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The microstructures of aluminium alloy metal-matrix composites manufactured by squeeze casting

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Squeeze-cast metal-matrix composite ingots have been manufactured by recasting A356/10% SiC_p and by melt infiltrating $A357/Al_2O_{3f}$. The resulting microstructures have been examined by optical and transmission electron microscopy. The primary aluminium in squeeze-cast A356/10% SiC_p exhibits a dendritic structure with eutectic silicon particles and SiC particulate distributed throughout the interdendritic regions. Unlike squeeze-cast monolithic A357, the primary aluminium dendrite arm spacing and eutectic-silicon particle size in squeeze-cast A356/10% SiC_p are not strongly affected by an increased cooling rate at high applied pressure. With low die and preform temperature, a high applied pressure is essential to obtain complete melt infiltration in $A357/Al_2O_{3f}$. During melt infiltration, the ceramic preform acts as a filter, preferentially allowing silicon rich liquid to pass through.

1. Introduction

Squeeze casting is a process in which an alloy melt solidifies under the direct action of pressure, in order to prevent the appearance of either gas or shrinkage porosity. There are two methods of manufacturing metal-matrix composites (MMCs) by squeeze casting: (1) recasting, in which particulate-reinforced MMC stock is remelted and then squeeze cast to produce a particulate MMC shaped component; and (2) melt infiltration, in which a ceramic fibre preform is inserted in a die, and then a molten monolithic alloy is squeeze cast to infiltrate the preform and produce a fibre-reinforced MMC shaped component.

The advantages of squeeze casting monolithic alloys have been discussed by Chadwick and Yue [1], and include elimination of gas and shrinkage porosity, reduction of metal wastage and improvement of mechanical properties. Squeeze casting MMCs is even more advantageous compared with conventional casting routes such as sand and investment casting, because of the poor fluidity of particulate MMCs and the difficulty of infiltrating ceramic fibre preforms [2, 3]. In addition, squeeze casting can be used to manufacture near net-shape components with local ceramic reinforcement in high-stressed locations [4].

The present paper describes the microstructures of squeeze-cast aluminium alloy MMCs manufactured by recasting particulate MMC stock and melt infiltration of ceramic preforms as a function of die, preform and melt temperatures and applied pressure, using a combination of optical and transmission electron microscopy (TEM).

2. Experimental procedure

Fig. 1 shows a schematic diagram of the squeeze caster, consisting of an instrumented Stenh-j 100 ton hydraulic press with a 50 mm diameter, 80 mm long, cylindrical cavity H13 steel die. The temperatures at the ingot centre and edge and in the die were measured using chromel/alumel thermocouples, and the resulting measured temperatures together with ram displacement and pressure were monitored continuously during squeeze casting using a Schlumberger 3531D data logger. Cylindrical squeeze-cast ingots were manufactured from: (1) monolithic A357; (2) recast Duralcan A356/10 vol % SiC_p (manufactured originally by stir casting); and (3) melt-infiltrated A357/Saffil 20 vol % Al_2O_{3f}. The compositions of the A356 and A357 aluminium alloys were Al–7 wt % Si–0.3 wt % Mg and Al–7 wt % Si–0.5 wt % Mg, respectively. The casting conditions for the monolithic and MMC ingots are listed in Table I. During remelting of the $A356/SiC_p$ MMC, the melt temperature was limited to below 850 °C, in order to prevent severe chemical reactions between the SiC particulate and the aluminium alloy melt.

The squeeze-cast ingots were cut with tool steel and diamond saws, ground with SiC papers and polished with diamond paste for examination in an Olympus BHM optical microscope. TEM samples were prepared by grinding 3 mm discs to a thickness of 70 μm, and then thinning to perforation in a Gatan twin-gun ion-beam miller at room temperature with a voltage of 4 kV and a current of 0.5 mA/gun. The resulting samples were then examined in a Phillips CM20 TEM.

