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Internal Combustion Engine: Piston Materials and Manufacturing Processes

Engineering Design and Materials ACHA4001

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1. Introduction

The piston is considered one of the most important elements of an internal combustion engine, pistons are exposed to several harsh conditions such as high temperature, high pressure, poor lubrication, and poor cooling condition. Pistons are generally designed to withstand poor operational conditions however, being the part that is more exposed to such harsh conditions pistons are more prone to wear and are often replaced after a certain mileage or engine working hours. As a result, manufacturers consider reliability and durability as top priorities when designing and producing a piston to meet the requirements needed for specific engine operations.

1.1 Aim

The aim of this study is to demonstrate different types of piston materials and discuss important elements such as physical properties and mechanical properties. Additionally, examining different types of manufacturing processes used for pistons, in which will be helpful to identify what material and manufacturing process is best to produce a high-quality piston for specific engine applications.

1.2 Objective

Upon completion of this study, the author must gain a better understanding of the physical and mechanical properties of piston materials as well as the efficiency of different materials that undergo different manufacturing processes. Furthermore, a better insight into the advantages and disadvantages of different manufacturing processes performed in piston production. The author must apply the knowledge to create and choose suitable tolerances for the piston, gudgeon pin, and connecting rod that is given for the second task of this study.

2 Material Properties

Lohakare, P. *et al.* (2022) pointed out in their research that due to the friction of the piston and piston rings against the cylinder wall, it loses 5% of the total fuel energy, and due to the heat created by the combustion of the air and fuel mixture, the piston can be exposed to such high temperatures, especially the piston crown ranging from 600 to 700 Kelvin K , the piston is also responsible for carrying the gas pressures that are transferred to the crankshaft where petrol engines bear 3 to 5 megapascal MPa and diesel engines could reach 6 to 9 MPa and for some diesel engines with high density, it could reach up to 20 MPa . Furthermore, pistons work in a reciprocating manner and engine speeds vary where normal production cars operate at 1000 to 6000 revolutions per minute RPM , and motorcycle engines operate at 1000 to 12000 RPM (Lohakare, P. *et al.*2022).

In the production of pistons, pure metals lack properties that meet the current mechanical component requirements, therefore manufacturers are using alloy materials that compose two or more metals that possess better properties than its counterpart (Kerni, Raina, and Haq, 2018). At present, there are various types of materials used in the production of engine pistons. The most common and widely used alloy is Aluminium alloys due to its excellent malleability, castability, thermal conductivity, corrosion resistance, high strength, and lightweight characteristics all of which are ideal for the production of automotive components (Kerni, Raina, and Haq, 2018).

Generally, the alloying elements for alloy materials are Aluminium AL , Silicon Si , Iron Fe , Titanium Ti , Copper CU , Nickel Ni , Magnesium Mg , and Manganese Mn these elements are present in different volume ratios which help to improve the physical, mechanical, and tribological property of the material(Kerni, Raina, and Haq, 2018). Research done by Ahmed, A. *et al.* (2016) investigated the addition of alloying elements such as Ni and Cu affects the strength and hardness of heat and non-heat-treated aluminium alloy pistons and improves their machinability. Mg improves the characteristics of work hardening, it also grants significant strength and great resistance to corrosion, but due to the good thermo-mechanical property, the maximum addition of Mg is only at 4-8 weight per cent $wt\%$. Mn enhances the tensile strength and substantially improves the low cycle fatigue resistance as well as enhanced resistance to corrosion (Ahmed, A. *et al.* 2016). Aluminium Silicon $Al-Si$ alloy is one of the most sufficient materials used in manufacturing engine pistons, Si being the main alloying element of this material it has three major categories Hypoeutectic $<12\% Si$, Eutectic $12-13\% Si$, Hypereutectic $14-25\% Si$. Although $Al-Si$ alloys obtain excellent properties, their microstructures become unstable above $230\text{ }^{\circ}C/530\text{ }K$ making them unsuitable for extremely high temperatures which can be regulated with the application of different heat and coating treatments (Ahmed, A. *et al.* 2016).

Figures 1 and 2 exhibit the mechanical properties such as the yield strength, fatigue strength, and density of the metallic elements.

