Inference of Optimal Speed for Sound Centrifugal Casting of Al-12Si Alloys

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True centrifugal casting is a standard casting technique for the manufacture of hollow, intricate and sound castings without the use of cores. The molten metal or alloy poured into the rotating mold forms a hollow casting as the centrifugal forces lift the liquid along the mold inner surface. When a mold is rotated at low and very high speeds defects are found in the final castings. Obtaining the critical speed for sound castings should not be a matter of guess or based on experience. The defects in the casting are mainly due to the behavior of the molten metal during the teeming and solidification process. Motion of molten metal at various speeds and its effect during casting are addressed in this paper. Eutectic Al-12Si alloy is taken as an experiment fluid and its performance during various rotational speeds is discussed.

INTRODUCTION

Centrifugal casting is a material processing technique in which the flow pattern of the molten metal during casting strongly affects the quality of the final product. Literature about fluid flow in centrifugal casting is very sparse. Theoretically, it should be possible to produce a true cylinder even when the mold is rotated at low speeds. But practically, the molten metal has to be accelerated to a certain speed to form a uniform hollow cylinder. Depending upon the conditions of the molten metal, there must be an optimum spinning speed, at which the molten metal will be picked up to form a true cylinder.

Jaluria[1] discussed the importance of fluid flow in material processing. He points out several aspects of fluid flow which changes the properties in various processing techniques. Bergeles[2] describes the modeling of the flow at mold surface in continuous casting. He validates the results against the experimental data conducted by cold work modeling. Janco[3] indicates several important parameters involved during the centrifugal casting process. He explains the design of gating, importance of rotational speed, mold dimensions, etc. But he has not done much to explain the importance of molten metal behavior during the process. Ping[4] has reported that no systematic investigation of microstructure evolution in centrifugal casting has been done, although this information is important to know the mechanical properties of the material. Chang[5] studied the influence of process parameters on the microstructure formation in vertical centrifugal casting, but not the effect of liquid metal during casting.

How would you…

…describe the overall significance of this paper?

Flow of molten metal plays a vital role in Al-Si alloys cast through centrifugal casting. Not much literature is available in this regard. An initial work in this area is reported in this article.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

Fluid flow in casting plays a predominant role in getting good quality cast tube. Not much literature highlights the importance in this area. Some work in this area is highlighted in this paper.

…describe this work to a layperson?

Generally, lay persons cast tube with no technical background regarding properties. This paper gives information on the effect of rotational speed on centrifugal casing, and, in turn, its mechanical properties, to improve the quality of the product.

Since this casting process (melt, mold and cast) is opaque in nature, visualization of the molten metal behavior is not possible. Moreover, high solidification rate also makes visualization of liquid behavior impossible. Three processes simultaneously take place during casting. The first is the fluid flow during rotation, the second is the thermal regimes and the last is the solidification process of the melt. Studying all these three overlapping processes is very difficult. Extensive research work has to be carried out to get an idea of the melt behavior during its rotation. Most of the studies of liquid metal behavior are done on continuous casting, where cold modeling experiments were compared with the final casting.[6–10] Similar attempts have to be carried out to understand the nature of melt during centrifugal casting.

Many experiments have been conducted to understand the behavior of liquids in a partially filled rotating cylinder.[11–13] These experiments have analyzed the liquid behavior in boilers, chemical engineering, etc. When a horizontal cylinder containing some liquid is rotated initially, it is able to hold a thin coating of liquid due to the combined effect of the viscosity and cylinder rotation. This uniform coating formed inside the cylinder surface is called “Couette flow.” During rotation at low speeds, the low viscous fluid tries to lift from the side wall and generates a recirculation zone. These recirculation zones are called “Ekmann flow.” With the further increase in angular velocity, a thick layer of liquid is dragged along the wall and imparts a solitary wave-like structure to the

