Develop an Al-alloy for high pressure-high temperature applications by enhancing thermo-mechanical properties

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Abstract. The aim of this research work is to develop an aluminium alloy which can be used in conditions like high temperature and high pressure. High pressure die castings, specially engine components of automobiles and heavy vehicles are the important components which need to survive in such challenging working environment. Silicon, Nickel and Chromium found to be suitable filler materials to be used in high pressure and high temperature conditions based on literature reviews. Based on the individual physical, chemical and thermo-mechanical properties of Si, Ni and Cr, these elements were selected as alloying elements and alloys Al-Si, Al-Si-Cr and Al-Si-Ni were prepared. The prepared samples were tested for various thermo-mechanical properties and the results were analyzed. Tensile strength values are obtained from hardness values based on Mayer's hardness. Thermal conductivity values were obtained from electrical conductivity values based on Wiedemann–Franz law. Void content is calculated from practical and theoretical density values. At the end of the research, the new aluminium alloys proposed in this work found to be better replacements for aluminium metal which is currently in use for many high pressure high temperature applications.

Keywords: Thermo-mechanical property, Al alloy, engine components.

1 Introduction

The automotive engines are to be operated in high temperature and under high pressure. Piston is the key component which has to undergo such challenging situation. Piston has to move back and forth rapidly; therefore, it must withstand high temperature, high pressure and also it should be wear resistant. For a long time, aluminium alloys are considered as the ideal material for piston. The high strength, good castability, wear resistance, low density and low thermal expansion make (Al-Si) alloys good for automobile industry [1]. But they still have disadvantages while considering their thermos-mechanical properties [2]. The focus of this paper is to find an aluminium alloy so as to reduce the drawbacks of piston alloy and to mitigate the issues in other related applications. It is sophisticate to identify an alloy (Al-Si, Al-Si-Cr and Al-Si-Ni) beyond technical and economic limitations to best suit the piston alloy by considering variation of thermal expansion and wear resistance.

2 Literature Review

M. Jinnah Sheik Mohamed mentioned in his paper that, the piston of internal combustion engines are alloys made up of Aluminium-Silicon cast alloys alloyed with Chromium, Nickel and Magnesium. The reason is the ability of high wear resistance and low thermal expansion coefficient. Al-Si cast alloys are suitable for application less than 230°C. Above this temperature the microstructure strengthening mechanism of these alloys become unstable. Addition of Ni to Al-Si piston alloy will improve the high temperature performance [1]. Cr increases strength at indoor and higher Temperature [3].

Al-Ni-Si alloys are used for a wide range of engineering applications because of their high strength, good wear resistance, good castability, light weight, and low thermal expansion [4]. Aluminium alloys are widely used in the automobile industry; it is particularly to reduce weight and thereby decrease fuel consumption and increase the efficiency [2]. Every 100kg weight reduction in the weight of the vehicle can save around 0.5l of petrol usage for 100 km drive [5 - 8]. Fuel economy can be significantly improved by reduction of weight in a vehicle [9, 10]. Onyebueke B Ifeanyi et. al. further mentioned that, Al-Si alloy is the most cast friendly Al alloy. Addition of Co, Cr, Mn, Mo and Ni improves strength at high working temperature. Strength and fatigue resistance can be improved by adding Copper without any harm to castability, but it will reduce corrosion resistance. Addition of magnesium increases the strength, especially after heat treatment, but it will affect ductility. The addition of Chromium to the Al-Si alloy sas a modifier at elevated temperatures suppresses the grain growth. It also decreases the vulnerability of the alloy to stress corrosion cracking. At elevated temperatures elements like Ni, Co, Cr, and Mo with high melting points defend the decline in strength to some extent [2]. From these literature reviews it can be observed that the strength is also playing an important role in the selection of piston alloy material. So it is appropriate to calculate the hardness and tensile values.

The reason behind the usage of Al–Si alloys as piston alloy over cast iron is its high thermal conductivity. The extraction of heat produced by combustion is more rapid in Al-Si alloys than cast iron. Low coefficient of friction and resistance to wear are the main features essential for engine block materials. Softening of hypoeutectic Al–Si piston alloys while operating in high temperature, requires high temperature strengthening of the Al–Si piston alloys. The thermal conductivity could be increased by liner-less Al–Si alloy cylinder blocks. The creep strength of the alloy improved by the addition of Nickel to the alloy; but, the effect of it is very small on the tensile strength at high temperature. The alloy containing Nickel has fatigue strength almost 20% higher than that of the Al-Si-Mg alloy [11]. The ductility of the material can be increased significantly by adding Nickel particles [12].

