

MATERIAL SELECTION REPORT

**Engineering Design and Materials
ACHA4001**

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1. Introduction

The following report will outline a design specification as well as a material and manufacturing process selection with consideration for the environments in which it will be used for a vital engine or suspension component from a road or race car made within the last 10 years. The component researched within this report will be a piston from a Mk6 Volkswagen Polo. The aim of this research will be to create a component that is the best possible combination of materials and manufacturing processes with a clear justification of the decisions made.

2. Component Design Specification

A piston needs to endure extreme conditions for prolonged periods of time with no defections or failures. It's expected that a piston will reach 300 degrees Celsius during heavy use (Dudareva, et al., 2017) due to the compressive forces generated by the piston itself during the compression stroke (University of Windsor, n.d.) as well as the heat generated by frictional forces. A piston also needs to withstand high amounts of pressure created by the gasses that are combusted. With that being said, the presence of gas also means corrosion resistance is important. There will also be constant engine vibration that the piston needs to withstand.

In terms of the material used, it'll need to be capable of withstanding the 300°C (Dudareva, et al., 2017) temperatures and beyond with minimal deformation and expansion. A high thermal expansion would mean the low tolerances needed for a piston would be ruined. The material also needs a very high fatigue strength given that "engines on newer cars have an average lifespan of around 10 years or 200,000 miles" (Wrench, 2020). Machinability and malleability are also important properties to consider depending on the chosen manufacturing process. The chosen material will also need enough strength to absorb the energy created by the combustion process without breaking or deforming. Toughness will also be very important as a piston is subjected to much wear and tear during its life cycle. A material with a toughness of up to 28MPa (Doddamani & Kaleemulla, 2016) should prove enough to withstand a piston's life cycle. On top of all this, the material also needs to be relatively light in order to efficiently handle the inertia of a functioning piston. Once the material has reached the end of its life cycle as a piston it's also imperative that it is recyclable and can be used for another purpose.

The chosen manufacturing process must be capable of manufacturing components with tolerances as low as 0.02mm (Federal Mogul Engine Solutions, 2022). The ability to manufacture complex shapes is also paramount as a piston is a relatively complex component. The selected manufacturing process must also have a low failure rate and produce high quality components. A failure in this regard would quickly be revealed in the high pressure environment of an engine cylinder. However, the quality offered by the manufacturing process must not come at the detriment of affordability. The component should still be reasonably inexpensive to manufacture due to the scale of its manufacturing.

3. Material Selection

The environment in which a piston operates means that only a metal can realistically be considered as a possible material for selection. Three metals stood out in particular as candidates to be the final material: steel, cast iron and aluminium.

3.1. Steel

The first material that could be a possibility is steel. Steel is a contender for its “incredible strength and durability” (Endura Steel, 2023) which are two important properties as gathered from the design specification. Steels can also be “resistant to temperatures over 500°C, maintaining their strength and other properties” (AZo Network, 2021) which also caters to the needs of the design specification. They are also “extremely malleable and allow great flexibility with acquiring different shapes” (Agni, 2018). Add to this that steel is completely recyclable (Recycle More, n.d.) and it seems to be a near perfect material for a piston. However, the one drawback of steel is its weight with a density of 7.80 -8.00 g/cc (grams per cubic centimetre) (MatWeb, n.d.)

3.2. Cast Iron

Another possible material for a piston is cast iron. It's cheaper than steel “because of the lower cost of material needed to produce cast iron.” (Rapid Direct, 2022). It's also “typically much easier to machine than steel” (Reliance Foundry, n.d.), the latter of which “causes more tool wear, resulting in higher production costs” (Reliance Foundry, n.d.). Cast iron can also be used at “up to several hundred degrees Celsius, without melting or deforming” (Skottsberg For Life, n.d.) which satisfies the design specification. Cast iron can also resist corrosion and has a high degree of durability thanks to its flake graphite form (Crescent, 2023). However, it does also have a much larger range of density than steel does at 5.54 – 7.81g/cc (MatWeb, n.d.) with the lowest value being a notable amount smaller than steel and the largest about the same as steel.

3.3. Aluminium Alloy

The final material to be considered for selection is aluminium alloy. With a melting point of 660.37°C (MatWeb, n.d.) and a much lower density of 2.6989g/cc (MatWeb, n.d.), it is better suited in the eyes of the design specification than the first two materials discussed. The lower density will also help in this particular case as the engine in a Volkswagen Polo is small and will benefit more from lighter materials being used. It's also important to note that aluminium alloy specifically is what's being discussed as unalloyed aluminium's “strength and wear resistance are too low” (Mahle International GmbH, 2016). Aluminium is also “more

machinable than other metals like steel and titanium” (Howard Precision Metals, n.d.) which will be of use when considering manufacturing processes.

