STRUCTURAL QUALITY OF SQUEEZE CASTINGS OF Al ALLOY AA603 AND AN Al_2O_3-603 Al COMPOSITE

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Abstract

This paper is concerned with macro- and micro-structures that develop during squeeze casting of a hypoeutectic Al-Si alloy (AA603 with about 7% Si and 0.5% Mg) and also a metal matrix composite consisting of the alloy AA603 reinforced with Al_2O_3-based microspheres. Some undesirable structural features were found to occur and these were often related to the fluid flow generated during mould filling and/or by the application of pressure. These features included segregation of eutectic, formation of primary Si crystals and segregation of ceramic microspheres.

1. Introduction

Squeeze casting [1-3] is a forming process, in which molten metal is injected into a die and then squeezed (or pressurised) in the die by a piston (or punch) as it solidifies. It combines casting and forging processes in one operation and is capable of producing castings of high structural integrity and near-net shape finish at a high production rate. It is a particularly important manufacturing process for the automotive industry [4,5].

The present work is concerned with the use of an indirect squeeze casting method. In this method, as schematically illustrated in Fig. 1, the die cavity is filled with molten metal by raising the piston at such a slow speed that no air entrapment nor turbulence at the melt front can occur (Fig. 1(a)) and then, when a layer of solid is formed around the casting, a pressure is applied by squeezing the casting with the piston (Fig. 1(b)). The pressure is exerted by the piston directly on the biscuit and is transferred to the component part of the casting via a runner. This casting mode has appreciable versatility in the component shape although the necessity of having the biscuit and runner results in inefficient material usage. The temperature distribution in the die is carefully adjusted so that any incipient porosity is filled by the melt driven by the applied pressure. A desirable solidification sequence is illustrated schematically in Fig. 1, where the biscuit section is maintained at a higher temperature than the remainder of the casting, so that it acts as a reservoir for supplying liquid metal to the component.

The application of pressure is necessary to force the melt into the incipient porosity through complex paths in the interdendritic regions [6] and also for creating an intimate thermal contact between the solidifying casting and the die [7,8]. This good thermal contact leads to a high cooling rate that produces fine microstructures beneficial for the mechanical properties of the casting, e.g.,

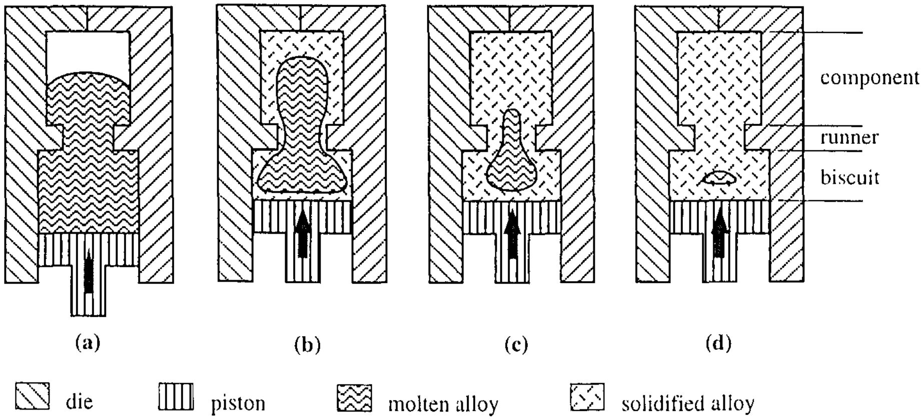

Figure 1. Schematic illustration of mould filling and solidification sequence in the indirect squeeze casting method.

ductility. The application of pressure can also produce certain side effects on the quality of the casting, particularly when the timing of the pressure application and/or the magnitude of the squeeze pressure are not properly optimised. This paper presents a number of macro- and micro-structures observed in squeeze castings of an AA 603 Al alloy and also of a composite which consists of 603 Al alloy reinforced with Al_2O_3-based ceramic particles. These defects were found to be typical of squeeze castings of hypoeutectic Al-Si alloys and were considered to be related to the application of pressure and/or fluid flow generated by the application of pressure.