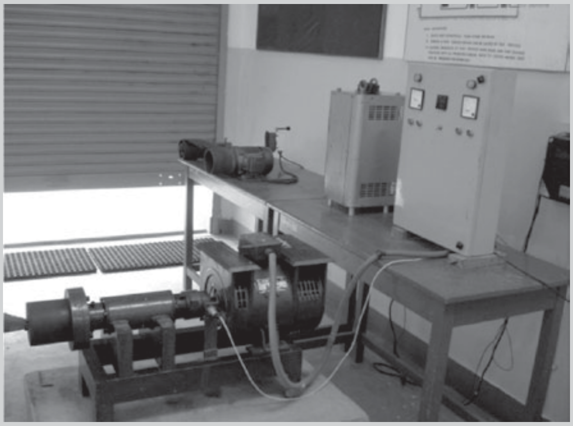

Figure 1. Actual centrifugal casting setup.

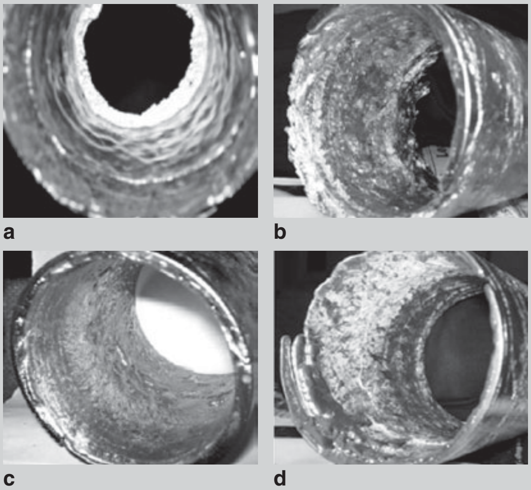

Figure. 2. Al-12Si casting (4 mm thick) (a) 200 rpm, (b) 400 rpm, (c) 600 rpm, and (d) 800 rpm.

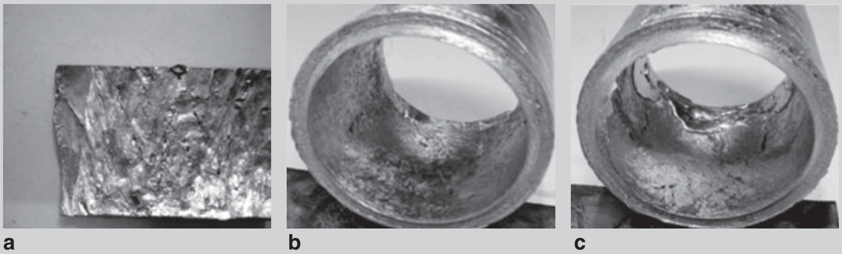

Figure 3. Al-12Si castings (6 mm thick): (a) 400 rpm, (b) 600 rpm, (c) 1,000 rpm.

Figure 4. Al-12Si casting (4 mm thick): (a) 600 rpm, (b) 800 rpm, (c) 1,000 rpm, (d) 1,200 rpm (L–R, respectively).

thick film. These wave patterns are usually approximate reflection symmetry about the vertical mid plane of the cylinder. These patterns are commonly known as "Taylor flows." From literature, there are no observations made on these flows in centrifugal casting. Probably there is no literature explaining the properties involved about these flows in comparing with actual casting. We have conducted cold modeling experiments and explained the properties influencing the fluids in a rotating horizontal cylinder.[14,15] These patterns are observed for low viscosity in cold modeling. Higher viscous fluids hardly generate Taylor flows, since it gets easily lifted by the mold at low rotational speeds. For a given diameter of the mold, these patterns are generated for the same range of rpm with a change in thickness of the cylinder. These flows are then compared with low melting metal tin.[16] Tin exhibited Couette, Ekmann, and Taylor flows when rotated at low rotational speeds. At optimum speed a uniform cylinder was obtained. Extending this work, the behavior of high melting eutectic Al-12Si alloy is studied to understand the role of optimum speed during this process. Influence of various casting variables such as mold rotating speeds, melt volumes or casting thicknesses on the flow patterns and solidification process in the centrifugal casting have been studied in detail.

