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EFFECT OF PROCESS PARAMETERS ON CENTRIFUGALLY CAST Al-Si FGM

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Abstract

Functionally Graded Materials (FGM) are such kind of materials wherein the properties and structure are varied from one end of the cast to the other intentionally. Centrifuge technique has been used in this study to produce Al-Si FGMs. Several process parameters determine the microstructure and the distribution of phases in the FG casting. These parameters include the size and initial concentration of alloying element, the centrifugal force, solidification rate, cooling rate. In this work an attempt has been made to produce FGMs using three different process variables such as mold temperature, melt temperature and mold rotational speed, their effect on the structure and properties. For this study Al-17wt%Si is used. From the results it is seen that for a particular melt and mold temperatures by increasing the mold rotation speed enhances the segregation of the Si particles at the one end of the casting. Similarly increasing mold or melt temperature only, increases the segregation.

Introduction

Functionally Graded Material (FGM) is a novel concept for the realization of innovative properties and functions that cannot be achieved by conventional homogeneous materials. FGM is a material that shows change in magnitude of property values from one end of a specimen or component to the other end. FGM has an intermediate layer whose structure, composition and morphology vary smoothly from one end of the specimen to the other end. These transition profiles are predesigned and intentional in order to achieve the desired properties [1]. FGMs multifunctional behavior and performance, enable wide scope for applications in aerospace, automotive, electronics, and biomedical sectors. The Functional gradient can be tailored to the specified service conditions, thus ensuring the best response of the system. One of the advantages of continuously varying volume fraction of the constituent phases is the elimination of stress discontinuity that is often encountered in laminated composites. Accordingly delamination problems are avoided and further the gradual transition also allows the creation of superior and multiple properties without any mechanically weak interface. Moreover, the gradual change of properties can be tailored to suit different applications and service environments.

In centrifugal casting process for producing FGM the alloy melt or alloy melt with reinforcement particle melt is subjected to centrifugal force. Two distinct zones, one with enriched and the other with depleted primary alloy phase and particles, with an intermediate graded zone are formed. The extent of particle segregation and relative locations of enriched and depleted particle zones within the casting are mainly dictated by the densities of the particles, melt temperature, melt viscosity, cooling rate, particle size and magnitude of centrifugal acceleration. Depending on the density of particles, the lighter particles segregate towards the axis of rotation, while the denser particles segregate away from the axis of rotation [2].

In this instead of traditional centrifugal process where in the molten metal is poured into a rotating mold a different process is used where the mold is stationary and liquid metal is poured into it. This technique is basically used to produce solid cylinders compared to hallow cylinders in horizontal centrifugal technique. The set up designed and developed in house. The work attempts to find the effect of the process parameters: mold temperature, melt temperature and mold rotational speed on structure and hardness and also on the gradation along the length of the specimen.

Experimental Details

In this process the centrifugal force magnitude ‘G’ is given by the Eq. 1

$$G = \frac{\omega^2 R}{g} \tag{1}$$

where ‘R’ is the radius of the arm in meters, ‘ω’ is the arm rotational speed in rad/sec and ‘g’ is the acceleration due to gravity. The ‘G’ plays an important role in positioning the reinforcement during solidification. FGMs with ex-situ and in-situ reinforcements can be processed by this technique. When particle-containing slurry is subjected to centrifugal force, two distinct zones, one with enriched and the other with depleted particles are formed, separated by an intermediate graded zone. It is reported [3] that the extent of particle segregation and relative locations of enriched and depleted particle zones within the casting are mainly dictated by the relative densities of the particle and liquid, teeming temperature, melt viscosity, cooling rate, particle size and magnitude of centrifugal acceleration. The lighter particles segregate towards the axis of rotation, while the denser particles move away from the axis of rotation. The particles such as SiC, alumina and zircon in Aluminum alloy system will settle away from the axis, while the lighter Si, graphite, mica will drift towards the axis. In this work the forced segregation of hard in-situ Si particles towards the upper regions (towards the axis) of the casting by centrifugal forces provides a unique approach to production of the FGMs. This region has higher surface hardness and wear resistance in the casting, while retaining high levels of toughness in the rest of the regions.

