Open Access Journal

Journal of Sustainable Research in Engineering 1 (2) 2014, 51-56

Journal homepage: www.jkuat-sri.com/ojs/index.php/sri/index

Investigation on Hardness of Gravity Die Cast Secondary Al-10Si Piston Alloy with Trace Addition of Sr, Fe and Mn

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Abstract This paper investigates the effect of minor elements on Brinell hardness properties of Al-10Si alloy. This investigation was carried out with the aim of improving the properties of recycled cast Al-Si alloys so as to enhance their performance. The research therefore came up with the most suitable level of element composition that gives the recycled Al-Si alloys enhanced mechanical properties. The results obtained are deemed beneficial to the local foundries that utilize scrap aluminium alloys to cast their products both for commercial and domestic purposes. Al-Si alloys were produced using gravity die casting process upon which strontium, iron and manganese were added in varying proportions. T6 heat treatment procedures were also carried out on the obtained casting in order to determine the effects of heat treatment on Al-Si alloys. Addition of Sr at weight levels of 0.025%, 0.048% and 0.06% increased the Brinell hardness by 4.64%, 11.42% and 14.57% respectively. The results on addition of Fe at 0.50% and 0.78% weight levels showed improved alloy hardness by 3.48% and 2.15% respectively. Addition of Fe combined with Mn at levels of 0.50% Fe and 0.25% Mn resulted in hardness increase of 8.61% while a combination at 0.78% Fe and 0.39% Mn levels resulted in increasing the material hardness by 6.46%. Upon heat treating the base alloy material, its hardness value improved compared to its non-heat treated value. T6 heat treated alloys with 0.025%, 0.048% and 0.06% Sr levels showed hardness increment by 7.83%, 14.94% and 25.30% respectively. In addition, the heat treated alloys with Fe levels at 0.50% and 0.78% resulted in increased hardness by 5.42% and 4.46% respectively. On the other hand, when the Fe levels were neutralized with Mn at ratio of 2:1, the heat treated alloys bearing 0.50% and 0.78% Fe resulted in hardness increase by 12.05% and 10% respectively.

Keywords Al-Si alloys, Brinell hardness, Gravity die casting, Minor element, T6 heat treatment.

1. Introduction

Today's automobiles are characterized by an enhanced growth in inclusion of safety and luxury accessories [1]. A feature that car manufacturers have employed to reduce vehicle weight and consequently fuel consumption has been through the replacement of components made of cast iron with Al-Si alloy castings. Previous studies have revealed that a 10% increase in vehicle weight leads to an increased fuel consumption of about 5.5% [2]. Al-Si alloys are most widely used in automotive industry because of their associated excellent characteristics. They have relatively low density and good mechanical properties [3] that are enhanced through heat treatment. In addition, Al-Si alloys possess excellent casting properties [4]. The Al-Si alloy offers improved hardness and strength with superior wear resistance ability and good surface finish [5].

It has been established that a wide range of metals can be added to aluminium [6] in order to enhance its mechanical properties. The metals commonly alloyed with aluminium are silicon (Si), iron (Fe), lithium (Li), strontium (Sr), manganese (Mn), silver (Ag), tin (Sn), zinc (Zn), magnesium (Mg), titanium (Ti) and copper (Cu). The high hardness of the silicon particles is useful for wear resistance [7].

The effects of the major alloying elements in Al-Si alloys are well known and documented. The studies on the effects of the minor elements are necessary in order to improve mechanical properties of Al-Si alloys. Therefore, the contribution with regard to these minor elements is required.

The need for Al-Si alloys with enhanced hardness characteristics necessitated this study. The work reported focused on the study of hardness behavior of eight Al-Si alloys produced with varying levels of Sr, Fe and Mn elements through gravity die casting. This mode of alloy production was found appropriate because it leads to superior mechanical properties in the casting.

