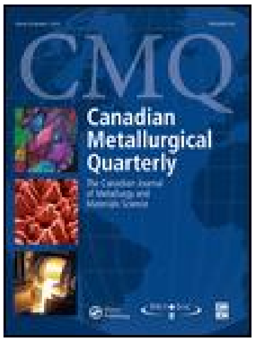

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INFERENCE OF OPTIMAL SPEED FOR SOUND CENTRIFUGAL CASTING OF TIN

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Abstract — During centrifugal casting when a mould 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 guessing but based on experience. The defects in the casting are mainly due to the behaviour of the molten metal during the teeming and solidification process. The motion of molten metal at various speeds and its effect during casting are addressed in this paper. Tin is taken as an experiment fluid and its performance during various rotational speeds is discussed. The microstructures and hardness of all the castings are also investigated.

Résumé — Lors de la coulée centrifuge, lorsqu'un moule est mis en rotation à basses et à très hautes vitesses, on trouve des défauts dans les pièces moulées finales. L'obtention de la vitesse critique pour des moulages sans défauts ne devrait pas résulter d'une estimation, mais devrait se baser sur l'expérience. Les défauts des pièces moulées sont principalement dus au comportement du métal fondu lors du procédé de coulée et de solidification. Dans ce document, on considère le mouvement du métal fondu à des vitesses variées et son effet lors du coulage. On considère l'étain comme fluide expérimental et l'on discute de son rendement lors de diverses vitesses de rotation. On étudie également la microstructure et la dureté de toutes les pièces moulées.

INTRODUCTION

One of the most crucial areas of research in fluids engineering today is that of material processing. The important underlying features involved in fluid flow and their effect on material processing needs to be studied thoroughly. One aspect that is missing in the literature is quantitative information on the dependence of the quality of the product on the fluid flow.

Centrifugal casting is one of the material processing techniques 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 mould 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 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 change the properties in various processing techniques. Bergeles [2] described the modelling of the flow at mould surface in continuous casting. He validates the results against the experimental data conducted by cold work modelling. Janco [3] indicated several important parameters involved during the centrifugal casting process. He explained the design of gating, the importance of rotational speed and mould dimensions but he did not throw much light in explaining the importance of molten metal behaviour during the process. From the literature, it is seen that most of the work has been carried out in the fluid behaviour of the molten metal during continuous casting [4-8]. These researchers investigated the parameters affecting the casting through cold modelling. Ping [9] reported that no systematic investigation of microstructure evolution in centrifugal casting has been done which is an important factor in understanding the mechanical properties of the material. Chang studied the influence of process parameters on the microstructure formation in vertical centrifugal casting [10], but did not explain the effect of liquid metal during casting.

When the molten metal is poured inside the surface of a rotating true centrifugal casting mould, it is not all picked up immediately. The friction between the molten metal and the mould leads to rotational velocity which is imparted to the liquid. The liquid gets a lift from the inner surface of the mould and covers the mould fully as a thin layer of melt. The rest of the molten metal experiences a drag. With optimum spinning speed, all the melt will be picked up and held firmly against the mould wall forming a uniform thickness liquid cylinder which finally solidifies. At speeds below the critical value, some liquid fails to move along the inner surface of the mould and leads to imperfect casting. Excessive speed of rotation also produces a poor casting because of hot tears. In this paper, the behaviour of molten tin is studied in order to understand the role of optimum speed during this process. The influence of various casting variables such as mould rotating speeds, melt volumes or casting thicknesses on the flow patterns and solidification process in the centrifugal casting resulting in a good casting and its microstructure are studied in detail.

EXPERIMENTAL DETAILS

The experimental apparatus consisted of a centrifugal casting machine where a mould was connected through a shaft to a 2 HP DC motor (Figure 1). The speed of the motor could be varied from 20 rpm to 2000 rpm. A mould with dimensions 8.1 cm in diameter, 14 cm in length and 6 mm in thickness was chosen for the experiment.

Tin was chosen as the experimental fluid because of its low melting point and ease of handling. Here we focussed only on the molten metal behaviour during rotation and its effect on mechanical properties. Initially, the mass required to form a 2 mm thick hollow casting was calculated and melted to a temperature of 450 °C. It was then poured through a spruce into the mould rotating at 200 rpm. Similar procedures were adopted for 4 mm and 6 mm thick castings. Again for this thickness, the castings were made at different spinning speeds. Similar procedures were carried out for a teeming temperature of 350 °C of the melt.

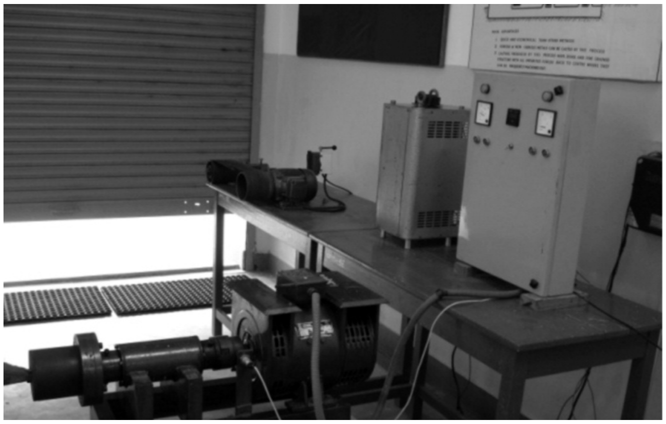


Fig. 1. Actual Centrifugal Casting Setup.

RESULTS AND DISCUSSIONS

Appearance of the Castings

Melting temperature at 450 °C: Visual observations of different fluids partially filling a rotating cylinder indicate the existence of certain critical value of the angular velocity for the formation of hollow liquid cylinders of uniform thicknesses. At values of the angular velocity larger than the critical one, the flow is without separation and below these critical speeds the fluid exhibits instability. This behaviour of fluid is a complicated issue thus better understanding needs to be developed.

