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Formation of a graphite-rich zone in centrifugally cast copper alloy graphite composites

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The formation of the graphite-rich zone in centrifugally cast copper alloy containing originally 7 and 13 vol % graphite particles, cast at 800 and 1900 r.p.m. was studied as a function of the rotational speed of the mould and the volume fraction of graphite particles. The calculated recovery of graphite particles in copper alloys was found to be around 99% and 95%, for 7 and 13 vol % graphite particles originally added to the melts, respectively. The ratio of the thickness of graphite-rich zone to the casting thickness was observed to increase with increasing volume fraction of graphite particles and with decreasing rotational speed of the mould. These ratios were found to be between 0.56 and 0.76 for centrifugal casting of copper alloy containing 7 and 13 vol % graphite particles, respectively, cast at 800 r.p.m.; the corresponding ratios were between 0.42 and 0.71, respectively, for the alloys cast at 1900 r.p.m. The ratio of the thickness of the graphite-rich zone to the casting thickness has been discussed in terms of the velocity of the particle and the solid/liquid interface.

1. Introduction

The stir-casting technique, involving mixing of particles in the melt prior to solidification, has been widely used for solidification synthesis of cast metal-matrix composites, due to its simplicity. However, this technique has several problems: (i) a frequently observed poor wetting of ceramic particles by the melt, requiring external forces to introduce the particles into the melt, (ii) the flotation or sedimentation of particles in the melt due to the density difference between the particle and the melt [1, 2], (iii) the segregation of particles in the last-freezing interdendrite regions, due to the rejection of the particles by the solidifying interface. However, unlike in gravity casting the centrifugal casting technique of melts containing suspended particles leads to the segregation of particles in the inner periphery or the outer periphery of the centrifugal casting, depending on the density difference between the particles and the melt. This centrifugal casting provides selective reinforcement as a result of segregation of the particles to the inner or outer periphery of the centrifugal casting [3]. It therefore presents an ideal technique to produce components such as cylindrical bearings, where tribological surfaces, are required only at the inner surfaces of cylinders. In fact, the concentration of particles to the inner periphery for bearing-type applications leads to other benefits, including reduced requirements of the dispersoid compared to castings where the particles are uniformly distributed. In addition, the outer periphery of the casting remains free from dispersoids, leaving their properties intact.

Surey and Lajoy [4] showed that the concentration of SiC particle near the outer periphery of a centrifugal casting of an aluminium alloy containing SiC particles, increases with increasing rotational speed of the mould. Recently, Kang and Rohatgi [5] numerically calculated the variation of the volume fraction of the particle in the particle-rich zones, and the movement of the solid/liquid interface in the cylindrical casting of aluminium and copper alloys containing SiC, alumina, and graphite particles. Rohatgi *et al.* [6] used a centrifugal casting technique to concentrate graphite particles near the inner periphery of cylindrical castings of copper alloys, which can be applicable for producing bearing and cylindrical plumbing components which require machinability only on the inside periphery. They also showed that the segregation of the graphite particles near the inner periphery reduces the friction coefficient and the wear rate at the inner periphery, as compared to the graphite-free outer periphery.

The tribological properties of centrifugal castings in the particle-rich zone are affected by the microstructure and the thickness of the particle-rich zone of a centrifugal casting. Parameters, including the properties of the particle and the melt, the melt temperature, the mould temperature and the rotational speed of the mould, influence the microstructure and the thickness of the particle-rich zone of the centrifugal casting. Therefore, the relationship between the microstructure of the particle-rich zone and the processing parameters must be understood to obtain a particle-rich zone which provides optimum properties.

In addition, the cooling rate, which influences the velocity of the solid/liquid interface growing from the outer mould, affects the thickness and the microstructure of the graphite-rich zone of centrifugal castings. Generally, in metallic systems, the thickness of the particle-rich zone was calculated using a modified Stoke velocity, including the effect of the particle volume fraction on the viscosity of the melt [7]. This equation is obtained using the force balance between the centrifugal force and the drag force acting on a single particle. For this equation to be applicable to the multiparticle system in the melt, the viscosity of the melt, depending on the particle volume fraction, is incorporated into the equation. Therefore, the more reliable terminal velocity of the particle under the centrifugal force, depending on the volume fraction of the particle, is required to predict the thickness of the particle-rich zone.

