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RUNNER ANGLE MODIFICATION FOR ENHANCED MACROSEGREGATION REDUCTION IN ALUMINIUM-ZINC ALLOY

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ABSTRACT

Macro-segregation is an irreversible defect in non-ferrous alloy casts. This can only be significantly minimized by controlling the melt and its flow trajectory during casting. The study identified runner angle inclination as a critical parameter that impacts the development, size and volume of macro-segregation occurrence in binary alloys. The methodology entails variation of runner angles to include 90°, 105°, 120°, 135°, and 150° at a constant casting speed of 100mm/s being the optimum casting speed established in previous study. The casts microstructure was examined using both optical and electron microscopes complemented with energy dispersive spectrometry. Results show that runner position at 120° is the most appropriate for the casting of aluminium-zinc alloy as this gave a highly homogeneous distribution of solute element in the microstructure with corresponding improved mechanical properties

KEYWORDS: Runner angle; Macro-segregation; Aluminium-Zinc alloy; Microstructure; Mechanical properties

1. INTRODUCTION

Solidification is a complex phase of molten metal transformation. The process involves the movement of individual atoms in the liquid to a more stable position in the solid alloy lattice. It has been established that flow pattern of atoms in a molten metal during solidification affects the composition of the casting (Mechighel and Kadja, 2007). The difference in composition at macroscopic level is what is referred to as macro-segregation which usually affects the mechanical properties of cast products. It is established that macro-segregation cannot be easily remedied owing to its long range distance (1cm - 1m) where diffusion becomes ineffective (Byungsoo, 2002; Weitao, 2005; Jafari *et al*., 2010). Studies have shown that both melt condition and mold feeding parameters are critical factors that affect the extent of macro-segregation propagation (Thammachot *et al*., 2012; Dong et al., 2017). Determination of optimal casting parameters by trial and error in the past had not been quite successful hence, the imperative to determine the best combination of parameters such as casting speed, runner angle, cast geometry, mould type and solute concentration. Proper selection of these parameters is capable of mitigating turbulence which often develops within the mold during pouring. This will in turn significantly reduce the occurrence of macro-segregation and its attendant adverse effect on mechanical properties of the casting. The runner angle of inclination is known to impact significant effect on the quality of cast product. Although several previous studies considered the effect of size and dimension of runner on cast products, however, little or no attention has been given to this vital aspect of the gating system (Ahmed and Hashim, 2011; Umesh and Patil, 2018; Sultana et al., 2019). Generally, the causes of casting defects such as porosity, improper solidification, air entrapment, mold erosion and segregation are known to be directly related to imperfection in the gating system design and feeding techniques (Majidi and Beckermann, 2018). According to Rasa et al (2020), a gating design which ensures reduced head height, increased in diameters of runner, sprue, and in-gates as well as a pressurized system will reduce the incidence of these defects.

The current study seeks to establish the best runner inclination during casting with the aim of inducing segregation-free microstructure possible in cast aluminium-zinc alloy.

2. EXPERIMENTAL METHODOLOGY

In this experiment, temperature measurements provided an insight into the transient phenomena during solidification while post solidification analysis such EDS, SEM and Optical analysis provided detailed macro-segregation measurements and characterization 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 Eq. 1 (Obiekea et al., 2018). In the present research the casting speed was controlled by maintaining a consistent pouring height of 500mm and this culminates into a casting speed of 100 mm/s based on Eq. 1.