2. Experimental

The machine used to produce most of the casting samples in the present work was an UBE 250 tonne HVSC squeeze caster. Two different dies were used: one was for casting tensile bars and the other for casting cylinders. The cylinder die was designed to have a simple geometry that would avoid any problem arising from die filling. The two materials that were cast were the hypoeutectic Al-Si alloy AA603 containing about 7% of Si and 0.5% Mg, and a Comral 90F™ metal matrix composite developed by Comalco Research Centre, Australia [9]. Comral 90F composite consists of the alloy AA603 reinforced with Al_2O_3-based ceramic microspheres. The average diameter of the spheres was about 20 μm and the volume fraction of these spheres in the composite was approximately 20%. During the preparation of the composite by means of liquid metal technology, the microspheres had interacted with the alloy and formed a layer of spinel ($MgAl_2O_4$) [10] that enabled the spheres to be wetted with the melt and created a strong bond between the spheres and metal matrix after the melt solidified. The tensile bar samples of Comral 90F composite used in this study were cast on an UBE 350 tonne HVSC squeeze caster and provided by Comalco Research Centre.

3. Results and Discussion

3.1. Al cell size and coarseness of eutectic Si

In order to determine the influence of pressure on the solidification of AA603 alloy, the examination of the cell size of Al dendrites and the morphology of eutectic Si particles was carried out in regions close to the top of the cylindrical castings. These regions solidified soon after the mould had been filled and suffered less influence from fluid flow generated by the application of pressure in a late stage of solidification. Figure 2 shows optical micrographs taken respectively from the surface and central regions of two castings, in which the applied pressure was 29 and 88

MPa respectively. These two pressures were close to the lower and upper limit of the UBE 250 tonne HVSC squeeze casting machine. It appeared that the change of pressure from 29 to 88 made no significant difference to the microstructure. The Al dendrites were finer near the surface than in the central region and fibre-like Si crystals in the eutectic could be seen in the central region, while near the surface they were too fine to be resolved by optical microscopy. The morphological changes of the microstructure from the surface to the centre could be attributed to the fact that the cooling rate was higher near the surface than in the centre. A typical result of dendrite cell measurements across the diameter of these cylindrical castings is plotted in Fig. 3. The cell size was about 4 μm near the surface and about 17 μm in the centre. It seemed that, for the cylindrical castings, the pressure of 29 MPa was high enough to create an intimate contact between the casting and mould wall since a further increase in pressure did not make any appreciable change to the cell size.

3.2. Shrinkage porosity and centre-line segregation

Elongated shrinkage pores (or shrinkage pipes) were frequently found near the axial region and close to the biscuit in the cylindrical castings which had short biscuits (i.e., a small amount of metal left in the biscuit part after the mould was filled). Figure 4 shows photographs taken from two castings of the alloy AA603 squeezed at 50 MPa (a) and 82 MPa (b) respectively. Note that from Fig. 4 to Fig. 6, "M.P." indicates the photograph of a sample taken after mechanical polishing, while "M.E." indicates that of a sample after macro-etching. Note also that the macro-etching reveals not only the grain structure but also the eutectic rich regions in dark contrast.