In this study, centrifugal castings of C90300 copper alloys containing relatively high volume fractions of graphite particles, namely, 7 and 13 vol %, were cast at 800 and 1900 r.p.m., respectively. The recovery of graphite particle has been calculated. Also, the terminal velocity of the particle under the influence of centrifugal forces was obtained analytically, depending on the particle volume fraction and the rotational speed of the mould. Based on this, the formation of the graphite-rich zone has been discussed according to the solid/liquid inferface velocity.

2. Experimental procedure

C90300 copper alloy was melted in a graphite crucible using an induction furnace. 5 μm graphite particles and 1.5 wt % Ti (used as wetting agent) were mixed into the copper alloy to synthesize copper alloy melts containing 7 and 13 vol % graphite particles. The mould inserted in the horizontal centrifugal casting machine was preheated at 200 °C. At the melt temperature of 1050 °C, the molten copper alloy was poured into the horizontal centrifugal casting machine to cast cylinders of copper alloy originally containing an average of 7 vol % (2 wt %) and 13 vol % (3.6 wt %) graphite particles. The copper alloy containing 7 vol % graphite particles represents melts in which 7 vol % graphite particles were added, and the copper alloy containing 13 vol % graphite particles represents the melts in which 13 vol % graphite particles was added. The outer diameter of the cylindrical castings was 9.5 cm, the wall thickness was 1.5 cm and the speeds of rotation were 800 and 1900 r.p.m. The length of the casting was 13 cm.

Microstructural observations were made in the graphite-rich zone and in the graphite-free zone of centrifugal castings. Chemical analysis of different parts of the castings was done to evaluate the distribution of the graphite particles according to ASTM 665 (1996).

3. Calculation of the particle-rich zone

A particle subjected to centrifugal forces in the melt moves to either the outer or the inner periphery, depending on the density difference between the particle and that of the melt. Particles lighter than the liquid are segregated in the inner periphery, and particles heavier than the liquid move to the outer periphery. Generally, the terminal velocity of the particle under centrifugal forces can be obtained using the modified Stoke velocity [7]

$$V_s = \frac{r\omega^2 \Delta\rho d_p^2}{18\mu_c} \quad (1a)$$

where [8]

$$\mu_c = \mu(1 + 25V_p + 10.05V_p^2) \quad (1b)$$

and r is the distance between the particle and the centre of the mould, ω is the angular velocity, $\Delta\rho$ is the density difference between the particle and the melt, d_p is the diameter of the particle, μ_c is the viscosity of the melt containing particles, and μ is the viscosity of the monolithic melt. As can be seen from Equation 1a, the terminal velocity is obtained using the force balance between the centrifugal force and the drag force acting on a single particle. The presence of several particles in the melt leads to a decrease in the individual particle velocity due to an interaction between particles. To overcome the effect of the particle volume fraction, the terminal velocity of the particle, depending on the particle volume fraction, has been obtained by incorporating the viscosity term, which depends on the particle volume fraction, as can be seen from Equation 1a.

In this study, because the particles which were originally distributed uniformly in the melt, are moved to the inner periphery due to centrifugal force, the terminal velocity of the particle is obtained using the force balance between the centrifugal force and the drag force acting on the particle. Fig. 1 shows a schematic representation of the system of centrifugal casting. In this study, to simplify the problem of the movement of graphite particle in the copper melt under the influence of the centrifugal forces, we neglect the following: (i) the deviation from sphericity in the shape of the particle; (ii) particle agglomeration; (iii) the wall effect; (iv) the pressure due to the neighbouring particle; (v) the variation in the particle size; and (vi) the non-steady state movement of the particle.

Because the copper melt containing graphite particles is incompressible, the particle moving to the inner periphery at the interface between the particle-free zone and the particle-rich zone leads to the flux of the liquid to the outer periphery, depending on the volume fraction of the particles incorporated. The mass balance due to the movement of the particles in the melt is given by

$$\frac{1}{r}\frac{\partial(V_{p,r}\varepsilon_p + V_{l,r}\varepsilon_r)}{\partial r} = 0 \quad (2)$$

where ε_p the volume fraction of the particle, ε_l is the volume fraction of the liquid, V is the velocity, p and l denotes the particle and the liquid, respectively. On the other hand, the movement of the particle under centrifugal forces leads to a drag force on the particle. The force balance between the centrifugal force and