The AMAG Company in its report of 2012 mentioned that, the addition of alloying elements will reduce the thermal conductivity considerably. In Al-Si cast alloys, both electric conductivity and thermal conductivity decline very closely linearly with increasing Nickel content. It is essential to understand the effects on thermal conductivity due to addition of Nickel. For applications under high temperature, Nickel is considered as an important alloying element with Al-Si cast alloys. Heat produced in compression cycle of a working engine need to be removed as fast as possible in order to avoid hot spots and thermal stresses on the surface of the piston. Therefore, high thermal conductivity is also having a major impact on selection of the material for piston [13]. Aluminum has a conductivity-to-weight proportion twice that of copper and its strength to-weight proportion is 30% more noteworthy than copper [14].

3 Methodology

The samples were prepared on burnout furnace. The Aluminium rod is cut in to small pieces and the surface is cleaned. Then it is introduced in a crucible made of silica and kept inside the burnout furnace. The time, maximum temperature and temperature increasing rate were set. Chromium, silicon and nickel were preheated and added according to the decided percentages to molten aluminium-which is taken out of the furnace at 750^0C. Then the crucible containing this mixture was stirred well to emphasize the uniform mixture of all the components throughout the sample. Again it was kept inside the furnace for some time. Then the crucible was taken out of the furnace, stirred well and the slag formed on the surface of the molten mixture was removed. Then it was poured into the preheated split type mould and allowed to cool for room temperature. Finally, the prepared samples were removed.

Impact of Ni and Fe in Al-Si alloys with Si content above 5% dramatically reduces corrosion resistance, fluidity and plasticity [3]. So in our studies we didn’t add Ni or Cr above 5%. Different combinations of Al-Si, Al-Si-Cr and Al-Si-Ni matrix were prepared to analyze the variation of different parameters. The percentage addition of these elements is given in table. 1. Pure sample of Aluminium also prepared.

Table 1. Percentage addition of filler materials to base metal aluminium.

Sample	Aluminium	Silicon	Chromium	Nickel
Al	100%			
Al-2%Si	98%	2%		
Al-4%Si	96%	4%		
Al-2%Si2%Cr	96%	2%	2%	
Al-2%Si4%Cr	94%	2%	4%	
Al-2%Si1%Ni	97%	2%		1%
Al-2%Si2%Ni	96%	2%		2%
Al-2%Si3%Ni	95%	2%		3%

3.1 Vickers Hardness Test

The Vickers hardness testing method is based on optical measurement system. The micro hardness test is conducted according to ASTM E-384 procedure. The tests are conducted using an indenter, which may specify a range of light loads to make an indentation on the sample and then it is measured, calculated and converted to a hardness value. It is very useful and a wide variety of materials can be tested. Since the indentation needs to be observed through microscope, the test samples must be highly polished. A square based, pyramidal shaped diamond inventor is used for testing the Vickers hardness. The range of loads can be from 10gmf to 1kgf. The hardness values obtained here are of the average of 10 readings. Tensile values are calculated using the equation 1. This equation is used in several researches [15 - 17]. Tabor has developed an empirical correlation between hardness and tensile strength. This way of tensile and hardness testing methods is possible upon metals Al, Cu, and steel; but not in Mg. The presence of profuse twinning at low stress levels can be the reason for this in magnesium. Meyer, in 1908, propose this relationship $H_m = 4w/\pi r^2$ (Meyer hardness has the dimensions of stress) Hm = 2.8 σ [17]. A cold worked material's yield stress is given by $\sigma_y = H/3$. This formula is applicable for brass, steel in either the hot tempered or cold rolled condition, and aluminium alloys in either the cold rolled or aged condition. Marcinkowski et al. found that for annealed Fe-Cr alloys, this expression appeared to be σy ~H/5 due to some strain hardening. Speich and Warlimont showed that for some low carbon martensites and Fe-Ni alloys, σy ~ H/4 [15]. Here Hv represent Vickers's hardness and σ represent tensile strength. The derivation of tensile flow curves from hardness measurements is important from two viewpoints. First, the preparation and testing of a hardness testing sample need very less expense, experience and time than the tensile testing sample. Secondly, without destructing the component the flow curves could be obtained. This feature is smart from the production expense point of view.