2. Experimental Procedure

The chemical composition of the alloy as obtained through spark emission spectrography is shown in Table 1. Alloy A360 was cast into 5kg capacity ingots in an oil fired crucible furnace at temperatures of 720 ^{o}C. The ingots were then charged in a ceramic crucible in electric muffle furnace model SEF-401 at temperatures of 750 ^{o}C. Subsequently, the base alloy was modified by addition of Al-10Sr, Al-25Fe and Al-25Mn. Element addition was carried out on the melt at various levels of investigation which included as-cast, 0.025% Sr, 0.048% Sr, 0.06% Sr, 0.50% Fe and 0.78% Fe. In addition, combined levels of 0.50% Fe with 0.25% Mn and 0.78% Fe with 0.39% Mn were undertaken. Cast plates were produced via gravity die casting process using the die shown in Figure 1. The obtained plates were sectioned in order to discard the edges as shown in the schematic representation in Figure 2. The specimens were machined to dimensions of 24mm by 24 mm by 24 mm and prepared to metallographic standards according to ASTM E10-12 for Brinell hardness testing.

The T6 heat treatment process was undertaken for each level of investigation. The procedure involved subjecting the castings to solution heat treatment. This procedure involved heating the casting to a temperature of 495 ^{0}C for a period of 8 hours so as to allow the attainment of maximum solute strengthening. Quenching was then carried out in hot water at a temperature of 80 ^{0}C for a time duration of 30 seconds. Finally, artificial aging procedure was performed at a temperature of 190 ^{0}C for a period of 8 hours. This was done to enable the attainment of precipitation hardening. The surfaces to be analyzed were polished up to a quarter micron.

The Leco advanced micro-indentation testing system model LV-800AT was used to obtain hardness results. A static load of 29.42N was applied on the polished surface of specimen and maintained for a dwell time of 10 seconds. The time period allowed was sufficient to ensure that the plastic flow of the metal had ceased. Up to three indentations were made on every test piece and their average value used to depict the BHN.

Table 1: Chemical Composition (% Wt) of the Al-Si alloy

Si	Fe	Cu	Mn	Mg	Ni	Zn
10.6	0.43	0.503	0.203	1.24	1.11	0.12

Sn	Ti	Pb	Sr
<0.05	0.0614	<0.05	<0.0005

3. Results and Discussion

The influence of Sr, Fe and Mn elements on the Brinell hardness of secondary A360 alloy were investigated and the results are shown in Table 2.

The table indicates that addition of 0.025%Sr, 0.048%Sr and 0.06%Sr increased the alloy hardness by 4.64%, 11.42% and 14.57% respectively when compared to the base alloy under study. On addition of 0.50%Fe and 0.78%Fe, it was noted that the Brinell hardness increased by 3.48% and 2.15% respectively. In order to determine the deleterious effects of Fe on Al-Si alloy, combination of 0.50%Fe and 0.25%Mn portrayed a hardness increase of 8.61% compared to the base alloy. Similarly, it was noted that addition of 0.78%Fe and 0.39%Mn combination improved the alloy hardness by 6.46%.

Further tests were also carried out on the alloy. T6 heat treatment procedures depicted various results on hardness. T6 heat treated base alloy had an average BHN of 83.0 compared to its as-cast BHN of 60.4. Analysis showed that BHN increase had been achieved through the T6 heat treatment procedure. The T6 heat treated specimen bearing 0.025%Sr, 0.048%Sr and 0.06%Sr showed an increase in hardness values by 7.83%, 11.94% and 25.30% respectively. The alloy consisting of 0.50%Fe upon heat treating improved its hardness by 5.42%while its counterpart with 0.78%Fe depicted an improved hardness by 4.46%. When iron was combined with manganese and the specimen heat treated, at levels of 0.50%Fe and 0.25%Mn, the hardness improved by 12.05%. Similarly, a combination of 0.78%Fe and 0.39%Mn resulted in hardness increase by 10% compared to its heat treated base alloy.

The average trends in Brinell hardness values with various levels of elements studied are compared in Fig. 3. The microstructures of the developed alloys as studied through the Leco optical microscope model LV-800AT are as shown in Fig. 4.