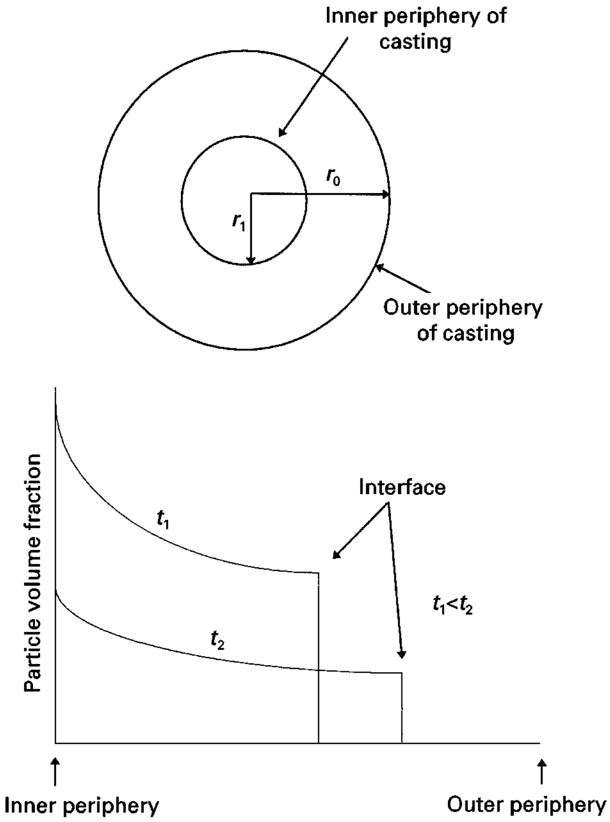

Figure 1 Schematic representation of the movement of the interface between the particle-free zone and the particle-rich zone under centrifugal force.

the drag force under the steady-state condition is given by

$$\varepsilon_p r\omega^2(\rho_p - \rho_l) = F_D \tag{3}$$

where ω is the angular velocity, ρ is the density, r is the radial distance, and F_D is the drag force.

The drag force acting on the particle in the liquid can be written as [9]

$$F_D = \frac{3}{4} C_D \frac{\varepsilon_p(1-\varepsilon_p)\rho_l(V_p - V_l)^2 f(\varepsilon)}{d_p} \tag{4}$$

where d_p is the diameter of the particle, C_D is the drag coefficient, and $f(\varepsilon) = (1-\varepsilon_p)^{-2.65}$ is an interaction term due to the presence of the particles. Equation 3 gives the centrifugal force acting on the particle moving under the influence of the centrifugal casting. This is equal to the drag force in the absence of acceleration. In this analysis, Equation 4 is assumed to be the drag force acting on the particle moving under the influence of centrifugal forces; because no rigorous expression is available for the drag force under centrifugal forces, we have used the equation available for drag force under gravity conditions (Equation 4) to calculate the drag force under centrifugal forces. It can be noted from Equation 4 that factors, such as the particle size, volume fraction of the particle, density of the melt, velocity of the particle and the melt, and the drag coefficient, influence the movement of the particle under the centrifugal force.

Generally, it is assumed that the movement of the particle under the centrifugal force generates not the turbulence on the surface of the particle, but the creeping flow. Under creeping flow, $C_D = 6d_p/\rho_l(1-\varepsilon_p)$ in Equation 4 [9]. Therefore, Equation 4 can be reduced to

$$F_D = \frac{18\mu\varepsilon_p(1-\varepsilon_p)^{-2.65}(V_p - V_l)}{d_p^2} \tag{5}$$

From Equations 2, 3 and 5, the velocity of the particle can be given by

$$V_p = \frac{r\omega^2(\rho_p - \rho_l)d_p^2(1-\varepsilon_p)^{3.65}}{18\mu} \tag{6}$$

Equation 6 shows that the velocity of the particle in a melt containing a given volume fraction of particles, moving under centrifugal force, depends on the properties of the melt and the particle, as well as the rotational speed of the mould. Also, it can be noted from Equation 6 that the particle velocity decreases with increasing particle concentration, due to the interaction between the particles in the melt.

When the particle moves toward the inner periphery, integration of Equation 6 yields the travel distance of the particle under centrifugal forces

$$r = r_o \exp\left(-\frac{(1-\varepsilon_p)^{3.65}\omega^2(\rho_p - \rho_l)d_p^2}{18\mu}t\right) \tag{7}$$

where r_o is the outer diameter of the centrifugal casting.