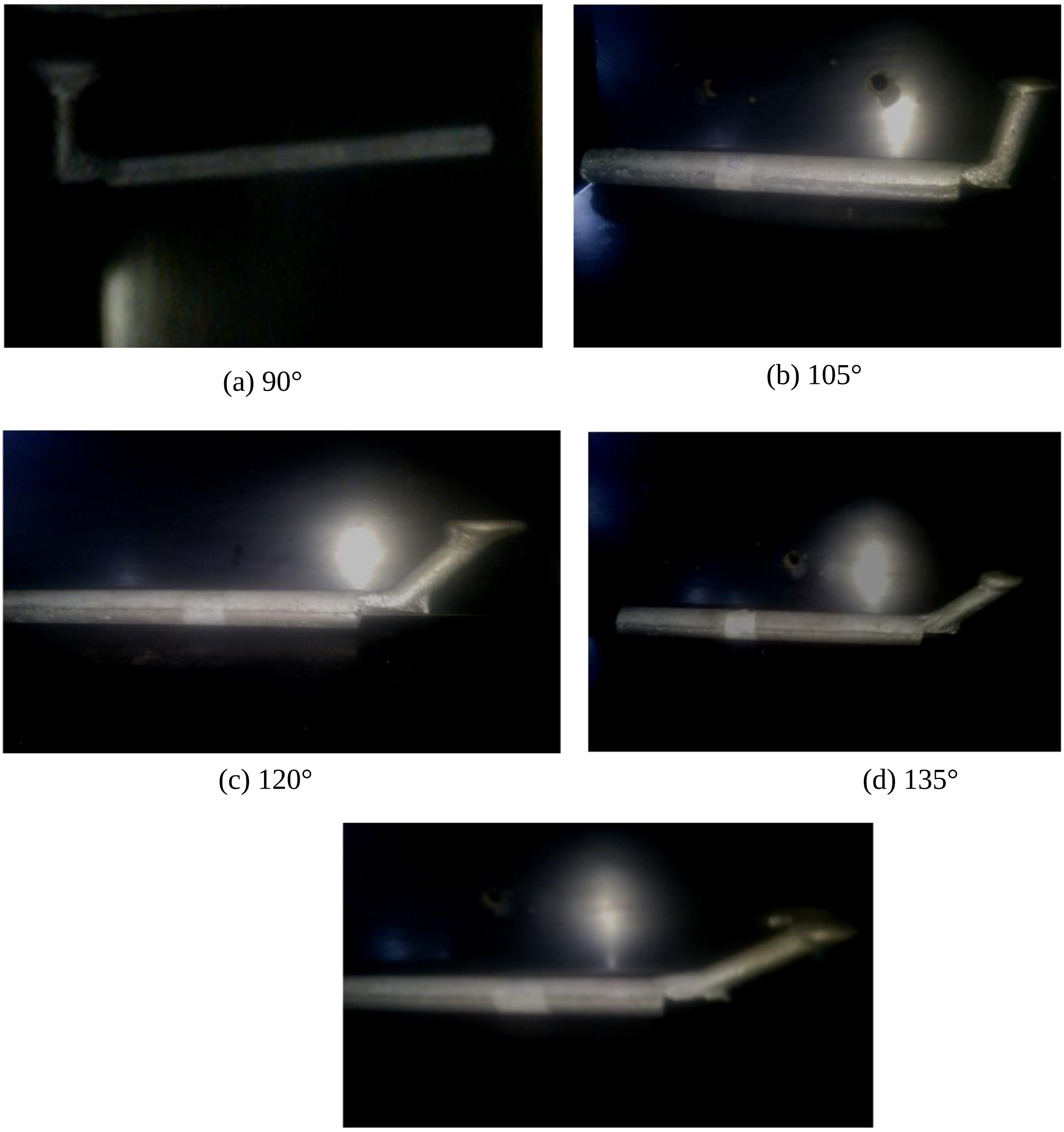
$$V = (2gh)^{0.5} \tag{1}$$

2.1. Materials, Melting and Mold Design

Commercial aluminum (1000 series) ingots as well as zinc scraps were mechanically sectioned into small pieces suitable for charging into a crucible furnace. Melting of the charges was carried out in batches according to the material formulation shown in Table 1. Aluminum with a higher melting point of about 660 °C was first charged followed by zinc scraps. The molten metal was mechanically stirred continuously using a long steel tong to achieve uniform distribution of alloying elements. Meanwhile, silica sand molds having cylindrical cavities of 30 mm by 300 mm were incorporating the new runner design inclined at 900, 1050, 1200, 1350 and 1500 to the mold inlet. The mold is 20 mm thick each runner dimensions consist of 10 mm diameter and 8 mm long. In order to incorporate the runner at the various angles stated above. A technical drawing was done and this was conceptualized into the mode design. During casting, temperature variation of the melt before and after casting was taken using a highly sensitive TP-02K type thermocouple with temperature range from -50 °C to 750 °C. Fig.1. shows the casts produced at varied runner angles.

Table 1. Table headings are placed above the table.

Sample ID	Wt. % Al	Wt. %Zn
A	95	5
B	90	10
C	85	15
D	80	20



(a) 90° (b) 105°

(c) 120° (d) 135°

(e) 150°

Fig. 1. Cast samples at varied runner angles.