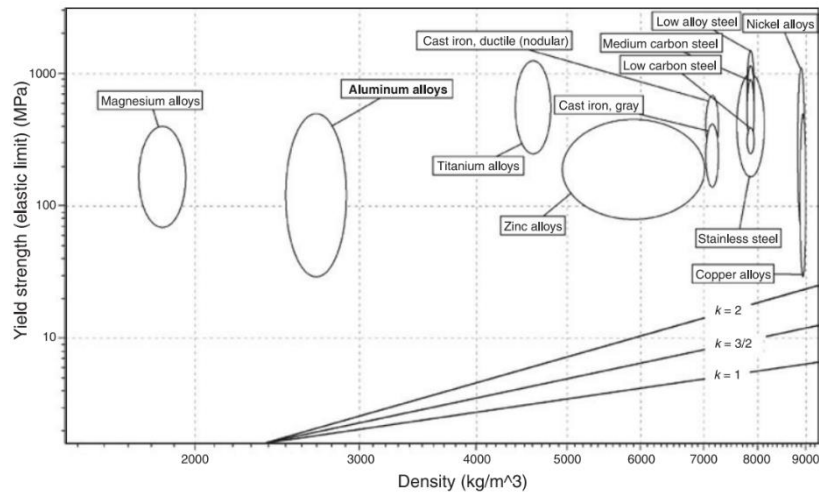


Figure 1. Yield Strength (Ashby, M.F. 2017)

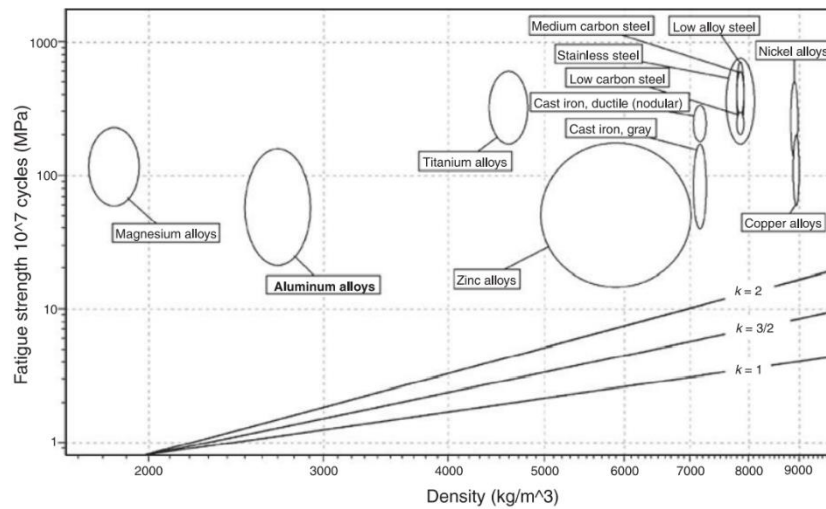


Figure 2. Fatigue Strength (Ashby, M.F. 2017)

Apart from mechanical properties, another important element that is highly considered for piston manufacturing is the thermal properties. In this classification, there are two important temperatures Melting Point T_m , and Glass Transition Temperature T_g , these temperatures directly associate with the solid bond strength. Crystalline solids contain a sharp melting point, while non-crystalline solids have a narrow melting point, the T_g temperature represents the transformation of a pure solid to a molten liquid (Ashby, M.F. 2017). Another essential temperature of the designing stage is the temperature use range where Maximum Temperature T_{max} and Minimum Temperature T_{min} help to identify the peak

temperature of the material where it functions moderately without chemical change or excessive creep, in addition, thermal conductivity is an important element where the amount of heat is directed through the material at a stable position (Ashby, M.F. 2017).

Material	$M_1 = \lambda/\alpha$ (W/m)	$M_2 = E^{1/2}/\rho$ (GPa ^{1/2} /(Mg/m ³))	Comment
Silicon	6×10^7	5.2	Excellent M_1 and M_2
Silicon carbide	3×10^7	6.4	Excellent M_1 and M_2 but more difficult to shape than silicon.
Copper	2×10^7	1.3	High density gives poor value of M_2 .
Tungsten	3×10^7	1.1	Better than copper, silver or gold, but less good than silicon or SiC.
Aluminium alloys	10^7	3.3	The cheapest and most easily shaped choice.