A number of experiments were conducted in an effort to better understand the behaviour of liquids in a partially filled rotating cylinder [11-15]. These experiments were conducted to analyze the liquid behaviour in boilers and chemical engineering analyses. 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 the '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 the 'Ekmann flow'. With a further increase in angular velocity, a thick layer of liquid is dragged along the wall and imparts a solitary wave-like structure to the thick film. These wave patterns are usually an approximate reflection symmetry about the vertical mid-plane of the cylinder. These patterns are commonly known as 'Taylor flows'. There are no observations made on these flows in centrifugal casting in the literature and most likely there are no studies explaining the properties involved about these flows in comparison with actual casting. We have conducted cold modelling experiments and have explained the properties influencing the fluids in rotating horizontal cylinders [11,16]. We have shown that these patterns are observed for low viscosity in cold modelling. Higher viscous fluids hardly generate Taylor flows, since they are easily lifted by the mould at low rotational speeds. For a given diameter of the mould, these patterns are generated for the same range of rpm with the change in thicknesses of the cylinder.

Considering the 2 mm thick casting of 200 rpm (Figure 2a), evidence for Ekmann flows was observed in the casting. At a low volume fraction, the molten metal caused it to solidify very fast and the impressions of the secondary flows were seen at the ends of the casting. But even at increased speeds of 400, 600 and 1100 rpm, a uniform cylinder casting cannot be realized due to increased cooling and solidification rates where freezing the liquid is too fast to form a uniform hollow cylinder (Figures 2b, 2c and 2d). Molten metal to form a 4 mm thick cylinder was poured into the mould and not all of it was picked up immediately. It tried to move in the axial direction because of its high fluidity. During low rotational speed of 200 rpm (Figure 3a), a thin layer of the metal is carried by the mould surface and it simultaneously hits the other side of the mould and then moves in the reverse

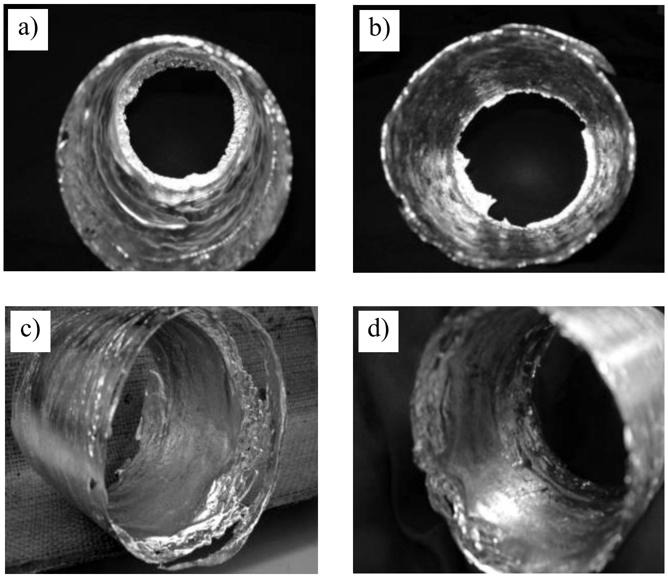


Fig. 2. Casting for 2 mm thick tin at a) 200 rpm, b) 400 rpm, c) 600 rpm, d) 1100 rpm.

direction undulating the liquid surface in the axial direction. A hollow cylinder with irregular shape was formed at the final casting. Initially the molten metal had low viscosity but thickened gradually until it reaches its freezing point. But the process could not be followed right through because of the opaque nature of the metals and moulds. The Couette flow might be formed at a low speed of rotation. Moreover, the liquid metal is lifted by the side wall and it exhibits an 'Ekmann flow' of the molten metal. At 400 rpm (Figure 3b), a thick layer of melt is picked up from the melt pool and a series of patterns known as the 'Taylor flow' forms. These patterns also depend on the viscosity of the molten metal. At a further increase in speed to 600 rpm, (Figure 3c), the liquid metal spread easily and was lifted uniformly along the mould's inner surface. It formed a full liquid cylinder avoiding all these types of flows. At a further increase in the spinning speed to 800 rpm, the driving force was large which made the melt move along the circumference of the mould. Some portions of the melt escaped and moved axially and finally solidified. Here thick portions formed at one portion and thin at another (Figure 3d).

Similarly, for a 6 mm thick liquid cylinder Taylor patterns were observed at 500 rpm (Figure 4a) where the liquid metal was in turbulent mode. When the mould was rotated at 600 rpm (Figure 4b) a full cylinder casting of tin was formed. It is also to be noted that for low volume fraction, Ekmann flows were observed and its impression casted, but with an increase in volume fraction, Ekmann flows were not observed. With an 8 mm thick casting, a full cylinder is formed at 600 rpm (Figure 4c).

During rotation at low speeds, the melt exhibits these flows initially because of its low viscosity. These observations were also seen in water having low viscosity. As viscosity changes gradually, probably these flows held stationary and its impressions were observed in the final casting. For a given dimension of the mould, a uniform liquid cylinder was formed at a particular rotational speed and varied linearly with the thickness of the liquid cylinder [11]. This explanation differed in the case of centrifugal casting. When there was an increase in the thickness of the casting, the volume of the melt charged into the rotating mould led to an increase in the contact area of poured metal. This led to a larger area of the metal to drive along the inner