2.2. Characterisations

The cast samples were subjected to spectrometric analysis (Table 2), thermal analysis, mechanical characterization and microstructural analysis. The thermal analysis was carried out from the onset of casting where the temperature profile of the solidifying melt was continuously obtained. This was accomplished by inserting a thermocouple along the centerline of the mold. The data obtained from this procedure are employed in ascertain the cooling dynamics with the corresponding microstructure induced in the cast samples. The Instron Universal Tester model 3309.n electromechanical testing machine was employed in the samples mechanical properties which include; tensile strength, ductility, and modulus of elasticity. The cast samples microstructural features were analysed usi,ng both optical and electron microscopes complemented by energy dispersive spectroscopy. Weck's reagent, which is made up of 100 ml water, 4g KMnO4 and 1 g NaOH was used to etch the polished mirror-like surfaces of the specimens.

Table 2. Spectrometry Analysis.

S/N	Sample ID	% Al	% Zn	% Si	% Mg	% Fe
1	A	93.000	5.000	1.400	0.050	0.550
2	B	89.000	10.000	0.490	0.010	0.500
3	C	81.000	15.000	2.000	0.160	1.840
4	D	77.000	20.000	1.940	0.970	0.090

3. RESULTS AND DISCUSSION

3.1. Thermal analysis

The temperature profile in Fig. 2 for 5, 10, 15 and 20wt%Zn as considered in this study exhibit a similar trend. It explains the phase change that occurred during the solidification process. The casting operation was carried out with thermocouple inserted along the centerline of the cast. This is to ensure the continuity of the measured temperature profile. The temperature profile of the solidifying metal is significant in interpreting the fluidity behavior, casting speed and the eventual emergence of microstructure and mechanical property of the cast (Kiavash 2011). Notably, in Fig. 2 the temperature of the melt upon pouring dropped instantly within the temperature range 670- 650 °C owning to the release of latent heat of solidification. This observation remains fairly constant for about 120 s up to the liquidus point (A) and thereafter, the cooling progressed until the molten metal reached the solidus point (B). For all the variation of sample considered, the critical fraction solid point C (point where liquid feed metal can no longer flow) were reached at the same time but at different temperature. Distinctively, the critical fraction solid point for casting with 5wt%Zn was attained at a higher temperature owing to less amount of solute content in the solvent (unsaturated solution) (JatothandNaika,2017).

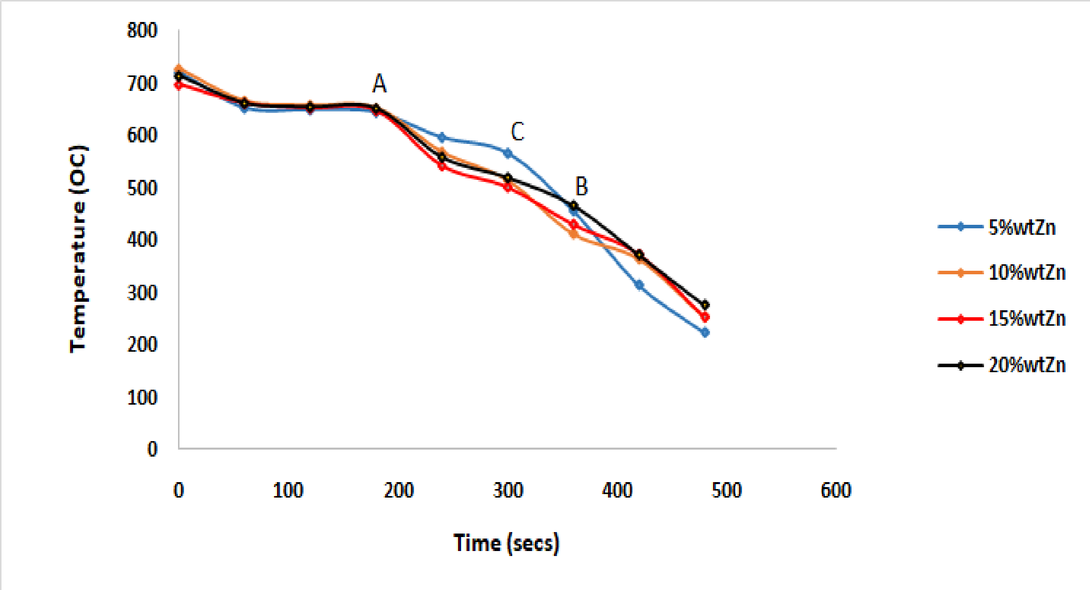


Fig. 2. Cooling curves for Al-Cu alloy.