From the results obtained, increasing the Sr content in Al-Si alloy from 0.025% to 0.060% weights resulted in increasing the hardness. This phenomenon can be attributed to grain refinement and modification. It is notable that after modification, the eutectic Si particles are spheroidized in the matrix of Al as shown in Fig. 4 (d). A study conducted earlier [8] showed that alloy hardness can be improved by between 20-40% using Al-10Sr modifier. In another study [9] on microstructural and mechanical properties of eutectic Al-Si alloy using gravity-die and sand casting, it was argued that Sr modification led to an increased hardness due to grain refinement.

The effect of Fe on the hardness property of Al-Si alloy is that as Fe levels increased from 0.43% to 0.50%, the hardness of Al-Si based alloys increases. However, a slight drop in BHN was observed when Fe was doped at levels of 0.78%. Previous studies have reported that Fe increases hardness [10], while other authors have shown that the presence of Fe reduces the hardness and resilience [11] in Al-Si alloys.

In order to ameliorate the harmful effects of Fe in the Al-Si alloy used in the study, Mn element was utilized as a neutralizer. Theoretically, the presence of Si, Fe and Mn in aluminium causes various precipitates to form during solidification of the alloys [12]. A previous study [13] on the macro-hardness testing carried out using Brinell hardness testing machine showed that addition of 0.4% Mn to the alloy increased the hardness for both the as-cast and age-hardened conditions. The age-hardened samples had better mechanical properties than the as-cast ones. In the same study, it was argued that the explanation for the increase in hardness as the %Mn increases up to 0.4% and then fell sharply at 0.5% Mn may be probably as a result of the formation of fine dispersoid of (Mn, Fe)Al and α(Al-Si-Fe-Mn) constituents. It also noted that the Mn-rich precipitate nucleated preferentially and created a pinning action which inhibited the movement of the dislocations. Therefore, this increased the strength and hardness of the alloys. Upon carrying out age-hardening on the alloy, the variation in the mechanical properties is in line with other studies on the effect of precipitation on mechanical properties [12].

The grain refinement effect of transition metals causes the grain size of the alloys to be smaller than the base alloy [14], which results in the increase of the hardness for as-quenched transition metal added alloys. In the investigation of hardness characteristics of Al-Si-Mg alloy [15], it was concluded that T6 heat treatment can be successfully used as a method of improving the hardness of the alloy.

Table 2: Summary of Brinell hardness test results of A 360 alloy

Alloy	Condition	Avg. BHN	Standard deviation	% change in BHN
Base alloy	As-cast	60.4	1.56	-
	T6 h/t	83.0	1.06	-
Base alloy + 0.025% Sr	As-cast	63.2	0.35	4.64
	T6 h/t	89.5	1.05	7.83
Base alloy + 0.048% Sr	As-cast	67.3	0.44	11.42
	T6 h/t	95.4	0.23	14.94
Base alloy + 0.060% Sr	As-cast	69.2	1.85	14.57
	T6 h/t	104	4.92	25.30
Base alloy + 0.50% Fe	As-cast	62.5	0.23	3.48
	T6 h/t	87.5	1.03	5.42
Base alloy + 0.78% Fe	As-cast	61.7	0.38	2.15
	T6 h/t	86.7	0.40	4.46
Base alloy + .50% Fe + 0.25% Mn	As-cast	65.6	0.53	8.61
	T6 h/t	93.0	1.31	12.05
Base alloy + .78% Fe+0.39% Mn	As-cast	64.3	0.31	6.46
	T6 h/t	91.3	0.53	10

Fig. 4(a) shows the microstructure of the base alloy in as-cast mode. It has the lowest proportion of alloying elements compared to the other alloys under investigation. The micrograph depicts mainly the Al-Si eutectic bearing coarse Si grains. The Fe present (0.43%) allows the formation of β-Al_5FeSi through a ternary reaction. Previous studies on microstructure have described them as thin platelets interspersed with the Si particles [16]. Fig. 4(b) shows the microstructure of the alloy upon varying the Sr levels up to 0.025 %. The microstructure of the alloy with 0.048% Sr levels is shown in Fig. 4(c). In addition, Fig. 4(d) shows a micrograph of an alloy containing 0.06 % Sr. Increasing Sr to 0.025, 0.048 and 0.06 % changed the morphology of the eutectic Si to a very fine fibrous form with a great deal of branching and interconnection.