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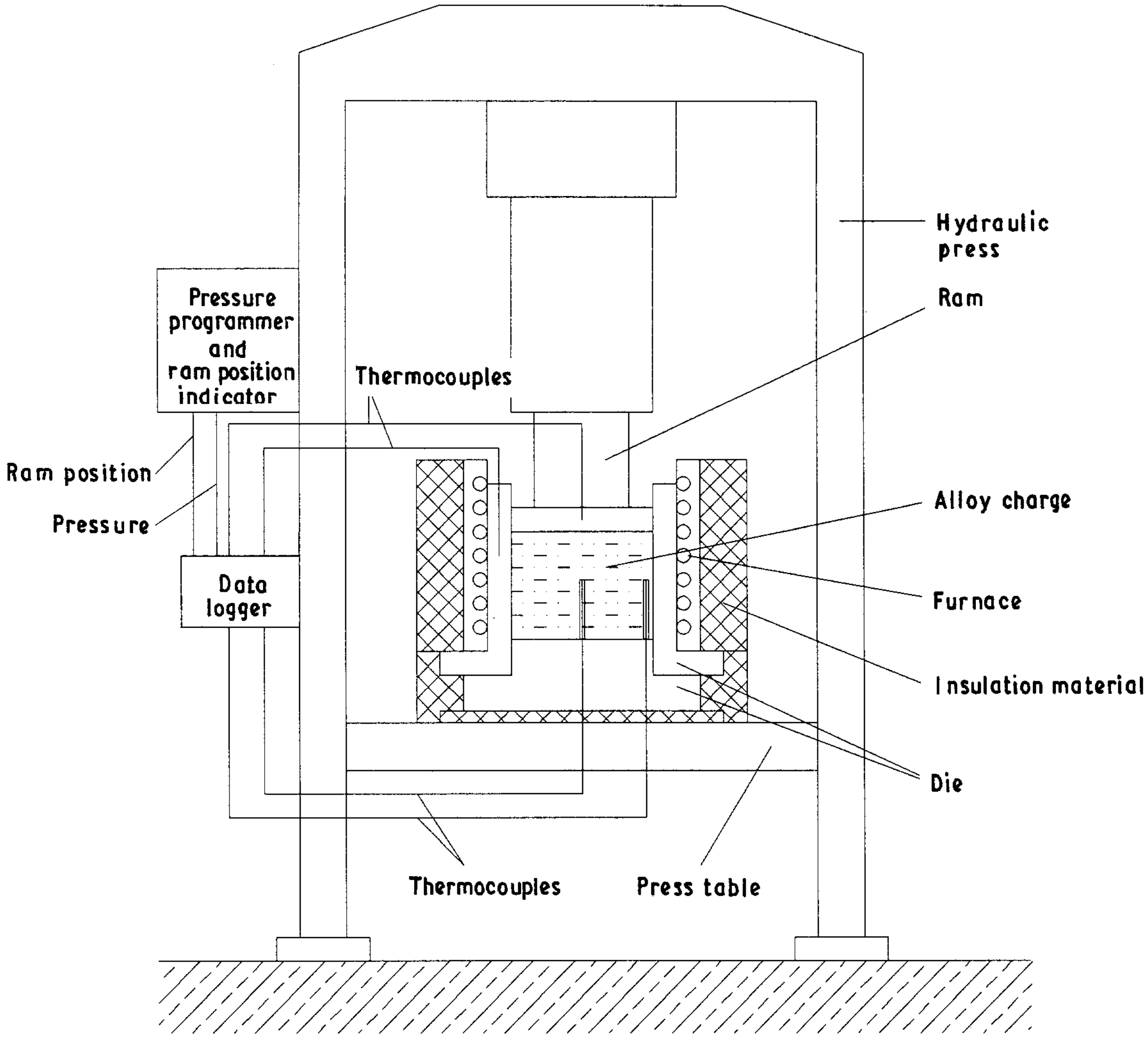


Figure 1 Schematic diagram of the squeeze caster.