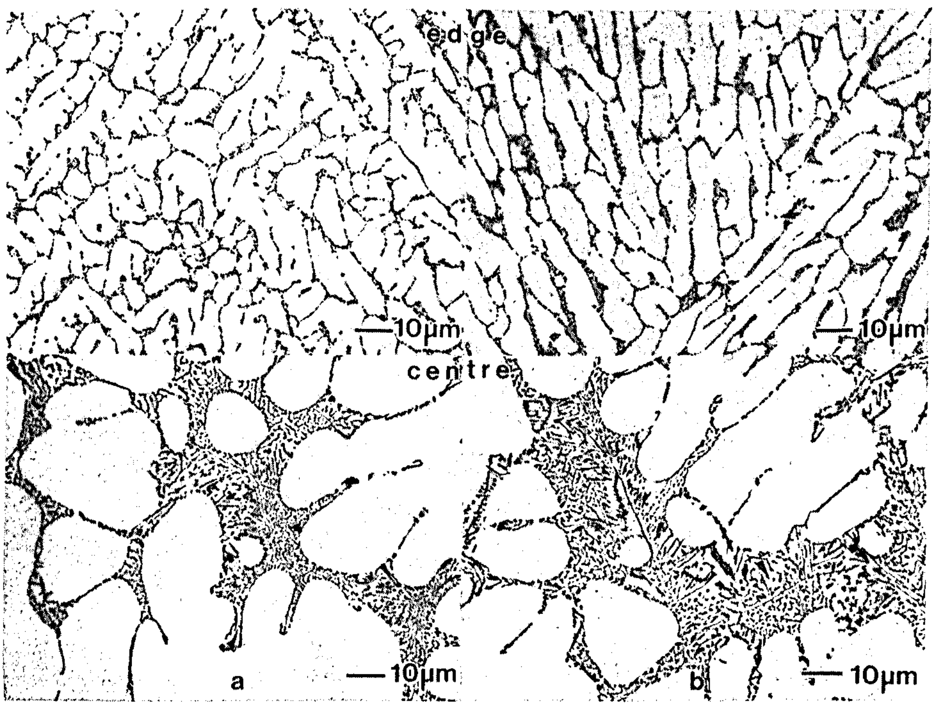

Figure 2. Optical micrographs of two castings of AA603 Al alloy squeezed with pressure of 29 MPa (a) and 88 MPa (b) respectively.

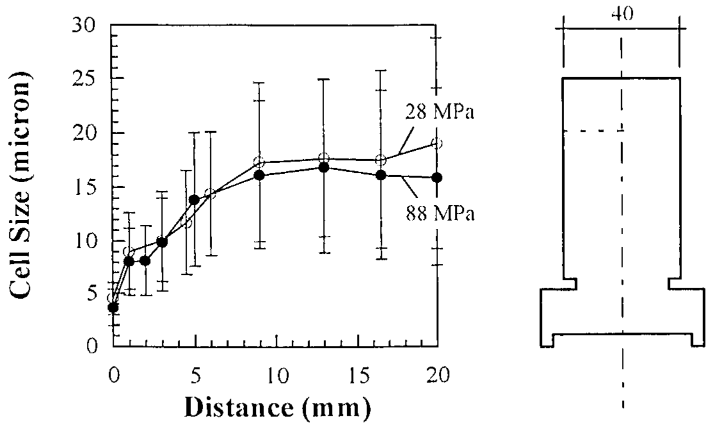

Figure 3. The results of dendrite cell size measurements on two castings squeeze cast at 29 MPa (a) and 88 MPa (b) respectively. The corresponding positions of the measurements are indicated by the horizontal dashed line in the sketch of the casting.

