Fractography, Fluidity, and Tensile Properties of Aluminum/Hematite Particulate Composites

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(Submitted 11 November 1997; in revised form 15 September 1998)

This paper examines the effect of hematite (iron oxide) particles on the fluidity of the molten composite as well as the tensile properties and fracture behavior of the solidified as-cast aluminum composites. The percentage of hematite in the composite was varied from 1 to 7% in steps of 2% by weight. The vortex method was employed to prepare the composites. It followed from the results obtained that the ultimate tensile strength and Young's modulus of the composite increased while the liquid fluidity and solid ductility decreased with the increase in hematite content in the composite specimens. The fluidity of the liquid was greater in a metal mold than in a sand mold, and it decreased with an increase in reinforcing particle size and increased with pouring temperature. The presence of the reinforcing particles altered the fracture behavior of the solid composites considerably. Final fracture of the composite occurred due to the propagation of cracks through the matrix between the reinforcing particles.

Keywords aluminum, composites, fractography, hematite, tensile properties

1. Introduction

The ever increasing quest for newer and lighter materials with high specific strength and stiffness coupled with major advances in processing techniques has catalyzed technological interest in the development of numerous high-performance composite materials, which are emerging as serious contenders to traditional engineering alloys (Ref 1). The development of metal matrix composites (MMCs) has been one of the major innovations in the field of materials in the past few decades. The family of MMCs, which are formed by reinforcing metallic materials with high strength ceramic phases, exhibits advantages over the characteristics of the unreinforced matrix including high strength, high specific modulus, and high specific stiffness.

Aluminum alloys have received considerable attention as matrix materials for composites due to their unique combination of good corrosion resistance, high electrical conductivity, and excellent mechanical properties (Ref 2). Aluminum alloy particulate reinforced composites are potentially attractive for many engineering applications. Some of the typical particulate phases used are graphite, mica, silica, zircon, alumina, and silicon carbide (Ref 3). Though ceramic particles and fibers with high strength and stiffness are being considered as reinforcements for MMCs, early studies centered on the incorporation of metal particles and wires into metals.

The interest in reinforcing aluminum alloy matrices with ceramic particles has been generated by the low density and high strength of the ceramics and also by their availability. In the automotive industry, the SiC-particle reinforced aluminum composites are used for pistons, brake rotors, calipers, and liners where they exhibit enhanced strength and wear resistance (Ref 4).

The matrix microstructure on which the properties of the materials depend is considered unaffected by the presence of the reinforcement. When the concentration of the reinforcement is high and when there is a large disparity between the properties of the two phases, such as elastic modulus and coefficient of thermal expansion, the reinforcement-matrix interaction may be strong enough to affect some of the properties.

As the particle reinforced MMCs are being considered widely for sophisticated applications, economical production becomes increasingly more important, and their commercial utilization becomes rather wide. Hence the need for knowledge about these materials from processing to mechanical behavior becomes most urgent. Moreover, although significant research has been devoted to the development and application of the new MMCs, still very little information exists about the basic mechanisms responsible for their properties. In view of these facts, the evaluation of properties of aluminum-base composites becomes important. This study is of prime importance since most of the work on MMCs deals with ceramic reinforcement, and little attempt has been made to reinforce metal alloys with non-ceramic particles. Thus, this study examines the effect of a nonceramic particle on the fluidity, fracture, and tensile properties of the composite.

2. Experimental Procedure

2.1 Processing of Composites

Aluminum alloy 6061 (with composition in wt% of Cu, 0.25; Si, 0.60; Mg, 1.00; Cr, 0.25; and Al, balance) was used as the base matrix. Hematite particles of 80 to 100 μm were used as the reinforcement, and hematite content in the composite was varied from 1 to 7% in steps of 2% by weight. A liquid metallurgy technique was used to fabricate the composite materials in which the hematite particles were introduced into the molten pool through the vortex created in the molten metal by the use

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of an aluminite-coated stainless steel stirrer. The coating of aluminite on the stirrer is essential to prevent the migration of ferrous ions from the stirrer material into the molten metal. The stirrer was rotated at 550 rpm and the depth to which the stirrer was immersed was about one-third the depth of the molten metal pool from the bottom of the crucible. The pre-heated (500 °C) hematite particles were added into the vortex of liquid melt which was then degassed using pure nitrogen for about 3 to 4 min. The resulting mixture was tilt poured into preheated permanent molds.