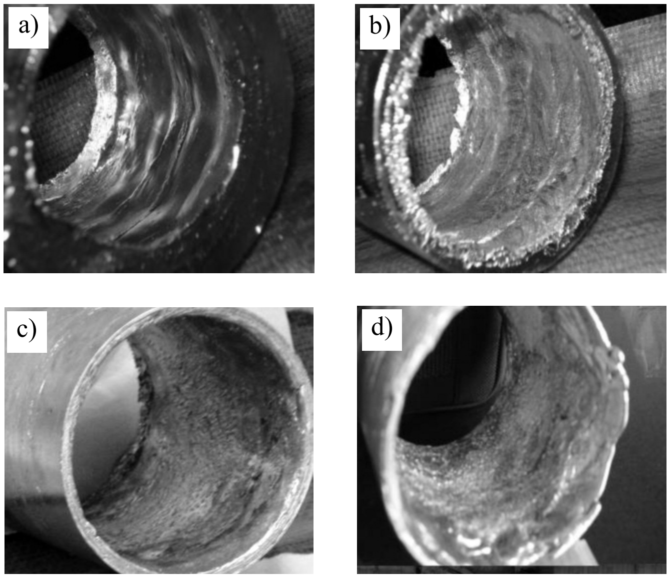


Fig. 3. Casting for 4 mm thick tin at a) 200 rpm, b) 400 rpm, c) 600 rpm, d) 800 rpm.

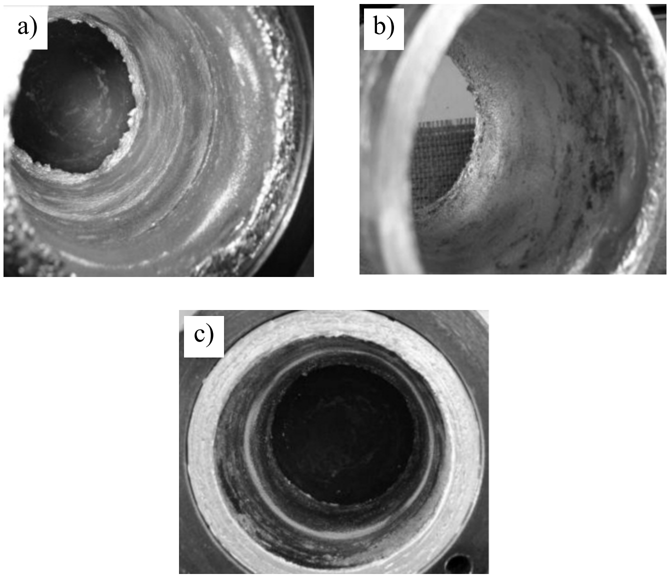


Fig. 4. Casting of tin at 6 mm thick at a) 500 rpm, b) 600 rpm and c) 8 mm thick at 600 rpm.

surface of the mould. This holds true even in cold modelling where it has constant viscosity but in the melt, viscosity gradually changes. The melt during rotation initially covered the entire circumference of the mould and solidified forming a thin strip of metal. This was due to the rapid cooling of the molten metal coming in contact with the cold mould. The subsequent layer of the molten metal then came in contact with metal which had already solidified and the driving force of the melt increased gradually. Simultaneously, the viscosity of the molten metal reduced. Probably due to this reason with an increase in thickness of the casting tube, the rotational speed required for the formation of uniform cylinder takes place at same range of rotational speeds.

Melting Temperature at 350 °C: The change in the pouring temperature also influenced the appearance of the casting. For 2 mm thick as shown in Figure 5, a proper casting was not done due to lack of fluidity and low pouring temperature for different speeds. When a cast is made at 4 mm thickness, a Taylor flow at 600 rpm was seen (Figure 6a) and a full cylinder was formed at 800 rpm (Figure 6b). A similar case was also seen at a 6 mm thickness (Figures 6c and 6d). Apart from the rotating speed, the appearance of the casting also depended on the pouring temperature. Here with the lack of fluidity and low pouring temperature the speed must be increased correspondingly.

Microstructure of the Casting

In general, there are two interlinked factors that influence and control the formation of grains. The first is the existence of a substrate in the melt that can act as nucleation sites. Second, there has to be sufficient under-cooling to facilitate the survival and growth of the nuclei. Hence, the grain structure size and shape depends on the mould temperature and melt superheat. The mould temperature was kept constant at 30 °C for every casting.

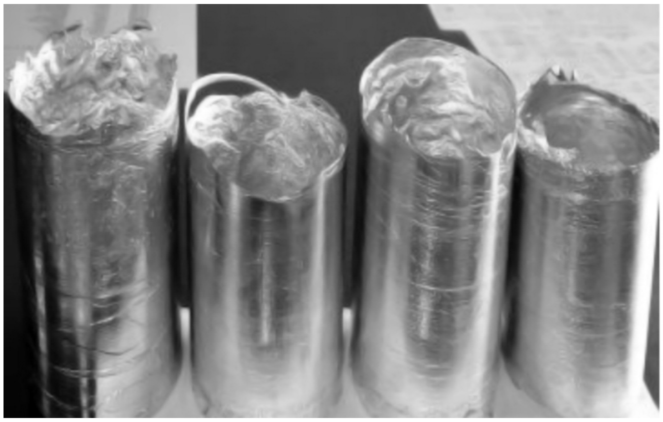


Fig. 5. Casting of 2 mm thick cylinders at 100, 200, 800, 1600 rpm from left to right, respectively.