3.4 Final Selection

Overall, aluminium is the material with the best suited properties for use in a piston and satisfies the most of the points raised in the design specification. However, there are varying types of aluminium each with their own advantages and disadvantages. For this particular use case, 4000 and 6000 series aluminium are the two best options; specifically 4032 series aluminium and 6061 series aluminium. 4032 series aluminium is generally used for “applications requiring better performance at higher temperatures” (Smiths High Performance, n.d.) whilst 6061 series aluminium is “used in certain heavy-duty structural applications” (Howard Precision Metals, n.d.).

	4032 Series Aluminium	6061 Series Aluminium
Density	2.68g/cc	2.7g/cc
Melting Point	532°C - 571°C	582°C - 652°C
Thermal Conductivity	138W/m-K	167W/m-K
Modulus of Elasticity	78.6GPa	68.9GPa
Ultimate Tensile Strength	379MPa	310MPa
Yield Strength	317MPa	276MPa
Fatigue Strength	114MPa	96.5MPa
Hardness (Brinell)	120	95
Machinability	70%	50%

Table 1 – 4032 Series Aluminium Values (MatWeb, n.d.), 6061 Series Aluminium Values (ASM Inc., n.d.)

As seen from the table above which displays all the characteristics that are important for a piston’s use case, the two materials have very similar properties with a few key differences. 4032 series aluminium is a slight bit less dense at 2.68g/cc (MatWeb, n.d.) which could be beneficial, however, 6061 series aluminium has a higher melting point and thermal conductivity at 582°C - 652°C and 167W/m-K (ASM Inc., n.d.) which would help the piston dissipate its heat more efficiently. Despite these thermal benefits, 4032 series aluminium is the stronger material for this use case thanks to its increased hardness, higher machinability, better fatigue strength and yield strength. The advantage held by the 4032 series aluminium in these properties simply cannot be overturned by 6061 series aluminium’s superior thermal capabilities.

4. Manufacturing Process Selection

4.1. Forging

The first manufacturing process to be discussed is a common one used within the piston industry: forging. The forging process involves heating the aluminium to a set temperature below its melting point before applying a pressing force to get it into the desired shape (Yamaha, n.d.). The aluminium alloy also retains its original strength as it isn't melted during the process (Yamaha, n.d.) unlike other manufacturing processes such as casting. This is vitally important for the piston as the material has been chosen for its original strength in the first place. However, forging does come with its disadvantages. A major one is that forging "may create parts that do not meet the requirements for high tolerances" (Great Lakes Forge, n.d.) which is true for a piston and falls short of the needs of the design specification.

4.2. 5 Axis CNC Milling

5 axis CNC milling is a manufacturing process that mills the final component out of a billet rather than pressing a billet into shape. A 5 axis CNC milling machine can "move along the three linear axes (X, Y and Z) and rotate around the other two axes (A and B)" (Xometry, 2023) and can use these two added axes to "generate intricate geometries" (Xometry, 2023). This makes it possible for a piston to be manufactured with CNC milling's exceptionally small tolerances that can be as little as 0.0025mm+- (Xometry, 2023) which is very fitting for the piston's design specification. However, CNC milling comes at the cost of both a very high initial investment and maintenance costs to keep them running afterwards too (Xometry, 2023).

4.3. Laser Metal Fusion Printing

The third and final manufacturing process to consider is laser metal fusion printing. This is an "additive manufacturing method where a workpiece is built up gradually in a powder bed" (TRUMPF, n.d.). Printing the piston ends up "saving weight and increasing efficiency in comparison with cast objects" (MPulse, n.d.). However, despite the technology having come a long way in a short space of time, more traditional manufacturing processes still have the edge for now. This is partly due to the longer build times printing brings with it (3Deo Metal 3D Printing, n.d.) as well as the available materials for printing being limited and in some cases taking years for the correct combination of parameters for a successful print to be found (3Deo Metal 3D Printing, n.d.).

4.4 Final Selection

Despite its previously stated issues with tolerance, forging is the best process for the Volkswagen Polo piston and the one that best fits the needs of the design specification mostly thanks to the fact that it's a "cost-effective manufacturing process that can result in significant savings compared to machining from solid" (Brockhouse, n.d.). This means that even if a few pistons are out of tolerance and discarded, the overall cost will still remain smaller than the other manufacturing processes. As stated in the design specification, marginal gains in manufacturing shouldn't come at the detriment of cost. Most other elements of forging are positive ones such as the material retaining its original properties post process (Yamaha, n.d.) and the shape of a piston being easily forged.

5. Conclusion

To conclude, this report set out to create an adequate design specification for a Volkswagen Polo's piston and to follow that up with research of both possible materials and manufacturing processes for that piston. The combination of 4032 series aluminium and forging that was eventually selected is one that is already seen very often for the manufacturing of a piston. This shows how much streamlining has already been done for this component and how no other combination of materials and manufacturing has yet surpassed it despite the rise of new technologies such as additive manufacturing and CNC milling.

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