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Mechanical Properties, Material and Design of the Automobile Piston: An Ample Review

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Abstract

This paper is about the mechanical properties and shape of the automobile piston in the engine. Currently downsizing of the engine is attractive field for the research which benefitted in the reduction of fuel consumption and emission pollutants from the engine. While on the other side various pressure boosters attached with the engine piston-cylinder to maintain the output power at the bar/more than the bar. These attachments cause to produce high stresses and displacement vectors in the piston-cylinder and the gas forces generated during the combustion cause to produce thermal stresses on the face of the piston which sometime may leads to the failure of piston material. To withstand all these problems the material must be strong enough. Al-Si alloy is the main alloy material to manufacturing the piston because of low co-efficient of thermal expansion, minimum weight, high hardness and strength and good wear resistance properties. In result; Shallow depth Combustion Chamber (SCC) is most suitable for low speed while Omega Combustion Chamber (OCC) is preferred for high speed, but both combustion chamber produce high amount of NOx. Maximum suitable percentage is of Si is up to 12% to 19%. While centrifugal casting is most right method to manufacture the piston and heat treatment at 540°C for 8 h and aging at 190°C for 8 h is correctly choice to achieve optimum mechanical properties by heat treatment. The ingredient material of the Al-Si alloy, the casting techniques and heat treatment techniques directly affects the mechanical properties of the piston in downsizing engine. A very careful observation is required during the manufacturing of automobile piston to achieve desired mechanical properties.

Keywords: Alloying Elements, Casting Techniques, Hypereutectic Al-Si Piston alloy, Mechanical Properties, Shape of the Piston

1. Introduction

The automobile piston must have enormous strength and heat resistance properties to resist gas pressure and inertia forces. Also it should have minimum weight to minimize the inertia forces also it should have rigid construction to endure thermal, mechanical distortion and sufficient area to avoid undue wear[1]. Automobile piston is an extremely key part of combustion engine, fulfilling several functions as transfer of gas force, kinematic guidance (sometimes with cross head), sealing (in combination with piston rings) and Shaping the combustion chamber[2–5]. The output of automobile engine strongly depends on piston performance (shape, piston combustion area, piston displacement, and etc). As per the indicated thermal efficiency of the engine, the piston area and the piston displacement are important and the shape of the piston can also vary it. This is the basis, that it is important to design this part of combustion engine, particularly when design of engine is modified/changed. Also modern research worked on the downsizing of the engine which benefitted not only reduction in CO_2 but also reduction in the energy consumption by decreasing the swept volume. While on the other side there are lot of complications in downsizing the engine: Affecting the thermal loading (Mean effective pressure), mechanical loadings, high levels of stresses in the combustion chamber and many more. Such as observed an increment of 41.7% of the translation

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vector displacement and Huber–Mises stresses increased by 35.9% when the piston was downsized up to 13%[6]. Combustion chamber means the shape of the automobile piston which directly affects the combustion, performance and emission characteristics. The piston geometry has enormous influence on the development of combustion at different load's criteria[7]. On the performance side; SCC (Shallow depth Combustion Chamber) is most suitable at low engine speed; whereas at high engine speed, OCC (Omega Combustion Chamber) is most appropriate and as a result, SCC will produce relatively higher NO_x when compared to OCC at low engine speed criteria. Similarly, the high output of OCC bowl geometry could generate a high NO_x emission at high engine speed condition[8] and the brake thermal efficiency is more, reduction of particulates.

COx and Unburnt Hydrocarbons (UHC) in Toroidal Combustion Chamber (TCC) compared to the other two, however NOx were to some extent more for TCC and it has enhanced combustion characteristics at baseline then other two combustion chambers[9] as shown in Figure 1.