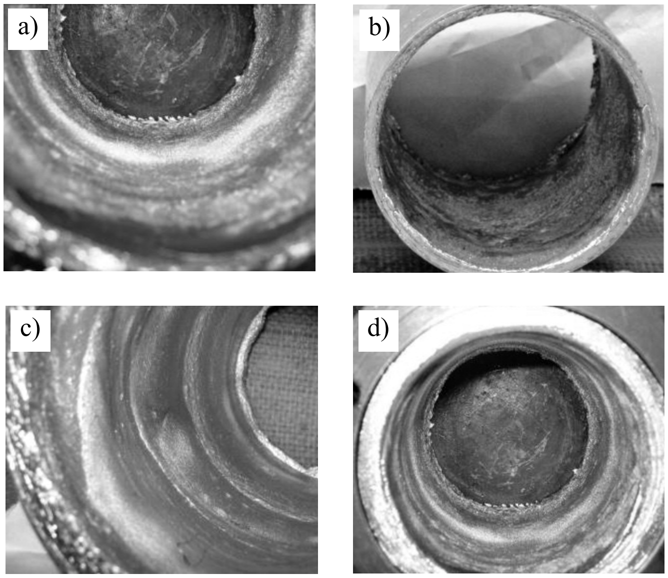


Fig. 6. Casting of tin of 4 mm thick at a) 600 rpm, b) 800 rpm and 6 mm thick at c) 600 rpm and d) 800 rpm.

Melting Temperature at 450 °C: The solidification structure of the castings is of great importance because of its role on mechanical properties. A fine equiaxed grain structure is required in order to obtain homogenous and isotropic mechanical properties. The present study compares the microstructure of tin castings of various thicknesses cast with increased rotating speed.

The microstructures at the outer, middle and inner surfaces of the casting were studied. The microstructure for a 2 mm thick casting was not evaluated since it was not possible to cast a full length cylinder. Upon pouring the molten metal into the rotating mould, many crystals nucleated on the cold wall mould as a result of super cooling. These chilled crystals formed the outer skin of the casting. This structure in the outside wall depended on the thermal fluctuation of the liquid metal. The metal then gradually solidified towards the inner region. Hence, the metal will be undercooled at the middle and inner surface of the castings. At the inner surface, deflections of columnar grains were frequently observed in the centrifugal casting, when the casting was prepared at low rotational speed. This deflection in the microstructure was probably due to the Taylor flow which is exhibited by the molten metal.

For a casting for 4 mm thick made at 200 and 400 rpm, due to a small centrifugal force, the molten metal lifts and slips along the cylindrical surface leading to cooling of the liquid. Columnar grains seen at the outer surface and Figure 7a seems to prove this point. The chilling effect was quite small and the skin of the fine grains was too thin to be noticed. During the solidification process, the well oriented dendrite structure grew from the chill zone and continued towards the inner surface.

The formation of dendrite begins to breakdown with an increase in spinning speed. At 400 rpm, dendrite structures formed at the radial direction of the casting because the molten metal was influenced by the Taylor flow leading to turbulent stage (Figures 7d, 7e and 7f) but the arrangements of the dendrites were set in a radial direction. With an increase in mould speed to 600 rpm, a thick fine structure was clearly seen in the outside surface of the casting due to the chilling effect of the metal coming in contact with the mould (Figures 7g, 7h and 7i). The chilling effect on the

