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Effects of Casting Speed and Runner Angle on Macrosegregation of Aluminium-Copper Alloy

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ABSTRACT

During the solidification of binary metal alloys, chemical heterogeneities at product scale over a long distance range (1cm-1m) develop and this has detrimental effect on the resulting mechanical properties of cast products. Macrosegregation is of great concern to alloy manufacturers and end users as this problem persist. In this study, the use of process parameters namely casting speed and runner angle to reduce macro-segregation in aluminum-copper binary alloy solidification is reported. The results from optical microscope, scanning electron microscope and energy dispersive spectrometry show that these parameters significantly influenced the development, size and volume of macrosegregation. The combination of parameters namely the pouring height between 96 mm/s, 100mm/s, and runner angles between 1200, 1500 produced less segregations with improved mechanical properties within standard specification. The modulus of elasticity (6800 MPa), tensile strength (110 MPa) and 2.5 % elongation obtained in this study are within standard 7100 MPa, (88- 124 MPa) and (1-25 %) respectively for this class of alloy.

1. Introduction

Casting is one of the oldest and most widely used metal manufacturing process. Although the manufacturing process is versatile, it is not free from flaws such as micro-segregation, macro-segregation, porosity, surface roughness, cracks, tearing, blows and cold shuts. These distortions in any casting are costly and corrective operations are required to finish the casting were possible. Macro-segregation unlike microsegregation (that can be removed through subsequent hot working or annealing) cannot be easily removed as it occurs over a long range of distance (1cm - 1m) where diffusion becomes ineffective [1, 2].

The phenomenon is significant in large casting (D > 40 mm) but also becomes a factor to consider in small or medium size castings (D < 20 mm or (D > 20 mm) with relatively high partition coefficient (k). This is very common with aluminium and copper alloys [3, 4]. Distortion is created by the deformation occurring throughout solidification and in further cooling during the casting process. Macro-segregation is caused essentially by fluid flow rather than solute diffusion at macroscopic scale. However, the problem of macro-segregation is more complicated than just solute diffusion and redistribution. Factors that can play out during solidification [5] include: density and compositional changes due to temperature changes within a phase (natural convection); the action of gravitational field on a density gradient (buoyancy driven flows); drag forces from melt convection or from solid motion; external forces such as magnetic fields and forces applied on the surface (forced convection); solid stress due to solidification contraction or expansion (as a result of temperature variation or solid state phase transformation) and metallostatic pressure.

The quality of the final product in terms of microstructural evolution, metallurgical and mechanical properties is determined right from the onset of the casting process by the interaction of various casting parameter hence, these can be controlled for optimum yield. Most of the casting defects such as bad surface, improper filling, flow marks, cold shuts are caused due to improper gating. The location, size, and type of gate are three important factors in gating [6]. The solidification structures including the total grain number and the dendrite morphology can affect the centre macrosegregation. These are also a direct consequence of process parameters such as casting speeds, solute field, temperature field and flow field during solidification. When metal is poured, it flows from

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the pour cup or sprue cup into the sprue. Then, it flows through the gate and runner system and into the mould cavity.

The runners are the horizontal hollow channels that connect the bottom of the sprue to the mould cavity. The region where any runner joins with the cavity is called the gate. Inclination of this part of casting set has significant effect on the quality of the cast product. The solution to turbulence that results into macrosegregation in binary alloy castings can be attributed to synergy between the position of the runner in the mould and the height at which pouring of molten is done. Establishment of best angle of pouring that is, runner inclination will help to avoid turbulence at the incipient of molten metal entering into the mould. Though several studies have been conducted on the effect of size and dimension of runner on cast product but, the impact of the inclination of this has not been considered as there exist little or no information and data on this process parameter. Hence, this study is aimed at determining the pouring height (casting speed) and runner angle suitable for minimal macro-segregation in solidifying aluminium copper alloy. Having a consistent pour rate is important to this process. A steady pour avoids overflowing the pouring cup and ensures that the gate and runner system is completely full at all times during the pour [7]. Keeping the gating and runner system full and at the appropriate angle ensures an uninterrupted mould fill which could otherwise result in additional casting defects.