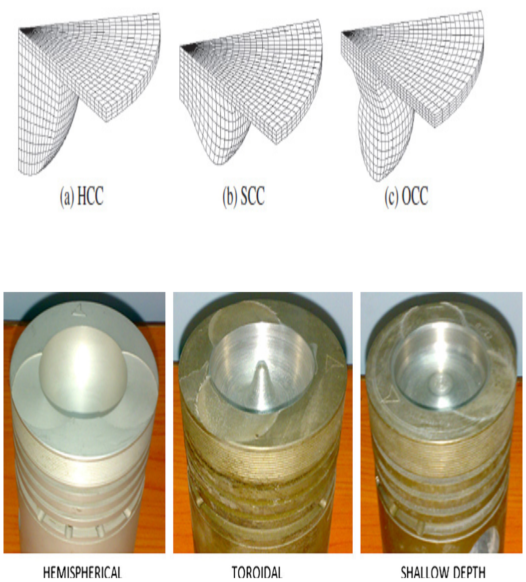

Figure 1. Three different combustion chamber.

The Stratified Flame Ignition (SFI) hybrid heat release process, spark timing is efficacious to govern CA ^{0}50, Indicated Mean Effective Pressure (IMEP) and maximum Pressure Rise Rate (PRRmax) regardless the piston designs, Start of Ignition (SOI) timings and direct injection ratios at the same combustion criteria for three different piston shapes as shown in Figure 2[10].

Figure 2. Three different shapes of piston.

In continuation with the piston shape the flat-with-center-bowl piston outcomes in about 51% more tumble ratio and for in-cylinder flows 21% more turbulent kinetic energy, improvement in mixture stratification in connection with 33% higher evaporation rate. While for flat, inclined and inclined with center bowl designs of piston: It was concluded by the authors that 35% higher percentage of fuel evaporation at 1500 rev/min speed in four stroke engine[11].

Also it was experimentally found that the rate of heat release increased by the enrichment of fuel–air mixture. It also changes the location of peak of in-cylinder pressure to prior start of combustion. For richer fuel–air mixtures, Exhaust Gas Regulator (EGR) was comparatively less effectual due to dominance of 'rate of heat release', which was considerably high[12]? In this ample review paper the focus on the material composition and casting techniques best suited for good mechanical properties of the automobile piston alloy, while some literature discussed about the design of the piston for good combustion performance.

2. Material Composition

Hypereutectic Al-Si alloys are one of the widely used alloys in cylinders, cylinder heads, cylinder liners and pistons of the automobile engines. It is because of many good properties such as: Corrosion resistance, excellent wear resistance, low density, low coefficient of thermal expansion, high specific strength and many more[13].

While in comparison the hypoeutectic Al-Si alloys contains ductile primary Al which forms and propagates dendritically, and a needle-like brittle hard eutectic Si phase. Eutectic Al-Si alloys composed of an Al–Si eutectic phase while hypereutectic alloys normally hold coarse, primary angular Si particles together with a eutectic Si phase[14,15].

The alloying elements Cu, Mg, Fe, Ni, Mn, etc can be utilized to increase the different properties of hypereutectic Al–Si alloys[16]. Aluminum-Silicon (AI-Si) alloys are widely used materials comprising 85% to 90% of the total aluminum cast parts manufactured for the automotive industry. Focusing on the Si existence in weight percent (wt.%), the Al-Si alloy systems characterized into three major groups: hypoeutectic (<12% Si), eutectic (12-13% Si) and hypereutectic (14-25% Si)[17]. Above 230^0C the microstructure may become unbalanced for Al-Si, therefore; many A1-Si alloys are not applicable for high temperature applications just because the tensile and fatigue strengths are not as adequate as required in the temperature range of 260°C-370°C[18,19]. The FGM (Functionally Graded Material) pistons with A390 (Al: 74-78, Si: 16-18, Cu: 4-8, Mg: 0.4-0.7) and A3 90-0.5% Mg created. The results were compared with piston produced by gravity casting technique showed graded distribution of primary silicon from the head portion towards skirt of the piston and a eutectic composition in the skirt region resulted in increment in hardness towards the head region and significant improvement of the wear properties of the piston head[20].