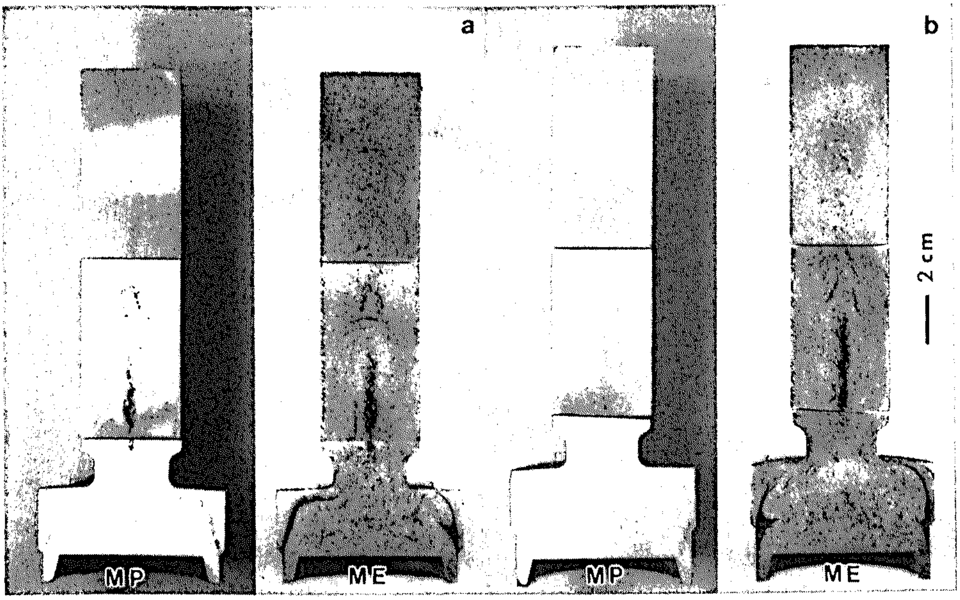

Figure 4. Photographs of two sectioned cylindrical castings of alloy AA603 with short biscuits squeezed at 50 MPa (a) and 82 MPa (b) respectively. "MP" indicates the sectioned surface after mechanical polishing and "ME" is the surface after macro-etching.

As can be seen in Fig. 4, the top part of the castings had good structural integrity, while there were some shrinkage pores in the middle of the cylinders and even a large shrinkage pipe (Fig. 4(a)) in the axial region near the biscuit. For the casting shown in Fig. 4(b), the biscuit contained more metal and the shrinkage pipe appeared to have been almost completely filled with melt rich in silicon.

It seemed that in a late stage of solidification the pressure applied had squeezed the biscuit section of the casting and injected the remaining liquid from the biscuit into the incipient pores in the cylinder section. The concentration of the remaining liquid, particularly in the interdendritic regions, should be rich in silicon, since eutectic solidifies last. It is probable that such remaining liquid had been squeezed out of the biscuit and filled the incipient pores in the axial region of the castings as shown in Fig. 4. The amount of metal in the biscuit of the 82 MPa casting seemed to be large enough to provide the liquid required for filling the porosity almost fully since there was only a small cavity left (Fig. 4(b)), while that of the 50 MPa casting seemed to be so small that only a small portion of the shrinkage pipe was filled by silicon-rich liquid (Fig. 4(a)).

Figure 5 shows photographs of two castings from alloy AA603 which had a large biscuit volume and were squeezed at 29 and 70 MPa respectively. Apart from some fine shrinkage pores in the axial region of the 29 MPa casting, the overall structural quality of these two castings was very good. Centre-line segregation of eutectic can be seen in both castings, but the size of the regions of segregation was smaller than that of the 82 MPa casting shown in Fig. 4(b). This improvement in structural integrity could be attributed to the increase in biscuit volume of these two castings. With a large biscuit volume, a larger amount of melt remained in the biscuit as the solidification of the cylinder was about to finish, and therefore this remaining melt was not as silicon-rich. Transfer of the melt with a lower silicon concentration to the incipient porosity in the cylinder section resulted in a lower overall amount of eutectic segregation.

An interesting effect, shown in Fig. 5, is that an increase in squeezing pressure from 29 to 70 MPa resulted in the elimination of the fine pores, indicated by the arrows for the 29 MPa casting. This observation suggests that during solidification, although the casting is under a certain pressure, the growth of Al dendrites can block the path for the liquid to fill the incipient porosity. This is likely

