Review Paper

International Journal of Research and Review
Vol. 10; Issue: 8; August 2023
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Evolution of Materials for Internal Combustion Engines Pistons

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DOI: https://doi.org/10.52403/ijrr.20230827

ABSTRACT

Piston is one of the most important components in an internal combustion engine which transfers combustion energy to the crankshaft via a connecting rod. Increase in an engine's efficiency has somehow necessitated improvement in the piston. This improvement can be achieved by better piston design or using material with superior mechanical properties. Engineers have experimented with different materials for pistons since the introduction of internal combustion engines. This paper reviews the evolution of materials for pistons since the beginning of automotive industry to present day and analyses the properties that attracted engineers to use these materials. The paper also focuses on newly developed materials that have the potentials to replace current piston materials and the work that is taking place. The current trend of changing from diesel to petrol in small internal combustion engines and the affect this will have on piston materials has been analysed.

Keywords: Aluminium, Combustion Engine, Nanostructured, Piston Material, Piston.

1. INTRODUCTION

The automotive and transport industries without a doubt have played an important role in the development of humanity; while on the other hand, they have caused bigger danger to the human being's life environment by creating global warming [1]. There is therefore an ever-increasing pressure on the automotive industry for a greater overall efficiency that have challenged the designers to further push the performance envelope for many engine components. The solution was found in mass reduction of key engine components coupled with higher service temperatures [2]. Improving the efficiency of an internal combustion engine has somehow necessitated the improvement in piston (Figure 1) [3]. Piston works in high pressures and temperatures compared to other engine components and being exposed to some serious mechanical and thermal loading [4]. To withstand these loadings, a piston needs a robust design as well as material with good mechanical properties.

Figure 1. Piston for KTM 450 motorbike engine.

Piston design is an engineering challenge due to the piston's multi-performance nature, complex physics and uncertainty in its operating conditions. If not designed properly, it increases friction and noise, thus leads to reduction in the engine's efficiency and life [5-6]. Even though piston design is directly related to the piston material, but it is not the focus of this paper and is therefore not discussed in detail.

Racing engineers in the early 20th century realised that an engine power/performance could be increased by increasing the mean piston speed (MPS) and piston mass had to be minimised to increase MPS [7]. This initiated an extensive search for materials with better mechanical properties and since then engineers have experimented with different materials and the trend is to continue into the future with the introduction of new materials. The purpose of this paper is to review some of the materials used for pistons along with its pros and cons as piston materials. The paper also reviews the materials that have the potentials to be used in piston applications in the future and the research that is currently taking place.

2. PISTON MATERIAL REQUIREMENTS

Most of the pistons in contemporary gasoline vehicles are made of one or the other aluminium alloys which in itself indicates some properties or combination of properties that make aluminium alloys particularly suitable for this purpose. These properties can be best discovered by considering the requirements a piston material has to fulfil and the functions a piston has to perform.

The very first function of a piston is to transfer the combustion gas energy to the crankshaft through a connecting rod, and to act as a seal against the combustion products and oil in the crankcase. In addition, it must transmit the combustion heat to the atmosphere via the rings and the cylinder cooling jacket. It must perform these functions as silently as possible, without breaking or distorting under the thermal or mechanical stresses. As well as it should avoid changing the shape or size under the influence of heat and without throwing excessive load upon itself or its accessories such as the connecting rod, the gudgeon pin or the crankshaft. The piston must neither be eroded nor burnt by the combustion products and the wear should be kept to the minimum upon both piston and the mating surfaces. Furthermore, the piston be cheap both in itself as a material and in production [1, 8-9].

A piston has to be strong enough to withstand the combustion pressures and the inertial forces generated by its own mass and motion. The strength should be maintained throughout its working temperatures range, which lies between -30 °C and 300 °C in case of petrol and as high as 350 or 400 °C for diesel engines. The suitable piston material therefore should possess the following properties.