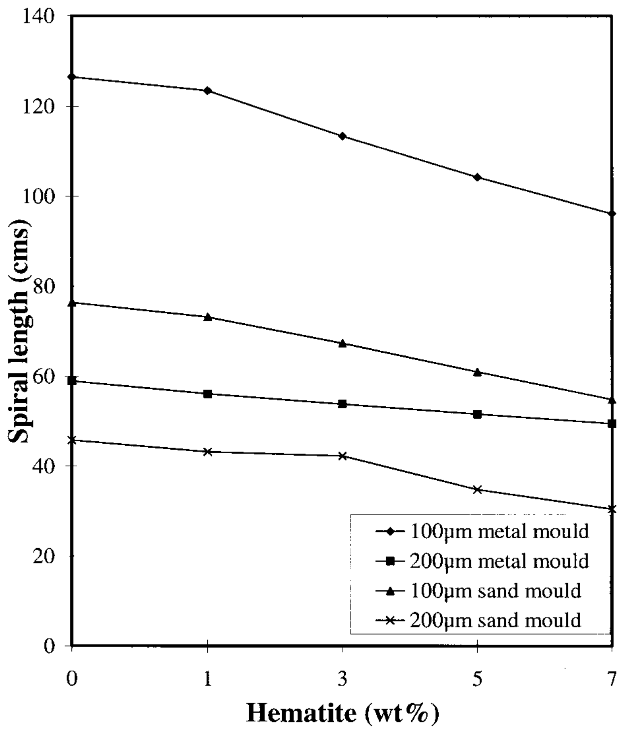

Fig. 1 Spiral length as a function of hematite content at 700 °C

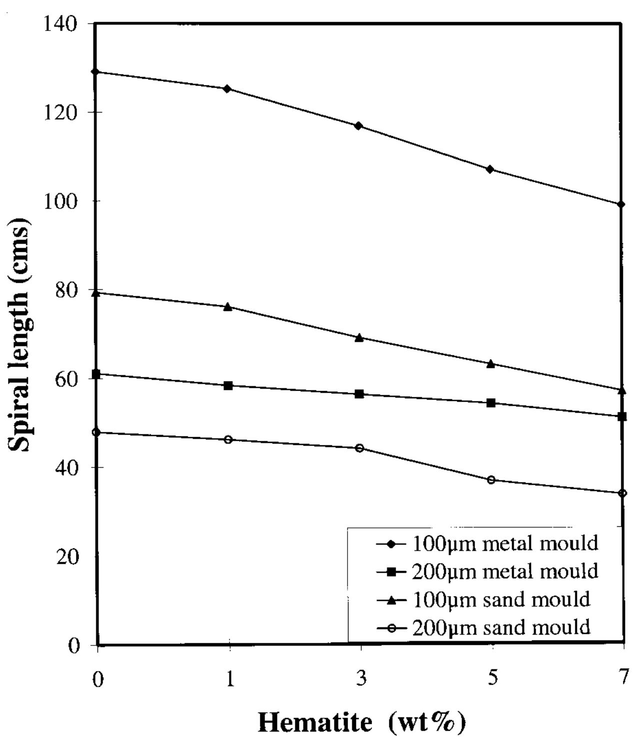

Fig. 2 Spiral length as a function of hematite content at 720 °C

2.2 Testing of Specimens

All the tests were conducted in accordance with ASTM standards. Many of the earlier experimental works have used straight flow channels for fluidity tests. However, due to the disadvantage of excessive length and sensitivity of the straight flow channel to angle, such testing has been discontinued in favor of the spiral test. The fluidity tests used a spiral fluidity tester where the length of the solidified spiral was taken as the measure of the fluidity of the material. The fluidity of the composite material was tested at the three temperatures 700, 720, and 740 °C and at two particle sizes of 100 and 200 μm. Four spirals were cast for every material parameter.

