Evolution of Micro Structural and Mechanical properties of Al-10 Wt. %Cu Alloy Processed Through Centrifugal Casting At Different Rotational Speeds of the Die

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Abstract: Aluminium and its alloys normally solidify as columnar structure with finer grain size which results in improved microstructure and good mechanical strength.Al-10 wt. % cu alloy was produced using centrifugal casting technique by varying the rotating speed of the die on the time of solidification. The microstructure and mechanical behaviour are affected greatly by the solidification rate. In centrifugal casting faster solidification rate obtained compared to that of conventional casting (stir) method even though many parameters directly effect the solidification and the parameters may be listed as die wall thickness, temperature of pouring the metal in the molten state and the die rotating speed. This paper focus on the microstructure and mechanical properties of Al-10 wt.% cu alloy processed at various die rotational speeds of 700 rpm, 800 rpm and 900 rpm. Since rotational speed has direct effect on solidification, microstructure, hardness and tensile strength. The result shows that microstructure variation shows morphological changes of the secondary phase (Al_2Cu) phase by decreasing in porosity. On the other hand mechanical properties, increases hardness values 97±52, 87±39 and 114±32 Mpa, and tensile strength is 56±5, 60±7 and 64±9 Mpa as compared to the lower casting speed at 700 rpm.

Index Terms: Aluminium alloys, Centrifugal casting, Solidification, Die speed and Grain size

I. INTRODUCTION

Al-10 wt. % cu alloys are the structural materials extensively used in aeronautics, automobiles and general engineering works. Al-10 wt. % Cu alloys are a high strength, light weight, heat treatable age hardenable alloy [1-2]. The alloy is processed through conventional casting method, which exhibit coarse dendritic microstructure because of slow cooling rates and hence mechanical properties cannot be achieved for normal applications [3-6].Alloys produced by stir casting process results in larger time consumption, weaker in microstructure, decreases in mechanical properties and making the process very expensive[7].

As compared to other methods centrifugal casting holds major advantages like minimum defects and minimum cost involved and hence have high efficiency and many applications. Although many researchers are working on different casting methods through the work and literature it can be stated as the centrifugal casting is the better method [8-9]. In the concentrated casting process cylindrical components are produced with varying mechanical properties. A mould which is permanent is rotated at higher speeds about its axis. The rejection of molten metal takes place due to the centrifugal force towards interior wall of the mould where the solidification takes place aftermath cooling. Even though the centrifugal casting is advantageous over any other casting process there are several parameters which influence the properties of the casting and the parameters are die wall thickness, temperature of pouring the metal in the molten state and the die rotating speed. Due to the variation in the parameters the end responses which may be affected are flow of the fluid rate of solidification and thermal characteristics. Fine equiaxed granular structure is obtained in the casting due to faster rate of solidification and centrifugal force to gain isotropic and homogeneous properties. Rate of solidification is the major parameter which influences the microstructure and hence it is necessary to understand and obtain optimal design of the casting process [10]. Liquid metal density incessantly increases while the solidification and the cooling rate is affected (increased) majorly by the rotational speed with a square proportion [10]. A very small portion of the research is concentrated on the rotational speed of the die with the help of centrifugal force eventhough many researchers worked on the casting process of Al-Cu alloy..

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II. EXPERIMENTAL PROCEDURE

A. MATERIALS

Different materials which is used for the experiment is commercially pure aluminium in the form of small ingots, high purity copper in the form thin wires and pure graphite crucible was used in this work. The base material used in this work is pure aluminium, and 10 wt. % of pure copper was added to form Al-10 wt. % cu alloy. The chemical compositions of the two alloys are shown in Table 1.

Table 1: Chemical composition of the alloys used in the experiment

Element	Cu	Mn	Cr	Fe	Ni	Zn	Mg	Si	Ti	Sn	Al
Wt.%	2.65	0.002	0.002	0.049	0.051	0.059	0.002	0.06	0.005	0.019	Bal.

