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The Fluidity of a Model Recycle-Friendly Al-Si Cast Alloy for Automotive Engine Cylinder Head Application

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Abstract— **This study investigated the fluidity of a model recycle-friendly Al-Si cast alloy for automobile engine cylinder head application. The fluidity measurements were carried out using spiral sand moulds fabricated from silica sand bonded by sodium silicate/CO_2. The fluidity of the base alloy was found to possess excellent flow length in a curved channel while the addition of 0.02% Sr was observed to reduce the fluidity by 5.2%. The increase of iron content of the base alloy to 0.38% Fe decreased the fluidity by 21.9%. This is attributed to the formation of intermetallic phases that blocks the interdendritic channels which are responsible to compensate for solidification shrinkage. However, combined addition of 0.9% Fe and 0.45% Mn was observed to reduce the fluidity by 12.1%.**

Keywords— Aluminium Recycling, Al-Si, Fluidity, Al-Si modification Fe –intermetallics

I. INTRODUCTION

Automotive components are currently manufactured from different Al-Si alloys. The production of these components from primary aluminium alloys has become a huge burden in terms of economic benefits and environmental aspects. Hence, recycling aluminium alloys is adopted as a strategy in foundry industries for production of various components in the transport and other structural applications [1, 2]. However, the recycled alloys are prone to various deleterious effects on castability and mechanical performance mainly because of the high levels of impurity elements [3]. The situation is more complicated for products such as automotive engine cylinder heads which are routinely produced from a wide variety of cast aluminium alloys. The mechanical properties and castability of Al-Si alloys are known to be affected by many factors. Castability, especially fluidity depends on a number of variables such as channel thickness, melt head, mould temperature, superheat, alloying composition and inclusion [4, 5]. Fluidity is highly affected by degree of superheat. The increase in melt temperature by 1ºC, in the temperature interval 700-730ºC increases the fluidity length by 1% [6]. The presence of oxide inclusions decreases fluidity, particularly at low pouring temperature [7]. A Solid oxide film might form a continuous wrapping around the stream and restrict the melt flow depending on the strength and specific gravity of the film [8]. Fluidity in foundry is expressed as a distance a molten metal flows in a mould of constant cross-sectional area before it stopped by solidification [5]. Spiral test experiments are usually conducted to determine the fluidity of cast aluminium alloys. Bouska [9] conducted spiral tests and showed that increase strontium significantly decreases the flow length of the aluminium melt. The effects of titanium and strontium on the fluidity of liquid A319 and A356 alloys were investigated by Sanchez et al [10]. It was found that increase in titanium enhances the fluidity of the A319 alloy due to its high potential to refine the grain size. Further, the fluidity index of the A356 alloy was found to increase with the increase of Sr. Strontium addition at levels 0.015% and 0.02% were found to increase fluidity while addition of 0.28% Al-5Ti-1B and combined addition of 0.02% Sr and 0.28% Al-5Ti-1B decreases fluidity of alloys LM25 and LM27 [11]. Addition of grain refiner on alloys of AlSi7Mg and AlSi11Mg was reported to affect fluidity. For both alloys, an increase in fluidity is observed as the content of grain refiner increases above 0.12% Ti, while the fluidity is diminished with increased grain refinement below 0.12% Ti. Moreover, refinement of the alloys with 0.015%wt B shows the highest fraction solid at dendrite coherency, the smallest grain size and the best fluidity [12].

A report by Sahoo and Sivaramakrishnan [13] shows that modification of Al-8.3wt% Fe-0.8wt% V- 0.9wt% Si alloy by Mg had much better fluidity than the unmodified. This is possible due to the formation of Mg phases which have high heat of fusion and hence delays the solidification of the alloy. Addition of 0.1%wt Cr to LM6 alloy has been reported to decrease fluidity due to formation of sludge [14]. A study made by Gowri and Samuel [15] on 380 alloys, indicated that with the addition of Fe content of 1.5 and 1.7wt% decreased fluidity by 4% and 6%, respectively. The additions of 1.3wt% Zn to the same alloy caused a decrease in fluidity of 5%.

Studies made by Mose et al [11] showed that increase of Fe level from 0.4-0.48% increased the fluidity of LM 25 alloy while increasing beyond this level decrease the fluidity of the alloy. In a similar research addition of Fe between 0.41 to 0.6% to the alloy LM27 has been shown to increase the fluidity.

The objective of this study is to investigate the fluidity of a model alloy developed from scrap cylinder heads with the addition of eutectic modifier (Sr) and with some level of impurity (Fe).