Figure 3 Materials to minimise thermal distortion (Ashby, M.F. 2017)

3 Material Selection

Material selection is considered a difficult stage of product manufacturing as engineers consider various circumstances such as material availability, expenditure, environmental impact, physical and mechanical properties, etc (Chatterjee, and Chakraborty, 2022). To create a more systematic way of selecting suitable materials Chatterjee, and Chakraborty, (2022) suggested the use of the Multicriteria Decision Making *MCDM* method which has been found as an efficient method to narrow down the choices for the material selection stage. Furthermore, there are a few *MCDM* techniques developed to assist the material ranking such as *VlseKriterijumska Optimizacija I Kompromisno Resenje VIKOR*, Technique for Order of Preference by Similarity to Ideal Solution *TOPSIS*, Analytic Hierarchy Process *AHP*, Multi-Objective Optimization on the basis of simple Ratio Analysis *MOORA*, Preference Ranking Organization Method for Enrichment Evaluation *PROMETHEE*, etc (Chatterjee, and Chakraborty, 2022).

Maleque, and Salit, (2013) have suggested a huge selection of suitable materials for piston production in their research, however, this study will only be focusing on the most prevalent materials such as Gray Cast Iron *GCI*, *Al-Si* alloy, *Ti* alloy, *Ni* alloy, and Aluminium-metal Matrix Composite *AMC*. *GCI*: Due to its inexpensive cost, great heat stability, and manufacturing process, the *GCI* has become one of the top choices for the production of piston and piston rings, its graphite state behaves as a reservoir of oil that helps lubrication for dry starts or other poorly lubricated areas. *Al-Si* alloy: amongst the whole *Al* alloys category, *Al-Si* alloy became a prominent choice for piston materials owing to its excellent strength-to-weight ratio, and low thermal expansion coefficient, *Al-Si* alloy also plays a huge part in most substantial operations due to their desirable features such as machinability, castability, weldability, and corrosion resistance. *Ni-alloy*: nickel alloys are developed to help achieve the optimum oxidation resistance, traditionally *Ni-alloys* contain approximately 60% of *Ni*, unlike the current *Ni* alloys that have a lower amount of *Ni* with less than 40% although current *Ni-alloys* contain significantly better properties (creep and oxidation properties) than its counterpart. *Ti-alloys*: Titanium has been considered one of the top-tier materials because of its superior strength and mass reduction capabilities which is highly sought after in the field of racing and widely used in other high-performance applications not only in the automotive industry but also in aviation and marine machinery. *Ti-alloys* offer high corrosion resistance, high thermal strength, low density, and low elastic modulus ranging from 55 to 114 gigapascal *GPa*. *AMC*: *AMC* materials are assumed to produce an approximately 60-65% reduction in weight in comparison to the *GCI* materials, and due to the increased amount of mass reduction *AMC* pistons can improve fuel consumption efficiency. However, the *AMC* materials have a significantly poor friction property, therefore at high-speed engine operation, the *AMC* piston can cause a significantly greater wear rate than the *GCI* piston. The only real advantage of *AMC* materials is the inexpensive manufacturing and fuel consumption efficiency (Maleque, M.A., and Salit, M.S., 2013).

Material	Properties						
	1	2	3	4	5	6	7
	Friction coefficient	Wear rate ($\times 10^{-6}$ mm ³ /N/m)	Thermal capacity, (KJ/Kg-K)	Thermal conductivity (W/m-K)	Specific gravity (Mg/m ³)	Yield strength (MPa)	Tensile strength (MPa)
Gray cast iron	0.41	2.36	0.46	80	7.2	460	455
Ti-alloy	0.34	246.3	0.58	17.58	4.42	700	1,014
Ni-alloy	0.39	5.32	0.41	12.6	8.4	851	1,100
Al-alloy	0.36	2.89	0.714	190	2.73	480	510
Aluminium matrix composite 1	0.35	3.25	0.98	155	2.7	276	310
Aluminium matrix composite 2	0.44	2.91	0.92	180	2.8	425	485
Titanium matrix composite	0.31	8.19	0.51	17.85	4.68	700	1,029

Figure 4. Candidate Materials and its Properties (Maleque, M.A., and Salit, M.S., 2013).

4 Manufacturing Process

The manufacturing process is the final stage of piston production, there are numerous techniques that are being operated namely Casting, Moulding, Deformation, Powder method, Composite forming, and Additive manufacturing are the primary shaping techniques each used accordingly depending on the intended use, materials, shape, size, precision, and quantity. Although the manufacturing process is not limited to such processes mentioned, there are other aspects that are equally important such as machining, heat treating, and coating (Ashby, M.F. 2017).

However, this section will only be focusing on Casting and Deformation (hot and cold forging) processing techniques because these two are the main shaping techniques that are widely used in the piston manufacturing process.