B. Centrifugal Casting

A resistance furnace is used to melt pure Al and Cu at 750^0 for a duration of 3 hrs to obtain Al-10 wt. % cu alloy. When the centrifugal motor rotated continuously, pouring of the molten Al-10 wt. % Cu was done in the permanent mould preheated at 100°C. The mould rotation speeds of the die considered for the experiment were 700, 800 and 900 rpm, respectively [11-12]. The rotational direction was clockwise. Fig 1 shows the experimental setup used in this work.

Fig.1: Centrifugal casting experimental set up

Figure 1shows the experimental setup of centrifugal casting, consisting of a mild steel cylindrical die fixed to a driving flange. This driving flange is connected to the shaft of a 3hp DC motor, where the speed can be varied from 0 to 1500rpm with high accurate speed controller. The flow of metal into the mould is confined in the horizontally oriented, axially rotating cylindrical die. Centrifugal castings are obtained at three different speeds, 700, 800 and 900 rpm. At 700rpm (low rotational speed) lifting up of liquid metal starts due to which the rate of cooling is very low but as the speed reaches to 800 rpm rate of cooling is fast paced due to the turbulence created and as the speed is increased to 900 rpm uniform layered casting is formed due to high rate of cooling. [9]. Molten metal is poured to the rotating die at 600 ^{0}C to produce the casting. Figure 2 shows the centrifugal casting metal at three different speeds.

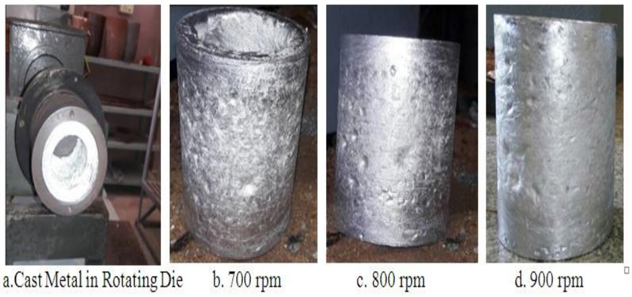

Fig.2: Centrifugal cast metal at three rotational speeds of the die.(Size Ø100mm, 150mm long and 5mm wall thickness.)

C. Machining Operation

After the cast metal was produced, the metal was allowed to solidify at room temperature for 2 hrs. Than the cast metal was machined on a lathe machine at 1200 rpm. The test samples are prepared using wire EDM cutting machine in according with the ASTM standards for metallurgical and mechanical characterization (13).

D. Metallurgical Characterization

The samples were prepared for microstructural characterization with different grading of emery papers (1/0, 2/0, 3/0 and 4/0). Samples were polished using polishing machine with alumina oxide powder and diamond paste at a speed of 400rpm to remove the surface cracks and porosity so as to produce smooth and flat surface. The polished samples of centrifugal cast alloy with different rotational speed of the die were etched with kellers reagent(190ml of water+3ml of HCL+5ml of HNO_3+2ml of HF) to study microstructural behavior and the specimens were examined using optical microscopy(OM) Metascope (India) and scanning electron microscopy (SEM) fitted with lithium-doped silicon energy dispersive X-Ray spectrometer(EDS) of AMETEK process. The grain sizes of the cast alloy were measured by line intercept method. (ASTM E112-96).

E. Mechanical Characterization.

a. Hardness test

The hardness of samples for three rotational speed of the die 700, 800, and 900 rpm at three locations was measured using Wilson hardness, Tukon 1102 Vickers hardness tester (China) using a load of 50 N and held for 10 sec. The hardness was measured at inner, middle and

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outer locations and the average value of 3 indentations was taken.

b. Tensile test

As per the ASTM E8/E8M-04 (13) standard tensile test samples of 25-mm gauge length and 4-mm thickness and 100 mm overall lengths were produced. CNC wire cutting electronic sprint cut machine (India) is used to machine and obtain sub-sized tensile specimens. From 3 different speeds 3 different specimen were selected and subjected to tensile test using KIC-2-1000 C, Capacity 100KN universal testing machine (KALPAK, India) at room temperature until specimen gets fractured.