- A sufficiently high tensile, compression, creep and fatigue strengths at the operating temperatures range. It should have enough impact resistance to handle any unfair load that the piston is subjected to.
- The material should have low density.
- A high thermal conductivity to protect the piston from weakening due to higher thermal stresses generated by the combustion temperatures and also to avoid detonation or pre-ignition. Detonation results in considerable power loss and further increases stress on the engine components.
- Excellent bearing properties so that the friction between the piston and the cylinder wall can be as low as possible which will minimise the risk of engine seizure.
- A low thermal expansion coefficient to retain the shape and size, but high yield and creep strengths to avoid collapsing under the loads at operating conditions. It should not suffer large permanent growth and be sufficiently free from internal stresses to prevent distortion when heated [8-9].

3. PISTON MATERIAL EVOLUTION

Earlier designers had a limited list of materials to choose from when designing a component; however, that list has grown significantly due to the developments in materials. The materials for piston applications also evolved ever since starting with the cast iron to super alloys in the present. The evolution of materials for piston applications in chronological order is given below.

3.1 CAST IRON

The reputation of cast iron in the human development cannot be disputed and it has proved its durability and strength ever since. Effectively only cast iron and steel were the preferred materials for pistons in the earliest internal combustion (IC) engines due to their high melting points of 1230 °C and 1350 °C respectively [10]. The Lenoir gas engine which later became petrol Otto-cycle engine in 1883 was first built by Daimler and had combustion temperatures reaching over 2000 °C. The cost then dictated cast iron and became the primary piston material until 1906 in racing cars while used in the passenger cars till much later. The marginally improved casting quality after 1906 enabled some engineers to still use cast iron and one such example was Mercedes M93654 which had cast iron pistons and won France Grand Prix (GP) in 1914 [7].

Cast iron was used in many key engine components including the pistons for a long time due to its lower cost, better wear resistance and coefficient of thermal expansion [9, 11-12]. It is well known that cast iron can maintain its tensile strength at temperatures of up to 425 °C, enabling to design a piston with centre of the piston's crown remaining hot while the ring zone cool. This reduces the lubrication consumption and therefore reduces wear [13-14]. Kirloskar et al. [13] have conducted a study using a new engine design and found that low engine oil consumption is achieved only by cast iron piston and liner design. Superior strength and wearing qualities of cast iron compared to aluminium alloys requires less piston-to-cylinder clearance hence decreases the risk of engine seizure [12].

Even though cast iron is three times denser than aluminium, but has higher strength so pistons can be made with thinner sections to achieve some mass reduction. To maintain the status of the dominant piston material, in 1950 metallurgists developed a new type of cast iron called nodular cast iron (NCI) which was a mix of iron, graphite (carbon) and other elements for enhanced physical properties. Nodular cast iron had higher tensile strength and hardness while its derivative compact graphite iron (CGI) had even better tensile strength, hardness and greater resistance to fatigue cracks, making it an ideal material for piston applications [15]. Karl Schmidt GmbH, a German company has developed a one-piece (monobloc) piston with nodular cast iron (NCI) that can be used in applications ranging from of 120–400 mm bore sizes. The piston can withstand mean effective pressure of 16–22 bar making it suitable for passenger cars [16]. Another company KOMATSU developed NCI piston for heavy diesel engine using permanent mould casting technology and proved to be more durable and reliable than conventional aluminium piston [17-18].

Although cast iron has so many advantages as a piston material, but its use is not wide spread especially in Europe due to the casting quality control and technological difficulties. Sand casting has been used as a method for cast iron pistons and it is very difficult to maintain quality and avoid casting defects such as inclusions and insufficient modularization. There is no effective economical means of maintaining quality of the products and secondary processes are required which increase the production cost, hence the advantages of cast iron pistons cannot be realised [19].

3.2 STEEL

Racing engineers in the early 20th century realised that an engine's performance could be increased by increasing the mean piston speed (MPS) and piston mass had to be minimised to increase the MPS. Therefore, they switched to steel from cast iron since steel has 4 times the tensile strength of cast-iron at room temperature so piston sections could be machined thinner to achieve mass reduction. It is believed that Frederick Lanchester first used steel piston in 1905 for his touring car which was later adopted by

Maurice Sizaire in 1907. Maurice machined the pistons from solid steel billets and used them in his pioneering and successful long-stroke 1907 Coupe del' Auto 1.2 L engine [7].