The micro-hardness of the Al12Si4Cu2Ni2.6Mg (in wt.%) aluminum piston alloy reached to 1.88 GPa when all the Cu, Ni, Mg dissolved 3.63 wt.% equally with Si dissolved in the α-Al matrix, and increment to 2.02 GPa. However; only the solid-solved Si precipitates to forming nano-particles[21]. The effects of Mg on the microstructure in hypereutectic Al–Si alloys resulted that the volume fraction of primary Mg_2Si particles augmented linearly with increase of the Mg content, but the average size of Mg_2Si particles does not shown a significant change[22]. Adding up the 10% volume fraction of Si particles in LM13 alloy by Friction Stir Processing (FSP) and improved the hardness, elongation and tensile strength of the as-cast metal[23]. And by using Rotating Magnetic Field (RMF) that the Si content has noticeable effect on the thickness of Si-rich layer shaped around the sample and impurity contents in the purified Si[24].

319 type aluminum cast alloys are frequently employed in the automotive industry require better mechanical and thermal properties and to obtained them through precipitation and artificial aging treatments to the casting parts. This can be achieved the best set of mechanical and thermal properties with addition of Sr modified alloy having 0.4 wt% Mg (319 aluminum alloy + Mg + Sr)[25]. Hypereutectic Alx%Si0.8Sc alloys (x = 13, 16, 19 and 22 wt.%) showed higher amount of stresses and tensile strength in contrast to their binary alloy counter parts which was attributed to the bi-modal size distribution of the strengthening phases in the shape of nano scale V-phase and submicron of the size 10 μm silicon particles[26]. The effect of Sr on the mechanical properties and the microstructure of Al12Si4Cu2Ni0.8Mg alloy produced by gravity casting resulted good mechanical properties. The results of SEM, EDS and XRD showed 05 types of different intermetallic phases: Al2Cu, Al7Cu4Ni, Al3CuNi, AlSiFeNiCu and Al5Cu2Mg8Si6 and also results found an increment from 196MPa to 249MPa, 176MPa to 207MPa and 0.74% to 0.95% in ultimate tensile strength, 0.2% yield strength and percentage elongation respectively when percentage of Sr increased from 0.02 % to 0.04%[27]. Molybdenum disulphide (MOS_2) powders 40 μm particle size added in Al-2024 aluminum alloy composite through stir casting. Up to 4% of MoS_2 resulted in increment in the hardness and tensile strength[28]. While in the research on Al18SixZr alloy, the flake like ZrAlSi particles reduced 7.28% tensile strength, 3.23% elongation and 8.85% yield strength. The block like ZrAlSi particles resulted an increment of 15.28% tensile strength, 12.94% elongation and 14.75% yield strength for the elevated temperature piston alloy[29]. By considering the effects of Ni and V on the piston alloy, the traces of them were added in A356 piston alloy and were produced by sand and permanent mold casting and also T6 heat treatment was also done on them. This resulted that Ni reduced yield strength by 87% and ultimate tensile strength by 37%. However; the addition of V cause to increase 42% yield strength and 25% ultimate strength because of solutioning strengthening effect. Also after T6 heat treatment, A356 piston alloy produced by sand casting possessed slightly higher mechanical properties with V[30].

3. Casting Techniques

There are variety of casting techniques employed for the fabrication of automobile piston, each casting technique has its own impact on the microstructure, physical and mechanical properties and other basic properties necessary for automobile piston. The piston produced by centrifugal casting having SiC particles reinforced in hypereutectic AlSi piston alloy resulted as: 1. Centrifugal casting can be considered as a new and effective casting method for manufacturing of piston. 2. It has been shown through the results that the hardness increased from the piston skirt to the piston head and the average hardness value at piston head was 23.7HRB of the piston manufactured through centrifugal casting also it was found that the hardness value was even more when centrifugal casting piston was compared to the gravity permanent mold casting piston. 3. On the wear analysis the improvement was also observed by a value of 70.3% in the piston manufactured through the centrifugal casting to the gravity permanent mold casting. 4. While the coefficient of linear expansion of the piston was 15.3×10^{-6} K^{-1} and this value was 23.1% lower in the centrifugal casting then the gravity permanent mold casting[31]. To discuss on the Friction Stir Casting (FSP), it also produced good results for the manufacturing of the piston as this casting method resulted a significant betterment in tensile properties of AC8A piston alloy particularly in ductility. But both the tool rotation rate and traversing speed could affect the strength of FSPed piston and also in results the mechanical properties of AC8A cast by FSP were improved considerably specially elongation increased from 1% to ~15%. It is because of the many characteristics such as combination of dissolution, coarsening re-precipitation of strengthening precipitates which was affected by the FSP parameters[32]. While discussion on semi solid rheo die casting, the piston alloy Al20Si2Fe2Cu0.4Mg1.0Ni0.5Mn (mass fraction %) it at room temperature and 300^0C resulted an increment 230MPa ultimate tensile strength and 145MPa yield strength and in the temperature ranges from 25^0C to 300^0C the value of coefficient of thermal expansion (CTE) was 1.052 8×10−6 °C−1, the wear rate is 1.55% and the hardness of the alloy achieved as HB146.3with 2% Fe[33].