Various experiments have also been performed to understand the mechanisms associated with solidification processes and the development of macro-segregation. At the same time, many mathematical models have been developed to predict these phenomena through analytical or computational simulations. The need to validate mathematical model with experimental result has led scholars to perform a complementing experiment. Past studies have established the physics behind macro-segregation using analogue alloys. However, macrosegregation is a real life three dimensional problem and there has not been significant breakthrough recorded [8]. Zhenhu *et al.*, [9] employed Multi-pouring Technique (MP) in the study of macro-segregation by varying the influx with which molten metal is introduced into the mould. Comparison of results show that the multiple pouring process has some certain favourable effect on reducing the final macrosegregation as compared to the conventional constant concentration pouring process. However, the process is time consuming and seemly impracticable for large scale casting. In a study of evolution in grain size and macrosegregation as well as the solidification sequence of a direct chill cast AA5182 [10], it was found that strong macrosegregation of Mg, Mn, and Cr from centre to surface due to fluid flow and partitioning of solute elements between liquid and solid during solidification. Mg shows negative segregation at the centre and positive segregation at the surface.

Table 1. Nomenclatures

T	Time for pouring the molten metal, s
V	pouring speed, cm/s
H	Height of ladle above pouring basin, cm
g	Acceleration due to gravity m/s^2
Abbreviations	
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive spectrometry
ML	Metallurgical Length
ASTM	American Society for Testing and Materials
UTS	Ultimate Tensile Strength

2. **Experimental Methodology**

In this study, cast samples were produced from Al-Cu alloy, the process parameters that were considered are casting speed and variation in runner angle. For each parameter considered, the other was kept constant. For the first setup, five pouring heights between 100 and 500 mm at an interval of 100 were used and these pouring heights were subsequently used to compute the variation in casting speeds based on Equations 1 and 2 [11,12]. For the second set up, the runner angle was varied between 90 ^{0} and 150 ^{0} at an interval of 15 ^{0}. Post solidification analysis such EDS, SEM and Optical analysis provide detailed macro-segregation measurements. Tensile test reveals the effect of this defect on mechanical properties of the alloy. The average pouring time (seconds) for most castings is equal to the square root of the weight of casting. Pouring time is controlled by the mass flow rate in the pouring operation. The velocity and cross section of the stream normally determine the mass flow rate as shown in Equations 1 and 2.

$$V = (2gh)^{0.5} \tag{1}$$

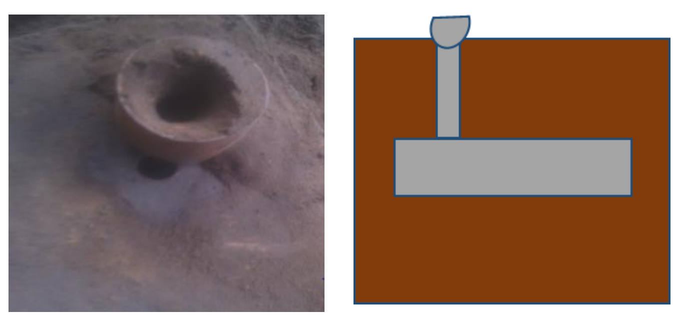
$$V = \frac{h}{t} \tag{2}$$

2.1. Materials and Melting

A 1000 series commercial Aluminum ingot with percentage composition shown in Table 2 were obtained from Qualitech Ojokoro, Lagos- Abeokuta Express road, Lagos, Nigeria and sectioned into smaller sizes suitable for melting. Copper scraps were sourced locally, recycled and used as alloying element. Melting was done in batches based on the required composition shown in Table 2. During the melting process, copper with a higher melting point of about 1084 ^{O}C was charged first into the furnace before Aluminum (see **Figure 2**). The molten metal was continuously stirred in order to ensure a near-uniform distribution of alloying elements. The total weight of charge for each specimen was about 1.6 kg. Furthermore, sand moulds with cylindrical cavities of 30 mm by 300 mm were prepared from green sand with other additives and binders. The mould is 20 mm thick with a runner of 10 mm diameter and 8 mm long. Figure 1a and 1b shows the experimental set up for the cast and Figure 2a and b are actual and filleted samples.