Pistons made of steel have dominantly been used in heavy duty diesel engines (11-16 litre displacement) where extreme operating conditions made it impossible to use an aluminium alloy. The in-cylinder pressure reaches 25–31 MPa in these engines coupled with a minimum mileage requirement of one million miles; an aluminium alloy's thermal load and fatigue life properties are insufficient to meet these requirements.

European regulations require car manufacturers to reduce CO_2 emissions to 95 g/km by 2024 and a major part of their strategy was diesel engine cars since diesel produces 15% less CO_2 than petrol. In addition, the fuel economy and tax incentives made diesel cars more attractive option to the consumers and led to 50-70% market share in Europe (Figure 2). Aluminium alloy pistons are sufficiently fulfilling petrol passenger's car requirements where the peak pressures & mileage stay below 10 MPa and 200,000 miles respectively. However, high speed diesel engines normally run at 20 MPa peak cylinder pressure and to meet the fatigue life requirements at this pressure, an aluminium alloy piston has to have a fairly tall compression height. In contrast, steel piston can sustain pressures higher than 20 MPa without the need for tall compression height. This poses a significant challenge to aluminium dominance in high-speed diesel engine [20].

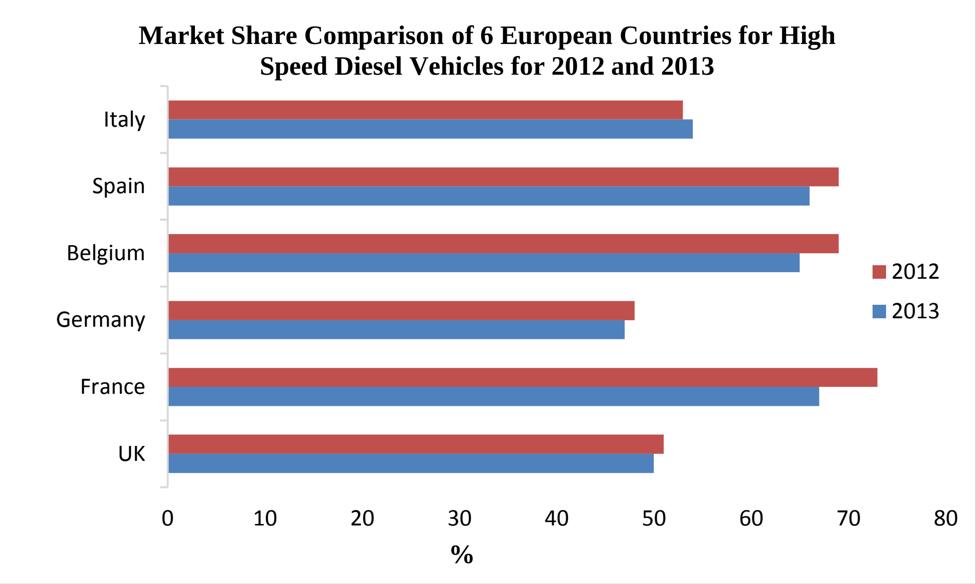

Figure 2. A comparison of high-speed diesel vehicle market share of 6 European countries for 2012-13 [20].

The recent award-winning discovery for a steel piston came from Daimler AG, that developed a steel piston with lightweight aluminium housing for mass-manufactured Mercedes-Benz E 350 BlueTEC car [21]. The piston reduced CO_2 emissions by 2–4% compared to a similar aluminium alloy piston. The poor thermal conductivity of steel increases the component temperatures and leads to higher thermodynamic efficiency and as well as the smaller expansion of a steel piston reduces the friction loss due to smaller the tolerance requirements between piston and cylinder liner. Furthermore, steel properties lead to improved piston strength, robustness and durability which can be achieved with smaller compression height; therefore, piston mass can be reduced despite increase in material density [20, 22].