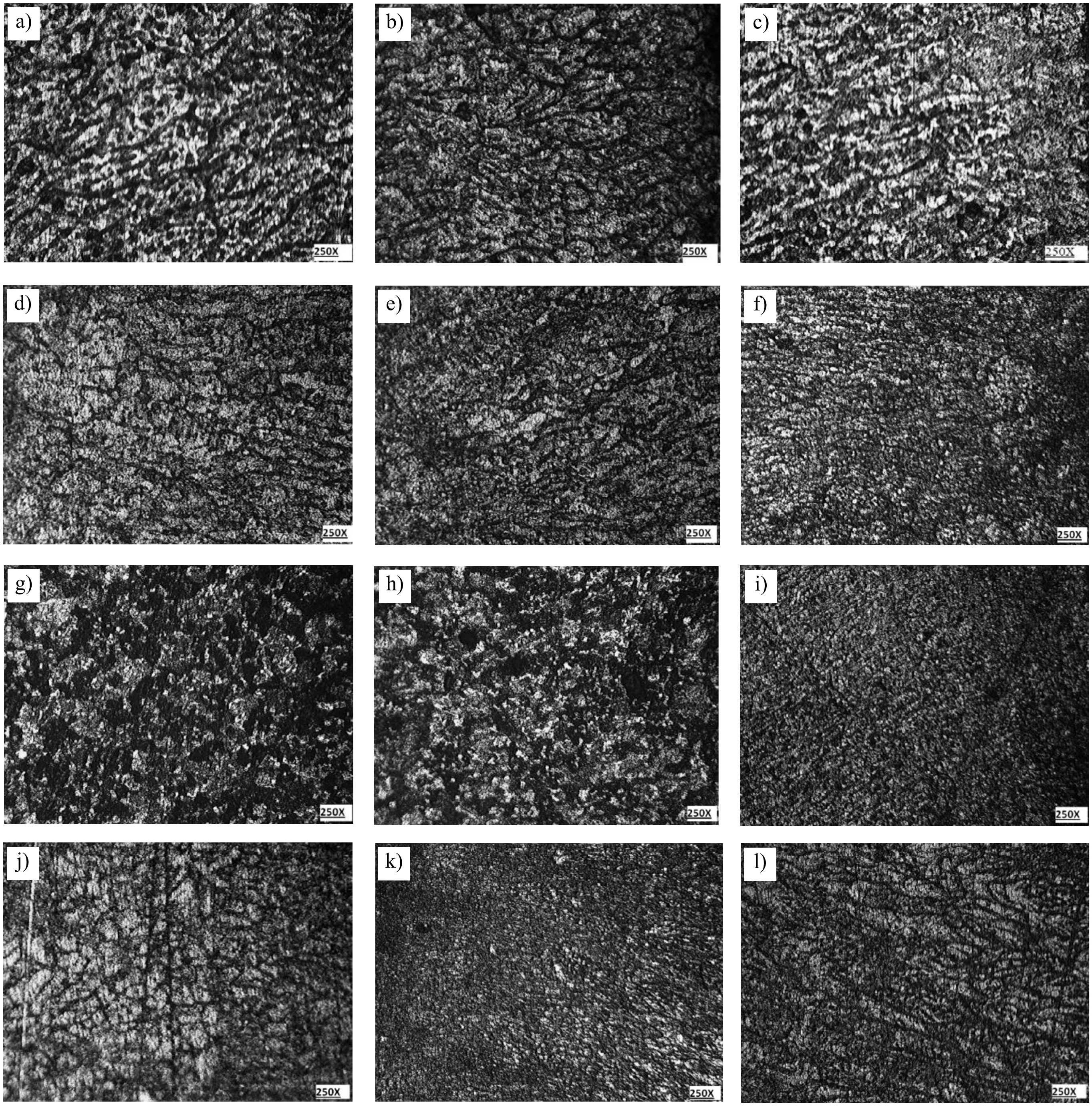


Fig. 7. Microstructure of 4 mm thick tin at a) 200 rpm inner surface, b) 200 rpm middle surface, c) 200 rpm outer surface, d) 400 rpm inner surface, e) 400 rpm middle surface, f) 400 rpm outer surface, g) 600 rpm inner surface, h) 600 rpm middle surface, i) 600 rpm outer surface, j) 800 rpm inner surface, k) 800 rpm middle surface and l) 800 rpm outer surface of the casting.

casting depended on thermal mass of liquid metal and relative movement between the liquid metal and inner surface of the mould. The metal moved in a streamline direction along the axis and was simultaneously lifted forming a uniform cylinder and thus had a high solidification rate. Hence, a fine equiaxed grain structure of the casting was seen at 600 rpm at all the points in the radial direction of the casting. With an increase in speed to 800 rpm, the metal rather than spreading out along the axis, moved along the circumferential direction of the mould. The metal will be stable after being lifted by the mould and the formed casting will have a thick section at one side and a thin section at the other. Taking the microstructure across thick section, fine structures were seen at the outer surface due to chilling effect of the molten metal. The solidification process at the middle and inner region takes place through conduction. Hence dendrite structures were formed at these regions of the casting (Figures 7j to 7l).

Similarly, with a 6 mm thickness, the volume of the molten metal was large when compared to a 4 mm thickness. At 500 rpm, the molten metal is in a turbulent stage. Here, dendritic structures are arranged in an irregular pattern because of an increased volume of molten metal. The molten metal disturbs the growth of the dendritic structure in the radial direction and hence irregular sized and improper orientation of the structure was seen at 500 rpm (Figures 8a, 8b and 8c). However, with an increase in speed to 600 rpm, molten metal was in a static state where it formed a uniform cylinder crossing turbulent stage. Hence, fine grains were observed at these rpm as shown in Figures 8d, 8e and 8f.

Melting Temperature at 350 °C: The microstructure for tin casted at 4 mm and 6 mm thicknesses is shown in Figures 9 and 10. There was a noticeable change in the microstructure with varied pouring temperatures. A dendrite structure was seen for 4 mm thick casting rotated at 600 rpm (Figures 9a to 9c) due the turbulent mode of the molten metal forming a Taylor series in the final casting. At 800 rpm (Figures 9d to 9f), a fine structure was seen due to the formation of a uniform cylinder cast tube. Even at 6 mm thick, a dendrite structure was seen at 600 rpm (Figures 10a to 10c) and a fine structure at 800 rpm (Figures 10d to 10f).

DETERMINATION OF HARDNESS VALUES

The hardness values of the sample were determined using the Brinell hardness test with a 5 mm steel ball indenter. A thorough cleaning of the mating surface of the indenter, plunger rod and test samples so as to remove dirt, scratches and oil was conducted. This was followed by calibration of the test machine using the standard block. The outer surface of the sample was placed on the die, which acted as a 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 and zero datum, a position was established. The load was then removed by returning the crank handle to the latched position. The hardness value was read directly from a semi-automatic digital scale. Five readings were taken for each sample with the average value taken as the hardness value for each sample.