II. EXPERIMENTAL METHODS

A. *Alloy Preparation*

A model secondary alloy investigated was obtained by melting different aluminium engine cylinder head scraps in a 70 kg capacity oil fired graphite crucible furnace to 730˚C. And then cast into conical 4 kg capacity ingot molds fabricated from silica sand bonded by sodium silicate/CO_2 binder, targeting to avoid the iron pick up that could be generated when using ingot moulds of mild steel sheets. The model secondary alloy obtained from scrap cylinder heads is coded as KA1 and is found to be approximately equivalent to the JIS-AC2B standard alloy. The chemical composition of this base alloy is given in TABLE 1.

TABLE 1. Chemical composition (in wt. %) of the secondary Al-Si alloy.

Alloy	**Si**	**Cu**	**Mg**	**Fe**	**Mn**	**Ti**
KA1	6.01	2.62	0.24	0.28	0.21	0.02
	Zn	**Cr**	**Ni**	**Pb**	**Sn**	
	0.12	0.02	0.02	0.01	0.01	

B. *Preparation of Spiral Moulds*

The mould used for testing the fluidity of the alloy was fabricated from silica sand bonded by sodium silicate / CO_2. The mould consisted of a pouring basin incorporated with the cope, a rectangular tapered sprue with small circular section that extended to the drag, and spiral cavity completely in the drag and the wide opening of the cavity was also pointing upward. The dimensions of the mould were 290mm x 275mm x 40 mm and with pressure head height 99 mm. The moulds were fully vented during fabrication to remove the moisture. An aluminium spiral pattern was cast in already existing permanent spiral mould that had been designed and machined from cast iron during a previous study [11]. The pattern was then subsequently used in the preparation of the spiral sand moulds. Moreover, the spiral pattern geometry was as show in Fig. 1. The spiral pattern, the complete set-up and sectional view of the fluidity mould used for successive casting are also indicated in Fig. 2.

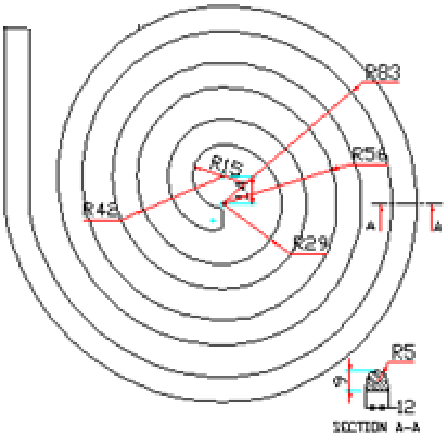


Fig.1 Dimensional details of the spiral fluidity pattern (in mm)

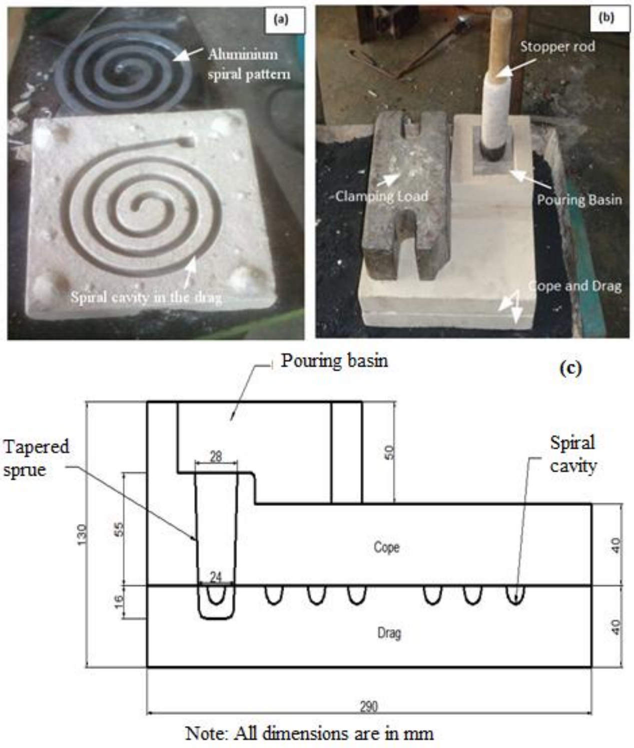


Fig. 2. (a) The spiral pattern and the mould (b) complete set-up of the spiral fluidity mould (c) The sectional view of the fluidity set-up

C. *Element Additions*

In this study, the effect of Fe, Mn and eutectic Si modification by Sr on the fluidity of model secondary alloy was investigated. The Sr modifier was available in the form of Al-10% Sr master alloy metallic rods while Fe and Mn were available as Al - 75% Fe and Al - 75% Mn briquettes. The effect of Sr was investigated by through addition of 0.02 wt.% Sr while that of Fe was investigated by increasing the Fe content in model alloy to 0.38 wt.% and 0.9 wt.%. However, the 0.9 wt. % Fe alloy also included a Mn addition of 0.45 wt. %.