Equation 7 shows that the thickness of the graphite-rich zone varies with time due to the movement of the solid/liquid interface. The thickness of the graphite-rich zone is found to be $(r - r_i)$ and the casting thickness is $(r_o - r_i)$. Therefore, the ratio of the thickness of the particle-rich zone to the casting thickness, X, can be expressed as

$$X = \exp\left[-\frac{(1-\varepsilon_p)^{3.65}\omega^2(\rho_p - \rho_l)d_p^2}{18\mu}t\right] - \frac{r_i}{r_o}\left(1 - \frac{r_i}{r_o}\right)^{-1} \tag{8}$$

where r_i is the inner diameter of the centrifugal casting.

As can be seen from Fig. 1, the volume fraction of the particle at the interface changes with time. At the initial time the graphite particles in the melt are assumed to be distributed uniformly. When the particles move to the inner periphery due to centrifugal forces, the volume fraction of the particles in the graphite-rich zone increases. In order to express the variation of the particle volume fraction in the graphite-rich zone with the thickness of the graphite-rich zone, it is assumed that the volume fraction of the particles in the graphite-rich zone is uniform. Under this condition, the ratio of the volume fraction of the particles in the graphite-rich zone to the volume fraction of the particles in the initial melt, can be expressed in terms of the ratio of the cross-section of the centrifugal casting to the cross-section of the graphite-rich zone

$$\frac{\varepsilon_p'}{\varepsilon_p} = \frac{r_o^2 - r_i^2}{r^2 - r_i^2} \tag{9a}$$

TABLE I Thermophysical properties of copper and graphite particles used in this work

Property	Magnitude	Reference
ρ_l	8.24×10^3 (kg m^{-3})	[10]
ρ_p	2.3×10^3 (kg m^{-3})	[11]
μ	4.5×10^{-3} (Pa s)	[10]

and therefore

$$\varepsilon'_p = \varepsilon_p \left[\frac{1 - x^2}{(r/r_0)^2 - x^2} \right] \tag{9b}$$

where $x = r_i/r_o$, ε'_p is the volume fraction of the particle in the graphite-rich zone, and ε_p is the initial volume fraction of the particle in the melt.

Substitution of Equation 9b into Equation 8 yields the ratio of the thickness of the particle-rich zone to the casting thickness, X, depending on the volume fraction of the particle and the rotational speed

$$X = \exp\left[-\frac{(1 - \varepsilon'_p)^{3.65} \omega^2 (\rho_p - \rho_l) d_p^2}{18\mu} t \right] - x(1 - x)^{-1} \tag{10}$$

4. Results and discussion

The microstructure of centrifugally cast copper alloys containing graphite particles was observed, depending on the rotational speed and the volume fraction of graphite particles. The dependence of the thickness of the graphite particle-rich zone, obtained from the terminal velocity of the particle, on the rotational speed and the volume fraction of the graphite particles, was compared to the experimental value. The terminal velocity of the particle and the thickness of the graphite-rich zone in relation to the casting thickness were computed by using the foregoing mathematical model and the value of properties of the copper alloy and graphite particle, as given in Table I.

4.1. Microstructure observations

Graphite particles in a copper melt under a centrifugal force move to the inner periphery due to its lower density than that of the copper melt, leading to the formation of a graphite-rich zone near the inner periphery of the centrifugal casting. Fig. 2 shows the microstructure near the inner periphery of centrifugally cast copper alloy containing 7 vol % graphite particles, cast at 800 r.p.m., indicating that graphite particles are segregated near the inner periphery of the centrifugal casting due to the lower density of the graphite particles compared to that of the copper melt; in addition, the graphite particles appear to be segregated in the interdendritic region due to the pushing of the graphite particle by the solid/liquid interface. The particle-pushing phenomenon has been explained according to the critical interface velocity, below which the particles are pushed by the interface, and above which they are engulfed by the interface. In view of this, it can be inferred from this figure that the graphite particles are pushed by the solid/liquid interface due to its lower velocity than the critical interface velocity. The microstructure also shows the presence of porosity, in addition to the graphite particles.