The experimental apparatus consists of a centrifugal casting machine, where a mold is connected through a shaft to a 2HP DC motor (Figure 1). The speed of the motor can be varied from 20 rpm to 2,000 rpm. The mold dimensions are 8.1 cm diameter, 14 cm length and 6 cm thickness.

RESULTS AND DISCUSSION

Appearance of the Castings

Melting Temperature at 800ºC

In this experiment, molten metal to form 4 mm thickness cylinder is poured into the mold and all of it is not picked up immediately. It tries to move in the axial direction because of its high fluidity. During low rotational speed of 200 rpm (Figure 2a), a thin layer of the metal is carried by the mold surface and simultaneously, it moves along the axis. The inner mold surface is covered with the molten metal, forming Couette Flow. The end wall also lifts the molten metal and forms Ekmann flow. Initially the molten metal has low viscosity and forms Couette and Ekmann flows. Further increase in the rotational speed of the mold to 400 rpm enables the rapid movement of the liquid metal along the axial direction resulting in the formation of Taylor band in the final casting (Figure 2b). The Taylor bands are formed at the time of teeming of the melt where it possesses low viscosity. A uniformly thick full cylinder is observed at 600 rpm (Figure 2c). This is possible due to the molten metal getting along the circumference of the inner mold, thus avoiding other types of flows. The driving force acting on the molten metal is sufficient so that it is carried along the inner surface of the mold before it gets solidified, forming a full uniform cylinder. If the rotational speed is further increased to 800 rpm, an irregular pattern or shape is seen in the final casting as shown in Figure 2d. This is possibly due to the quick lifting of the liquid metal, hence limiting its axial movements.

In the case of 6 mm thick cast tube, if the rotational speed of the mold is increased to 400 rpm the liquid metal is in turbulent mode and a series of band patterns (Taylor Flows) are observed in the final casting (Figure 3a). A full uniform cylinder casting is possible to be obtained at 600 rpm (Figure 3b). The molten metal is found to be picked up rapidly and also held firmly to the mold without slippage or raining at this speed. Further increase in rotational speed to 1,000 rpm leads to a disturbed surface on the final casting (Figure 3c).

During rotation at low speeds, the melt exhibits these flows initially because of its low viscosity. These observations are also seen in water having low viscosity.[14,15] As viscosity changes gradually, probably these flows held stationary and its impressions are observed in the final casting. For a given dimension of the mold, a uniform liquid cylinder is formed at a particular rotational speed and varies linearly with the thickness of the liquid cylinder. This explanation differs in the case of centrifugal casting. Here the volume