It is known that Fe is highly soluble in liquid aluminium alloys; however, it has a very low solubility in the solid, and tends to combine with other elements to form intermetallic phase particles of various types. As these Fe particles increase, the detrimental effects on mechanical properties also increase. The high Fe proportions lead to large and thin platelet phases. These phases act as inclusions [17]. The harmful intermetallics contribute to the slight decline in BHN of the alloy.

In this study, Mn was used to alter the deleterious effects of Fe-rich platelets in the microstructure on the hardness property of the alloy. Mn added at 0.25% weight to an alloy containing 0.50% Fe possesses an α-phase of $Al_5(FeMn)_3Si_2$ which ties up the extra Fe in the Chinese script phase. Its micrograph is shown in Fig. 4 (g). Studies have shown that this phase reduces the embrittling effect of the thin platelets [18]. Likewise, Fig. 4(h) is a micrograph of an alloy with 0.78% Fe in combination with 0.39% Mn. When Fe and Mn are added to the Al-Si alloy, the microstructural appearance and the entire mechanical properties of the alloy change. The increased Fe addition causes a slight increase in the lattice constant [19], therefore enabling more intermetallics to be formed. Mn accelerates the nucleation of Fe based intermetallic crystals and its presence in the alloys causes a considerable decrease in the length of fine β-Al_5FeSi phase. In Mn-modified alloys, an effect of α-phase on hardness is less detrimental compared to β-phase. It is also noticeable that a higher Mn level leads to an increased percentage of α-intermetallic.

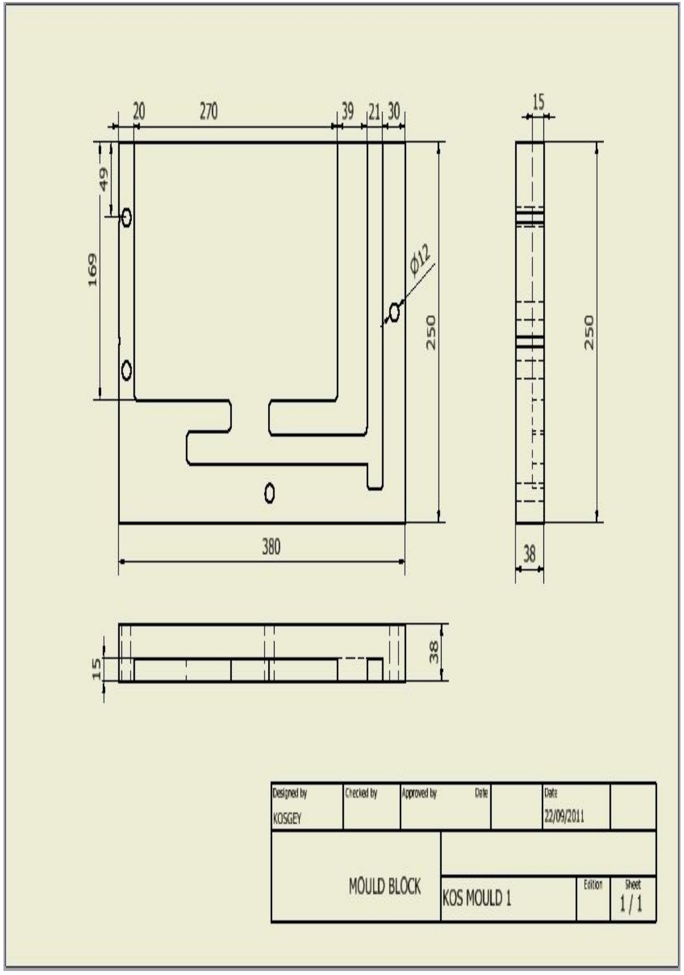


Fig. 1. Dimension details (in mm) of one half of the permanent die mold.

	As cast Brinell hardness	Microstructure	T6 heat Brinell hardness	Microstructure	

Fig. 2. Representation of the sectioned casting.