In this study the centrifuge technique is used to process the functionally graded alloy and composites. The centrifugal force progressively increases the volume fraction of the Si reinforcement within the liquid Al matrix along the radial direction, owing to the density difference between the materials (ρ_{Al}=2700 kg/m^3, ρ_{Si}=2300 kg/m^3). A centrifuge machine was built for this purpose and tested for reproducibility. The centrifuge machine is shown in Fig. 1. The difference between this machine and the commonly used machine is that, in this machine the pouring is done while the mold is stationary and machine operates on vertical axis. Thus, centrifugal forces are not applied immediately as in the traditional casting methods since the mold takes some time to reach its casting speed. The principal advantage of this is good mold filling combined with microstructural control, which usually results in improved mechanical properties. Apart from high production rate, time saving, and ability to cast different shapes on reproducible basis, it can produce a stable system based on the in situ nucleation and growth of the reinforcement from the parent melt.

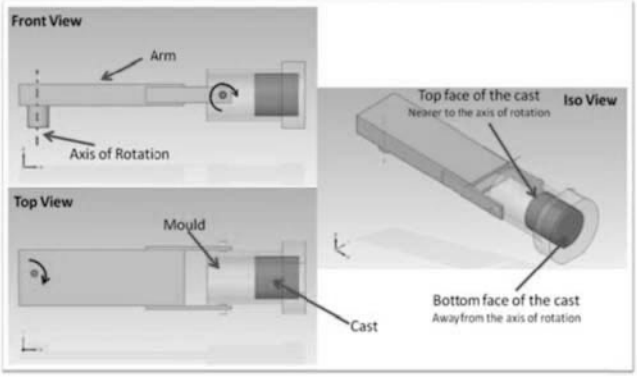

Fig. 1 Figure showing arm, mold and casting of the centrifuge machine

Several parameters determine the microstructure and the distribution of phases/ particles in the FG casting. These parameters include the size and initial concentration of particles / alloying element, the centrifugal force, solidification rate, cooling rate, which in turn are controlled by: temperature of the mold and pouring temperature [4]. The process parameters used in the present work are provided in Table 1.

Table 1 Process parameters for centrifuge casting

Process parameters	**Levels**
Melt Temperature (T_P), °C	800, 900
Mold Temperature (T_m), °C	30 (room temperature), 180
Rotational Speed, rpm	200, 300, 400
'G' Number	22.35, 50.3, 89.42
Silicon wt.%	17

In the present work Brinell Hardness tester (model BV-120) is used which confirms to IS-Specification 1754. Prior to the testing, the specimen is cleaned to remove dirt and oil on the surface. The type of indentor and the load to be applied are selected in accordance with ASTM E-10. The hardness is measured along the length of the cast specimen for every 4mm from top to bottom of the casting. At least five readings are taken perpendicular to the longitudinal axis. The final BHN value for each specimen is arrived at considering the statistical variation. Hardness is calculated for all the cast FG under different process parameters.