Al–Si base composites reinforced with different contents of Ni and nano-Al_2O_3 particles manufactured by squeeze casting caused ultimate tensile strength is increased by adding the Ni and nano-Al_2O_3 particles up to 10 and 2 wt.%, respectively. The composite material reinforced with 5 wt. % Ni and 2 wt. % nano-Al_2O_3 particles showed superior ultimate tensile strength and better ductility compared with any other added particles[34]. Hyper eutectic Al–23Si–8Fe–5Mn (wt%) alloy fabricated by the unique method of combining centrifugal spraying and hot die forging. The fabricated samples of Al23Si8Fe5Mn alloy were compared to a commercial casting Al12Si1Cu1Mg1Ni alloy and resulted that at room temperature. Both alloys have almost same mechanical properties but Al23Si8Fe5Mn alloy showed significantly good thermal stability. Also the authors of this research claimed that combination die forging with the centrifugal spraying method is most suitable for manufacturing piston using AlSi piston with rich iron percentage[35]. With Al13.5Si4.6Zn at different temperatures range from 660^0C, 690^0C and 720^0C using gravity casting and squeeze casting for comparison purpose. The results found that the casting temperature had an influence on mechanical and thermal properties of the alloy. Also it was found that 720^0C temperature is the most suitable temperature for this alloy producing through gravity casting[36]. The discussion on the stir and compo casting techniques used for the manufacturing of piston using A356 aluminum piston alloy with Al_2O_3 composites. It resulted in significant increment in strength and hardness when 3wt% of nano Al_2O_3 and 5wt% of micro Al_2O_3 reinforced for compo casting technique. While 2wt% of nano Al_2O_3 and 5wt% micro added for stir casting. Also the values for ductility in compo casting samples were more than the stir casting samples. But further addition of Al_2O_3 cause to reduce the ductility for both casting techniques[37].

4. Future Challenges

The engineering world is converted in small weight and lessen in dimension of the engineering components while maintaining the performance at the bar or even better. Still there are many challenges to achieve these two objectives. Mainly the introduction of new composites may help to overcome the obstacles and many researchers concluded new composites having better properties and suitable in performance. But the casting, fabrication, machining and heat treatment techniques may alter the properties.

Keeping the same or better performance and lessen the dimensions of the piston, the material of piston must be withstand to high temperature and pressure during the combustion in downsized engine. Al-Si alloy is most suitable material for production of automobile piston by addition of some other alloying elements such as Cu, Mg and Ti also some other elements are present in smaller amounts in piston alloy but Si is the main alloying element. Aluminum has the main ability to resist the wear, having high specific strength, low cost and light weight. 12% of Si is the exact proportion in the AlSi piston alloy at which it is fully soluble at operating temperature but either less or more than 12% of Si, there will be two separate phases in the solidified crystal structure of AlSi piston alloy. By increasing the percentage of Si then the exact soluble percentage (12%) the microstructure and mechanical and thermal properties changes and the percentage are varied as per the requirement of application of the automobile piston. However; at a blend of 25% silicon (maximum limit of hypereutectic AlSi piston alloy) the reduction in the strength may occurred and thus for better mechanical and thermal properties the percentage is varied from 14% to 25% with special molds, casting and heat treatment techniques. Hypereutectic aluminum piston alloy gives better mechanical and thermal properties then any other aluminum cast piston. However; they are not as strong as forged piston but in cost comparison they considered as economical with good strength.