Furthermore, there has been a great amount of research denoted to find lower cost steel replacement for the current expensive steel. Chen and Worden [23] have investigated to substitute ISI-4140H piston crown material with lower cost micro-alloyed steel (MAS) and found that it is feasible to use MAS with a redesign of the piston. These new lower cost steel substitutes further toughen the competition between aluminium and steel pistons. Performance of steel pistons can be further enhanced by applying coatings, similar to aluminium alloy pistons. Buyukkaya [22] has conducted a study of applying ZrO_2 based film called functionally graded material (FGM) to steel pistons that resulted in 17% increase of maximum surface temperature which improves the thermodynamic efficiency.

Surprisingly, in rush to reduce CO_2 emissions by incentivising diesel and therefore switching from petrol to diesel in high-speed engines (HSEs) in 1985, created an air pollution problem which led to thousands of extra deaths due to the toxic gases generated by burning diesel. Diesel produces 15% less CO_2 than petrol, but produces 4 & 22 times more nitrogen oxide (NO_2) and particulates respectively which penetrate through lungs, heart and brain [24-25]. Incentivizing diesel is widely criticised now and the UK government has introduced toxins tax on diesel cars which is £20 to enter major UK cities [26]. The government is also drawing up plans for diesel scrappage scheme to cut emissions where the diesel car owners will be subsidised £ 3500 to switch from diesel to petrol. A poll by the AA in February 2017 found that 68% of the diesel car owners surveyed support such schemes which shows the changing perception of the general public towards diesel cars [27-29]. The recent Volkswagen emission scandal hit the final nail in the coffin and the long-range future of diesel passenger cars is severely threatened [30-31]. This leap back to petrol will also block steel's future role as a piston material in passenger cars where aluminium alloys are well-established.

3.3 CONVENTIONAL ALUMINIUM ALLOYS

An aluminium piston design was first proposed in 1913 for the Kaiserpreiz aero-engine, but it was simply rejected on the basis of aluminium's lower strength and melting point. It was believed that the material was not strong enough and would not withstand the combustion temperatures since the material's melting point is only 659 °C. Despite the low melting point and reduced hot strength, some designers still tried aluminium in search of lighter materials for pistons. It was the discovery of age-hardening in 1909 by Alfred Wilm that enabled aluminium alloying to achieve higher strength. Aluminium alloy pistons were first fitted by Miller in a 1914 GP Peugeot which finished second in a 500-mile Indianapolis race in 1915 and its sister car won in 1919. It was discovered by the early aluminium alloy piston users that the low melting point was irrelevant since aluminium alloys had 4.5 times thermal conductivity of cast-iron and the heat could efficiently be passed to the cooled cylinder wall. Better thermal conductivity of aluminium alloys allowed compression ratios to be raised without knocking thus improving engine performance. The piston's crown temperature was measured to be 200 °C lower than cast iron [7].

Aluminium alloys have become the preferred piston material due to their specific characteristics such as low density, high thermal conductivity etc. [32]. Aluminium alloy pistons for passenger cars were first introduced in the late 1950s as standard parts in the V-8 cast iron engines [33]. Nearly 85–90% of the cast parts produced for automotive industry are aluminium-silicon (Al-Si) alloys and aluminium is the second most used metal in the world [32, 34]. Al-Si alloy system falls into 3 major groups; hypoeutectic (<12% Si), eutectic (12-13% Si) and hypereutectic (14-25% Si), however most of the Al-Si alloys are not useful for high temperature applications (<232 °C) due to their inferior tensile and fatigue strengths at elevated temperatures [32].

Al-12wt% Si alloys in particular are famous among the groups of aluminium alloys called piston alloys [35]. They have better mechanical properties at higher temperatures and as well as excellent abrasion and corrosion resistance, low thermal expansion coefficient and higher strength-weight ratio [36]. The addition of other alloying elements such as, Ni, Cu, Mg and Fe in Al-Si alloy can further improve the material's performance in piston applications [37].