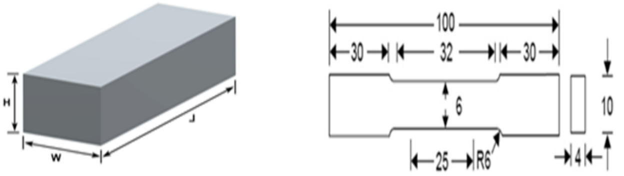

Fig.3: Metallographic and Tensile test sample (25mm gauge length, 4mm thickness)

III. RESULTS AND DISCUSSIONS

A. Microstructural Characterization

Figure 3 shows the Centrifugal cast metal at 700,800 and 900 rpm rotational speeds of the die having dimensions, width100mm, 150mm long and 5mm wall thickness . Initially a thin metal is solidified and formed on the entire circumference as the molten metal during rotation first occupies the entire circumference of the rotational mould. This is because of the direct contact of the molten metal with the mould due to faster cooling. The alternate layers of the molten metal then come in contact with the metal which was already solidified. As pouring of molten metal is continuous with respect to the rotating dies alternate layers of metal will be formed one on the other due to which the complete metal gets solidified. As a result, for the rotational speeds of 700 and 800 rpm the thickness of the casting is increased thereby decreasing the grains size. When the rotational speed of the die increased to 900 rpm, and pouring molten metal to the rotating die, it starts lifting up and later forms continuous metal layer hence grain sizes are finer than at 700 and 800rpm. But at 900 rpm as there is a direct pouring of metal lifting and rapid solidification takes place, hence fine grains are formed at 900 rpm as compared to lower rotational speeds of the die (700 rpm and 800 rpm). Microstructural changes in grain size are measured using line interceptor method and grain sizes have been obtained at three rotational speed.

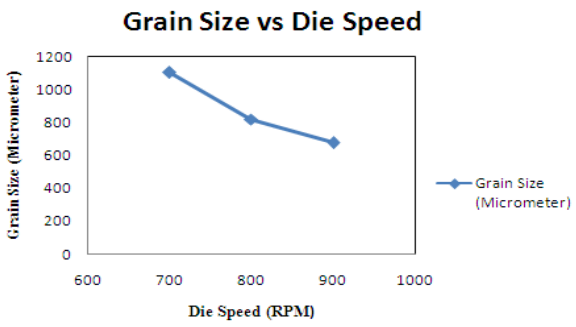

Fig.4: Grain size vs. Different speeds of the die

Figure 4shows the grain size versus rotational speed of the die. It can be noticed from the graph that for the die speed of 700rpm the grain size measured is 1125µm, whereas for the speed of 900rpm the average grain size is decreased to 50% and is 640µm. hence as the speed increased there is decrease in grain size and the grains becomes finer, this is due the rapid solidification.

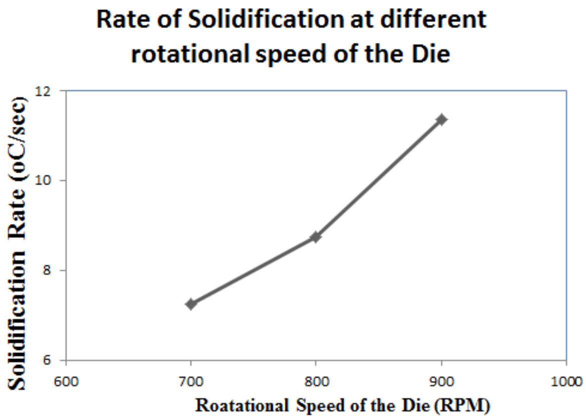

Fig.5: Solidification rate (^{o}C/sec) vs. Speed of the die

Figure 5 indicates rate of solidification vs. different rotational speed of the die. It is clearly seen that the solidification rate is increased due to the increase in rotational speed. At 700 rpm grain size obtained is 1125 µm and the corresponding solidification rate is 7.25^{o}C/sec, the solidification rate obtained for 800 and 900 rpm were 8.75^{o}C/sec and 11.36^{o}C/sec respectively. Through the optical Microscopy it can be concluded and stated as the rotational speed has major influence on microstructure. The lifting of the molten metal is immediate with the increase in the rotational speeds from 700 to 900 rpm when poured into the mould which is rotating. The solidification rate is slower at 700 rpm as compared to other 2 speeds. Poor castings may be the result of high rotational speeds which are the cause for disturbance and waviness at the interface surfaces. At higher speeds that is at 800 rpm and 900 rpm the metal gets solidified layer by layer and because of the increase in surface friction the solidification rate becomes is rapid. Fine grain castings are having good mechanical properties and which leads to harder than the castings with coarse grains at different speed of the die.