$$Hv \approx 3\sigma \tag{1}$$

3.2 Density Calculation

The two major defects occurring in casting process which strongly weaken the fatigue strength are porosity and oxide enclosures [11]. Increase in porosity leads to poor tensile and fatigue strength. [18, 19]. The void content is under control in current research. It did not exceed more than 2%. Equation 2 is used to obtain the theoretical density of an alloy in terms of weight fraction.

$$\rho_{ms} = 1/ [(w_a/\rho_a) + (w_s/\rho_s) + (w_n/\rho_n)] \text{ or } \rho_{ms} = 1/ [(w_a/\rho_a) + (w_s/\rho_s) + (w_c/\rho_c)] \tag{2}$$

The weight fraction and density are represented by w and ρ respectively. The suffix a, s, n, c and ms stand for aluminium, silicon, nickel, chromium and the mixture respectively. The usual water immersion technique is used to calculate the actual density (ρ_{cm}) of the specimen experimentally. Equation 3 is used to calculate the volume fraction of voids (Vv) in the alloy. Here ct is theoretical density and cp is practical density

$$Vv = (\rho_{ct} - \rho_{cp})/\rho_{ct} \tag{3}$$

3.3 Thermal Conductivity

Parameters that improve Thermo-Mechanic Fatigue (TMF) resistance are high thermal conductivity and low thermal expansion coefficient [20 - 22]. Thermo-mechanic Fatigue resistance is improved by decreasing thermal expansion coefficient [11], and Ni decreases the coefficient of thermal expansion of Al alloys [3]. The thermal conductivity value of pure aluminium of the current experiment is very close to that of theoretical value.

At moderately low temperatures, the ratio of thermal conductivity K to electrical conductivity σ is proportional to absolute temperature, with a proportionality constant called "the Lorenz number" $L=2.45\times10^{-8}\,\mathrm{W\,\Omega/K^2}$. This is known as Wiedemann–Franz law [23, 24]. In the current studies, the resistance is measured with a milli-ohm meter. It has precision of 0.01milli-ohm. Subsequently, the value of resistivity and conductivity is determined by using appropriate equations 4 and 5. Wiedemann–Franz law (equation 6) is used to find the thermal conductivity values from electrical conductivity values. In 1853 Gustav Wiedemann and Rudolph Franz reported that κ/σ has approximately the same value at the same temperature for different metals. Wiedemann–Franz law is named after this incident.

$$V = IR \tag{4}$$

$$R = \rho l/A \tag{5}$$

$$k/\sigma = LT \tag{6}$$

4 Results and Discussion

4.1 Density Values

Weight of the component should be considered while deciding material for piston alloy. From table.2 it can be observed that the density values of aluminium alloys are not varying significantly while comparing it with the density of aluminium sample. As mentioned earlier, the decrease in weight of the components is highly appreciated in the automobile industry. In current studies, the density of Al-Si alloy or Al-Si-Ni alloy or Al-Si-Cr alloy samples did not show a wide variation. Rather, Al-2%Si, Al-2%Si2%Cr and Al-2%Si1%Ni shows very close density values to that of aluminium. Since there is no significant increase in weight, the new proposed materials will neither lead to the increase in weight of parts nor to the decrease in performance of the vehicle.

Table 2. Theoretical and practical density values.

Sample	Theoretical density (g/cm^3)	Practical density (g/cm^3)	Void content
Al	2.7	2.66	1.481%
Al-2%Si	2.6917	2.65	1.549%
Al-4%Si	2.6828	2.62	2.34%
Al-2%Si2%Cr	2.725	2.662	2.311%

Al-2%Si4%Cr	2.76	2.71	1.811%
Al-2%Si1%Ni	2.71	2.682	1.033%
Al-2%Si2%Ni	2.729	2.717	0.439%
Al-2%Si3%Ni	2.7484	2.723	0.924%

4.2 Hardness and Tensile Values

The equation 1 is used to calculate the tensile values from hardness values. It can be noticed from the graph that, the hardness and tensile values are increased with the addition of Si and Cr. But with the addition of Ni, the hardness and tensile values started decreasing after 2% addition of Ni. It can be concluded that 2% Ni addition would be the optimum value to obtain better results. These results are shown in Fig. 1. Due to the better results obtained for hardness and tensile results of aluminium alloys than aluminium, the suggestion of new proposed alloys to automobile industry is meaningful.