3.4 MAGNESIUM ALLOYS

Having succeeded with aluminium alloys and the search for even lighter piston materials led engineers to experiment with magnesium alloys. Magnesium is 36% lighter than aluminium and with the melting point of approximately same as aluminium (649 °C) [38]. Most commercial magnesium alloys for the automotive are Mg-Al based alloys and limited to temperatures below 125 °C due to their rapid degradation of mechanical properties especially creep resistance. The addition of rare-earth elements such as Yttrium (Y) and Gadolinium (Gd) can increase the creep resistance up to 300 °C, but increases the material's cost hence the advantage of mass reduction is lost [39]. The most important reason magnesium alloys are not widely used in pistons is due to their lower thermal conductivities compared to aluminium alloys. Magnesium thermal conductivity is nearly 60% lower than aluminium which means more cooling is required to keep the magnesium alloy piston temperature in range to prevent auto-ignition [40].

The first forged magnesium alloy piston was presented in Berlin in 1921 that won the piston design competition and was later used in Mercedes GP 4.5L engine. Mercedes at least finished the 431 km long Targa Florio race in 1922, but magnesium alloy pistons were not used in later Mercedes. Villiers tried magnesium alloy piston in Bugatti 1.5L engine in 1923 and found that after little running the pistons crown were nearly burnt. No known engineer has followed Mg-alloy pistons ever since and seems to be a dead end [7]. However, improvements in material processing methods and piston coatings may make engineers to re-think magnesium-alloy as a piston material for racing applications in future [40].

3.5 CARBON OR GRAPHITE

The research department of Daimler-Benz in Germany has worked for three and half years in a joint project with several partners on the development of carbon/graphite piston without any fibre reinforcement. The density of graphite is much lower than aluminium alloys and has lower thermal expansion coefficient and higher resistance to heat. However, the tensile strength at room temperature is comparably lower than aluminium alloys while its strength slightly increases with temperature. It also has good damping capacity therefore transmits less noise during operation and its excellent frictional properties making it impossible for piston to scuff [41-42].

A carbon piston was designed and manufactured by turning and milling from the solid using CNC (Computer Numerical Control) machines. The piston was fitted into Mercedes-Benz model 190 E which is a four-stroke, four-cylinder gasoline engine with a displacement of 2 litres and bore of 89 mm. The piston was equipped with the standard rings and connecting rod. The piston was found in excellent condition after 56 hours of bench testing with alternating loads. After validating the first piston on a test bed, 3 more pistons were manufactured in 1989 and the fully furnished engine was tested for further 120 hours where the engine run at full load nearly 40% of the time. The pistons were inspected again and were in excellent condition, the engine was then installed in a test car. The car was tested and used by colleagues from the department in city and long distance traffic. The car fitted with all carbon pistons accumulated 15000 miles in total without any trouble. For safety of the driver, the engine speed was limited to 4500 rpm and during the road test the engine performed very well all the time [41].

The engine with graphite piston showed very clear improvements with regards to emissions and fuel consumption without any optimization to the piston and engine. A reduction of 10% in piston mass was achieved while the value for fuel consumption improvement was only 3%.

Comparatively to the aluminium piston, the graphite piston did not show any disadvantages, but before graphite piston will be suitable for mass production, there are at least two pre-requests that have to be accomplished. First, the improvement of the tensile strength and second, the need for economic production process to enable mass manufacturing of graphite [41].

3.6 COMPOSITES

The higher specific strength of composites has attracted engineers to use them in different applications and piston is no exception. A composite is defined as combination of two or more materials that has superior properties than the individual material. Bi-metallic pistons where aluminium alloy pistons are strengthened with steel inserts are not considered as composite pistons hence not discussed here. The different fibre reinforced composites used in piston applications are given below.