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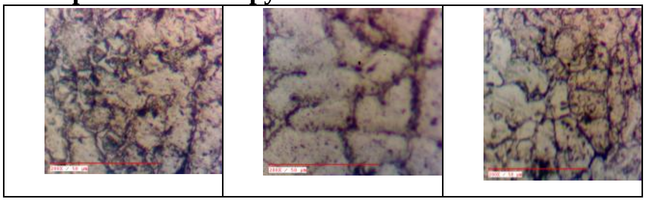
B. Optical Microscopy



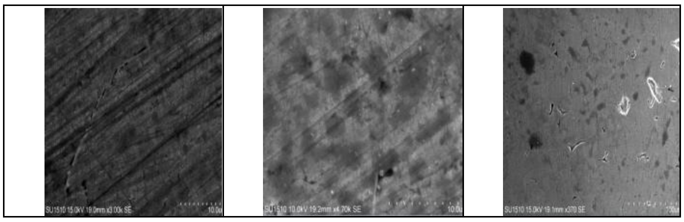
Fig(a): 700 Rpm Fig(b): 800 Rpm Fig(c): 900 Rpm

Fig. 6: Optical micrographs forcentrifugal casting of Al-10 wt.% Cu alloy at different rotational speeds of the die at 50µm

Figure 6 shows the microstructures of Al-10 wt. % Cu alloy with various mould rotation speed. From the above micrographs for the mould rotation speed at three different rpm, the solidification structure of the casting is entirely dendritic with very limited equiaxed grain structure. Comparing Fig.6 (a) with Fig.6 (b), and 6 (c) at 50µm it is noted that there is a negligible difference in grain size. This is due to the cooling rates at different the rotation speed of the die 700, 800 and 900rpm. It is clear that grain size decreases gradually with increasing the centrifugal radius, and that at the same centrifugal radius, the grain size at 900 rpm is finer than that at 700 rpm. As the centrifugal radius increases, finer microstructure is formed, as speed increases grain size decreases and porosity decreases. Hence 900rpm gets good results.

C. Scanning Electron Microscopy

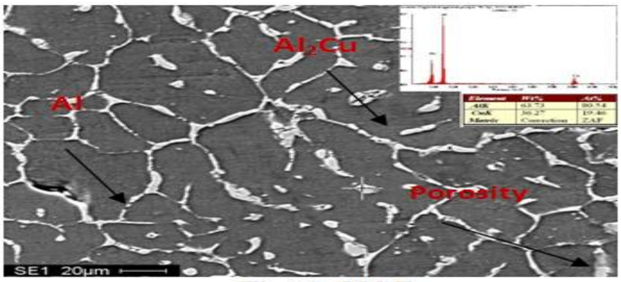
Figure 7shows the microstructure of centrifugal-cast Al- 10 wt. % Cu alloy. The content of white phases (area %) and the effect of rotation speed on it are shown in Fig.7. From Figs.7 it can be seen that the contents of white phases and Cu increase with the increase of rotation speed for the same position. As the centrifugal radius increases, the contents of white phases and Cu are basically the same at 700 rpm, while it increase at 800 rpm and 900 rpm. The increasing rate of the contents of white phases and Cu at 900 rpm is higher than that at 700 rpm with increase of the centrifugal radius. During the Al-10 wt. Cu % alloy solidification process, the eutectic reaction takes place and forms simultaneously α phase and Al_2Cu phase. The α-phase produced by eutectic reaction grows adherently to the primary α-phase. The Al_2Cu phase distributes at the grain boundaries of α-phase. This is because the Al-10 wt,%Cu alloy used in this experiment is a hypoeutectic alloy, and divorced eutectic partially transforms during the eutectic reaction. With further decrease in temperature, the Al_2Cu phase precipitates from the α-phase. The white phases in SEM image consist of Al_2Cu phases precipitated from the α-phase and the divorced eutectic, as well as normal eutectic microstructure. Because of centrifugal force the α-phase moves towards the rotating center while the Al_2Cu phase moves away the rotating center, resulting in the segregation. With increase of the centrifugal radius and the mould rotation speed, on the one hand, resulting in higher amount of white phase and Cu, and on the other hand, the amount of α-phase also increases because the eutectic and the cooling rate increases [9, 11]. But the effect of the compositional segregation is the primary reason for the α phase increase.



