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STUDY OF MACROSEGREGATION EFFECTS ON THERMAL AND ELECTRICAL CHARACTERISTICS OF ALUMINUM-COPPER ALLOY

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Abstract: Macrosegregation phenomenon regardless of casting size often induces high partition coefficient (k) impacting adversely the thermal and electrical properties of cast binary alloy. In this study, an experimental investigation of macrosegregation propagation in aluminum-copper alloy solidification is reported. Al6wt. % Cu was produced at varied pouring heights including 100 mm, 200 mm, 300 mm, 400 mm and 500 mm. The combinations of optical, scanning electron and energy dispersive spectrometry were used to evaluate the extent of segregation in the casts while the electrical and thermal conductivity properties were determined using Wiedemann-Franz Law. Results show that the Al-Cu cast at a pouring height of 400 mm demonstrated the highest electrical and thermal conductivity of 55 %IACS and 2.1437 W/mK 10^{-6} respectively. This compared well with established standard values in application such as heat exchangers and electronic sensors. The occurrence of minimal macrosegregation at 400 mm pouring height may be attributed to appropriateness of melt-flow regime resulting in desirable microstructure that prevents long-range solute/solvent segregation.
Keywords: macrosegregation, Al-Cu alloy, electrical conductivity, thermal conductivity

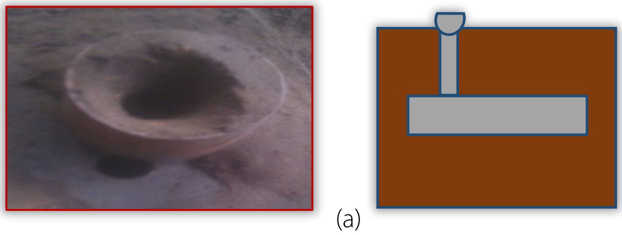
INTRODUCTION

Solidification phenomenon involves liquid-to-solid phase transformation along a moving interface, which is often accompanied by the release of latent heat energy (Nastac *et al*., 2016). Generally, the solidification of castings with columnar structure usually give rise to castings rich in solute at the centre than the skin. This is attributed to solute rejection from the first solidified solid into the liquid just ahead of the solid-liquid interface. For short distance variation in chemical composition, microsegregation occurs but this can be remedied through a simple annealing heat treatment procedure. However, when inhomogeneity in chemical composition occurs over a long range, it produces macrosegregation, which cannot be removed by any heat treatment procedure. The problem of macrosegragation is a common occurrence in aluminium and copper alloys castings (Ahmadein et al., 2015). It is reported that macrosegregation is caused mainly by fluid flow rather than solute diffusion at macroscopic scale (Tveito et al., 2012). The solute diffusion layer is pictured as been much smaller than the actual dimension of the volume element. According to Beckermann, (2008), macrosegregation is more pronounced and problematic in castings with diameters between 20 mm and 40 mm resulting in a relatively high partition coefficient. The solute diffusion and redistribution invariably impacts the mechanical, electrical and thermal properties of the cast.

As-cast structures with macrosegregation of alloying elements also contain impurity elements, gases and shrinkage pores as well as undesirable macroscopic constituents. These constituent have the tendency to affect the overall conductivities of the cast owing to discontinuity created in heat flow. Due to the difficulty of direct and accurate determination of thermal conductivity, it is necessary that another physical property is coupled to thermal conductivity (Clemens, 2000; Volklein *et al*., 2009). One of such methods is based on Wiedemann-Franz Law for metals. This law stipulates that thermal conductivity approximately tracks electrical conductivity. This is predicated on the fact that freely moving valence electrons transfer not only electric current but also heat energy. However, the general correlation between electrical and thermal conductance does not hold for other materials (Clemens, 2000). Electrical and thermal conductivity being a measure of transport of properties can be subjected to the same physical laws. For this reason, any theoretical predictions and general experimental findings established for the flow of heat in metal alloy or composites are generally applicable to both properties. Theoretical studies (Ahmed *et al*., 2013) have shown that thermal conductivity of alloys in relation to composites is a function of volume fraction, distribution and thermal conductivity of the constituting elements. The existence of a thermal barrier at the interface owing to inhomogeneity in chemical composition and different intermetallic phases formed can bring about inconsistency in the flow/transport of electrical and thermal properties from one point to another. This assertion is yet to be experimentally verified hence the current study focuses on the effect of macrosegregation on thermal and electrical characteristics of aluminum-copper alloy.