Results And Discussions

Microstructure And Gradation Of Si

The segregation and precipitation of Si at the top of the casting during the centrifuge casting is attributed to the density difference between the Si and the melt. The Si crystals are pushed to the top by the centrifugal force acting downward. The mold rotational speed, the mold and teeming temperatures have strongly influenced the structure development and the distribution of the primary Si. During mold rotation, the particle suspended in the liquid is subjected to centrifugal force acting on a particle given as $mr\omega^2$ and the gravitational force given by mg. The ratio of the centrifugal force to the gravitational force is called the gravitational coefficient (G) or G number. The rim thickness is defined as the thickness of the Si rich (primary) layer which indicates the extent to which particles have segregated along the length of the specimen. The rim thickness decreased with increased mold speed for a given mold and teeming temperature. This is attributed to the increase in cooling rates at higher rpm. It can be noted that, as the angular velocity increases, the G factor increases. Since the centrifugal force acting on the particle is G times higher than the gravitational force, the role of gravitational force can be ignored. Thus as the rotational speed increases, the force acting on the particles to segregate is expected to increase, as is observed in the study. For the casting produced under the lower levels of teeming and mold temperatures i.e 800°C and room temperature respectively, the specimen centrifuged at 22.3G (200rpm) showed no remarkable gradation of Si. The rim thickness of Si is observed to be 26mm. The maximum primary Si volume % obtained at this 'G' force is 8%, slightly higher than normal primary Si in this alloy. Similarly we can see from Figs. 4.41and 4.42 that, for casting produced at 300 rpm speed, the transition from hypereutectic microstructure to that of fine eutectic takes place at about 23mm (rim thickness) from the top surface. The primary Si is about 9%. At 400 rpm we can observe a rim thickness of 16mm and a volume fraction of 14%.

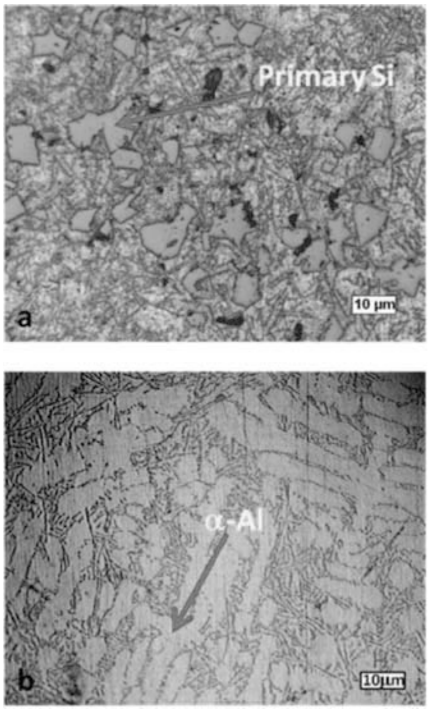

Fig. 2. The microstructure of the Al-17wt%Si FGM cast at, T_P=800°C, T_m=Room temp., G=22.3(200rpm). a) Top end showing primary Si, b) Bottom end showing primary α-Al dentritic structure

For the FG alloys cast at 800°C pouring temperature, the influence of higher mold temperature is studied at different rpm's for evaluating the percentage Si segregated and the rim thickness. In the present work mold temperature of 180°C is chosen. It was observed that at 22.3G (200rpm) the volume fraction of Si was 9% with a rim thickness of 24mm. At 50.3G(300rpm) and 89.42G(400rpm) the primary Si volume fraction was found to be 14% and 18%, whereas the rim thickness reduced to 21mm and 14mm respectively. This gives an indication that the segregation of the primary Si forming a narrow Si rich region is influenced by the mold rpm and also the solidification rate (influenced by the mold temperature).

The optical micrographs of specimens, show microstructures with a non uniform distribution of needle-like Si particles in the matrix of α-Al (eutectic) at the bottom of the casting. As we move towards the top region, micrographs showed similar microstructure, except with increasing primary Si concentration. At the top region of the casting, the FG alloy exhibits not only needle-like eutectic Si phase but also large faceted massive primary Si crystals that signify a high silicon hypereutectic microstructure. The bar graphs for volume fraction of primary Si against normalized thickness are shown in Fig. 3. The rpm influences primary Si free zone (compliment of rim thickness) and the PFZ increases as the speed (G force) is increased.