Table 2. Elemental Composition of 1000 Series of Aluminium alloy

Elements	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
Percentage composition (%)	0.03	0.15	0.02	0.02	0.15	0.02	0.06	99.8



(a) (b)

Figure 1. The experimental setup, (a) the actual mould setup and (b) Two dimensional setup of internal mould structure

(a) (b)

Figure 2. (a) Actual cast sample and (b) Feted Cast sample

Table 3. Percentage Composition of Aluminum Copper Alloy

S/N	Sample Designation	% Al	% Cu	% Si	% Mg	% Fe
1	A1	96.01	2.000	0.951	0.667	0.372
2	A2	94.80	4.000	1.063	0.039	0.098
3	A3	91.98	6.000	1.010	0.050	0.960
4	A4	88.66	8.000	1.832	0.131	1.377

2.2. Tensile Test

The tensile testing was conducted using an Instron Universal Tester model 3309.n shown in **Figure 3**a with the Blue Hill data acquisition software. Cylindrical sample with a reduced gauge section as show in Figure 3b was tested. The reduced gauge section ensured that the highest stresses occurred within the gauge and not near the grips of the Instron load frame. This prevents strain and fracture of the specimen near or in the grips. The reduced gauge section of each specimen was about 12.7 mm. The samples were machined to ASTM E8 standards. The purpose of this experiment was to gather information about the behaviour of each material under load.

(a) (b)

Figure 3. (a) and (b) represents a typical Instron load frame and reduced gauge section specimen

2.3. Sample Preparation for Microstructural Examination

The sample preparation and optical analysis were done in the Metallurgical Laboratory of University of Lagos, while the SEM and EDS were carried out in Covenant University, Ota, Ogun State. The coupons for microstructural analysis were sectioned from the extremes and middle of the cast samples. Furthermore, the coupons were wet ground on a rotating disc covered with an abrasive emery paper, with grit sizes from 120, 240, 320, 600 and 1200 until the desired smoothness was achieved. Polishing was done using alumina powder on a rotating wheel covered with cloth impregnated having fine abrasive compound. A Colour "Tint Etching" Weck's Reagent was used for the etching process (100 mL water+ 4 g $KMnO_4$ + 1 g NaOH) used at room temperature. The surface of the polished sample was swabbed with this solution for about 15 s. This reaction dissolves the amorphous layer and reveals the actual microstructure of the sample. The etched coupons were carefully washed, dried to avoid accidental scratches on its surface. These were mounted on the microscope for examination and the images produced were projected onto a computer screen for view. 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. This machine is very proficient in imaging and X-ray analysis of sample. The Phenom ProX is able to generate actual three-dimensional images of microscopic structures of materials and also determine their elemental composition via fully integrated and specifically designed EDS detector. EDS is a technique that analyzes X-rays generated by the bombardment of the sample by an electron beam. EDS elemental analysis is fully embedded into the Phenom ProX system. X-ray detector and control software are combined in one package.

2.4 Limitations of the Study

- The suggested methodology though contributed significantly to reduction of macro-segregation requires greater precision and expertise in the mould design and preparation in other to accurately position the runner in the right angle that will minimize segregation.
- Also the melting process of the Aluminium was done under normal atmosphere. A control atmosphere could have ensured a clean melt that would have reduced the level of macro-segregation in the matrix better than what is achieved in this study.
- The temperature measurement with the use of pyrometer was not the best that could be used. If the mould has inbuilt temperature measuring device better temperature gradient would have been captured during cooling and solidification.

3. Results and Discussions

3.1. Effects of Varied Casting Speed on the Cast Microstructure

Casting speeds were calculated based on Equation 2 and **Figure 4** was obtained. For all sample grades with 6 wt. % Cu, the segregation of solute atom was more visible towards the periphery of the cast and the centre of the billet was depleted of solute. The sample with 96 mm/s casting speed shows more uniform distribution of solute element than at other casting speeds and therefore less segregated.

In general, at higher casting speed the temperature of the cast billets increases and widens the mushy zone due to a reduced heat withdrawal. Consequently, the isosolidus and isoliquidus curves become longer and also cause an increase in the metallurgical length (*Metallurgical length,* ML). The ML is generally defined as the distance from the liquid level in the continuous casting mold to the location in the caster where the cross-section finally becomes fully solid. The higher casting speed prompt a drop in the shell growth as well as extending the mushy zone and this implies a longer local period of solidification. This explains reduced segregation at moderate (90-100 mm/s) casting speed as there was adequate diffusion within this zone, which allows uniform distribution of solute. However, this is contrary to reports by [13, 14, 15] where macro-segregation was observed to increase with increasing casting speed. These studies, however, did not consider the effect of runner angle inclination during casting.