3.2. SEM and EDS Analyses

Since degree of saturation (that is solute concentration effect) is known to aggravate macro-segregation, a less saturated solution of 5wt% Zn was considered for further analyses of macro-segregation. EDS Spot analyses of the various castings were carried out and the degree of segregation was calculated as ratio of solute concentration at a particular spot to mixture concentration (Wu et al., 2014). Fig. 3 shows a plot of degree of macro-segregation against distance across the billet. Typically, the curve showed a uniform segregation at the peripheral of the cast. This is consequent on the fact that as molten metal is poured into the mold cavity; melt that comes in direct contact with the mold wall solidifies first leaving no time for solute diffusion. Moving away from the peripheral towards the centre, the cast witnessed more segregation as there is sufficient time for solute diffusion away from the solidifying front into the hot liquid pull at the centre hence, the centre of the cast is more segregated. A close observation of the curve shows that cast produced at 1050 and 1200 exhibited a better distribution of solute atom. This can be attributed to the appropriateness of the pouring pressure at the given runner angles. The other curves show more segregation of solute element across the entire length of the casting due to pouring pressure been too high or too low, which translates into turbulence or drag within the flow. Introducing the molten metal into the mold vertically (900) gives the fluid much momentum as it makes intense impact with the mould resulting in splashes, which creates ripples within the flow. Optical microscopy and Scanning Electron

Microscopy (SEM) were employed in the investigation of microstructure samples and EDS analysis was used to identify the composition of the phases as shown in Fig. 4 to 6. According to literature, it is difficult to determine extensively the phase morphology of Al-Zn alloy experimentally due to fast decompositional kinetics of the alloy (Yin et al., 2015; Lopez et al., 2017). Nevertheless, the presence of the following phases has been identified in aluminum zinc alloys: MgZn2 dark tones, Al23CuFe4 (white patches) and Al-matrix (ash) with irregular interconnected morphology. This is in congruence with intermetallic phases and solidification process identified in the literature (Miyazaki et al., 2001; Li et al, 2014).

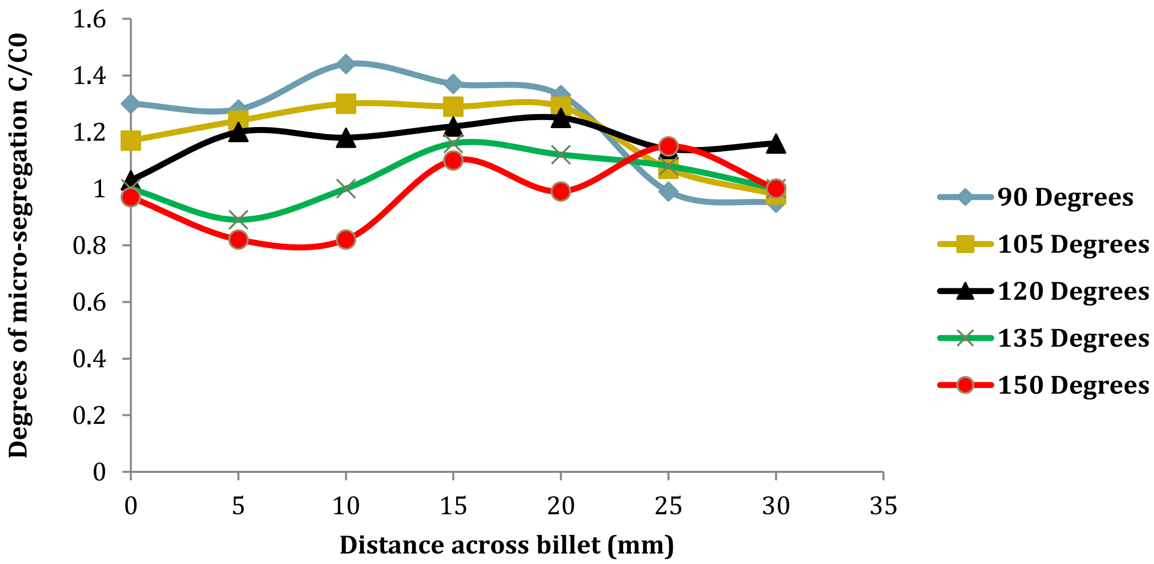


Fig. 3. Effect of variation of runner angle on degree of segregation of Al 5 wt. % Zn.