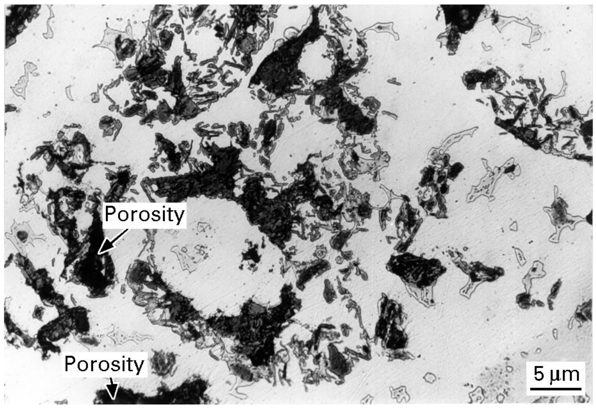

Figure 2 Microstructure near the inner periphery of the centrifugally cast copper alloy containing 7 vol % graphite particles, cast at 800 r.p.m.

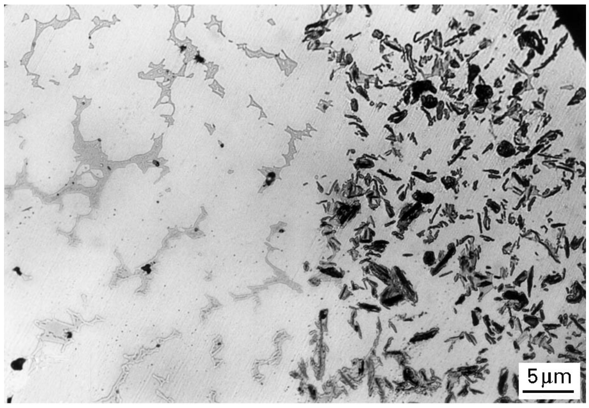

Figure 3 Microstructure near the inner periphery of the centrifugally cast copper alloy containing 7 vol % graphite particles, cast at 800 r.p.m. showing the boundary between the graphite-rich zone and the graphite-free zone.

Fig. 3 shows a boundary between the graphite-rich zone and the graphite-free zone, where graphite particles are segregated at the interdendritic region. Compared to Fig. 2, Fig. 3 shows that the distribution of the graphite particle is more uniform and the dendrite arm spacing near the inner periphery is smaller. This indicates that, as dendrite arm spacing is smaller, the particle is more uniformly distributed.

Fig. 4 shows the result of the chemical analysis of two copper alloys containing graphite particles from the inner periphery to the boundary near the graphite-free zone. Fig. 4a, for the alloy containing 13 vol % (3.6 wt %) graphite particles, shows that the graphite particles have concentrated near the inner periphery to an average of 19.3 vol % (5.44 wt %) graphite particles. Fig. 4b, for the alloy containing 7 vol % (2 wt %) graphite particles, shows that the graphite concentration averaged 13 vol % (3.6 wt %) graphite particles near the inner periphery. From Fig. 4a and b, it can be noted that, as the volume fraction of the

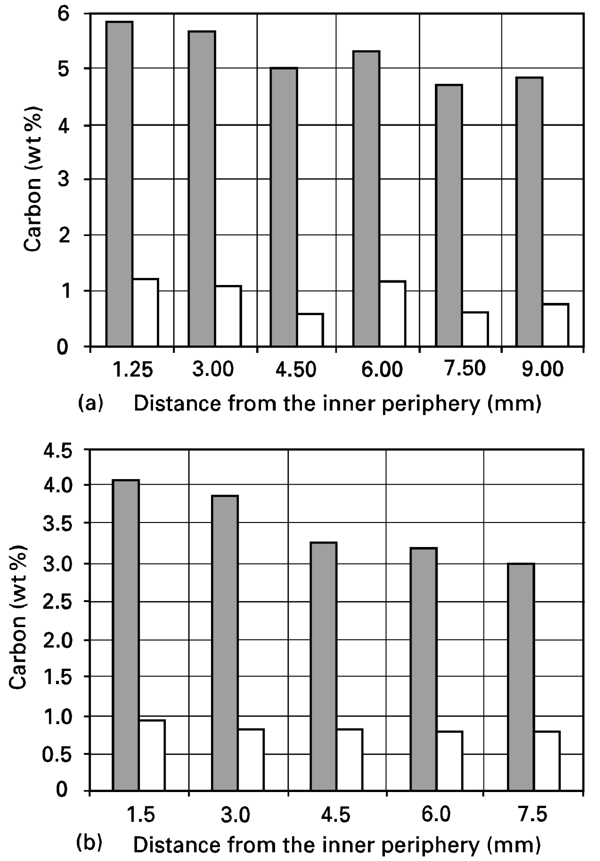

Figure 4 Distribution of graphite particles in a centrifugal casting of C90300 alloy containing (a) 13 vol %, and (b) 7 vol % graphite, cast at 800 r.p.m. (■) total carbon (□) combined carbon.

graphite particles in the starting melt increases, the volume per cent of the graphite particles segregated near the inner periphery, increases.