Optical microscopy and scanning electron microscopy were used to study the microstructure of the samples. Also, EDS analysis was used to identify the composition of the phases as shown in Table 2 and Figure 5-9. The following phases were identified in the microstructure of all investigated Aluminum alloys: α- Al matrix (ash), Al_5FeSi (brown), Al_2Cu (white) and different dark tones that indicate the presences of multicomponent phases containing Al, Cu, Si and Fe. This is in congruence with intermetallic phases as well as the solidification process identified by [16, 17, 18]. Fe occurs in Al-Cu alloys as impurity element, and its presence decreases the ductility of the castings by the formation of Fe-rich intermetallic compounds, particularly Al_5FeSi phase [19, 20, 21]. This is also responsible for the loss of permeability that occurs during alloy solidification. An additional SEM observation combined with EDS spot analysis for the investigated alloy was performed to identify the elemental composition and stoichiometry of the observed Cu rich phases. This analysis confirmed that Cu rich phases appear in all the morphologies with eutectic and fine eutectic types.

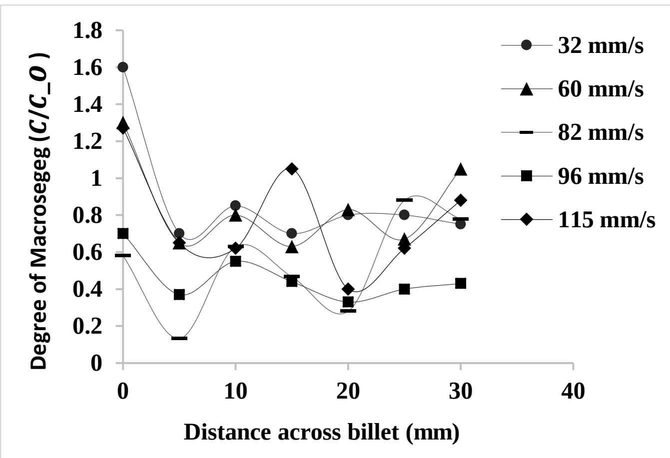
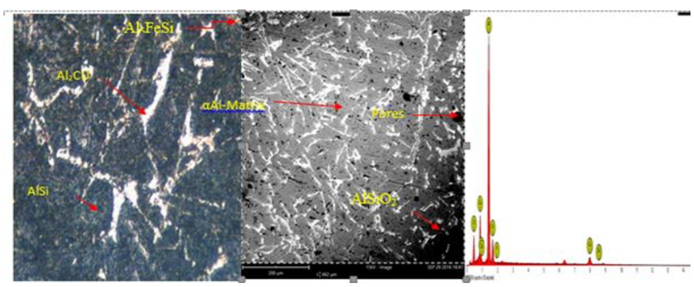
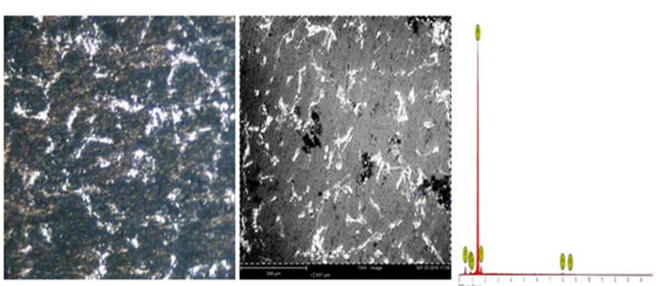


Figure 4. Effect of pouring height on relative segregation of Al 6wt. % Cu with casting speed



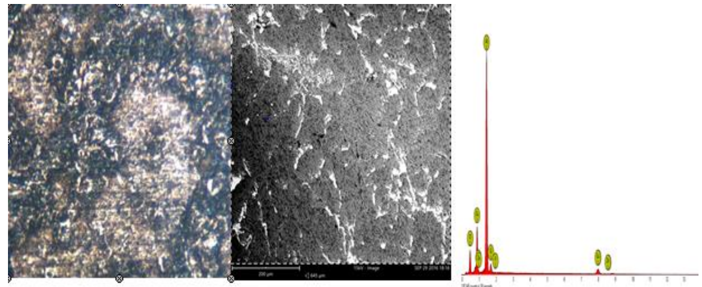
(a) (b) (c)