Fig(a): 700 Rpm Fig(b): 800 Rpm Fig(c): 900 Rpm

Fig.7: SEM Micrographs for Centrifugal casting of Al-10 wt.% Cu alloy at different rotational speeds of the die at 10µm

Figure 8 reveals, during the Al-10 wt. Cu % alloy solidification process, the eutectic reaction takes place and forms simultaneously α phase and Al_2Cu phase. The α-phase produced by eutectic reaction grows adherently to the primary α-phase. The Al_2Cu phase distributes at the grain boundaries of α-phase. This is because the Al-10 wt.%Cu alloy used in this experiment is a hypoeutectic alloy, and divorced eutectic partially transforms during the eutectic reaction. With further decrease in temperature, the Al_2Cu phase precipitates from the α-phase. The white phases in SEM image consist of Al_2Cu phases precipitated from the α-phase and the divorced eutectic, as well as normal eutectic microstructure. Because of centrifugal force the α-phase moves towards the rotating center while the Al_2Cu phase moves away the rotating center, resulting in the segregation. With increase of the centrifugal radius and the mould rotation speed, on the one hand, resulting in higher amount of white phase and Cu, and on the other hand, the amount of α-phase also increases because the eutectic and the cooling rate increases [9, 11]. But the effect of the compositional segregation is the primary reason for the α phase increase



Fig(a): 800 Rpm

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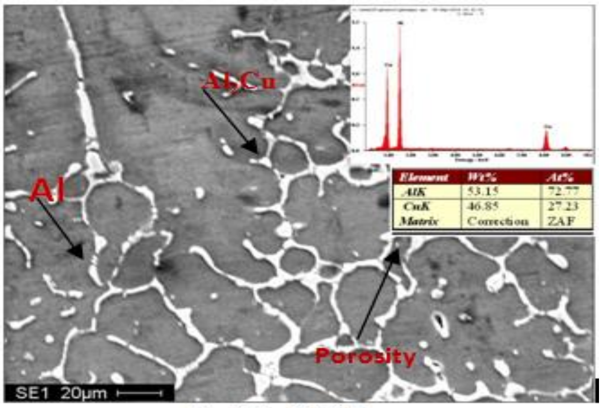

Fig(b): 900 Rpm

Fig. 8 EDS report of 800 rpm and 900 rpm for Al-10 wt.% Cu alloys showing the presence of Al_2Cu phase

D. Mechanical Properties

a. Vickers hardness test

Figures 9 depict the different locations of the specimen prepared for the hardness test along its radial direction of the fabricated hollow cylinder. From the table 2, it is found that there is a significant difference in the hardness values along the radial direction due to the different content and size of Cu particles. It is clearly seen that the hardness values have been decreased, the reason being non uniform cooling rate which directly affects the distribution of Cu particles during solidification at the mid part of the specimen. Due to the gas porosity the hardness values are low in the inner surface also and can be seen in the table [12]. With the average calculated and tabulated it can be stated the samples fabricated at700rpm speed gives the value of hardness with the medium value of 97±52Hv, while sample 2 which is fabricated with 800 rpm speed gives the lowest value with the average value of 87±39Hv which is because of the affect of cooling rate and viscosity of the molten metal during solidification process. Sample3 fabricated with 900 rpm speed provide with the highest hardness value with the average value of 114±32Hv.