D. *Melting and Pouring*

The ingots of the model alloy were heated to a temperature of 760^0C in an electrical resistance furnace located at University of Nairobi. The alloying process has been done when the temperature of the charged ingot reached between 730^0C to 750^0C. The pouring temperature of the molten metal was maintained within 720 ± 3^0C for all successive tests. K-type thermocouple was employed to measure the temperature of the molten metal while it was in the 4kg capacity SiC crucible. Pouring time range that is the time between filling the basin and removal of the stopper rod was kept the same for each experiment. The pouring basin was filled completely as fast as possible before and after the removal of the stopper rod to give the same head pressure for all successive tests. Three tests were taken for each of the alloy developed to incorporate the possible errors that could be emerge due to personal, mould and test variables.

E. Alloy Preparation

Specimens for microstructural analysis were sectioned 5 mm from the tip of the fluidity spirals. The specimens were polished with different grades of SiC paper and finally polished with diamond paste of decreasing grain size of 6µm, 1µm and 1/4µm. Optical micrographs were then taken using Optika-Optical Microscope B -353MET.

III. RESULTS AND DISCUSSION

TABLE 3. shows the average results of three test measured values and standard deviation of each of the alloy's fluidity length. From TABLE 3 it can be seen that there was a decrease in fluidity length of the alloy with the addition of modifier and impurity elements. With the addition of eutectic silicon modifier that is 0.02% Sr it has been observed to decrease the fluidity by 5.2% and an increase of iron content of the alloy to 0.38% Fe resulted a further decrease on the average fluidity length by 21.9%. Iron addition in combination with manganese in the ratio of 2:1 (Fe: Mn) was observed to decrease the flow length by 12.1%.

TABLE 3. Experimental results of the alloys fluidity test

Alloys	Average Length in (cm)	Standard deviation (cm)	Percentage Difference (%)
Base alloy (KA1)	116.5	1.6	-
KA1+0.02% Sr	110.5	1.8	5.2%
KA1 + 0.38% Fe	90.5	2.3	21.9%
KA1 + 0.9% Fe + 0.45% Mn	102.4	3	12.1%

Fig. 3 shows the effect of the alloying elements on the fluidity of the base alloy when they are added in small percentage. The bar chart shows the variation of average recorded fluidity length changes when alloying elements strontium, iron and manganese are added to the base alloy.

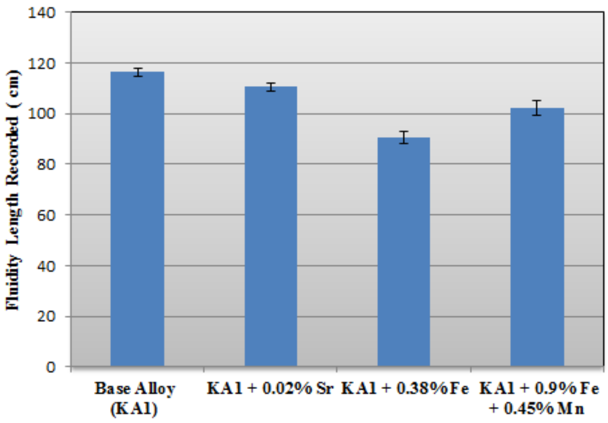


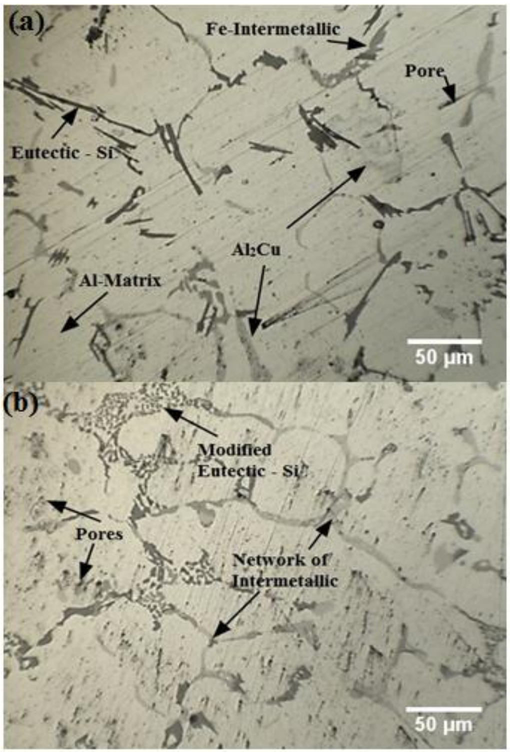
Fig. 3 Fluidity variation with Sr, Fe and combined Fe + Mn

The deviation of the measured test results are indicated by standard deviation. These deviations are associated mostly with mould parameters, temperature and personal errors. Such effects can be reduced through the proper control of mood parameters such as vent size and position and controlling of pouring temperature of each successive test. For instance if the vents (holes for escaping the gases from the mould) are on the cavity/channel, the flow of the molten metal will be obstructed therefore reduces the flow length. These effects were observed during the experiment which resulted in discarding the casting that had such defects.