Figure 5. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt. % Cu at 32 mm/s



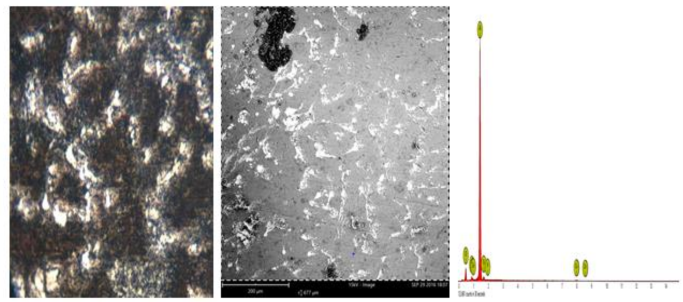
(a) (b) (c)

Figure 6. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt. % Cu at 60 mm/s



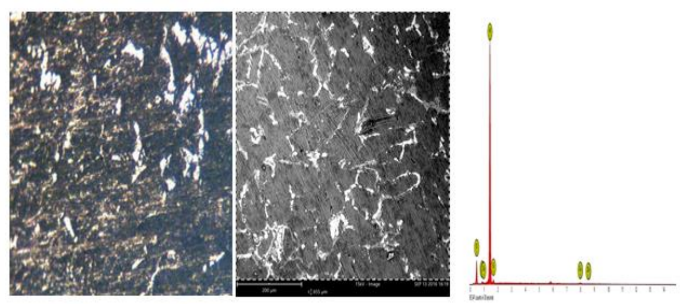
(a) (b) (c)

Figure 7. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt. % Cu at 82 mm/s



(a) (b) (c)

Figure 8. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt. % Cu at 96 mm/s



(a) (b) (c)

Figure 9. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt. % Cu at 115 mm/s

3.2 Runner Angle and Propagation of Macro-segregation

Figure 10 represents the effect of variation of runner angle between 900 and 1500 for the studied alloy. A close observation shows that cast produced at 900 runner angle shows ~0.7 % more macro-segregations than other samples. This is attributed to the turbulence generated within the flow as a result of the pouring pressure. Introducing the molten metal into the mould vertically at 900 gives the fluid much momentum as it makes intense impact with the mould resulting in splashes, which creates ripples within the flow. The results show that casts produced at 1200 and1500 have reduced macro-segregates, while the 1200 runner angle produces cast with more uniform distribution of macrosegregation. Thus, 1200 runner angle produced ideal pouring pressure. This is complimented by the optical and SEM micrographs in Figure 12 and 13 in which the intermetallic phases are more uniformly distributed.

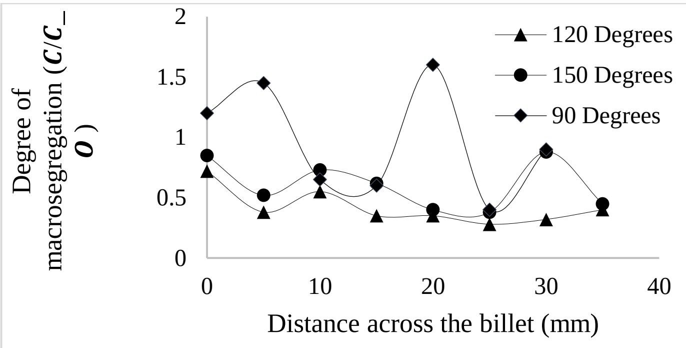
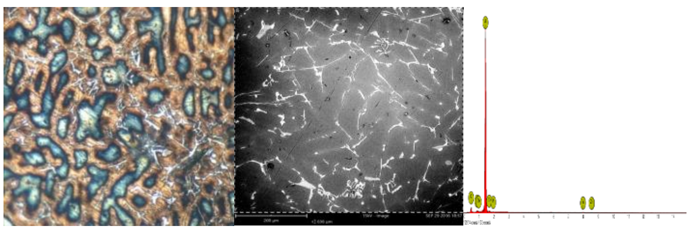
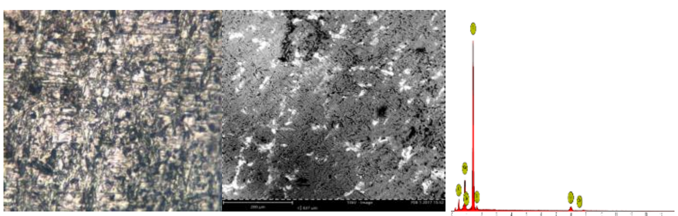