This result has revealed that, under the non-equilibrium conditions, a hypereutectic Al-17wt% Si alloy can have a hypoeutectic structure due to excessive under cooling. Depending on the fastest growing phase at a given undercooling condition, a structure which consists of both primary and eutectic phases or only the latter develops. In the aluminium-silicon system, the primary aluminium-rich phase grows dendritically, whereas the silicon-rich phase grows in a facetted manner. Compared to the dendritic phase, the facetted phase grows slower at under cooling. Relative high under cooling application on an alloy of a given composition causes dendritic growth in which one of the phases grows rapidly and the other phase solidifies between dendrites while lower under cooling leads to cellular growth. The difference between microstructures of both sides resulted from different cooling rates also under the influence of high G forces.

Similar to the controlling of solidification rate by changing the mold temperature, it can also be controlled by changing the teeming temperature. Hence the effect of teeming temperature on solidification rate and also the formation of primary Si is observed by casting the FG alloy at teeming temperature of 900°C under two conditions of mold namely, with and without preheating to 180°C. In either case the castings were prepared at three rpms as indicated above. The variation in % primary Si and rim thickness for two mold temperatures and three rpms and at a teeming temperature of 900°C is shown in Table 2.

Table 2. Percentage of primary Si and rim thickness for a T_P of 900°C

Mold Temp (°C)	Rpm		
	200	300	400
Room Temp	12% & 24mm	15% & 20mm	19% & 14mm
180	14% & 24mm	18% & 16mm	23% & 12mm