TABLE I Squeeze-casting conditions for monolithic A357 and A356/SiC_p and Al_2O_{3f} MMCs

Materials	Die temp. (°C)	Preform temp. (°C)	Melt temp. (°C)	Pressure (Mpa)
A357	300	–	700	0.1
A357	300	–	700	100
A356/10%SiC_p	300	–	700	0.1
A356/10%SiC_p	300	–	700	100
A357/20%Al_2O_{3f}	300	300	850	5
A357/20%Al_2O_{3f}	300	300	850	100

3. Results and discussion

Fig. 2 shows the measured temperature at the ingot centre as a function of time during squeeze casting of A356/10% SiC_p with applied pressures of 0.1 and 100 MPa. The measured ingot temperature dropped by about 85 K within 1s of applying a pressure of 100 MPa, because of the sudden increase in heat-transfer coefficient between the solidifying melt and the die. The strong effect of applied pressure on ingot cooling rate is in agreement with the result reported by Reddy and Sekhar [5]. Fig. 2 also shows that the matrix alloy had just begun to solidify when 100 MPa pressure was applied, i.e. not all of the matrix liquid solidified under high pressure.

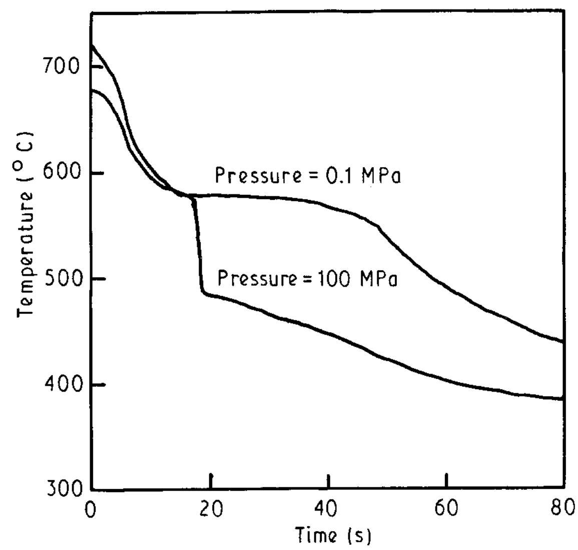


Figure 2 Measured temperature at the ingot centre as a function of time during squeeze casting A356/10% SiC_p with applied pressure of 0.1 and 100 MPa.

Fig. 3a–d show typical high- and low-magnification optical micrographs of the microstructures of monolithic A357 squeeze cast with applied pressures of 0.1 and 100 MPa. For both squeeze-casting pressures, the primary aluminium exhibited a dendritic structure,