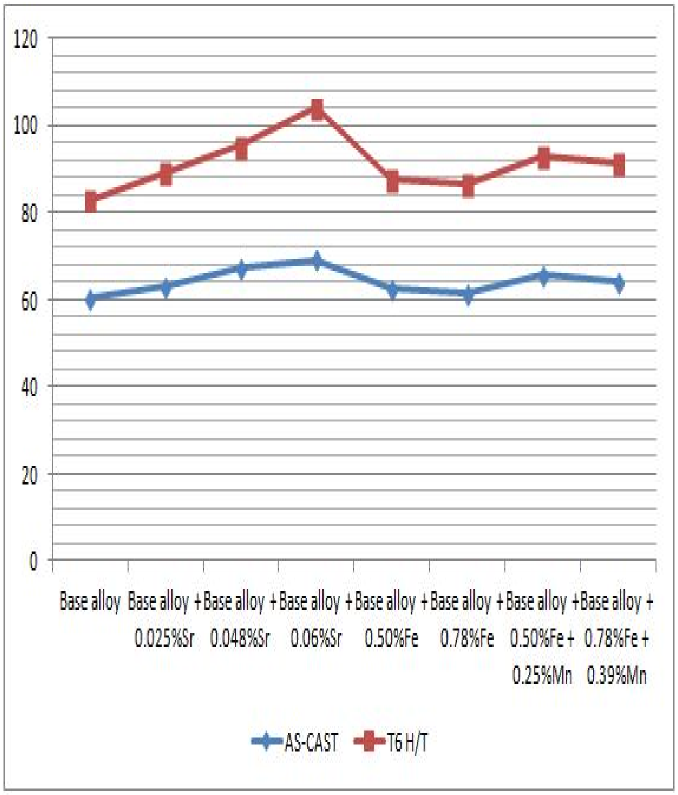
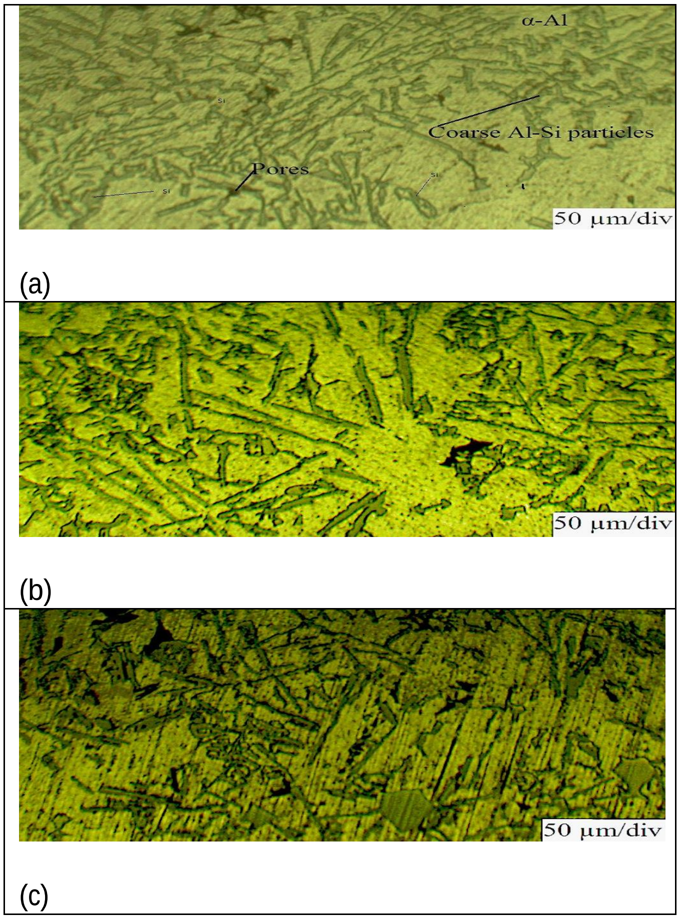


Fig. 3. Average Brinell hardness results for A360 alloy as a function of element addition as-cast and T6 heat treated.