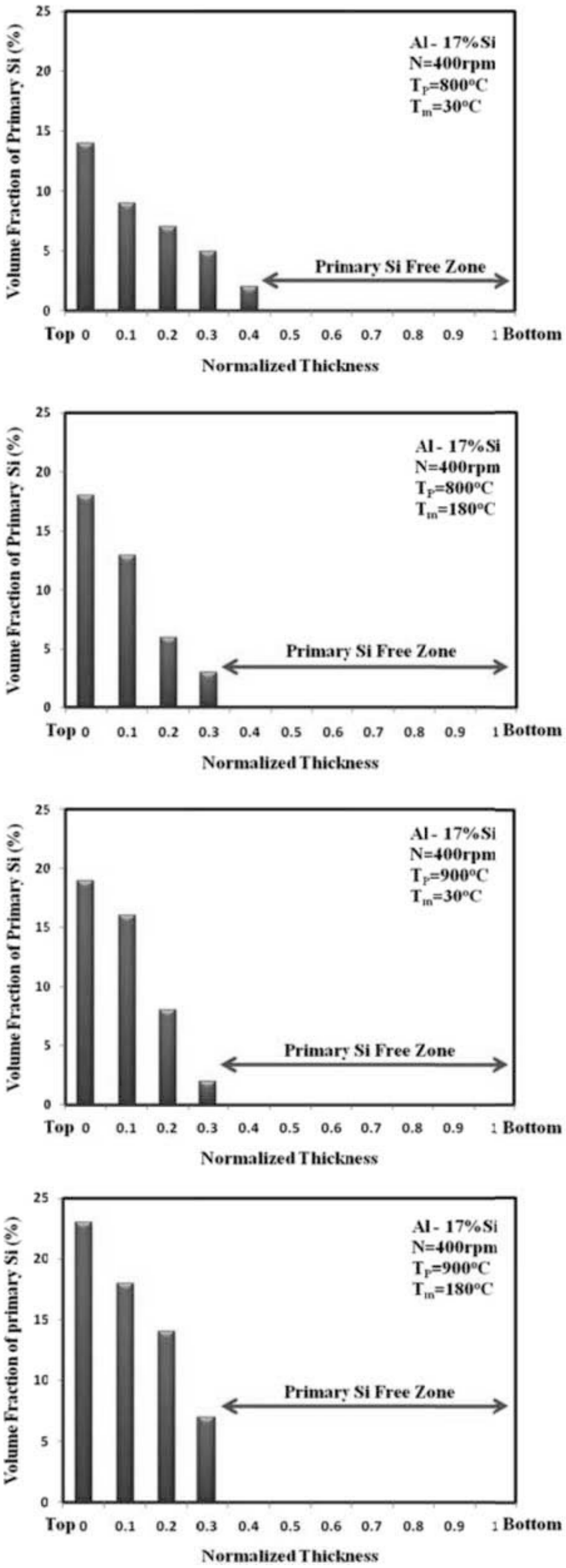

Fig.3 Distribution of primary Si From top end to bottom end for Al-17wt%Si FGM

Micrographs reveal the primary silicon particulates, of varying size, distributed randomly through the FG alloy matrix. FG alloy produced showed somewhat thick primary crystals with less sharp structures, resulting in greater strength and hardness. Also, due to the effect of high G forces the primary silicon crystals and eutectic silicon needles tend to spheroidize to a certain extent, i.e., sharp corners become rounded.

The non-uniform size and distribution of the particulates resulted in particulate-rich and particulate depleted regions. The particulates were aligned in the direction of G force. Besides the presence of block like silicon particulates, isolated pockets of a eutectic silicon phase, having a flake-like morphology with large aspect ratio, was also evident. Formation and presence of the particulate-like silicon phase is the end result of a competition between nucleation and growth in front of the solid / liquid interface in the top layer. The formation of large silicon particulates from the melt provides the necessary impetus for enhanced nucleation through an epitaxial growth mechanism. Thus, a highly heterogeneous mixture of microstructures eventually collects as a highly dense preform.

The microstructure of the preform is critically dependent on the concurrent and mutually competitive influences of solidification characteristics. The presence of a concentration gradient in front of the solid/liquid interface causes or promotes the dendritic or planar growth front to be replaced by an equiaxed structure. For the hypereutectic aluminium-silicon FG alloy, the silicon growth front rejects the aluminium atoms into the liquid alloy. Consequently, there exists a localized region having a low concentration of silicon present in front of the solid-liquid interface.

The distribution of primary Si from top to bottom surface of the centrifugally cast Al/Si FGM at 200, 300, 400rpm has shown a gradation. The most effective among all the castings is the casting processed at 89.42G (400 rpm). This has produced better volume % of primary Si at the top surface when compared to the other two. The comparison of distribution pattern of centrifugally cast FGM for 200rpm, 300rpm and 400rpm shows that there is a sharp transition between Si enriched and Si depleted zones in 400rpm casts. The primary Si particles formed are segregated as a graded layer in the top surface of the casting leading to a better hardness and improved wear resistance of that surface.

The origin of the graded structure is due to the density difference between melt and Si, wherein the density of the Si is much less and the centrifugal force enables stratification resulting from sedimentation a flotation of solids from liquids. Further partial separation of aluminum and Si in the melt occurred during the early stage of the centrifuging, resulting in the formation of a melt with compositional gradient prior to the crystallization of primary crystals. Such that the composition varies from hyper-eutectic to hypo-eutectic forms. Hence Si and aluminum crystals nucleate at top and bottom of the casting respectively [5].

The graded distribution of the primary Si is achieved at all the three rpms. Primary Si is a strengthening phase in Al–Si alloy, so the hardness is strongly affected by the primary Si content. The variation in distribution of volume fraction of Si along the length of the casting is studied. It is again seen that, as the rotational speed of the mold increases, the Particle Free Zone (PFZ) shifts to the left (towards the bottom of the casting) and the primary Si volume fraction increases. By subjecting a homogenous melt to a centrifugal force, a maximum volume fraction of 23% is obtained for the casting fabricated at 89.42G(400rpm) at the top end leading to a selective improvement in specific properties such as hardness and wear resistance. The region near the top surface is rich in primary Si whose concentration decreases towards the bottom. Further it is graded to needle shaped eutectic phase The region near the bottom of the casting shows a very fine primary Al dendrites structure. This is in agreement with observations made by earlier workers on similar works on similar materials [4, 6-7].