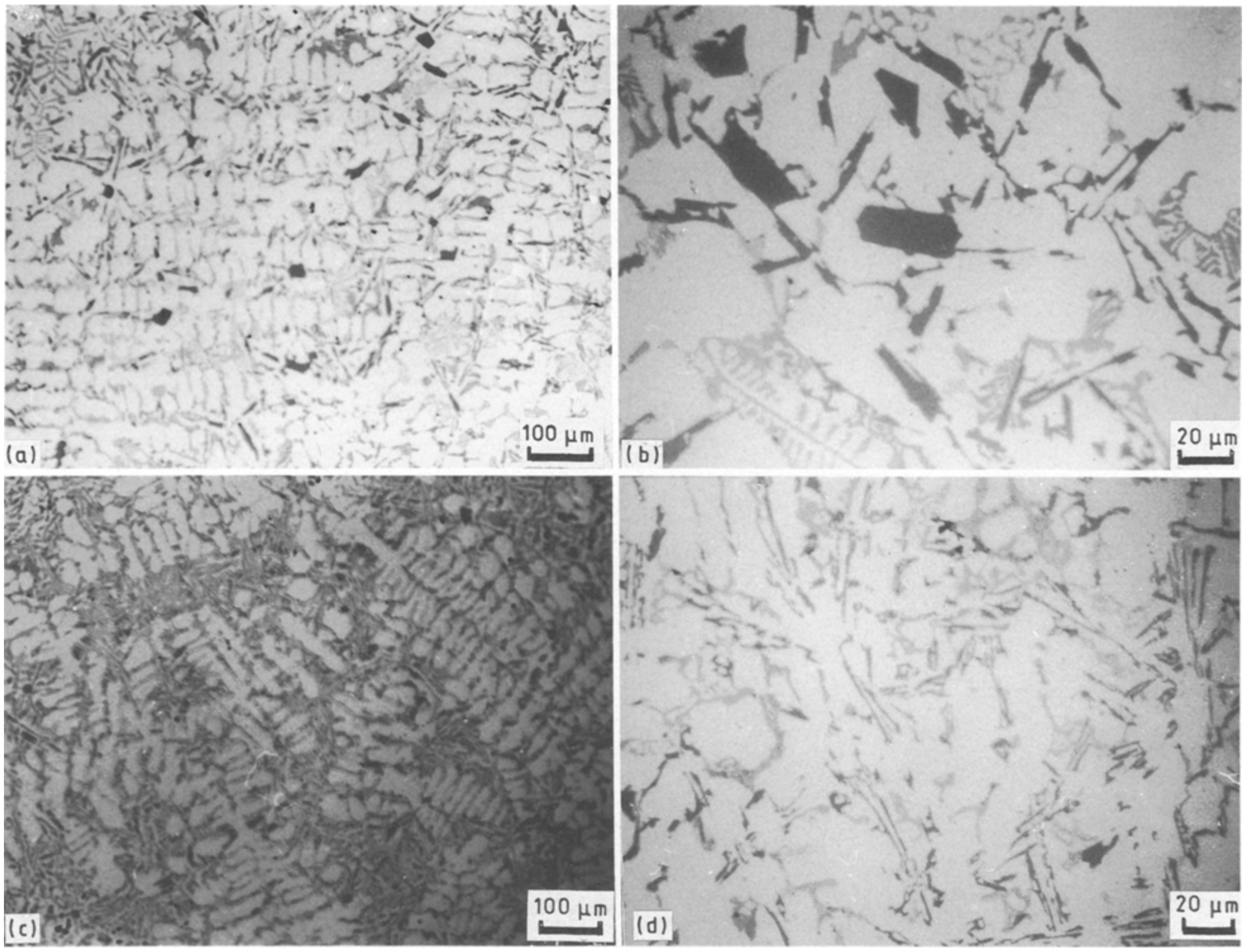


Figure 3 Optical micrographs of the microstructure of monolithic A357 squeeze cast with applied pressures of (a, b) 0.1 MPa, and (c, d) 100 MPa.

with a dendrite arm spacing which was only slightly reduced by the increased cooling rate at high applied pressure. The interdendritic eutectic silicon morphology was, however, strongly affected by the high applied pressure, with finer-scale eutectic silicon fibres and fewer coarse-faceted silicon particles.

Fig. 4a–f show typical low- and high-magnification optical micrographs of the microstructures of as-received and low- (0.1 MPa) and high- (100 MPa) pressure squeeze-cast A356/10% SiC_pMMC. In all cases, the microstructure consisted of a primary dendritic aluminium matrix, with eutectic silicon and SiC particulate distributed throughout the interdendritic regions. Recasting had no effect on the amount and distribution of the SiC particulate, but did refine the primary aluminium dendrite arm spacing and interdendritic eutectic silicon size. Increasing the squeeze-casting pressure had little effect on the primary aluminium dendrite arm spacing, similar to the monolithic A357 alloy in Fig. 3; and also had little effect on the interdendritic eutectic silicon particle size, unlike the monolithic A357 alloy in Fig. 3. This suggests that the solidification behaviour is different in squeeze-cast A356/SiC_p compared with squeeze-cast monolithic A357. At both pressures in the squeeze-cast MMC, some of the eutectic silicon particles are in contact with SiC particulate, as shown in Fig. 4d and f, indicating that SiC acts as a heterogeneous nucleant for the solidification of eutectic silicon [6], and ensures a refined silicon particle size. Fig. 5 shows a transmission electron micrograph of the microstructure of the A356/SiC_pMMC. Little or no chemical reaction between SiC and aluminium was observed in the TEM.