MATERIALS AND METHODS

Commercial aluminum (1000 series) ingots were obtained from Qualitech, Ojokoro, Lagos, Nigeria and mechanically sectioned at ambient temperature into smaller sizes suitable for melting. The copper scraps were sourced locally, reconditioned by removing all drib. The materials were then combined and used as alloying element according to the formation presented in Table 1. Melting was done in batches as Copper was charged first into the furnace before aluminum. The molten alloy was continuously stirred in order to ensure a uniform distribution of alloying elements. Casting of samples in sand moulds was carried out for five different pouring heights of 100, 200, 300, 400 and 500 mm. Figure 1 (a and b) show a typical sand mould used and graphic illustration of the internal configuration of the mould. It is to be noted that a thermocouple was inserted in the mould while casting was being carried out to ensure the continuity of temperature profiles measurement. The temperature profile data obtained helps in interpreting the melt- flow behaviour, casting speed, the microstructure and eventually the mechanical properties of the cast. The data was also used to generate the relevant cooling curves.



(a) (b)

Figure 1. Casting of samples in sand moulds
a) typical sand mould; b) graphic illustration of the internal configuration of the mould

Table 1: Spectrometric Analysis of Aluminum - Copper Alloy

Sample Designation	Wt.% Composition				
	Al	Cu	Si	Mg	Fe
A1	96.01	2.000	0.951	0.667	0.372
A2	94.80	4.000	1.063	0.039	0.098
A3	91.98	6.000	1.010	0.050	0.960
A4	88.66	8.000	1.832	0.131	1.377

Thermal conductivity & electrical conductivities tests

In these tests, the inverse of conductivity called resistivity was determined for aluminum-copper alloys using a BEKO power AB of TYPE – Rm 0606, 110/240V AC. The input current varied from 10 - 100 and 100 - 600 amperes within the ranges of 10 and 100 amperes respectively. For each sample, ten readings of resistivity were obtained and these data were further used to calculate both electrical and thermal conductivities. The following formula relates resistivity to electrical and thermal conductivity;

$$\sigma = \frac{1}{\rho} \quad (1)$$

$$k = \sigma LT \quad (2)$$

Where σ is the electrical conductivity in $\Omega^{-1}m^{-1}$, ρ is resistivity in Ω, k is the thermal conductivity in W/mK, T is the absolute temperature in K, and L is the Lorenz number, equal to 2.45 10^{-8} $W\Omega/K^2$.

Microstructural analysis

The techniques employed for microstructural study entail Optical, Scanning Electron (SEM) and Energy Dispersive (EDS) analysis. The specimens for microstructural analysis were sectioned at the edges and middle of cast samples. Grinding and polishing were done using emery papers of different grit sizes ranging from 120, 240, 320, 600 and 1200 until a mirror-like surfaces was achieved. Weck's reagent which is made up of 100 mL water, 4 g $KMnO_4$ and 1 g NaOH was used as etchant at room temperature. The surfaces of the polished samples was swabbed with the etchant for 15 s. The etched specimens were then carefully washed, dried to avoid accidental scratches on their surfaces. The specimens were then mounted on the optical microscope and images were obtained at 200 μm magnification. These same set of samples were used for both SEM and EDS analysis. A Phenon proX SEM machine with model number 80007334 and part number MVE0224651193 was used for this analysis.