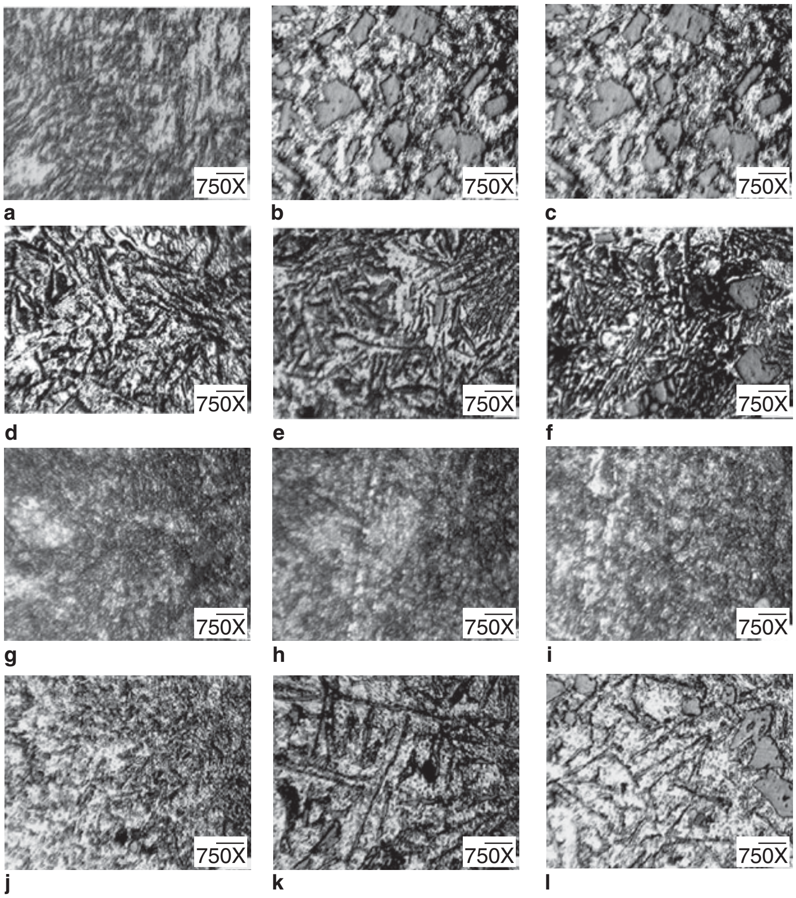

Figure 5. Microstructure of 4 mm thick Al-12Si at (a) 200 rpm outer, (b) 200 rpm middle surface, (c) 200 rpm inner surface, (d) 400 rpm outer surface, (e) 400 rpm middle surface, (f) 400 rpm inner surface, (g) 600 rpm outer surface, (h) 600 rpm middle surface, (i) 600 rpm inner surface, (j) 800 rpm outer surface, (k) 800 rpm middle surface, (l) 800 rpm inner surface of the casting.

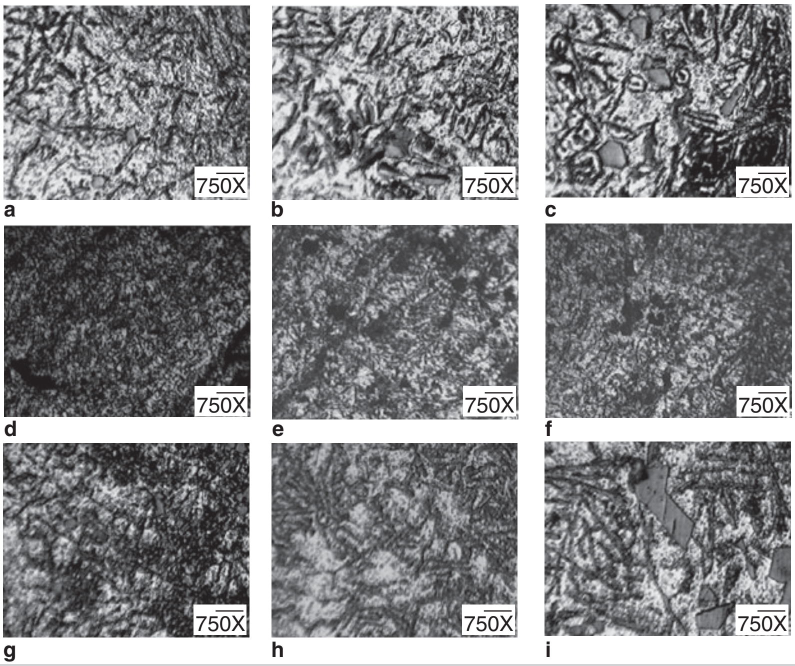

Figure 6. Al-12Si (6 mm thick) at (a) 400 rpm outer surface, (b) 400 rpm middle surface, (c) 400 rpm inner surface, (d) 600 rpm outer surface, (e) 600 rpm middle surface, (f) 600 rpm inner surface, (g) 1,000 rpm outer surface, (h) 1,000 rpm middle surface, and (i) 1,000 rpm inner surface of the casting.

