong reliable material for a piston in a 4-stroke engine but given that this report is aimed at a gasoline engine, as opposed to a diesel engine, then the more commonly used aluminium becomes the viable option. In summary, the combination of high strength, good thermal conductivity, and its lightweight nature, make it an excellent material for a gasoline fuelled internal combustion engine.

5 Manufacturing Process

Common manufacturing techniques seen in the Automotive Industry are casting and forging. This technical report will look at upset forging, a well-used option for pistons, and the type of casting considered is die casting, as the process is quicker than forging and is well suited for mass production of high-volume parts (*iqsdirectory.com*, 2023)

Aluminium is a great choice for either method, with a low melting point, it makes forming and shaping this raw material into a finished product an easier task, and this can also bring financial benefits.

5.1 Forging

Firstly, the manufacturing process of forging. Aluminium forging is created by heating and shaping billets of the material via mechanical pressure using a forging press. Although forging has its limitations with complex shapes, pistons do not fall into this category and it is a popular method of manufacturing, especially in racing pistons.

Aluminium, with its low melting point, can be forged at a lower temperature than other metals. Its low density means it does not retain heat well, this can be solved by using hot tooling to prevent the workplace from cooling rapidly during the forging process. The common forging temperatures range between 412°C and 468°C (*Clintonaluminium.com*, 2022).

Prone to fewer impurities than casting, the process aligns the grains structure of the material, causing a stronger, more uniform material. Resulting in a generally tougher and more durable product. In terms of surface finish, forged parts have a smooth finish from the process and there is little need for the parts to be machined after shaping. Forging ensures the elimination of porosity, non-metallic inclusion as well as other defects that could compromise the integrity and the performance of the piston (Prasad, et al, 2022).

Lastly, looking at costs, forging can become an expensive process due to the higher cost of equipment and skill required when compared to casting.

5.2 Casting

Die Casting is a method of manufacturing that creates the finished product by pouring molten aluminium into a pre-made mold and then allowing it to solidify. Casting can cope with more complex shapes and intricate designs is concerned, as forging hits its limitation far sooner in terms of complex designs.

The surface of die casting can leave parts needing further work. This is due to the rougher finish out of the cast, meaning more care must be taken during the quality control process, but a positive benefit of aluminium cast parts is that a layer of aluminium oxide immediately forms upon removal from the mold. This provides a form of protection against forms of corrosion such as rust (Alfred.org.uk, 2023).

Die Casting can consume a high amount of energy and is considered one of the most energy-intensive manufacturing processes. Melting metal consumes around 55% of the process, 22% for holding the molten metal, 11% during actual casting, 3% for trimming castings and 9% coming from other operational processes. Resulting in 2100kg of CO₂ per one tonne of finished aluminium casting (Anand et al, 2022).

5.3 Chosen Method

Comparing the two manufacturing methods, aluminium after the forging process is stronger and more durable compared to the casting alternative. Even with the slightly higher costs involved, these can often be offset by the product's longer lifespan and better performance.

5.4 Sustainability

The process of upset forging using aluminium is quite efficient as there is only partial heating necessary, this helps reduce energy consumption and lower CO2 emissions. During the forging process, very little material is wasted.

Aluminium can be 100% recycled. Green aluminium, also known as secondary aluminium, consists of recycled material. The use of secondary aluminium can cut energy during production by up to 90% when compared to virgin material (*Steinerglobal.com, 2023*).

6 Conclusion

In conclusion, after conducting research and analysis on pistons and the manufacturing process involved to produce them. It can be decided that aluminium is the best suited material for this chosen engine and fuel choice, it ensures the production of high-quality pistons capable of withstanding high pressure and extreme temperatures. This is due to its lightweight, high strength to weight ratio, and good heat dissipation properties, resulting in an ideal product for high performance applications.

Furthermore, forging is the most effective method for manufacturing pistons due to its ability to produce a stronger and denser final product. Forging ensures the elimination of porosity, non-metallic inclusions, and other defects, which can compromise the integrity and performance of the piston. Additionally, the control and precision offered by forging can result in less waste and leftover material, meaning it is better for the environment and will lower production costs overall.

Word Count: 2155

7 References

Aluminum Corrosion: Why it Happens and What to Do When It Does - Wiley Metal (no date).

Available at: <https://www.wileymetal.com/aluminum-corrosion-why-it-happens-and-what-to-do-when-it-does/> (Accessed: 15 March 2023).

Anand, A. *et al.* (2023) 'Integration of Additive Fabrication with High-Pressure Die Casting for Quality Structural Castings of Aluminium Alloys; Optimising Energy Consumption', *Trans Indian Inst Met*, 76(3), pp. 347–379. Available at: <https://doi.org/10.1007/s12666-022-02750-y>.

Aran, A. (no date) 'ITU Department of Mechanical Engineering MANUFACTURING PROPERTIES of ENGINEERING MATERIALS Lecture Notes'.