Figure 10. Effect of variation of runner angle on degree of segregation of Al 6wt.% Cu



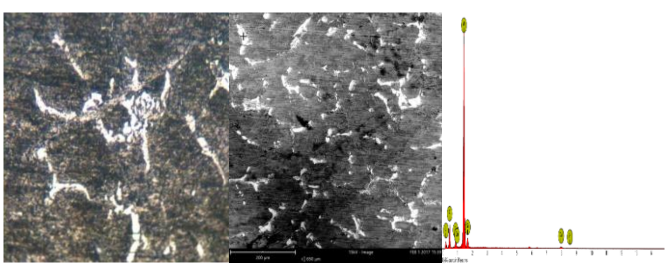
(a) (b) (c)

Figure 11. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt% Cu cast at 90^0



(a) (b) (c)

Figure 12. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt% Cu cast at 120^0



(a) (b) (c)

Figure 13. (a) Optical Micrograph (b) SEM Micrograph (c) EDS spectrum of Al 6wt% Cu cast at 150^0

4. Mechanical Properties

The alloy under process parameters selected exhibit linear stress-strain relationship up to a well-defined yield point. The linear portion of the curve is the elastic region and the slope gives modulus of elasticity or Young's Modulus.

4.1. Effect of Variation of Casting Speed and Runner Angle on Modulus of Elasticity

The modulus of elasticity in **Figure 14** describes material resistance to tensile elasticity along an axis when opposing forces are applied. In **Figure 14**, the cast produced at 60 mm/s has the highest elastic modulus (13354.4 MPa) follwed by 96 mm/s (9610.35 MPa) and 32 mm/s (9028.2 MPa), respectively. Cast produced at 115 mm/s has the lowest elastic modulus of ~ 8700 MPa. From the foregoing, casts at 115 mm/s with lowest moduli of elasticity gave a superior result as this indicates that the alloy can better withstand stress. The other alloys with higher elasticity moduli are therefore much stiffer [22].

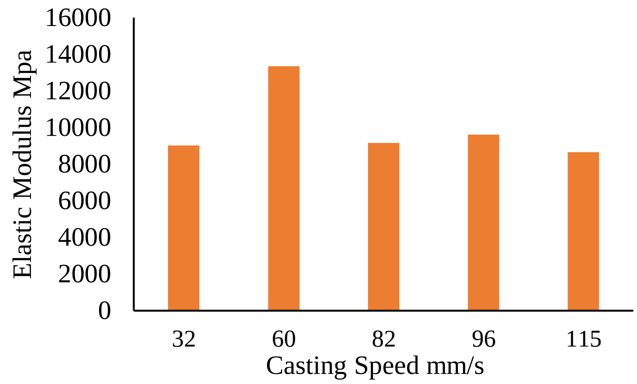


Figure 14. Modulus of Elasticity for Al 6wt. % Cu Alloy with Casting Speed

4.2. Effect of pouring height and runner angle on Utimate Tensile Strength

The ultimate tensile strength (UTS) is the maximum stress level on the engineering stress-strain curve that a structure under tension can withstand. All deformation before this point is uniform throughout the narrow region of the material. After which, subsequent deformation is confined to a small constriction or neck. As the area on which the load is acting reduces, a smaller load is required to produce a greater deformation. Figure 15 shows that the Al 6wt. % Cu alloy at pouring height of pouring height of 100 mm has the lowest UTS of 90 MPa. Pouring height of 400 mm produces heighest UTS of ~110 MPa. Projection from these analysis shows that samples with Ultimate tensile strength of 110 MPa will be a better material for structural applications requring greater strength . Thus, pouring height does have a significant effect on the UTS of the cast produced and this agrees with the experimental result on degree of segregation predicted in section 3.1. For variation in runner angle in Figure 16, the maximum UTS occur at 1350 with value of 104MPa. The minimum value attained at 1200 is 36MPa. The results above does shows that cast produced at 135^0 can withstand greater stress than all other samples.