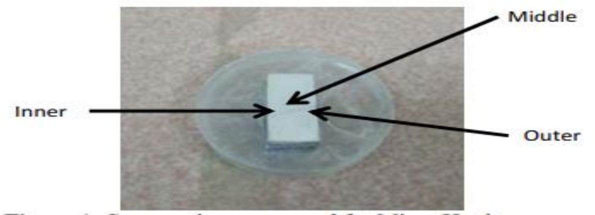

Fig.9. Cast specimen prepared for Micro Hardness test

Table 2: Vickers hardness test results.

Speed in rpm	location	Indentation diameter in µm	Hardness value (HV)	Average hardness value	Load in kgf
700	1 Inner	198.21	97.4	97±52Hv	2
	2 Middle	195.53	97.0		
	3 Outer	195.44	97.1		
800	1 Inner	209.14	84.8	87±39Hv	2
	2 Middle	204.75	88.5		
	3 Outer	207.39	86.2		
900	1 Inner	180.15	114.3	114±32Hv	2
	2 Middle	185.82	116.4		
	3 Outer	182.87	110.9		

From figure 11The results shows that, with increasing the centrifugal radius or mould rotation speed, the mechanical properties increase gradually. The ultimate tensile strength of three rotational speeds of the die was found to be 56±5Mpa, 60±7Mpa and 64±9Mpa respectively for 700, 800 and 900 rpm. From the above graph it can be concluded that with the increase in centrifugal radius, the mechanical properties of Al-10 wt.% Cu alloys are better at a rotational speed of 900rpm than at 700rpm. The betterment of the properties is because of the finer microstructure and the grain boundary which is strengthened which in turn results in the increase of resistance to dislocation. Comparison of graphs for ultimate tensile strength it can be concluded that the tensile strength and young's modulus are better for the specimens made under 900 rpm than that of specimens with 700 and 800 rpm. In all aspects the 900 rpm has yielded good results.

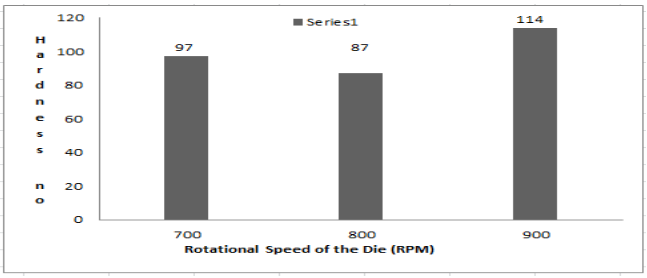

Fig.10: Vickers Hardness numbers for three rotational speed of the die

b. Tensile Test

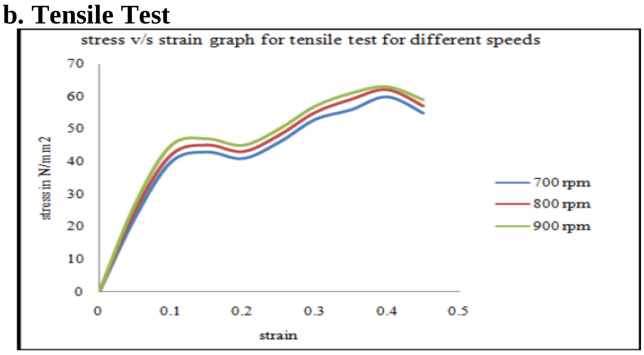

Fig.11: stress strain curve for different speeds

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I. CONCLUSION

With the results obtained it can be concluded that the rotational speed of the die is the major process variable in centrifugal casting. The grain size of Al-10wt% Cu is affected (decreased) with the increase in the centrifugal radius and rotational speed of the die with an increase in the white phase contents and Cu. It is also seen that the amplitude variation of microstructure of centrifugally cast alloy increases at 900 rpm as compared to other 2 speeds with the increase in the speed of rotation. The grain size can also be assessed depending upon the rate of solidification and can be conclude as the coarse grains are obtained at low solidification rate and the finer equi axed grains are obtained with a faster rate of solidification. The increase in the speed increases rate of solidification and the grain size. With lower speed grains are coarser but at 900 rpm the grains are fine and equi axed which makes the specimen hard which is proved with the highest VHN no and which is due to higher rate of solidification. A noticeable increase in the young's modulus can also be observed after the results of tensile test.

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