Fig. 4 and Fig. 5 shows the test result when the recycled aluminium alloy was solidified in the spiral cavity fluidity mould and micrograph of the cast spiral respectively.

Fig.4. The outcome of the alloy’s fluidity when it is solidified

Fig. 5 shows the microstructure of specimens taken 5mm away from the tip of the casting spiral. It shows the primary aluminum dendrites, eutectic, Fe-intermetallics, Cu-intermetallics and oxides. Fig. 5(a) reveals that the alloy contains some copper phases nucleated along the thin iron phases, eutectic and oxides. Uniform distribution of phases of the eutectic silicon and Fe- intermetallics were observed in this alloy and no network of intermetallis were observed that could choke up the flowing molten metal. However, in Fig. 5(b) it was observed that strontium modification resulted in a network of intermetallic phases. These structures can block the flowing molten metal and then decreases the fluidity of the alloy if they solidify early before a coherent solid network is formed.



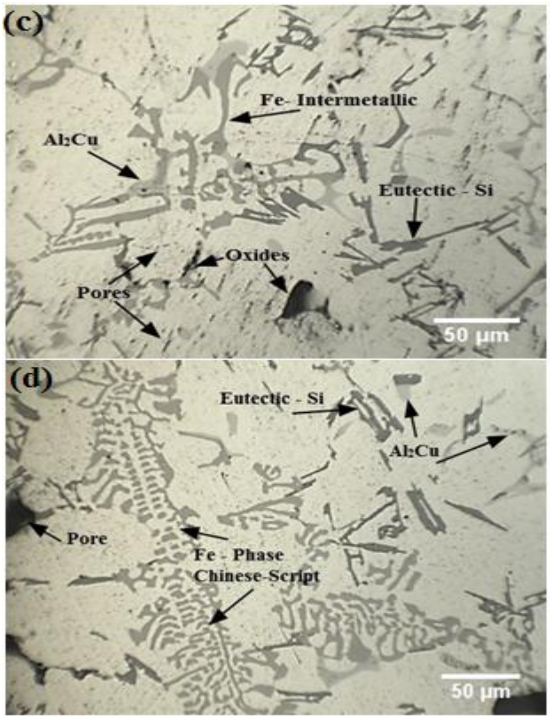


Fig.5 Micrograph of the alloys 5mm from the tip of the fluidity casting, (a) Base alloy (KA1), (b) strontium modified base alloy, (c) 0.38% Fe containing base alloy and (d) 0.9% Fe + 0.45% Mn containing base alloy

Although Sr has a wide range of significant advantages in comparison with other chemical modifiers such as Na and Sb in foundry during casting [16]; this study however, demonstrates that strontium reduces the fluidity of the alloy developed. Excess amount of Sr leads to porosity, which among others has been attributed to reduced surface tension of the melt and increased volumetric shrinkage [17]. Addition of Sr also leads to segregation of the Cu-containing phases to regions away from the Al-Si eutectic. This can lead to blockage of the interdendritic channels if blocky Al_2Cu phases are formed during solidification [18].

Addition of Fe to this alloy has been observed to produce various intermetallic phases which have the potential to reduce the fluidity of the molten metal. In addition, Fig. 5 (c) shows that a number of Al_2Cu phases formed in addition to eutectic Si and oxides. The microstructure of Fig. 5(d) shows an increased number of Fe - intermetallics in comparison with Fig. 5(c). Moreover, the neutralizing effect of Mn is observed to result in fine Fe – intermetallics in the 0.9% Fe containing alloy. This may explain the higher fluidity reported in this alloy compared to the 0.38% Fe containing alloy.

Increase in the iron level in an alloy generally leads to an increase in the amount of insoluble iron-rich bearing phases which can reduce the alloy's fluidity. The β-phases have largest surface to volume ratio, hence they have the largest interfacial region with the melt and are likely to be the most detrimental intermetallic in reducing fluidity [14]. Moreover, with an increase in size and amount of β and α phases, there is usually a concomitant increase in interconnected shrinkage porosity due to a reduction in the permeability/feeding in mushy zone.

CONCLUSION

This study shows that the base alloy possessed the best castability (fluidity) while the addition of eutectic modifier and the impurity level were observed to decrease the fluidity. The addition of modifier reduces fluidity by forming intermetallic network. The secondary alloy has high propensity to reduce its fluidity with small addition of Fe below its critical level. However, the neutralizing effect of Mn is observed to result in fine Fe – intermetallics in the 0.9% Fe containing alloy. Hence, neutralizing Fe with Mn at higher level of Fe plays a great role in giving the best fluidity.

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