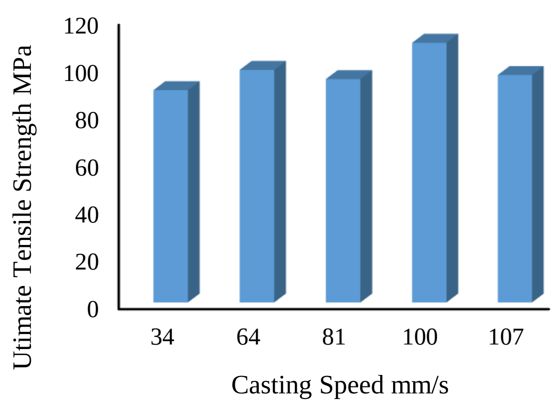


Figure 15. Ultimate Tensile Strength for Al 6wt% Cu at Varied Casting Speed

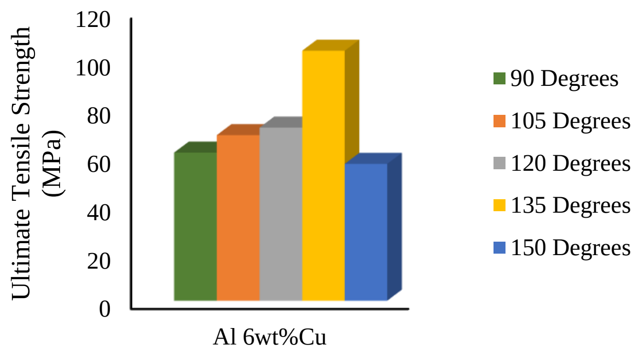


Figure 16. Ultimate Tensile Strength for Al 6wt. % Cu, at Varied Runner Angles

4.3. Effect of Casting Speed and runner angle on Percent Elongation

The percent elongation and the percent reduction in area provide information about the ductility of a material, and how much it can be stretched before failure. A close study of Figure 17 shows that, maximum percent elongation 2.4, 2.5 % was attained 82 and 96 mm/s. Also, maximum values occurred at runner angles 105^0, 120^0 and 135^0.

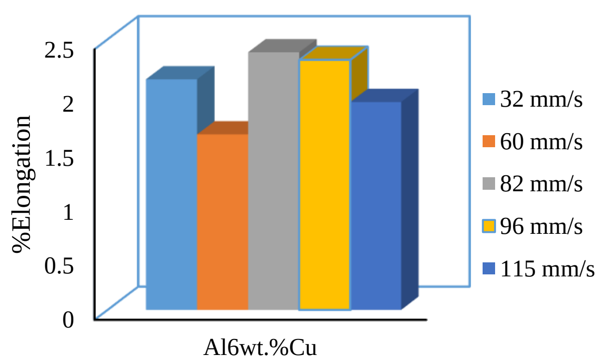


Figure 17. Percent Elongation for Al 6wt. % Cu at Varied Casting Speed

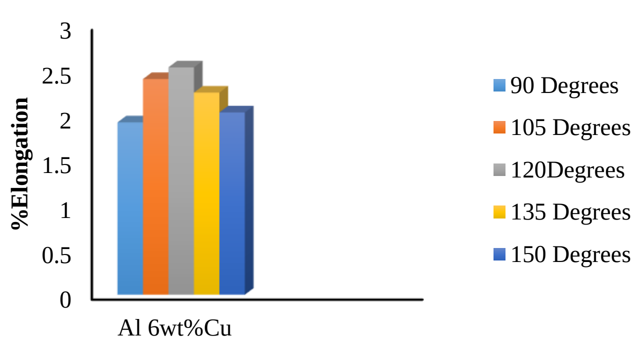


Figure 18.: Percent Elongation for Al 6wt. % Cu at Varied Runner Angles

5. Summary of Findings

From this study, ideal casting speed lies between 90 to 100 mm/s for minimal macro-segregations. Runner angle at 120^0 produced uniform solute element distribution for both alloys. Samples produced at 96 mm/s, 100mm/s, and 120^0 show less macro-segregates with superior strength characteristics (UTS-110 MPa, E -6800 MPa and elongation 2.5 %) that are comparable with standard (UTS,88- 124 MPa;,E- 7100 MPa and Elongation,1-25%) for this class of alloy.

6. Conclusion

From this experimental investigation casting speed and runner angle has direct consequence on the distribution and extent of macro-segregation of the solute and also influences the dendrite morphology. The trend portrayed by the mechanical properties as discussed in this work is in tandem with the result of process parameters. The property and quality of cast product is dependent on the interplay of these process parameters. Thus, the results of this study can be employed as input data in sand casting process to ensure significant decline in the high volume of produced defective castings that traceable to the generated macro-segregates.

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