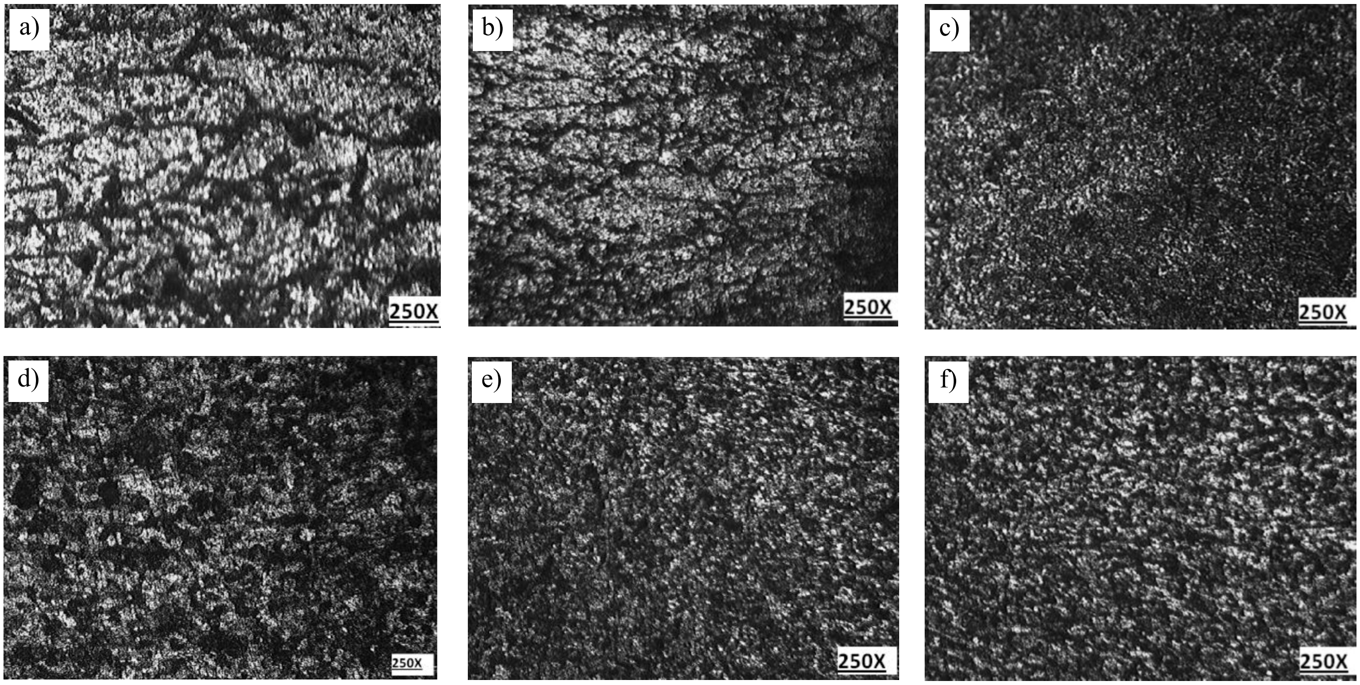


Fig. 8. Microstructure of 6 mm thick tin at a) 500 rpm inner surface, b) 500 rpm middle surface, c) 500 rpm outer surface, d) 600 rpm inner surface, e) 600 rpm middle surface and f) 600 rpm outer surface

Figures 11 and 12 show the hardness of the outer surface and inner surface with respect to rpm. It was seen that at a pouring temperature of 450 °C for 4 mm and 6 mm thick, a similar hardness for the outer and inner surface was seen at 600 rpm (Figure 11). But with the pouring temperature reduced to 350 °C, the outer and inner surface of the casting had same hardness at 800 rpm, for both 4 mm and 6 mm thicknesses (Figure 12).

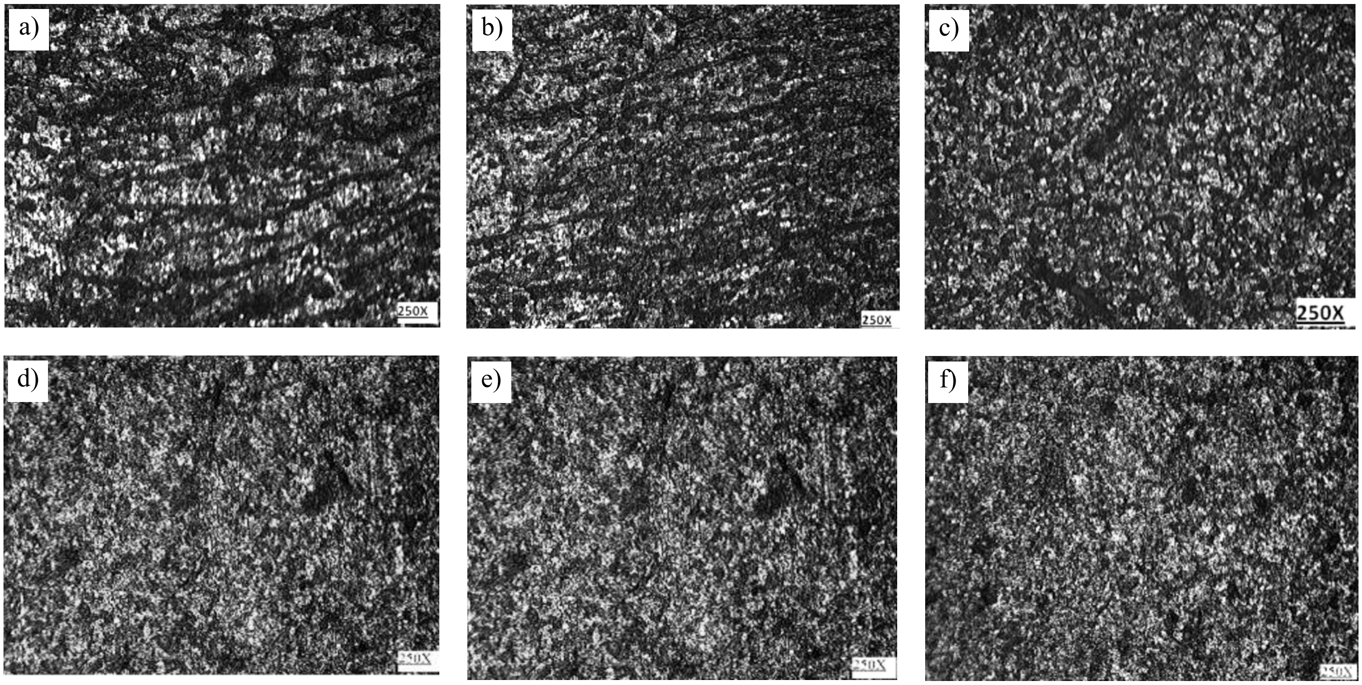


Fig. 9. Microstructure of 4 mm thick tin melted at 350 °C at a) 600 rpm inner surface, b) 600 rpm middle surface, c) 600 rpm outer surface, d) 800 rpm inner surface , e) 800 rpm middle surface and f) 800 rpm outer surface.