Baskar, G. *et al.* (2018) *Advances in bio-oil extraction from nonedible oil seeds and algal biomass, Advances in Eco-Fuels for a Sustainable Environment*. Elsevier. Available at: <https://doi.org/10.1016/B978-0-08-102728-8.00007-3>.

Effective recovery & quality improvement of aluminium scrap • STEINERT (no date). Available at: <https://steinertglobal.com/metal-recycling/aluminium-recycling/> (Accessed: 14 March 2023).

Everything You Ever Wanted to Know About Pistons – Feature – Car and Driver (no date). Available at: <https://www.caranddriver.com/features/a15109982/everything-you-ever-wanted-to-know-about-pistons-feature/> (Accessed: 15 March 2023).

Hayes, T.K., White, R.A. and Peters, J.E. (1993) 'Combustion Chamber Temperature and Instantaneous Local Heat Flux Measurements in a Spark Ignition Engine', *SAE Technical Papers* [Preprint]. Available at: <https://doi.org/10.4271/930217>.

Ho, H.N. (2018) 'Material recognition based on thermal cues: Mechanisms and applications', *Temperature: Multidisciplinary Biomedical Journal*, 5(1), p. 36. Available at: <https://doi.org/10.1080/23328940.2017.1372042>.

How Hot Does A Combustion Chamber Get In A Vehicle? [The Answer Might Surprise You!] (no date). Available at: <https://vehq.com/how-hot-does-a-combustion-chamber-get-in-a-vehicle/> (Accessed: 14 March 2023).

Mallick, P.K. (2020) 'Materials, Design and Manufacturing for Lightweight Vehicles', *Materials, Design and Manufacturing for Lightweight Vehicles*, pp. 1–488. Available at: <https://doi.org/10.1016/C2018-0-04153-5>.

Piston: Design, Functions, Materials, And Qualities - CarBikeTech (no date). Available at: <https://carbiketech.com/piston-design-functions/> (Accessed: 14 March 2023).

'Pistons and engine testing' (2016) *Pistons and engine testing* [Preprint]. Available at: <https://doi.org/10.1007/978-3-658-09941-1>.

Prasad, S.V.S. *et al.* (2022) 'The role and significance of Magnesium in modern day research-A review', *Journal of Magnesium and Alloys*, 10(1), pp. 1–61. Available at: <https://doi.org/10.1016/J.JMA.2021.05.012>.

RamaKrishna, A. *et al.* (2012) 'Design of a Rescue Robot Assist at Fire Disaster', *International Journal of Computer Applications*, 47(10), pp. 25–30. Available at: <https://doi.org/10.5120/7225-0056>.

Sharafudeen, R. (2019) 'Smart hybrid coatings for corrosion protection applications', *Advances in Smart Coatings and Thin Films for Future Industrial and Biomedical Engineering Applications*, pp. 289–306. Available at: <https://doi.org/10.1016/B978-0-12-849870-5.00010-0>.

Singh, U. *et al.* (2020a) 'Comparative analysis of different materials for piston and justification by simulation', *Materials Today: Proceedings*, 25, pp. 925–930. Available at: <https://doi.org/10.1016/J.MATPR.2020.03.078>.

Singh, U. *et al.* (2020b) 'Comparative analysis of different materials for piston and justification by simulation', *Materials Today: Proceedings*, 25, pp. 925–930. Available at: <https://doi.org/10.1016/J.MATPR.2020.03.078>.

Steel Pistons for Passenger Car Diesels | CompositesWorld (no date). Available at: <https://www.compositesworld.com/articles/steel-pistons-for-passenger-car-diesels> (Accessed: 15 March 2023).

Stojanovic, B. and Glisovic, J. (2016) 'Automotive Engine Materials', *Reference Module in Materials Science and Materials Engineering* [Preprint]. Available at: <https://doi.org/10.1016/B978-0-12-803581-8.01946-9>.

Thermal Conductivity and the Wiedemann-Franz Law (no date). Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/thercond.html> (Accessed: 15 March 2023).

Thermal Expansion - Linear Expansion Coefficients (no date). Available at: https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html (Accessed: 15 March 2023).

'UK Aluminium Industry Fact Sheet 2 : Aluminium and Corrosion' (no date). Available at: www.alfed.org.uk (Accessed: 19 March 2023).

Upset Forging Of Aluminum - Clinton Aluminum (no date). Available at: <https://www.clintonaluminum.com/upset-forging-of-aluminum/> (Accessed: 15 March 2023).

What is Ductility in Metals? Is it an Advantage for Alumium? (no date). Available at: <https://www.gabrian.com/what-is-ductility-in-metals-aluminum> (Accessed: 15 March 2023).

Yao, Z., Hu, K. and Li, R. (2019) 'Enhanced high-temperature thermal fatigue property of aluminum alloy piston with Nano PYSZ thermal barrier coatings', *Journal of Alloys and Compounds*, 790, pp. 466–479. Available at: <https://doi.org/10.1016/J.JALLCOM.2019.03.177>.