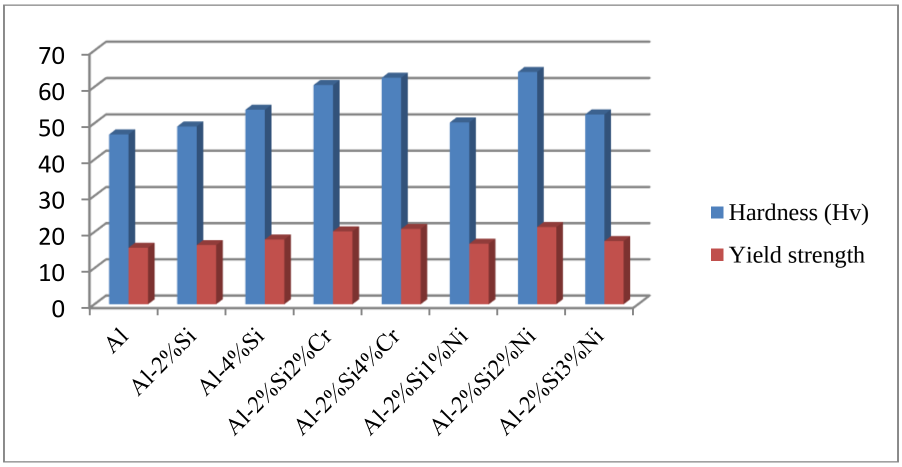

Fig. 1. Comparison of hardness and tensile values of samples

4.3 Thermal Conductivity Values

The thermal conductivity value of aluminium obtained in current studies (238.19 W/mK) and the theoretical value (which is varying from 236 W/mK to 240 W/mK with temperature) are more or less similar in value. So it can be assumed that the errors in this practical are negligible. As mentioned in the literature review, the thermal conductivity is also a vital factor while deciding a material for engine block and piston alloy. From the table 3, it is noticeable that the addition of foreign material to aluminium, slightly decrease the thermal conductivity. Except Al-4%Si and Al-2%Si4%Cr, the other compositions seem to have thermal conductivity which is acceptable when considering all the other aspects.

Table 3. Electrical and Thermal Conductivity values.

Sample	Electrical Resistivity (*10^{-8} Ωm)	Electrical conductivity (*$10^{7}\Omega^{-1}m^{-1}$)	Thermal conductivity (W/mK)
Al	3.073	3.254	238.1928
Al-2%Si	3.763	2.657	194.4924
Al-4%Si	4.617	2.165	158.478
Al-2%Si2%Cr	3.57	2.801	205.0332
Al-2%Si4%Cr	3.922	2.549	186.5868
Al-2%Si1%Ni	3.202	3.123	228.6036
Al-2%Si2%Ni	3.451	2.897	212.0604
Al-2%Si3%Ni	3.599	2.778	203.3496

5 Conclusion

Maximum hardness and tensile strength values are obtained for Al-2%Si4%Cr, Al-2%Si2%Ni and Al-2%Si4%Cr. These samples have far better results compared to other samples tested.

The density values of all the samples are almost equal to that of aluminium sample. Since the density values are not varying much, it can be stated that the weight will also be almost equal for all the samples. Due to this fact, the proposed material will not affect the weight of the vehicle; and thereby the performance of the vehicle will not be affected. Also the void content of the sample is ranging only from 0.4% to 2.4%.

The thermal conductivity of Al-2%Si1%Ni and Al-2%Si2%Ni are slightly lower than that of aluminium sample. It is a slight drawback that these samples can't conduct heat as fast as aluminium. But Al-2%Si1%Ni and Al-2%Si2%Ni will remove heat from engines in a slightly slower rate than aluminium. When considering other qualities, the slight reduction in thermal conductivity is acceptable.

When considering all the experiments, Al-2%Si2%Ni sample seems to be the better replacement for aluminium in high pressure and high temperature conditions, and it is followed by Al-2%Si2%Cr sample.

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