3.6.1. CARBON-CARBON REFRACTORY COMPOSITES

The first cooperative effort to design a piston using carbon-carbon composite as a replacement for aluminium alloys was called Advanced Carbon-Carbon Piston Program which started in 1986 and involved NASA (National Aeronautics and Space Administration) Langley Research Centre, US Army, Fort Eustis and Virginia. The primary objective was to develop and test all carbon-carbon pistons to be used in two-stroke engine for the US Army remotely piloted vehicle and later transfer the technology to other applications such as automobiles, light aircraft etc. Carbon-carbon refractory composite was developed by NASA in the early 1960s to be used in the rocket nozzle & nose cone of missiles. It was later also used in the wing edges of Space Shuttle and it is used in modern F1 car’s brakes. The composite has lower density & coefficient of thermal expansion, higher strength, stiffness & thermal conductivity than aluminium alloys and can maintain these properties at temperatures over 1400 °C. The mechanical properties of this composite can be tailored like any other composites depending on the applications [33, 43].

In total eight pistons were produced and tested in two and four stroke engines. It was found that carbon-carbon pistons can potentially enable high performance engines to be more efficient, reliable and have greater power output. However, similar to other composites the biggest obstacle to use this material in mass manufacturing production is the lack of economical production method [33].

3.6.2. ALUMINIUM METAL MATRIX COMPOSITES

Metal matrix composites (MMCs) are engineered combination of two or more materials, which exhibit better properties than those of ingredient materials. The advantage of these materials is that unlike monolithic materials, their properties can be tailored according to the desired engineering properties expected for components and thus offer a great flexibility to designers as a choice material for reducing weight of components. MMCs have shown potential as piston materials and are getting attraction [44].

The metal matrix used in MMCs is mainly an aluminium alloy due to its lightweight and other properties suitable for piston application as mentioned above. The reinforcement could be particulates or fibres, however fibre reinforcement is preferred to optimise wear, seizure resistant, thermal conductivity and strength at elevated temperatures [45].

Despite the superior performance recorded for such composites, their widespread application however is limited by the cost of fibres. This initiated a search for new type of fibre reinforcement which is not only cost-effective, but also possesses superior material properties to further improve MMCs performance for high temperature applications such as pistons. In one such attempt. Kim et al. [46] developed a fibre termed HTZ (High Temperature Zirconia) with chemical composition of 46-54% SiO_2, 26-34% Al_2O_3 and 16-24 ZrO_2 in wt%.

A composite was made using aluminium alloy A336 as a matrix with different volume fractions (7, 11 and 15%) of HTZ and 11% turned out to be yielding optimum mechanical properties. The mechanical properties characterised were strength, fracture toughness, wear resistance and heat conductivity. For preliminary test that lasted 50 hours at full load, the prototype piston was only reinforced locally at the top ring land and skirt regions. After inspection for wear, the piston was tested for further 500 hours at full load. The work concluded that HTZ reinforced composites can be applied in high performance engines [46]. Donomoto et al., 1983 also found that strengthening the top part of aluminium pistons coupled with fibre reinforcement leads to high performance and high load-bearing piston.

However, there are still some speculations around aluminium based MMCs that they too have inferior properties for high temperature applications such as pistons due to their strengthening phases becoming unstable at long term exposure to elevated temperatures [32]. In addition to this insufficient ductility and production issues further hampered their potential in automotive as piston materials [47].

3.7 NANOSTRUCTURED ALUMINUM OR SUPER ALLOYES

The conventional high-strength aluminium alloys are strengthened using various strengthening mechanisms such as grain size refinement and others [48]. To meet higher tensile strength requirements at elevated temperatures; different strengthening techniques have been considered to produce aluminium based nanostructured alloys. They can be produced using mechanical alloying, sever plastic deformation (SPD), melt spinning etc. To improve reinforcement particles distribution in the metal matrix, reactive mechanical alloying under hydrogen, nitrogen and ammonia are used. Secondary production processes such as extrusion and die compact are needed to produce the final bulk materials [48-49].

Nanostructured (NS) aluminium alloys have attracted significant attention during the last decade due to their superior mechanical properties compared to the conventional aluminium alloys. Several types of aluminium based nanostructured alloys have been developed with microstructures of nanometre-sized particles embedded in the aluminium matrix [50-51]. Many types of alloying materials are used, but the decreasing availability and high energy prices of some alloying materials have opened the door to an opportunity to use non-conventional elements such as Niobium (Nb) in nanostructured aluminium alloys. The use of Nb as a reinforcement has been explored by [34] and found that it can improve several properties such as strength, ductility, corrosion resistance and toughness in rapid solidified (RS) aluminium alloys.