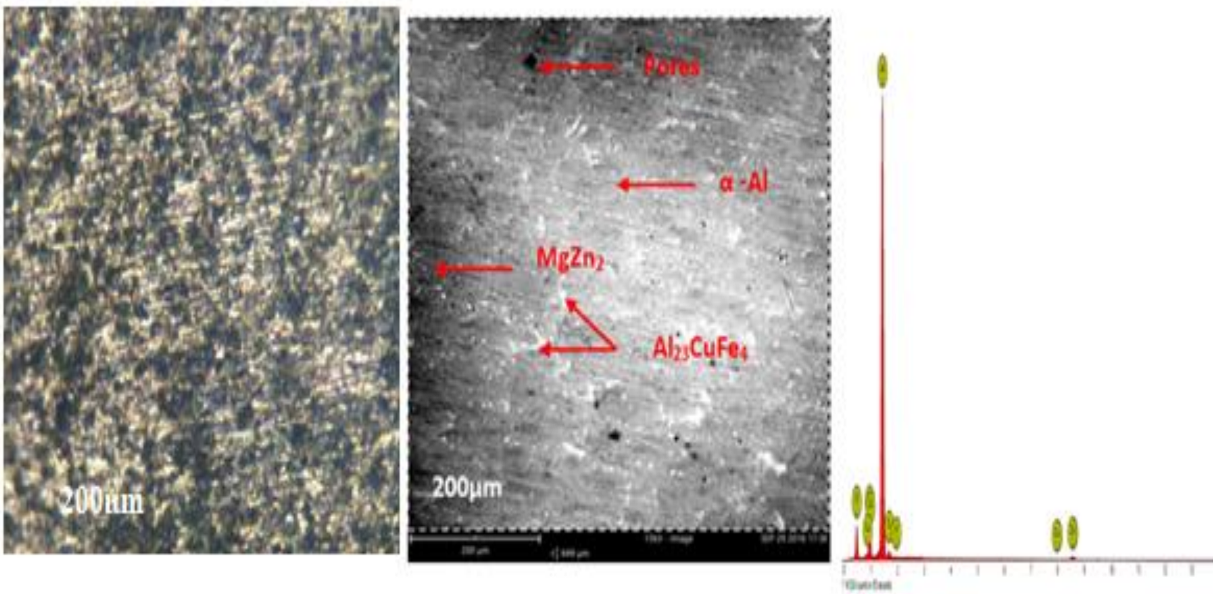


Fig. 4. Optical micrograph, SEM and EDS of Al 5 wt.% Zn at 90°

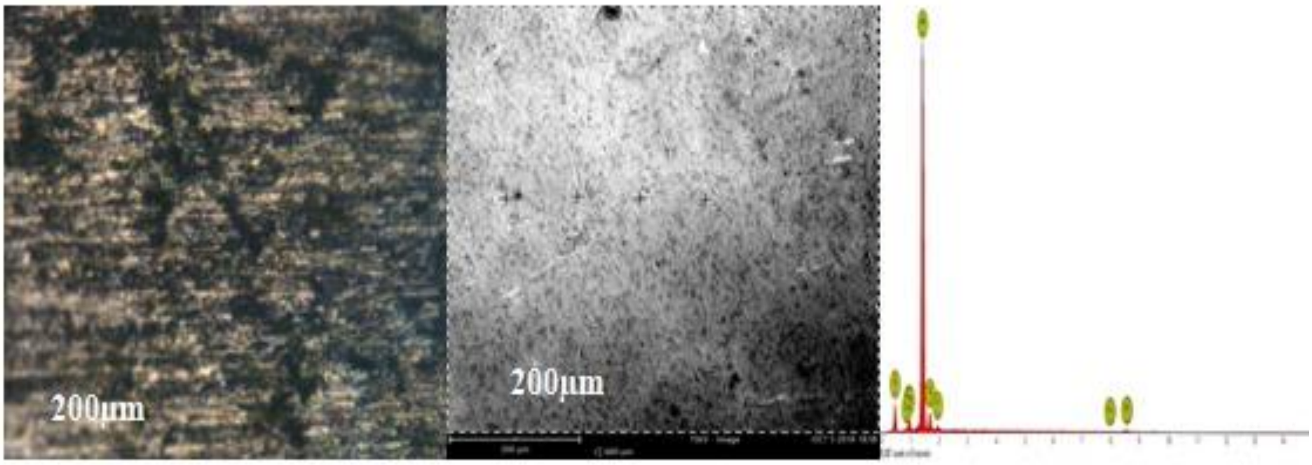


Fig. 5. Optical micrograph, SEM and EDS of Al 5 wt.% Zn at 1200.

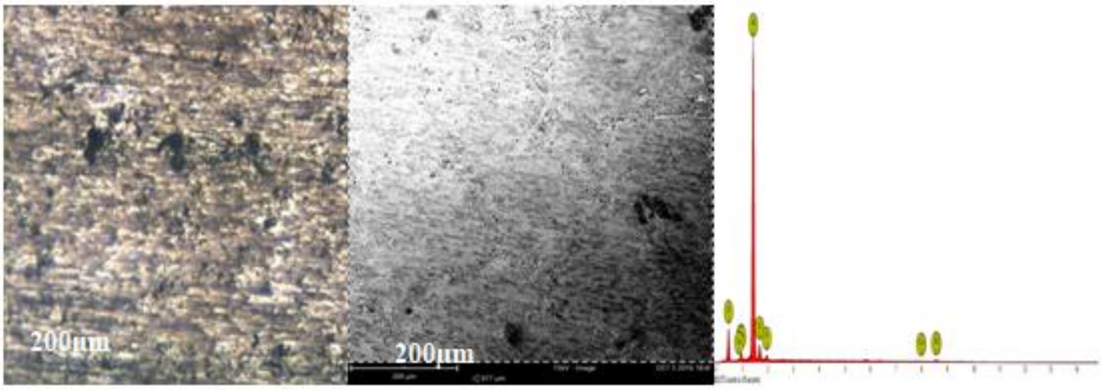


Fig. 6. Optical micrograph, SEM and EDS of Al 5 wt. % Zn at 150°

3.3. Analysis of Mechanical Properties

3.3.1. Modulus of elasticity

Modulus of elasticity as a ratio of stress to strain in elastic range of deformation describes the material resistance to tensile elasticity, which is the tendency