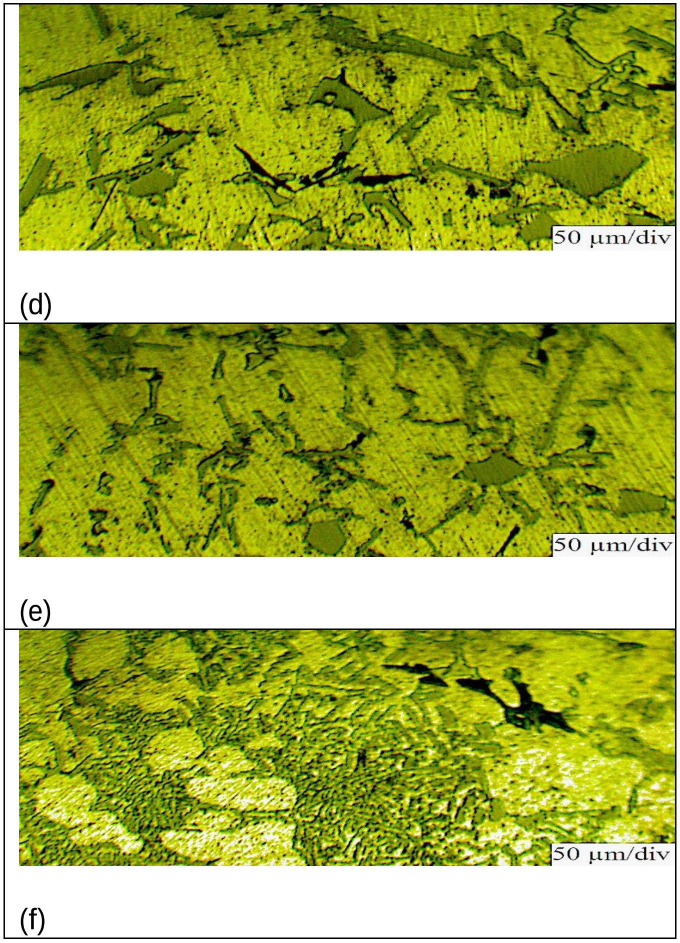


Fig. 4. Micrographs of the developed alloys; (a) as-cast base alloy, (b) Base alloy + 0.025% Sr, (c) Base alloy + 0.048% Sr, (d) Base alloy + 0.060% Sr, (e) Base alloy + 0.50% Fe, (f)) Base alloy + 0.78% Fe.

4. Conclusions

The research was undertaken to investigate the effect of Sr, Fe and Mn on hardness properties of die cast secondary Al-Si alloys. The impact of heat treatment on the castings was also investigated. The following conclusions can be drawn from this work:

(1) Addition of Sr to the Al-Si alloy at levels of 0.025%, 0.048% and 0.06% increased the alloy hardness by 4.64%, 11.42% and 14.57% respectively.

(2) Addition of 0.50%Fe and 0.78%Fe increased the Brinell hardness number by 3.48% and 2.15% respectively. However, combination of 0.50%Fe and 0.25%Mn portrayed a hardness increase of 8.61% compared to the base alloy while addition of 0.78%Fe and 0.39%Mn combination improved the alloy hardness by 6.46%.

(3) The T6 solution heat treatment procedure depicted varied mechanical properties of Al-Si alloy. The T6 heat treated specimen bearing 0.025%Sr, 0.048%Sr and 0.06%Sr depicted improved hardness by 7.83%, 11.94% and 25.30% respectively. An alloy of 0.50%Fe improved its hardness by 5.42% while with 0.78%Fe depicted an improved hardness by 4.46%. Upon neutralizing of Fe with Mn at 0.50%Fe and 0.25%Mn, the hardness improved by 12.05%. Similarly, a combination of 0.78%Fe and 0.39%Mn increased hardness by 10%.

Acknowledgement

The author gratefully acknowledges Jomo Kenyatta University of Agriculture and Technology for financial support through a graduate scholarship. The support from the Department of Mechanical Engineering is also acknowledged.

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