RESULTS AND DISCUSSION

Solidification dynamics of Al-Cu alloy

Figure 3 shows the cooling curves of the alloy casting as measured by the thermocouple. From onset of solidification, the casting temperature drops instantaneously to a range of 670- 650 ^{0}C, which is about the melting point of aluminum. This observation remains fairly constant for ~ 160-180 s, thereafter; the cooling rate progressed until the molten metal solidified completely. The stage at which the temperature is fairly constant is due to the release of latent heat of solidification. The temperature decreases rapidly with increasing time once the release of latent heat was completed. It should be noted that all these cooling milestone took place in quick succession and in a matter of minutes the entire Al-Cu casting attained a uniform temperature. This rapidity in solidification process can be attributed to high thermal conductivity of aluminum in the system.

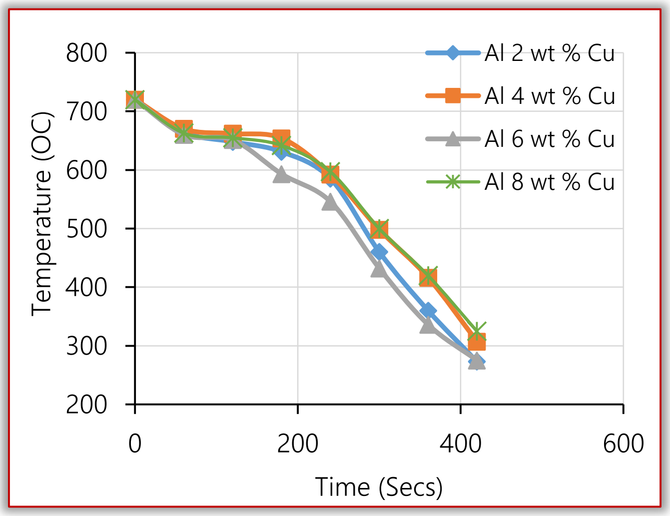


Figure 2: Cooling curves for Al-Cu alloy

Effect of varied pouring height on cast microstructure

The occurrence of solute atom segregation was more pronounced with samples containing 6 wt. % Cu (Figure 3). However, the segregation is observed to be more prominent towards the periphery of the cast while the center of the billet was highly depleted of the solute element. The sample at

400 mm pouring height exhibited a uniform distribution of solute element than at other pouring heights and therefore less segregated. Plate 1 shows respectively the optical scanning electron micrographs and EDS of cast samples. The major impactful phases Al-matrix are predominantly spherodised, $AlSiO_2$ crystals are homogenously distributed while some fringes of Al_5FeSi intermetallic are also observed. Conventionally, Fe appear in Al-Cu alloys as impurity element, and its presence often impairs ductility of castings by the formation of Fe-rich intermetallic compounds, particularly the Al_5FeSi phase (Malakhov et al., 2010; Nowotnik et al., 2007). Plates 2 – 5 revealed the variations that ensued with regards to the volume fraction, dispassion and morphology of the major phases within the matrices at different pouring heights. These varied microstructural features impact significantly the alloys thermal and electrical conductivities.

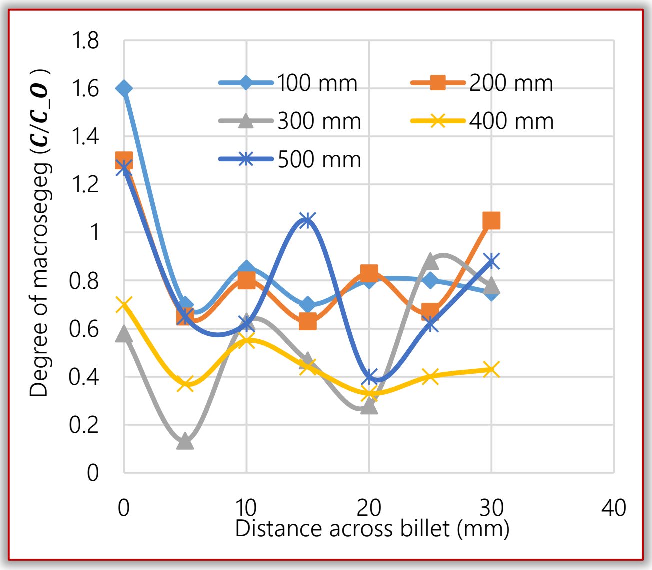


Figure 4: Effect of varied pouring height on relative segregation within Al - 6wt. % Cu Alloy