The mold and pouring temperatures play an important role in segregation of the alloying particles in a melt subjected to centrifugal action during solidification. This is true due to the fact that increasing the mold and teeming temperature decreases the solidification rate which allows more time for the particle to precipitate in the matrix and segregate towards the influential side depending on the density difference between the melt and particle. At teeming temperature of 800°C and mold speed of 200rpm, the rim thickness is 26 mm for mold at room temperature and 24 mm when mold is preheated to 180°C. Similar trend is observed at 300 and 400rpm. It is observed that when the mold temperature is increased the volume fraction increased by 12.5% for 200rpm, 55% and 28% for 300rpm and 400rpm respectively.

The rim thickness and volume fraction of primary Si show improved values at all the three rpms when the pouring temperature is increased to 900°C. Observing the values of the two parameters: primary Si and rim thickness that are evaluated at two mold temperatures and three rpms with the pouring temperature increased from 800°C to 900°C, it appears that the effect of increasing the teeming temperature is more predominant when the casting is done at higher rpm compared to the use of preheated mold.

From the above results it is clearly demonstrated that the minimum thickness of the rim (particle enriched zone) is achieved at higher mold temperature and increased teeming temperature at all mold speeds. At a particular speed with the increase in mold and teeming temperatures the particle enriched zone is narrowed and PFZ is clearly visible. An increase in the PFZ could be noted at all the mold speeds. It is also observed that an increase in mold temperature and teeming temperature increased the primary volume fraction of the Si at the top of the cast specimen. The combined effect of higher T_m, T_P and rpm used in the present work have provided best values of primary Si and rim thickness.

The properties of a casting significantly depend on the solidification time or cooling rate. This is controlled by either mold temperature or melt temperature. The fluidity of the melt is also affected by the melt temperatures. This increase in temperatures will decrease the heat transfer rate between the mold and the melt. This reduces the solidification rate and in turn, more time will be available for the formation of Si in the melt and its segregation to take place. At a slower solidification rate, the time to obtain a required rim thickness of the casting will be longer compared to that of a faster solidification rate.

When the melt is retained for a long time in the two-phase region above the eutectic time, the primary silicon gets more time to float to the top. Similarly when the teeming temperature is further increased which is above the liquidus temperature of the alloy, the time the liquid spends in the mold under the centrifugal force is further increased. As a result the particles are pushed towards the top and segregate.

Hardness

Hardness of Al-17wt%Si FGM specimens cast under 800°C melt temperature without preheating the mold is examined along its length. Specimen cast at 400rpm has exhibited maximum hardness of 68 BHN at the top surface and it also showed gradation in hardness from the top to bottom from 68 to 50 BHN. The hardness values and gradation did not change much at 300 rpm (66 to 48 BHN), However at 200rpm specimen showed much smaller hardness at the top (59 BHN) even though the Si gradient remained more or less constant. At the same melt temperature with preheating the mold to 180°C, specimen cast at 400rpm exhibited a maximum hardness of 79 BHN at the top surface. This is about 16% higher as compared to the mold at ambient temperature. Further the rim thickness also reduced when the mold is preheated but the hardness at the bottom of the specimen did not change. Similar results were obtained at 300 and 200 rpm also but with reduced hardness values at the top (74 and 68 respectively). The variation of hardness from top to bottom of the casting for two mold conditions and three rpms and at 800°C teeming temperature.

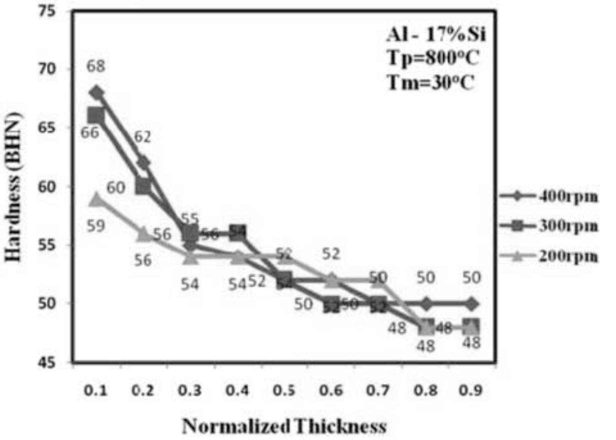

Fig. 4. Hardness of Al-17wt%Si FGM along the length of the casting for 800°C melt temperature without preheating the mold.