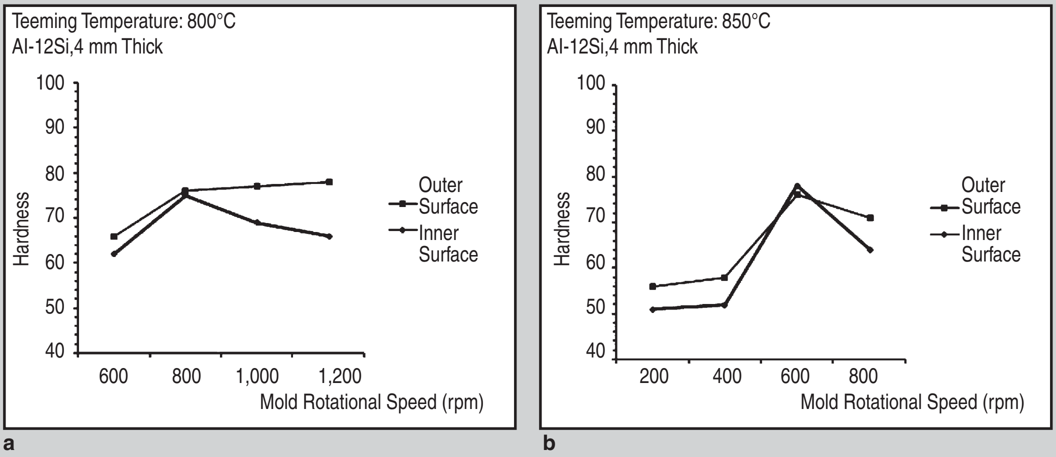

Figure 7. Al-12Si alloy (4 mm thick) hardness as a function of mold rotational speed, teeming temperature of (a) 800ºC and (b) 850ºC.

of the melt charged into the rotating mold leads into the increase in the contact area of poured metal. This leads to a larger area of the metal to drive along the inner surface of the mold. Moreover, the melt during rotation initially covers the entire circumference of the mold and solidifies, forming a thin strip of metal. The subsequent layer of the molten metal then comes in contact with the metal which was already solidified and the driving force of the melt increases gradually. Moreover, the viscosity of the molten metal also increases. Probably due to this reason, with the increase in thickness of the casting tube, the rotational speed required for the formation of a uniform cylinder takes place at same range of rotational speeds.

Melting Temperature at 850ºC

The change in the pouring temperature also influences the appearance of the casting. With the teeming temperature of 850ºC, for the cast made for 4 mm thick is shown in Figure 4. At 600 rpm, during teeming the molten metal into the mold, it gets a lift along the circumference of the inner surface of the mold avoiding axial movement and non uniform cast tube is formed. This is perhaps due to the increase in viscosity of the molten metal. It requires larger drive force to spread the molten metal uniformly and simultaneously getting a lift from the mold inner wall. This happens when the mold is rotated at 800 rpm, where a uniform hollow cylinder is formed. Again an irregular shaped cast tube is formed with an increase in rotational speed to 1,000 and 1,200 rpms.

Microstructure of the Casting

The microstructures of the Al-12Si alloys of 4 mm thickness, rotated at 200 rpm, 400 rpm, 600 rpm, and 800 rpm are shown in Figure 5. It is observed that the rotational speed had very strong influence on the microstructure of the specimens. At rotational speed of 200 rev/min., Figure 5a–c, the molten metal nucleates and a solid liquid interface is created. The temperature continues to decrease below the equilibrium freezing temperature and the liquid phase has transformed into a solid phase. Since there is more molten metal to solidify, the liquid phase exists for longer time. There are needle-shaped eutectic silicon at the outer surface and primary silicon at the middle and inner surface. Figure 5d–f shows the microstructure of the specimen cast at rotational speed of 400 rpm. The molten metal here was in turbulent stage forming Taylor flow. A large number of primary silicon has broken into smaller pieces at the middle and inner regions. Silicon with needle-shaped structure is exhibited at the outer surface. With the increase in rotational speed to 600 rpm, Figure 5g–i, the solidification rate was more at this stage. The molten metal crosses the turbulent stage rapidly and directly gets lifted by the mold inner surface forming a full cylinder. Fine silicon particles exhibiting good mechanical properties were observed across the section of the casting. With the increase in rotational speed to 800 rpm, Figure 5j–l, the molten metal gets lifted immediately after it is being poured onto the mold. Fine structures are seen at the outer surface due to chilling effect of the molten metal when it comes in contact with the cold mold. The metal gets a lift along the circumference of the mold and the heat transfer takes place only through conduction. A needle-shaped and primary silicon is seen at the middle and inner surfaces of the cast tube.