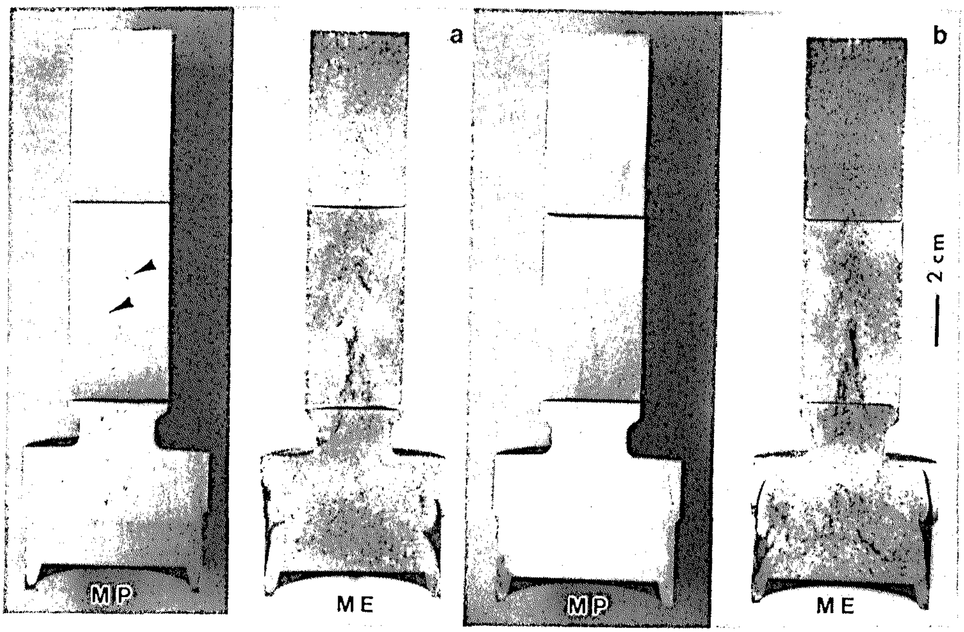

Figure 5. Photographs of two sectioned cylindrical castings of alloy AA603 with long biscuits squeezed at 29 MPa (a) and 70 MPa (b) respectively. "MP": after mechanical polishing, and "ME": after macro-etching. Arrows indicate fine porosity.

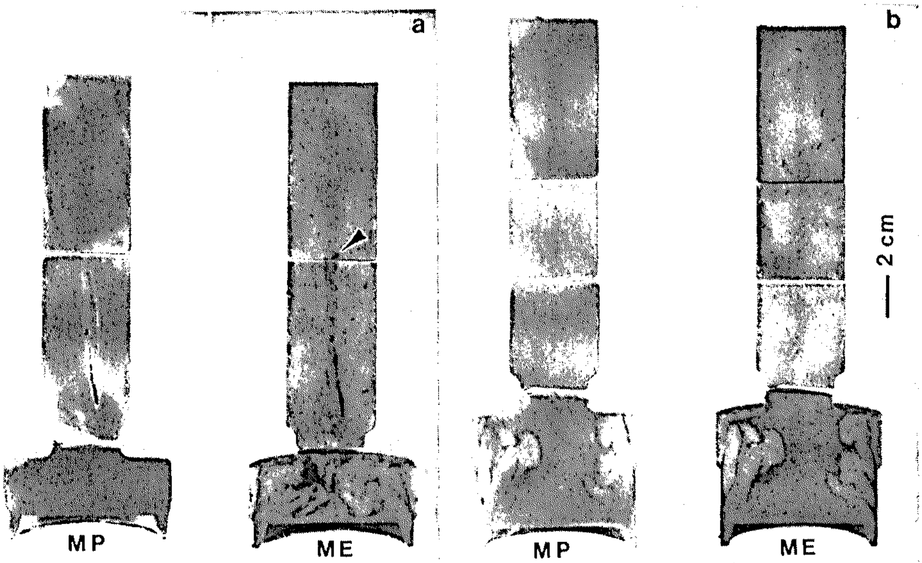

Figure 6. Photographs of two sectioned cylindrical castings of Comral 90F squeezed at 29 MPa (a) and 70 MPa (b) respectively. "MP": after mechanical polishing, and "ME": after macro-etching. Arrow indicates a region with a high density of microspheres.

to occur in the mushy region of the casting when the volume fraction of Al dendrites has reached a certain high level.