Casting: there are different types of casting techniques, gravity, friction stir, centrifugal, die-casting, investment casting etc. Casting can be done by pouring or forcing the liquid (molten metal for piston application) into the mould, therefore the design shapes for casting must be simple to allow the liquid to flow easily and be able to fill the mould without leaving any air pockets. The accuracy of the finished cast product range from substandard (sand casting) to optimal (die casting) (Ashby, M.F. 2017). *Al-Si* alloy Casting: Centrifugal casting has exhibited a significant increase in hardness that produced a value of 23.7 Hardness Rockwell B *HRB* from the piston crown to the piston skirt. Friction Stir Casting *FSP* has a very similar approach to centrifugal casting, *FSP* brought an enhancement of tensile strength and improved elongation from 1% to 15% (Ahmed, A. *et al.* 2016).

Deformation Process: on this technique, the materials can be shaped in different temperatures cold, warm, and hot correlated to the T_m of the material. Rolling, drawing, and cold forging ($T < 0.35 T_m$) take advantage of crystallization to achieve an optimum strength of the finished product at the cost of greater higher pressure. Warm working ($0.35 T_m < T < 0.55 T_m$) does not allow recrystallisation but grants reconstruction. Extrusion, hot rolling, and hot forging ($T > 0.55 T_m$) where the material is rolled or pressed into a die with controlled pressure. The high temperature causes simultaneous recrystallisation and lowers the yield strength of the material which allows for minimised shaping pressure (Ashby, M.F. 2017).

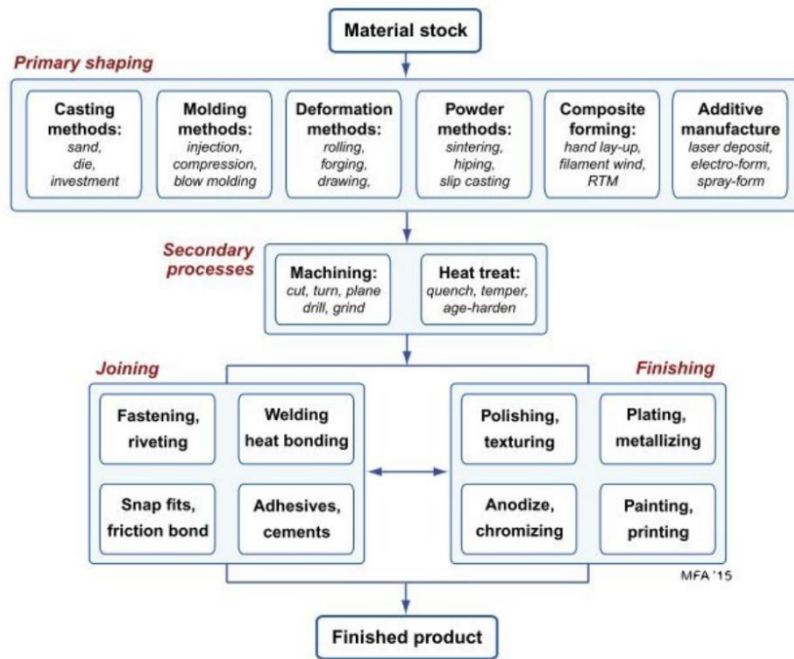


Figure 5. Manufacturing Stages (Ashby, M.F. 2017)

5 Conclusion

In order to produce a sturdy piston, material selection, and manufacturing processes are carefully selected with respect to the characteristics of the materials and the intended use of the finished product. It is also pointed out that the operational efficiency of a piston highly relies on its fundamental material and its physical characteristics. It is important to choose the most adequate material that will increase the piston efficiency and provide desirable characteristics such as lightweight, less corrosion, durability, and the ability to withstand distortion due to the forces acting inside the combustion engine.

The chosen vehicle for this study is a normal commuter car which is an Audi A3 with a 2.0-litre diesel engine. Therefore the author has chosen the Aluminium Silicon *Al-Si* alloy and casting (centrifugal casting) as the most suitable material and manufacturing process from an economical and practical standpoint. *Al-Si* alloys have a very good balance of physical and mechanical properties and can easily be improved with the addition of other alloying elements. Centrifugal casting is the most suitable method as it allows equal distribution of elements into the whole piston. The table below shows the measurements and tolerances for the chosen piston application.

	Piston	Gudgeon Pin	Pin Boss	Connecting rod
$\varnothing$ mm	81	21	21.05	23
Tolerance	+0.05	+0.02	+0.00	+0.02
	-0.1	-0.02	-0.00	-0.00

Table 1. Measurements and Tolerances (Aganon, 2023)

6 References

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