The hardness values at the top end of the casting are higher at higher G values (rpm). The rim thickness also reduces at higher rpm indicating that enhanced hardness values can be obtained over a short length of the specimen at higher rpm. This effect is further enhanced when the mold is preheated. The effect of the third variable in the process i.e the teeming temperature on the maximum hardness and rim thickness is also studied by using a teeming temperature of 900°C. Castings are produced at this temperature with two mold conditions and three rpms. It is observed that a maximum of 92 BHN is obtained at the top surface for the specimen cast with preheating the mold and at 400rpm. It also exhibited a good gradation of hardness from top to bottom face with the hardness at the bottom equal to 50 BHN. The variation of hardness from top to bottom of the casting at 900°C teeming temperature.

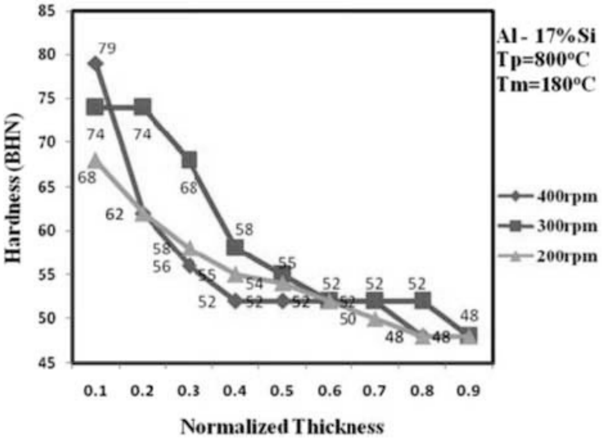

Fig. 5 Hardness of Al-17wt%Si FGM along the length of the casting for 800°C melt temperature with preheating the mold at 180°C.

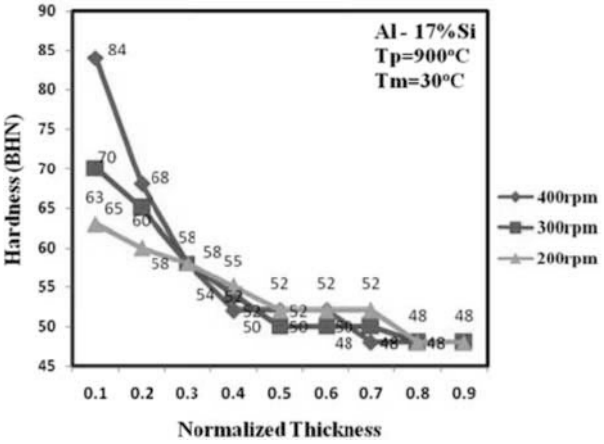

Fig. 6. Hardness of Al-17wt%Si FGM along the length of the casting for 900°C melt temperature without preheating the mold.

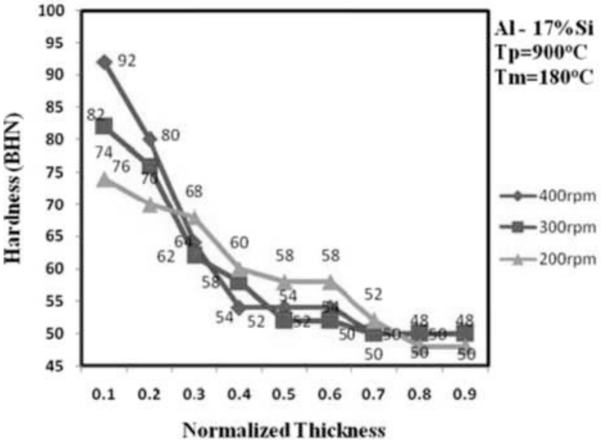

Fig. 7. Hardness of Al-17wt%Si FGM along the length of the casting for 900°C melt temperature with preheating the mold at 180°C.