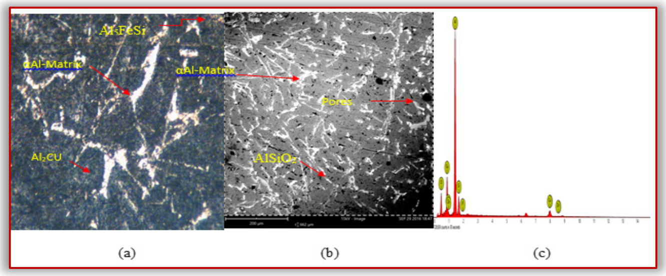


Plate 1: Micrographs of Al -6wt. % Cu 100 mm pouring height (a) optical (b) SEM and (c) EDS

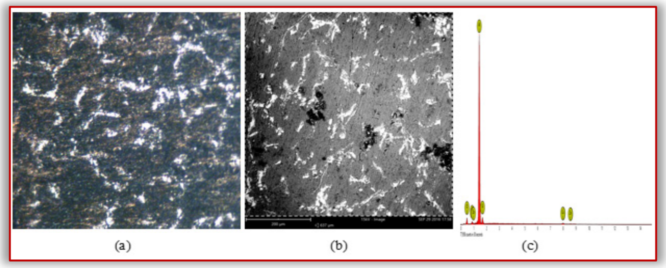


Plate 2: Micrographs of Al -6wt. % Cu 200 mm pouring height (a) optical (b) SEM and (c) EDS

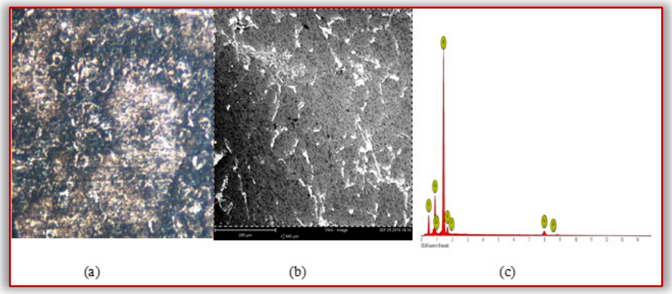


Plate 3: Micrographs of Al -6wt. % Cu 300 mm pouring height (a) optical (b) SEM and (c) EDS

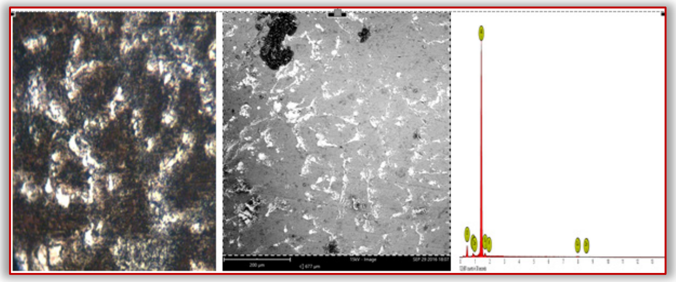


Plate 4: Micrographs of Al -6wt. % Cu 400 mm pouring height (a) optical (b) SEM and (c) EDS

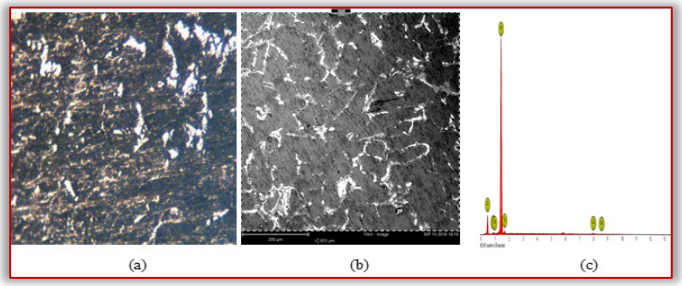


Plate 5: Micrographs of Al -6wt. % Cu 500 mm pouring height (a) optical (b) SEM and (c) EDS

Impact of Macrosegregation on Thermal and Electrical Properties of Al - Cu Alloy

Figures 5 and 6 illustrate the electrical and thermal conductivity characteristics of the Al-Cu alloy at varied pouring heights. From the figures, it is observed that the Al-Cu cast sample at a pouring height of 400 mm has the highest electrical and thermal conductivities of 55.3 IACS and 2.1437 W/mK respectively.