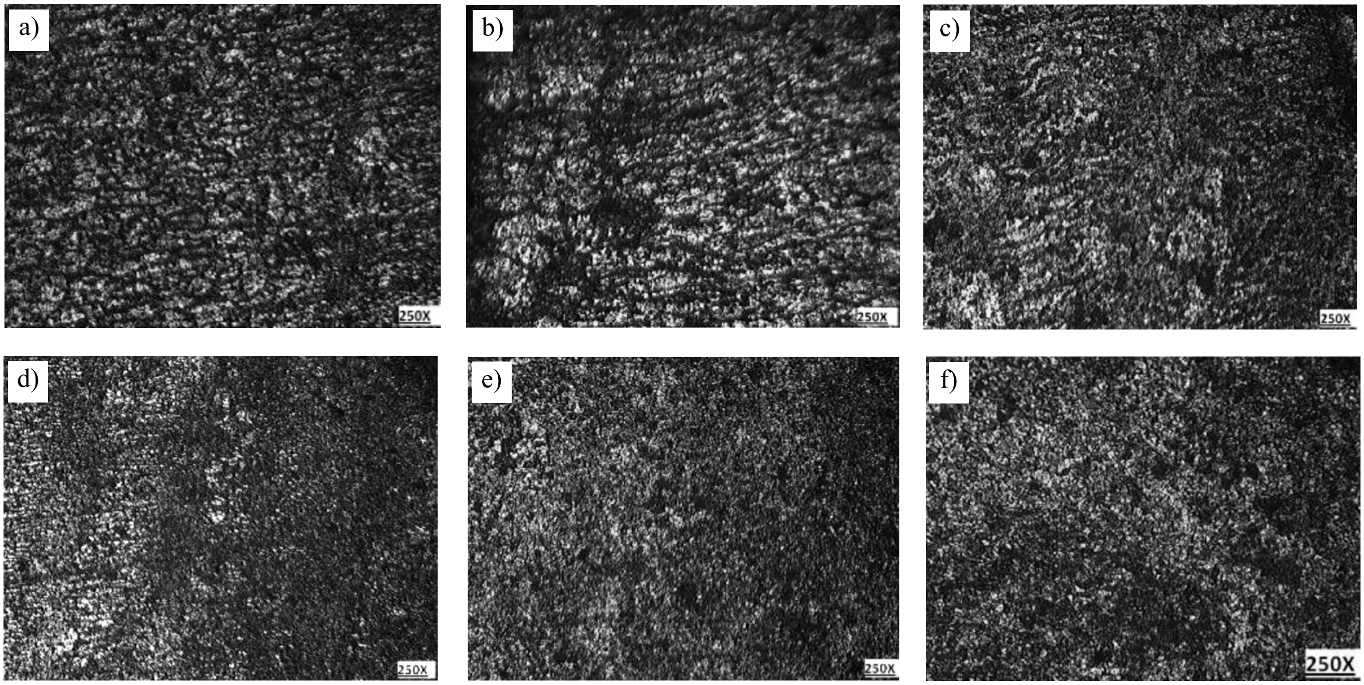
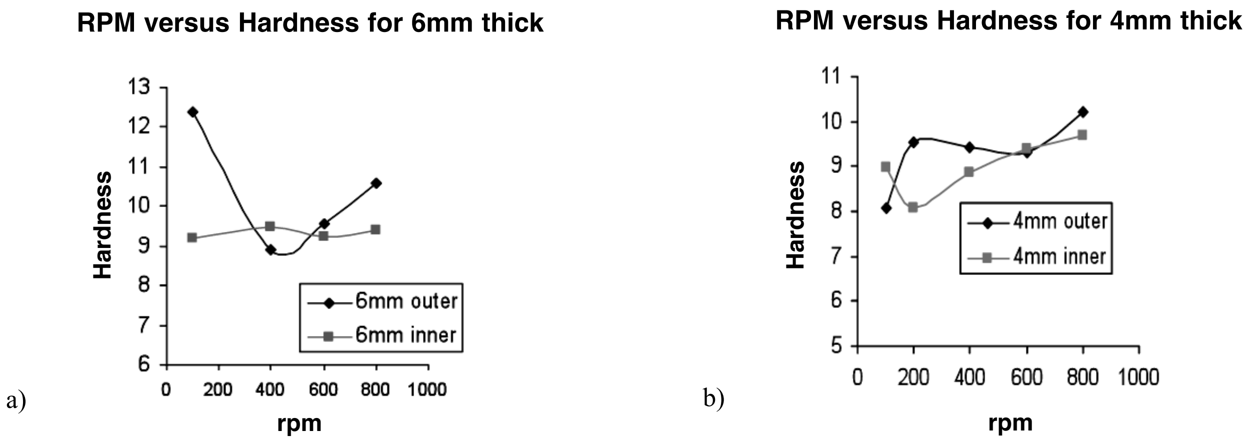
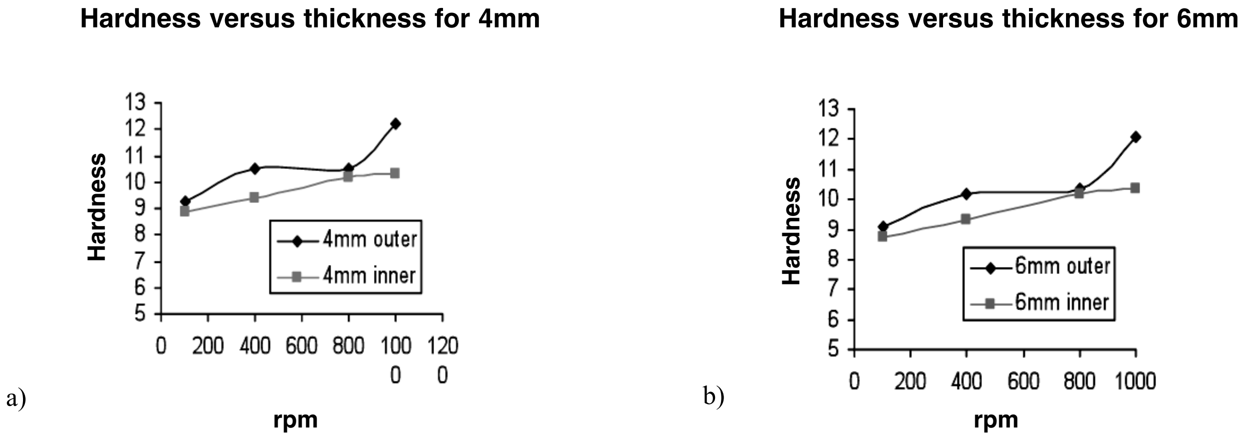