This increase in hardness is consistent with volume fraction of the Si particles present along the length and as the volume fraction of the harder reinforcement particle increases, the bulk hardness of the casting increases. Similar observations have been reported by Y Watanabe et al.[8].

It can be seen that the hardness increases with the centrifugal force or the mold speed. It has also been found that in the FGM the gradation becomes steeper (smaller rim thickness) with increasing the mold rotation speed (G number). This is in relation to the volume fraction of primary Si found in the cast specimens as discussed in the previous section.

Thus, during the formation of the graded composition in the FGM produced by the centrifuge method, on pouring the molten Al-Si alloy and rotating the mold, the α-Al primary crystals nucleate before the Si crystals form. However, at this time, volume fraction of solid is high enough, and the α-Al primary crystal particles cannot migrate any more. Therefore, α-Al primary crystal particles always migrate toward the bottom. Then, the remaining molten Al-Si alloy will solidify. At a eutectic temperature, 94% liquid phase with a eutectic composition will be retained, and the retained liquid phase may transform into the solid phase by the eutectic reaction. This means, the volume fraction of the Si increases toward the top position. The hardness of the specimen becomes larger than that of the bottom region, since the hardness of Al-Si intermetallic compound is larger than that of α-Al.

For given teeming and mold temperatures higher hardness at top end and smaller rim thickness (steeper gradation) are obtained at higher rpms. When the mold temperature is increased the hardness further increases but rim thickness decreases. Similar trend is observed when the teeming temperature is increased. Compared to T_P=800°C, T_m=30°C and 200rpm the hardness value improved by 15.25% when rpm is increased to 400. It further improved by 16.17% when T_m is raised to 180°C and by 16.45% when T_P is raised to 900°C. Thus the mold and teeming temperature and rpm affect the segregation of the primary Si towards the top of the casting. In the current work it was possible to produce FG alloy having different hardness values and gradation in that range. The highest hardness values and the smallest rim thickness were obtained under the processing conditions of: T_P=900°C, T_m=180°C and rpm=400.

Conclusion

1. Under the action of centrifugal force during the centrifuge casting, both the Al-Si alloys showed gradation in the distribution of Si phase from the top of the casting to the bottom of the casting. The gradation is characterized using percentage of primary Si segregation and the rim thickness. Three different rpms (400, 300 and 200) were used and observing the values for percentage of primary Si segregation and the rim thickness, it is concluded that the mold rpm has a significant effect on gradation and higher the mold rpm better is the gradation.

2. At each rpm of the mold the effect of pouring temperature and mold temperature was studied. From the results the conclusion drawn is that, higher pouring temperature and higher mold temperature provide better gradation at each rpm. The main reason for this is attributed to the temperature difference resulting in solidification which allow time for primary Si to grow from the melt. Further higher teeming temperature helps in retaining the melt for a long time in the two phase region above the eutectic temperature. The primary silicon gets more time to float to the top, the time the liquid spends in the mold under the centrifugal force is increased and as a result the particles are pushed towards the top and segregate.

3. The gradation is characterized by percentage of volume fraction of primary Si and the rim thickness at the top end of the casting. In case of both the alloys the percentage of volume fraction of primary Si is higher at the top end of the casting compared to the bottom end. Further under favorable conditions of rpm, teeming temperature and mold temperature this volume fraction improved and also produced better (lower) rim thickness values. The results of hardness studies further substantiated the above observations i.e., the microstructural and experimental studies through hardness were in good agreement with each other. This conclusion is based on the fact that the Si being a harder phase, the region where it is segregated is expected to show higher hardness and lower specific wear rate.

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