Fig. 6a–f show typical high- and low-magnification optical micrographs from different regions of the microstructure of A357/20% Al_2O_{3f} MMC melt infiltrated with an applied pressure of 100 MPa, die and preform temperatures of 300° C and a melt temperature of 850° C. With an applied pressure of 100 MPa, the 20 mm thick ceramic preform was fully infiltrated, leaving no porosity; but using the same conditions with a reduced applied pressure of 5 MPa, the ceramic preform was not fully infiltrated, leaving considerable residual porosity in the final MMC microstructure. This indicates that high pressure was essential to obtain full melt infiltration with low die and preform temperatures. With an applied pressure of 100 MPa, the Al_2O_3 fibres were homogeneously distributed throughout the aluminium matrix as shown in Fig. 6c, and were often in contact with each other, as shown in Fig. 6d. The primary aluminium exhibited a dendritic structure, with a dendrite arm spacing which was smaller in the MMC than in the monolithic alloy squeeze cast under the same conditions, as shown in Fig. 6b. Comparing Fig. 6b and f shows that the

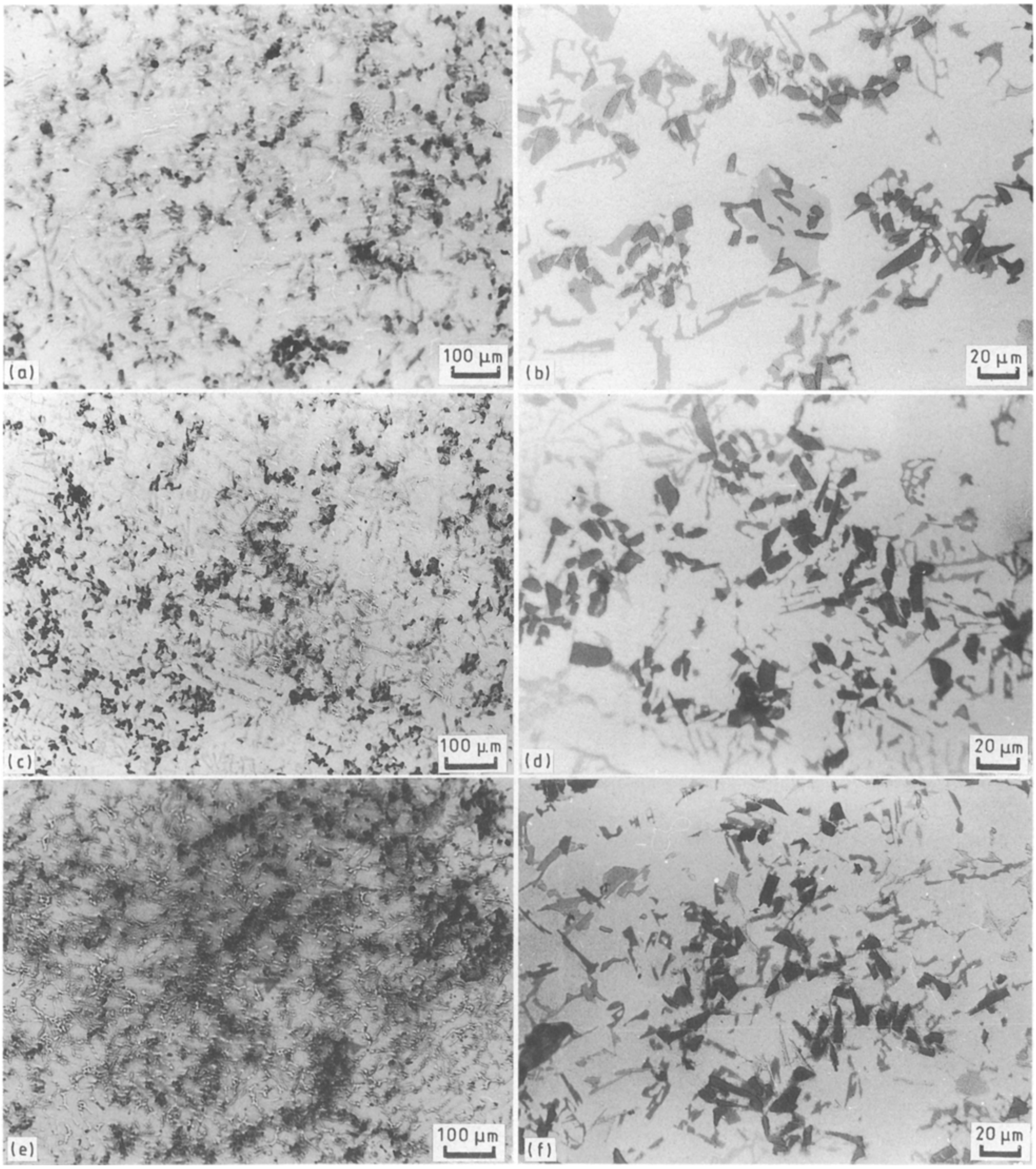


Figure 4 Optical micrographs of the microstructures of as-received and squeeze-cast A356/10% SiC_p: (a, b) as-received; (c, d) squeeze cast at 0.1 MPa; and (e, f) squeeze cast at 100 MPa.