In general, the piston material must possess the good wear, mechanical, thermal strength and the minimum thermal co-efficient. While the casting technique may select, this suited most for that. During the machining due to cutting and pressing force may alter the mechanical properties of the material, thus the heat treatment technique may select very carefully to regain original properties.

5. Conclusion

This paper is related to the automobile piston of the engine and discussing firstly the mechanical properties of the Al-Si alloy; mainly used for the manufacturing of the piston. Secondly the performance of the combustion chamber (piston shape). Al-Si alloys fall in to three major categories hypoeutectic (<12% Si), eutectic (12-13% Si) and hypereutectic (14-25% Si). Majorly hypereutectic Al-Si alloy is used for the manufacturing of the piston because of having low density, high specific strength, and low co-efficient of thermal expansion, excellent wear and corrosion resistance. These properties can be further improved by varying the amount of other alloying elements (Cu, Mg, Zn, Ni, Mn etc). It is concluded that above 450^0F the Al-Si alloy microstructure will be unstable and desired properties will be reduced. Si is the main ingredient of the Al-Si alloy to achieve better mechanical properties and by varying the distribution and particle size effects on the mechanical properties. The micro-hardness value increased from 1.88 GPa to 2.02 GPa when Si dissolved in α-Al matrix also the distribution and particle size depend on the casting techniques used for the manufacturing of piston. While focusing on the other alloying elements: Copper has influence to affect the hardness and strength of aluminum piston alloy at either heat treated or non-heat treated and also at ambient or at elevated temperature. Copper also increase the hardness and cause to improvement in the machinability of the aluminum piston alloy. The next element Mg in the aluminum piston alloy provides considerable strength and also improves the work hardening characteristics. Mg also imparts good corrosion resistance, provide extremely high strength and cause good weldability. The addition of Si and Mg together in the aluminum piston alloy improves the weldability, however; the maximum addition of Mg can be 4-8 wt% because of good thermo-mechanical properties. Nickel cause to improve the hardness while zinc addition has no any effects, it neither increase nor decrease the mechanical properties of aluminum piston alloy. Manganese addition increase the tensile strength also significantly enhances the low cycle fatigue resistance and improve corrosion resistance of the aluminum piston alloy.

While the literature review used in this paper describing that centrifugal casting method is the most suitable casting technique it is because this casting technique may distribute alloying elements equally along the circumferential of the piston skirt. But the rotation speed/feeding rate may change the desired mechanical properties. The second most effective casting method to get better mechanical properties is the friction stir casting method but again in this technique the rotation speed and transverse speed could affect the strength of the piston. The combination of centrifugal spraying and die forging is also suitable method for processing Al-Si based alloy for automobile piston. While in comparison of stir and compo casting processes, the ductility of compo casting is greater then stirs casting and in combination with compound loading; better mechanical properties and homogeneous structure can be achieve.

In general, the ingredient material of the Al-Si alloy, the casting techniques and heat treatment techniques directly affects the mechanical properties of the Al-Si alloy used for the high temperature application in which Si makes it hardened enough for usage but maximum suitable percentage is 12% to 19%, while centrifugal casting is most right method to manufacture the piston and heat treatment at 540°C for 8 h and aging at 190°C for 8 h is correctly choice to achieve optimum mechanical properties by heat treatment.

Discussing on the combustion side of the piston: The automobile piston is the main part of the combustion chamber and during the design of new engine it has prime importance. Various shapes of the piston were also discussed in this paper to argue on the combustion, performance and emission characteristics of the engine. Shallow depth Combustion Chamber is most suitable for low speed while Omega Combustion Chamber is preferred for high speed, but both combustion chamber produce high amount of NOx. The shape of the piston directly affects the combustion, performance and emission characteristics. The improper heat release causes to start of ignition before the settled value which leads to poor performance and also produce high pressure waves which almost cause the failure of the piston. While on the other side the application of piston in downsized engine grounds to research on the material of it having superior mechanical, thermal and thermal fatigue properties.

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