Figure 6 shows two cylindrical castings of Comral 90F composite. The casting shown in Fig. 6(a) had a short biscuit associated with a large shrinkage pipe while the other one shown in Fig. 6(b) had a long biscuit and was pore free. The extent of eutectic segregation in these castings was much less than that in AA603 Al-Si alloy (Figs. 4 and 5). As can be seen in Fig. 6(a), the top part of the shrinkage pipe seems to have been filled with remaining melt from the biscuit, but the proportion of eutectic in this region was much less than that in castings of AA603 Al-Si alloy. The difference in the extent of eutectic segregation between Comral 90F composite and AA603 could be explained by the fact that the composite has approximately 20% lower shrinkage than the normal alloy and also lower thermal conductivity. The lower contraction of the alloy generated less pores which had to be filled by the remaining liquid, and the lower thermal conductivity caused the casting to solidify more slowly, and therefore the remaining liquid was not as rich in silicon when the pressure was applied. The lower thermal conductivity of the composite possibly maintained a steeper thermal gradient in the casting when compared to the normal alloy, which could reduce the width of the mushy zone. All of these factors contributed to the lower amount of segregation observed in the castings of the composite.

As indicated by the arrow in Fig. 6(a), a region with a high density of microspheres was found at the top of the shrinkage pipe. The volume fraction of the spheres in this region was about 47%, as determined by an image analyser (Cambridge Instruments Quantimet 570). The average volume fraction elsewhere in the casting was about 26% under the same measurement conditions. It seemed that the spheres had been "filtered out" by the dendrite network as the fluid was displaced by the applied pressure.

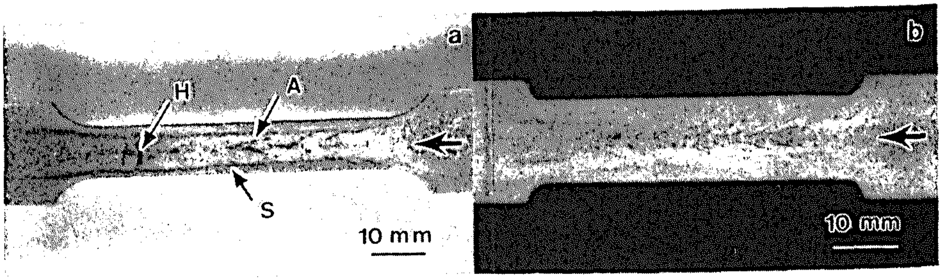

Figure 7. Photographs of sectioned cast tensile bars of alloy AA603 (a) and Comral 90F (b). The arrows indicate the feeding direction. S: slip band segregation; H: horizontal segregation; and A: A segregation.

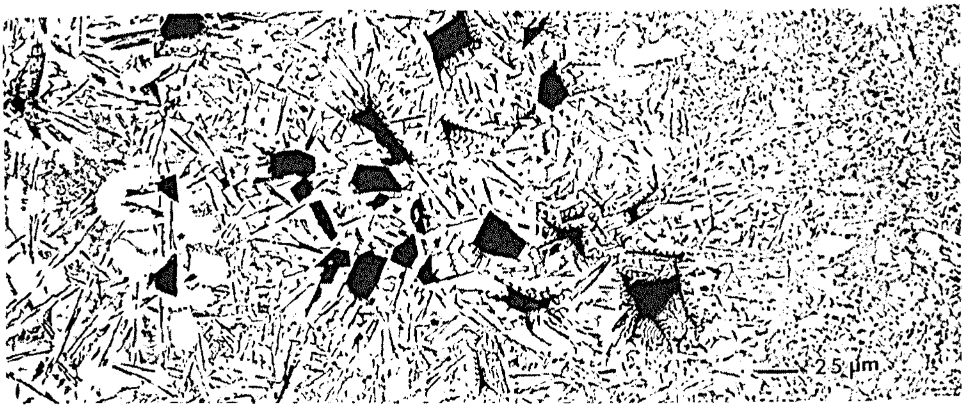

Figure 8. Optical micrograph showing coarse Si crystals found in a cylindrical casting of AA603 squeezed at 82 MPa.