With 6 mm thickness cast cylinder and with the increase in rotational speed to 400 rpm, the solidification rate increases and a fine structure at the outer surface is observed. Primary silicons were seen at the middle and inner surface due to low cooling rate (Figure 6a–c). With the casting made at 600 rpm, a fine structure is seen on the three surfaces indicating that it has good mechanical properties, Figure 6d–f. With the further increase in rotational speed to 1,000 rpm (Figure 6g–i), the molten metal gets lifted instantaneously and the solidification takes place due to conduction of the molten metal. Dendrite structures are seen at the middle and inner surface of the cast tube. Moreover, primary silicon is also seen at the inner surface due to low solidification rate.

During the teeming temperature of 850ºC, a fine equiaxed structure is observed along the radial direction for the cast tube prepared at a rotational speed of 800 rpm, whereas dendrite structure and primary silicon are noticed at the specimen cast at other rotational speeds of the mold.

DETERMINATION OF HARDNESS VALUES

The hardness values of the sample were determined using the Brinnel hardness test with 5 mm steel ball indenter. The thorough cleaning of the mating surface of the indenter, plunger rod, and test samples so as to remove dirt, scratches, and oil was done. This is followed by calibration of the testing machine using the standard block. The outer surface of the sample was placed on the die, which acts as support for the test samples. A minor load of 10 kg was applied to the sample in a controlled manner. Without inducing impact or vibration a zero datum position was established. The load was then removed by returning the crank handle to the latched position. The hardness value was read directly from the semi-automatic digital scale. Five readings were taken for each sample with the average value taken as the hardness value for each sample.

Figure 7 shows the hardness of the outer surface and inner surface with respect to rotational speed of the mold. It is seen that at pouring temperature of 800ºC and for 4 mm thick Figure 7a, a similar hardness for the outer and inner surface was seen at 600 rpm. But as the pouring temperature was increased to 850ºC, the outer and inner surface of the casting had same hardness at 800 rpm, for 4 mm thick cast tube Figure 7b.

CONCLUSIONS

The Al-12Si centrifugal castings were made at different rotating speeds and for different wall thicknesses of castings. From the above, the following points can be concluded:

- For 4 mm and 6 mm thick, it is seen that at lower rotational speed of the mold, the Couette, Ekmann, and Taylor flows will be prevalent leading to castings with irregular inner surface. For teeming temperature of 800ºC, a uniform hollow casting was obtained at 600 rpm and at teeming temperature of 850ºC, a full cylinder was formed at 800 rpm. An irregular shaped cast tube was formed with the above and below these rotational speeds.
- The centrifugal cast sample shows a fine to coarse microstructure from the outer to inner casting. Dendrite structures dominate at the lower rpm of the casting and at optimum speed of rotation of the mold, a fine equiaxed structure was seen at the outer and inner zones of the casting.
- The BHN was found to be the same at optimized speed and were varying at different speeds.

ACKNOWLEDGEMENT

The authors acknowledge Dr. N.R. Shetty, director, and Dr. H.C. Nagaraj, principal, Nitte Meenakshi Institute of Technology, Yelahanka, Bangalore for their kind support for this project.

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