of the alloy to deform along an axis when opposing forces are applied along that axis. The bar chart in Fig. 7 shows that all the samples for the various runner angles considered exibited appreciable modulus of elasticity (61, 81, 87, 61 and 80GPa) close to standard value of 71.7 GPa given in literature (Davis, 2001). The Al 5wt.% Zn cast at runner angle of 120° gave a peak value followed by runner positioned at 1050.

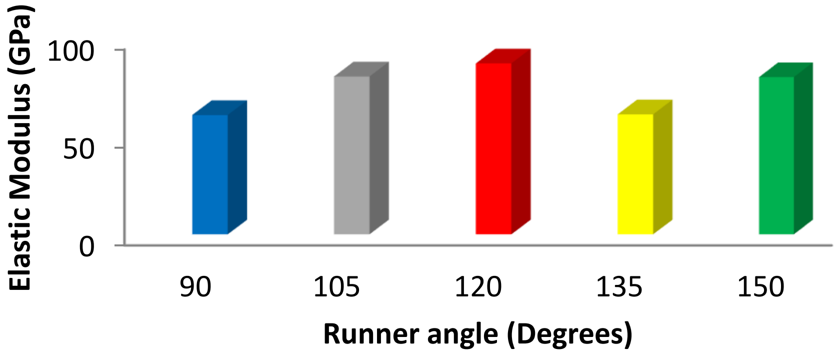


Fig. 7. Modulus of Elasticity for Al 6wt. % Cu, Al 5wt. % Zn Alloy for Varied Runner Angles.