Earlier work on the feasibility of the aluminium based nanostructured alloys in piston applications has been carried out by [52] & [35] at the Universities of Buenos Aires and Oxford Brookes respectively. The study done by [35] mainly consisted of simulations and mathematical modelling which concluded that a mass reduction of approximately 12% can be achieved when switch from conventional Al-Si alloy (Al 4032) to a nanostructured aluminium alloy. On the other hand, the work at Buenos Aires was based on the practical applicability of one the nanostructured hypereutectic aluminium alloys. The engine used was Renault C2L700 1.6L and for fair comparison of the engine performance, the engine was evaluated in two different states. For the first test, engine was tested in its original configuration with all its standard components and later with the new piston. The experimental results obtained were supported by the theoretical study of various factors involved in engine performance evaluation. The study found that change in material resulted in gain in engine's performance in terms of fuel consumption, torque and power [52].

The Pacific Northwest National Laboratory Richland in USA also worked (May 2011 – May 2014) on the development of nanostructured aluminium alloys having high temperature tensile and fatigue strengths that can facilitate applications in heavy duty diesel engine pistons. The partners in project were Cummins Inc., Transmet Corporation and Kaiser Aluminium. Cummins Inc. was the principal industry partner that facilitated most of the funding while Transmet Corporation and Kaiser Aluminium provided the expertise to mass manufacture the material using melt spinning and extrusion services respectively. The primary objectives were to evaluate candidate high temperature and high strength aluminium based alloys processed using rapid solidification methods and establish cost-effective processing methods that can preserve the desired microstructure and properties through the consolidation and forming steps (secondary production processes) [53].

The candidate alloy selected was Al-Fe alloy and the aim was to achieve strength in excess of 300 MPa at 300 °C. The project could not achieve the aforementioned target, but achieved yield strength and ultimate tensile strength (UTS) of 244 & 261 MPa respectively. The alloy strength is much better than conventional aluminium alloys. It was also found that melting spinning followed by extrusion consolidation is more cost-effective process to mass produce these materials than mechanical alloying. It is not known yet if the project had tested any component for application demonstration as planned, but before that could have happened, the consolidation and extrusion processes needed further optimisation to eliminate porosity and improve high temperature properties [53].

There is currently a project underway at Oxford Brookes University to assess the feasibility of a newly developed nanostructured aluminium alloy in pistons. The alloy has been mass produced by RSP Technology in Netherland using melt spinning followed by extrusion consolidation. The alloy has been developed by Prof. Fernando Audebert’s team at the Universities of Oxford and Benous Aires. The initial testing has shown promise and the alloy has significantly higher yield and ultimate tensile strengths than conventional piston aluminium alloys at elevated temperatures. A piston designed with and manufactured from the new material had 13.5% lower mass compared to the original piston of the test engine (KTM 450 XCF). The original piston was made from Aluminium alloy 2618 which is used in high performance engine such as the one used for the study.

4. CONCLUSION

A comprehensive literature survey was carried out on the development of materials for piston applications in internal combustion engines. The mechanical properties a material should possess to be used as a piston material were discussed with reference to the functions a piston performs. The pros and cons of each material and the properties that attracted engineers to use these materials were reviewed. The materials that are under development and have the potential to become future piston materials are also analysed. The paper also highlights the trend of changing from diesel to petrol in small high-speed engines which will further catapult the efforts to develop high temperature aluminium alloys.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: The authors declare no conflict of interest.

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How to cite this article: H. Adil, S. Gerguri, J. Durodola, F. Audebert, F. Bonatesta, F. Saporiti. Evolution of materials for internal combustion engines pistons. *International Journal of Research and Review*. 2023; 10(8): 203-214. DOI: *https://doi.org/10.52403/ijrr.20230827*

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