fraction of interdendritic eutectic silicon was higher just below the ceramic preform than just above it, indicating that the liquid silicon concentration increased during infiltration through the preform. In other words, primary aluminium solidified during infiltration and the ceramic preform then acted as a filter, preferentially allowing silicon rich liquid to pass through.

Fig. 7a–c show transmission electron micrographs of the microstructure of high-pressure melt-infiltrated A357/Al_2O_{3f}. The Al_2O_3 fibres exhibited a polycrystalline structure as shown in Fig. 7a, with an amorphous SiO_2 layer and some silicon particles at the Al_2O_3/Al alloy interface, as shown in Fig.7b and c.

4. Conclusions

Good-quality MMC ingots have been manufactured by recasting A356/10% SiC_p and by melt infiltration of A357 aluminium alloy into Al_2O_3 short-fibre preforms. The primary aluminium in squeeze-cast A356/10% SiC_p MMCs exhibits a dendritic structure with eutectic silicon particles and SiC particulate distributed in the interdendritic regions. Unlike the monolithic A357 alloy, the dendrite arm spacing of primary aluminium and the morphology of eutectic silicon particles in the squeeze-cast A356/10% SiC_p MMC is not strongly affected by the increased cooling rate at a high applied pressure. With low die and preform temperatures, a high applied pressure is

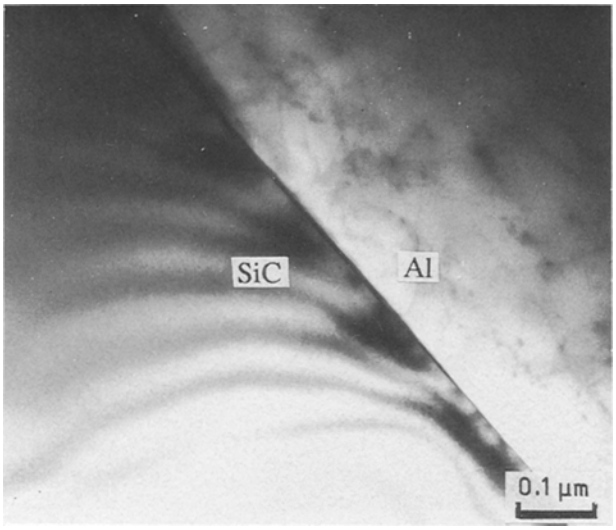


Figure 5 Transmission electron micrograph of the microstructure of A356/10% SiC_p squeeze cast at 100 MPa, showing the Al/SiC interface.