3.3.2. Utimate tensile strength

The ultimate tensile strength is the maximum stress level on the engineering stress-strain curve, i.e., the maximum stress that a structure under tension can withstand. All deformation before this point is uniform throughout the narrow region of the material. Thereafter, subsequent deformation is confined to a small constriction or neck and as the area on which the load is acting on reduces as a smaller load is required to produce a greater deformation. Fig. 8 shows that peak values of ultimate tensile strength occur at the runner angles of 90°, 150° and 120° with values 210 MPa, 205 MPa and 186 MPa respectively. While minimum values were attained at runner angles of 105° and 135° with values 172 MPa and 151 MPa respectively. From the above consideration, the cast produced at runner angle 150° and 105° for both alloy can withstand greater stress than all other samples and is comparable to standard value of 228 MPa for Al-Zn alloys as reported by Callister (2007).

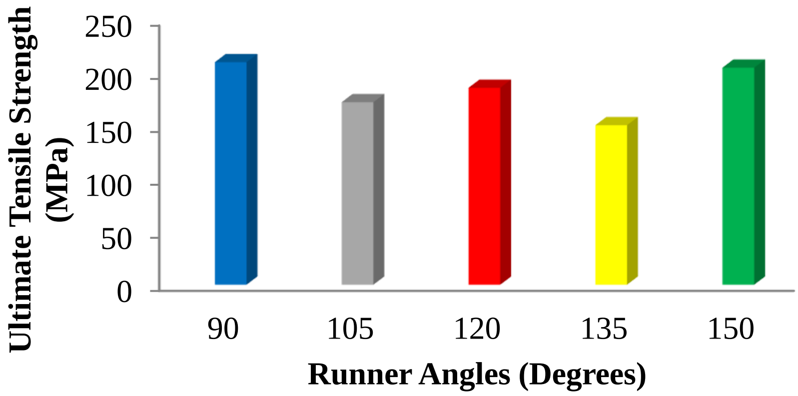


Fig. 8. Ultimate tensile strength for Al 6wt. % Cu, Al 5wt. % Zn alloy for varied runner angles.

3.3.3. Percent elongation

Percent elongation and percent reduction in area provide information about the ductility of the material, and it is a reflection of how much it can be stretched before failure. In Fig. 9, the cast produced at runner angles of 150°, 135°, 90°, and 120° attained a relative close values of 15.2%, 15.0%, 14.9% and 14.3% respectively, which is comparable to standard value (17%) reported in literature (Callister, 2007). Lower elongation(12.7%) occurred at 105° runner angle, which is an indication of low ductility. Generally, it could be inferred from the study that variation of percentage elogation in all the investigated samples demonstrated a random pattern.

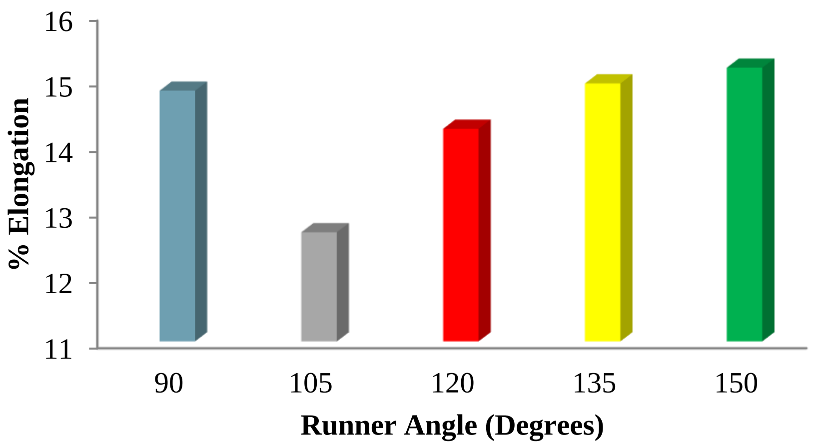


Fig. 9. Percent elongation for Al 6wt. % Cu, Al 5wt. % Zn alloy for varied runner angles.

4. CONCLUTION

1. The solution to turbulence that results into macro-segregation in binary alloy castings has been established. Synergy between the runner position in the mould and pouring of molten will help to avoid turbulence at the incipient of molten metal.
2. Casting produced at a runner angle of 120° gave a better distribution of solute and is less segregated. This is an indication that this angle is appropriate for proper runner positioning.
3. Also, the cast sample at this runner angle attained superior elastic modulus (87 GPa)and a moderate ultimate tensile strength (186 MPa)comparable to standard values (71.1 GPa and 288 MPa) established for aluminium zinc alloys.
4. The distribution of percent elongation as observed in this study show a random pattern though it is still within the range of standard value (17%).

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