Microstructural observations of the graphite-rich zone of centrifugally cast copper alloy originally containing 7 vol % graphite particles, cast at 800 r.p.m., show the segregation of the graphite particles near the inner periphery due to the lower density of the graphite particles than that of the copper melt, and the agglomeration of graphite particles at the interdendrite region, as can be seen from Fig. 2.

During synthesis of composites, all the particles added to the melt were not recovered in the castings. During mixing or pouring of the molten copper melt containing graphite particles into the mould, particles are lost, leading to a decrease in the recovery of the particles. In this study, titanium was used as a wetting agent to improve the recovery of graphite particles, because TiC formed on the surface of the graphite particle is wet-table by liquid copper. The recovery of graphite particles in the centrifugal casting is calculated by dividing the graphite volume fraction in the graphite-rich zone, which is converted to that at the initial surface area of the centrifugal casting by the originally added graphite particles into the copper melt

$$\text{recovery} = \frac{\varepsilon_p'}{\varepsilon_p} = \left[\frac{(r_t/r_o)^2 - x^2}{1 - x^2}\right] \quad (11)$$

where ε_p is the volume fraction of the particle added initially into the melt and r_t is the thickness of the particle-rich zone. ε_p' is estimated by measuring the average volume fraction of the particle at the particle-rich zone. As a result, the recovery of the graphite particles is 97% and 95%, for the copper alloys originally containing 7 and 13 vol % graphite particle, cast at 800 r.p.m., respectively.

4.2. The formation and thickness of the graphite-rich zone in centrifugal casting of a copper alloy

As mentioned earlier, the thickness of the graphite-rich zone in centrifugal casting of a copper alloy is important in terms of the tribological applications. The thickness of the graphite-rich zone depends on the velocity of the solid/liquid interface and the particle. As the rotational speed of the stirrer increases, the velocity of the particle increases due to the higher centrifugal force applied to the particle, and also as the volume fraction of graphite particle increases, the velocity of the particle under the centrifugal forces decreases, due to an increase in the interaction between particles. In this study the rotational speed of the mould and the volume fraction of the particle are variables in the terminal velocity of the graphite particle in the copper melt.

Table II shows the ratio of the thickness of the graphite-rich zone to the casting thickness for the copper alloys originally containing 7 and 13 vol % graphite particles, cast at 800 and 1900 r.p.m. This table shows that an increase in the graphite volume per cent increases the ratio of the thickness of the graphite-rich zone to the casting thickness. In addition, an increase in rotational speed decreases the ratio of the thickness of the graphite-rich zone to the casting thickness. This is due to the fact that an increase in the rotational speed of the mould increases the centrifugal forces acting on the particle, resulting in an increase in the terminal velocity of the particle and a narrow graphite-rich zone. The increase in velocity probably overrides the influence of the increase in speed of rotation on decreasing solidification time. The increase in the particle volume fraction decreases the particle velocity, due to an increase in hindrance between particles, leading to a thicker graphite-rich zone; this effect probably overrides any influence of the increase in graphite volume fraction on the solidification time.

TABLE II Ratio of the thickness of the graphite-rich zone to the total thickness of the centrifugally cast cylinder

Graphite volume per cent (%)	Rotational speed (r.p.m.)	X[a]
7	800	0.56
	1900	0.42
13	800	0.76
	1900	0.71

[a] X = thickness of the graphite-rich zone/total thickness of centrifugally cast cylinder.