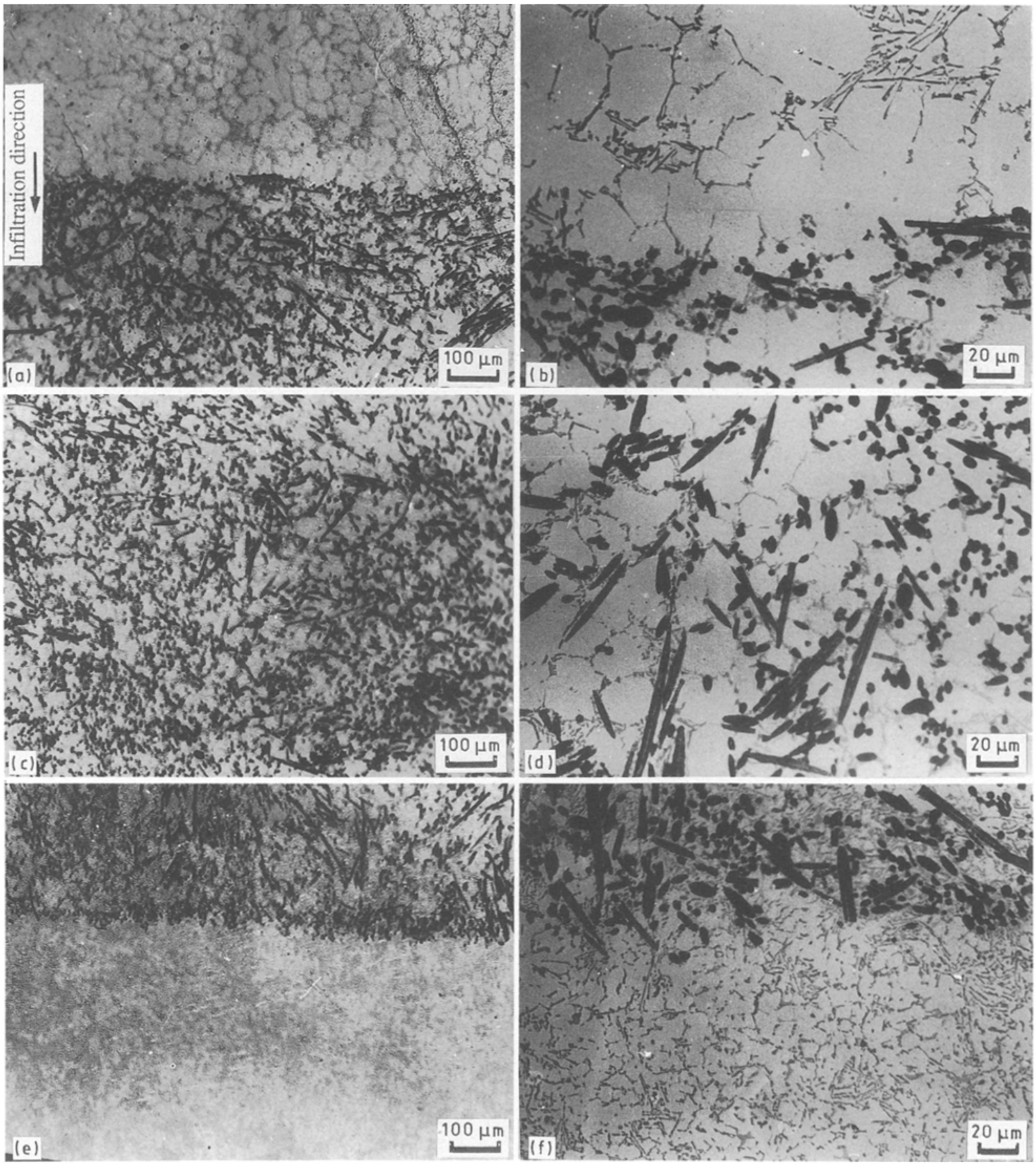
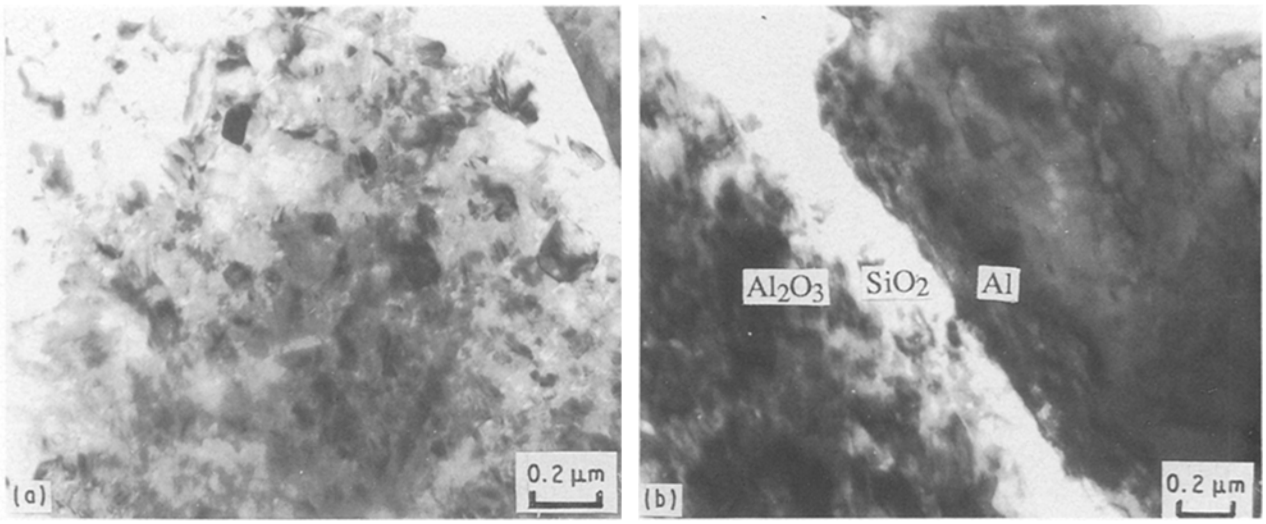