Figure 7 shows two photographs of macro-etched cast tensile bars of alloy AA603 (a) and Comral 90F composite (b). The extent of eutectic segregation appeared to be less in Comral 90F composite than in AA603. Eutectic segregation was found in different patterns as indicated by "S", "H" and "A" in Fig. 7(a). The mechanism for the formation of these eutectic-rich regions is still not well understood. It is believed that the fluid flow generated by application of pressure in the mushy state could have played an important role in the segregation processes.

3.3. Formation of primary Si crystals

Although AA603 is a hypoeutectic Al-Si alloy, large Si crystals (so-called primary Si crystals) have been observed in squeeze castings of this alloy. In the casting shown in Fig. 4(b), many large Si crystals were found at the top of the shrinkage pipe, which was filled with Si rich liquid. A micrograph showing these crystals is presented in Fig. 8. Normally, growth of primary Si crystals is limited by diffusion, and primary crystals cannot appear in a hypo-eutectic alloy. But large silicon crystals have been observed in stir-cast hypo-eutectic Al-Si alloys [11,12], where the fluid flow generated by stirring released eutectic Si particles from the liquid-solid interface into the bulk of the melt where they acted as nuclei for the Si crystals. It is thought that Si atoms rejected from the solidifying alpha-phase increased the Si content of the liquid and thus supported the growth of these free Si nuclei. It is likely that a similar mechanism is responsible for the large Si crystals found in the squeeze cast AA603 alloy. The pressure applied during the solidification could generate significant fluid flow to carry the Si crystals to the top of the shrinkage pipe and enable their growth to a large size by supplying them with sufficient Si atoms.

4. Summary

The structural quality of squeeze castings of AA 603 Al-Si alloy and of Comral 90F MMC has been investigated. It was found that:

* no microstructural changes were observed in cylindrical castings of alloy AA603 as the pressure was varied in the range from 30 to 90 MPa;

* the size of the biscuit was found to be critical for continuous feeding of incipient porosity during the whole solidification period;

* castings of Comral 90F composite suffered less eutectic segregation than those of alloy AA603;

* the segregation of eutectic seemed to be related to the fluid flow driven by the applied pressure; and

* the formation of large Si crystals in AA603 Al-Si hypoeutectic alloy may be associated with the growth of Si crystals in flowing melt.

Acknowledgements

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References

1. J.R. Franklin and A.A. Das, Br. Foundryman, vol. **77**, (1985),150.
2. G. A. Chadwick and T. M. Yue, Metals and Materials, Jan., (1989), 6.
3. J. Doric and S. K. Verma, "Squeeze casting", Metals Handbook, 9th Edition, vol. 15, (ASM, Metals Park, Ohio, 1988), 323.
4. C. B. Cowley, W. R. Thorpe, and B. I. Selling, IMMA Conference: Materials in the Automotive Industry, Melbourne, June 24 - 25, (1992).
5. S. Komatsu, Y. Kanoh, H. Fukube, and H. Manda, SAE Special Publication, n 815, 900009, (1990), 53.
6. Y. W. Lee,.E. Chang, and C. F. Chieu, Metallurgical Trans. B, vol. **21 B**, (1990), 715.
7. G. S. Reddy and J. A. Sekhar, Acta Metall., vol. **37**, (1989), 1509.
8. D. L. Zhang, C. Brindley, and B. Cantor, J. Materials Science, vol. **28**, (1993), 2267.
9. M. J. Couper, and K. Xia, Proc. 12th Risø International Symposium on Materials Science, Roskilde, Denmark (1991).
10. Ji-Yong Yao, G. A. Edwards, M. J. Couper, and G. L. Dunlop, Proc. Interfaces II, Ballarat, Victoria, Australia, (1993).
11. N. Apayadin, J. Materials Science Letters 1, (1982), 39.
12. K. Miwa, T. Kakamu, T. Ohashi, Trans. Japan Inst. Metals, vol. **26**, no. 8, (1985), 549.