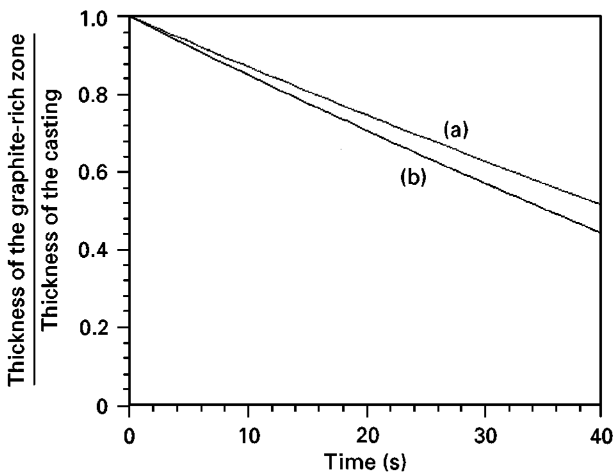

Figure 5 Variation of the ratio of the thickness of the graphite-rich zone to the thickness of the casting with time at the rotational speed of 800 r.p.m. (a) 13 vol %, and (b) 7 vol %.

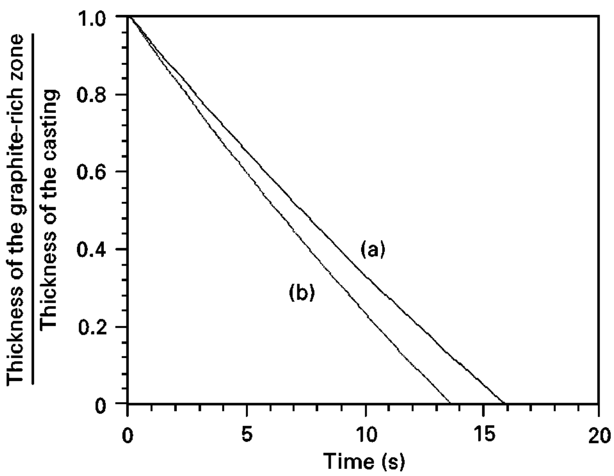

Figure 6 Variation of the ratio of the thickness of the graphite-rich zone to the thickness of the casting with time at the rotational speed of 1900 r.p.m. (a) 13 vol %, and (b) 7 vol %.

Figs 5 and 6 show the computed variation of the ratio of the thickness of the graphite-rich zone to the thickness of the casting with centrifuging time at the mould rotational speeds of 800 and 1900 r.p.m., respectively. These figures essentially calculate the progressive build up of the graphite-rich zone as a function of time of centrifuging. It is seen that X (the ratio of the thickness of the graphite-rich zone to the thickness of the casting) decreases with centrifuging time due to the movement of the graphite particles to the inner periphery of the centrifugal casting. Figs 5 and 6 also show that the value of X increases with the volume fraction of the graphite particles, due to hindrance of the movement of graphite particles. The time at which the calculated thickness of the graphite-rich zone becomes equal to the experimentally measured value of the graphite-rich zone can be obtained from Figs 5 and 6 (at the rotational speed of the mould of 800 and 1900 r.p.m. for 7 and 13 vol % graphite), and these are shown in Table III. This table gives an estimate of the time period for which the graphite particles were able to move to the outer limit of the graphite-rich zone during centrifuging; this time appears to decrease with increasing speed of rotation and with decreasing volume fraction of graphite particles.

TABLE III Calculated time for the solid/liquid interface to grow from the outer mould to entrap the particle

Graphite volume per cent (%)	Rotational speed (r.p.m.)	X	t^a (s)
7	800	0.56	35
	1900	0.42	8.9
13	800	0.76	15
	1900	0.71	3.5

[a] t is the time at which the calculated thickness of the graphite-rich zone becomes equal to the experimentally measured value of the graphite-rich zone obtained using Equation 10.

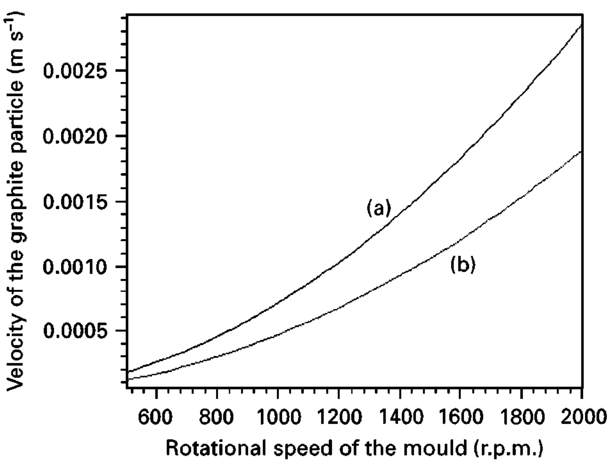

Figure 7 Variation of the velocity of the graphite particles with the rotational speed of the mould: (a) 7 vol %, and (b) 13 vol %.