Figure 6 Optical micrographs of the microstructure of A357/20% Al_2O_{3f} MMC melt infiltrated at an applied pressure of 100 MPa: (a, b) top edge, (c, d) middle part, and (e, f) bottom edge of the Al_2O_{3f} preform.



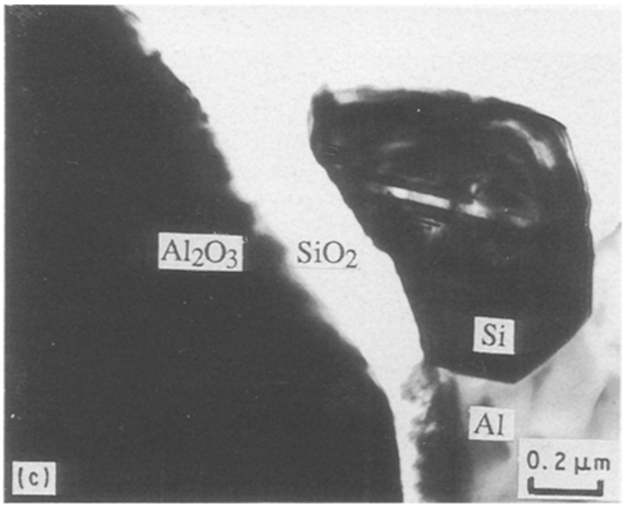


Figure 7 Transmission electron micrographs of the microstructure of A357/20% Al_2O_{3f} melt infiltrated at an applied pressure of 100 MPa, showing: (a) the polycrystalline structure of the Al_2O_3 fibres, (b) amorphous SiO_2, and (c) a silicon at the Al/Al_2O_3 interface.

essential to obtain complete melt infiltration in squeeze-cast A357/Al_2O_{3f} MMCs. During melt infiltration, the ceramic preform acts as a filter, preferentially allowing silicon-rich liquid to pass through.

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