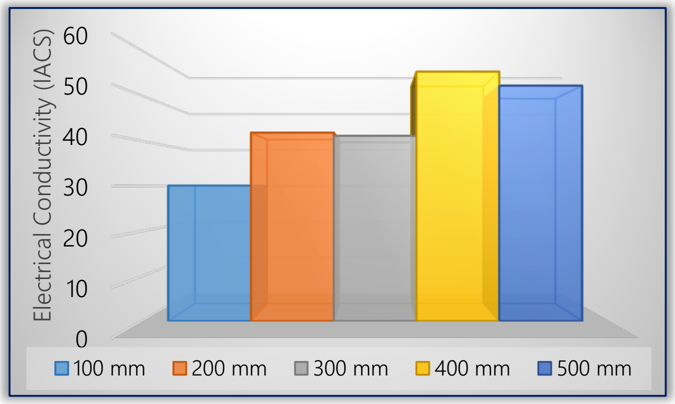


Figure 5: Electrical Conductivity of Al6wt%.Cu Alloy at Varied Pouring Height

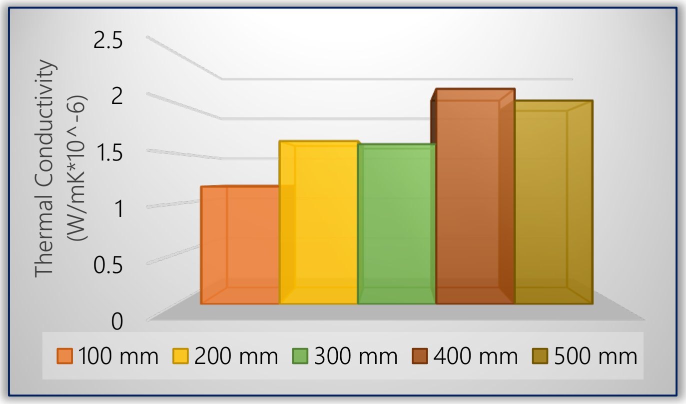


Figure 6: Thermal Conductivity of Al6wt%.Cu Alloy at Varied Pouring Height

It should be recall that cast alloy at 400 mm pouring height exhibited near-not segregation. Hence, confirms the fact that macrosegregation has great influence on the conductivity of cast samples. Low degree of segregation ensures a more coherent structure that engenders uniformity and consistency in heat flow.

According to Woodcraft (2005) and Zang and Wand (2015) relatively homogenous structure give rise to low thermal barriers, hence increase in thermal barriers are reduced, hence an increase in the thermal and electrical properties.

CONCLUSIONS

From this study, cast samples produced by pouring from spruce 400 mm height exhibited better and uniform distribution of solute/solvent elements resulting in minimal macrosegregation. The electrical and thermal conductivities at 400 mm pouring height also has the highest value (55.3 IACS and 2.1437 X 10^-6 W/mK) which compares well with standard values (59 IACS and 2.4878 X 10^-6 W/mK). Thus, 400 mm spruce height is deemed the optimum pouring height. It is concluded that the control of molten metal pouring height is critical in reducing the incidence of macrosegregation during solidification of molten binary alloy. The effect of this defect reduction translates into significant improvement in thermal and electrical properties of the cast alloy making it suitable for applications in thermal plants (cooling fins) and industrial refrigerating units.

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ACTA TECHNICA CORVINIENSIS BULLETIN OF ENGINEERING
ISSN: 2067-3809