Fig. 10. Microstructure of 6 mm thick tin melted at 350 °C at a) 600 rpm inner surface, b) 600 rpm middle surface, c) 600 rpm outer surface, d) 800 rpm inner surface, e) 800 rpm middle surface and f) 800 rpm outer surface.



a) b)

Fig. 11. rpm versus hardness at a pouring temperature of 450 °C at a) 4 mm thick and b) 6 mm thick.



a) b)

Fig. 12. rpm versus hardness at pouring temperature of 350 °C at a) 4 mm thick and b) 6 mm thick.

CONCLUSIONS

The tin centrifugal castings were made at different rotating speeds and for different wall thicknesses of castings. From the above, the following points can be assumed:

1. For a 2 mm thickness, a casting cannot be prepared due to low volume fraction because of high solidification rate of the molten metal.
2. For 4 mm, 6 mm and 8 mm thicknesses, it is seen that at lower rpm, the Couette flow, Ekmann flow and Taylor flow will be prevalent leading to castings with an irregular inner surface. If the mould is rotated at 600 rpm for given dimensions, a uniform hollow casting will be obtained.
3. 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 600 rpm a fine equiaxed structure was seen at the outer and inner zones of the casting.

The BHN was found to be same at optimized speed and varied at different speeds.

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REFERENCES

1. Y. Jaluria, "Fluid Flow Phenomena in Materials Processing- The 2000 Freeman Scholar Lecturer", *J. Fluid Engineering,* June 2001, vol. 123, pp. 173-210.
2. G. Bergeles, J. Anagnostopoulos, "Three Dimensional Modelling of the Flow and the Interface Surface in a Continuous Casting Mold Model", *Metallurgical and Materials Transaction B*, December 1999, vol.30B, pp. 1095-1105.

3. N. Janco, “Centrifugal Casting”, *American Foundry Men’s Society*, 1988.
4. B.G. Thomas, R.M. McDavid, “Flow and Thermal Behaviour of the Top Surface Flux/Powder Layers in Continuous Casting Molds”, *Metallurgical and Materials Transactions B*, August 1996, vol. 27B, pp. 672-685.
5. H. Fredriksson, C.M. Raihle, “In the Formation of Pipes and Centreline Segregates in Continuously Cast Billets”, *Metallurgical and Materials Transactions B*, February 1994, vol. 25B, pp. 123-133.
6. I.V. Samarasekera and J.K. Brimacombe, *Canadian Metallurgical Quarterly*, 1979, vol. 18(3), pp. 251-266.
7. I.V. Samarasekera, J.K. Brimacombe, R. Bommaraju, “Mould Behaviour and Solidification in the Continuous Casting of Steel Billets”, *ISS Transaction*, 1984, vol. 5, pp. 71-77.
8. R.B. Mahapatra1, J.K. Brimacombe, I.V. Samarasekera, N. Walker, E.A. Paterson and J.D. Young, “Mold Behaviour and Its Influence on Quality in the Continuous Casting of Steel Slabs: Part 1. Industrial Trials, Mold Temperature Measurements and Mathematical Modelling”, *Metallurgical Transactions B*, December 1991, vol. 22B, pp. 861-874.
9. Wu Shi Ping, Liu Dong Ronga, Guo Jing Jiea, Li Chang Yuna, Su Yan Qinga and Fu Heng Zhia, “Numerical Simulation of Microstructure Evolution of TI-6Al-4V Alloy in Vertical Centrifugal Casting”, *Material Science and Engineering A*, 2006, vol. 426, pp. 240-249.
10. S.R Chang, “Numerical Simulation of Microstructure Evolution of Al Alloys in Centrifugal Casting”, *ISIJ International*, 2001, vol. 41(7), pp. 738-747.
11. Mukunda Porakattu Gopal, Srikantha Rao Sasihitlu, Kiran Aithal Subbanna, Shailesh Rao Agari, “An Understanding of Fluid Behaviour in Centrifugal Casting”, AFI/TFI-2007, Commemoration of the 100th Anniversary of Tohoku University, December 14-15, 2007, Sendai, Miyagi, Japan..
12. S.T. Thoroddsen and L. Mahadevan, “Experimental Study of Coating Flow in a Partially Filled Rotating Cylinder”, *Experiments in Fluids*, 1997, vol. 23, pp. 1-13.
13. S.K. Wilson, R. Hunt and B.R. Duffy, “On the Critical Solutions in Coating and Rimming Flow on a Uniformly Rotating Horizontal Cylinder”, *J. Mech. Appl. Math*, 2002, vol. 55(3), pp. 357-383.
14. J.M. Lopez, F. Marques, A.H. Hirsa and R. Miraghaie, “Symmetry Breaking in Free Surface Cylinder Flows”, *J. Fluid Mech.*, 2004, vol. 502, pp. 99-126.
15. R.F Gans, G. Zupanski, “Generation of Vortices in a Partially Filled, Rapidly Rotating Cylinder”, *Experiments in Fluids*, 1988, vol. 6, pp. 279-282.
16. Shailesh Rao A, P.G. Mukunda and Shrikantha S Rao, “Experimental Studies of Flow Patterns of Different Fluids in a Partially Filled Rotating Cylinder”, *J. Applied Fluid Mechanics*, 2009, vol. 2(1), pp. 47-51.