The thickness of the graphite-rich region will also depend on the velocity of the solid/liquid interface if the velocity is above the critical limits to catch up with the moving particles, and above the critical velocity to entrap the particles. When the velocity of the solid/liquid interface is much lower compared to the particle velocity, as appears to be the case under the present experimental conditions, the thickness of the particle-rich zone is mainly affected by the terminal velocity of the particles. Kang and Rohatgi [5] reported that the numerically calculated velocity of the interface moving from the outer periphery in the copper alloy melt under the centrifugal forces is around 1.5×10^{-4} m s^{-1} at 1750 r.p.m. This velocity is much lower than the terminal velocity of the graphite particles in the melt at 800 and 1900 r.p.m., as can be seen from Fig. 7. As the rotational speed increases, the heat-transfer coefficient would increase, and therefore tend to decrease the solidification time. However, it is difficult to estimate the variation of the solidification rate with the rotational speed of the mould due to the lack of data on the dependence of the heat-transfer coefficient on the rotational speed. This could tend to increase the thickness of the graphite-rich zone with rotational speed if the thermal effects override the effects of increases in terminal velocity with speed, which apparently is not the situation in the present study. When the velocity of the solid/liquid interface is high enough to catch up with the particles moving towards the inner periphery in the liquid melt and to entrap the particles, the thickness of the particle-rich zone will be more dependent on the velocity of the solid/liquid interface rather than the terminal velocity of the particle in the melt. However, in our experiments, the observation that the graphite-rich zone decreases with increasing rotational speed, suggests that the effect of an increase in the thickness of the graphite-rich zone with rotational speed overrides the increase in heat transfer and decreased solidification time due to increased rotational speed. Therefore, in the present experimental conditions, the thickness of the graphite-rich zone is mainly controlled by the terminal velocity of the graphite particles. The presence of the graphite particles in the interdendritic regions in the graphite-rich zones (Fig. 3) suggests that the solidification front velocities in that region were lower than the critical solid/liquid interface velocity necessary to entrap the particles.

5. Conclusions

1. Centrifugal castings (o.d. 9.5 cm × i.d. 8 cm) of copper alloy originally containing 7 and 13 vol % graphite particles were cast at 800 and 1900 r.p.m. Microstructural observations and chemical analysis show that the content of graphite particles segregated and the amount of porosity was higher near the inner periphery compared to that near the graphite-free zone. Also, the microstructure in the graphite-rich and graphite-free zones indicates that the graphite particles are pushed in the interdendrite regions by the growing α copper dendrite.

2. The recovery of the graphite particles in the copper alloys, calculated based on the content of graphite particles in the graphite-rich zone, was found to be around 99% and 95%, for cases when 7 and 13 vol % graphite particles were originally added to the melt, respectively, before centrifugal casting.

3. Under the present experimental conditions, the velocity of the graphite particles appears to be much greater than the calculated velocity of the macroscopic solid/liquid interface moving from the outer periphery to the inner periphery at the two rotational speeds investigated. Therefore, the thickness of the graphite-rich zone is presumably controlled by the terminal velocity of the graphite particles. The terminal velocity of graphite particles increases with rotational speed and decreases with volume fraction. During solidification, the thickness of the graphite-rich zone progressively decreases with centrifuging time.

4. The thickness of the graphite-rich zone was observed (a) to increase with an increase in the original average volume fraction of graphite particles in the melt prior to centrifugal casting, and (b) to increase with decreasing rotational speed of the mould. The ratio of the thickness of the graphite-rich zone to the total casting thickness was found to be between 0.56 and 0.76 for 9 cm o.d. × 8 cm i.d. × 20 cm long centrifugal castings of copper alloy originally containing 7 and 13 vol % graphite particles, cast at 800 r.p.m.; the corresponding ratios were between 0.42 and 0.71 for the alloys cast at 1900 r.p.m. These observations confirm that the thickness of graphite-rich region is primarily controlled by the terminal velocity of the graphite particles in the liquid melt during centrifuging.

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