The tension tests were performed at room temperature using a universal testing machine. Tensile specimens of diameter 8.9 mm and gage length of 76 mm were machined from the cast composites with the gage length of the specimen parallel to the longitudinal axis of the castings. As many as eight tensile specimens were tested for each composite to circumvent the possible effects of particle segregation. The average value of the ultimate tensile strength (UTS) and ductility in terms of percentage elongation were calculated. An extensometer was used to measure the elongation of the specimens tested.

3. Results and Discussion

The results obtained are plotted in the form of graphs as shown in Fig. 1-5, which reveal the effects of hematite particles

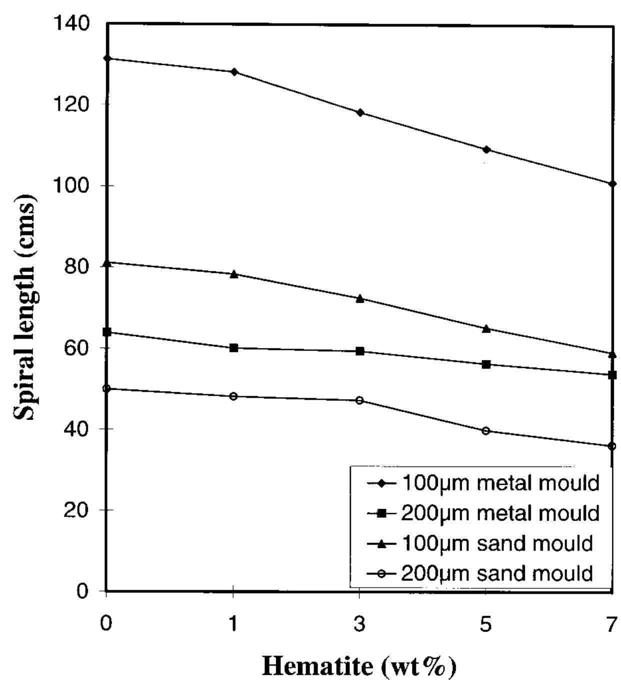

Fig. 3 Spiral length as a function of hematite content at 740 °C

on the various properties evaluated (fluidity, ductility, ultimate tensile strength, and Young's modulus).

3.1 Fluidity

The fluidity test is a measure of the distance the melt flows before solidification. The term fluidity, which encompasses the property of the flowability of the melt, is a dynamic criterion that measures the ability of the melt to flow in a large cross-sectional area of the mold. Flowability, which limits fluidity when heat and mass flow in the system cause premature freezing of the metal, is a more interesting and important property. It is of interest to characterize the flowability of the metal matrix composite containing reinforcing particles because this will determine the size and the shape of the obtainable castings (Ref 5).

The length of the fluidity spiral as a function of hematite content and temperature (700, 720, and 740 °C) are shown in Fig. 1-3, respectively. Each point on the graph is the average length of four spirals. Each individual value did not vary more than 2% from the mean value. It is clear from the results that the addition of hematite particles to aluminum matrix results in a decrease in the fluidity of composite. The decrease in composite fluidity increases with increasing weight percent of hematite. The reduction of fluidity of the aluminum matrix by addition of hematite particles can be due to an increase in the effective viscosity of the alloy matrix. Available literature suggests the viscosity of a liquid containing suspended particles is a function of the percentage of the particles present, and in general, viscosity increases with an increase in the percentage of particles, thereby decreasing the fluidity. The most probable explanation for the decrease in spiral length at high weight fractions of reinforcement is that a chemical reaction leads to an increase in viscosity (Ref 6). Investigators are also of the opinion that the distribution of particles in a casting, and presumably in a melt, is not perfectly uniform, and these factors also can increase viscosity (Ref 7).

Kolsgaard and Brusethaug (Ref 8) have reported that the fluidity decreases with an increase in the reinforcing particle size. In the present case it also is observed that the fluidity decreases as the particle size is increased from 100 to 200 μm.

It follows from Fig. 1-3 that the spiral length is greater in the case of metal molds than in the case of sand molds, everything else being equivalent. This is obviously due to the greater resistance offered by the sand grains to the flow of the molten metal. The resistance offered by the metal molds to the flow of the molten metal is significantly lesser, due to the greater spiral length.

The increase in flowability is a linear function of the pouring temperature. This is clearly evident from the graph shown in Fig. 4. Figure 4 is drawn from the values obtained for the test conducted using a metal mold and reinforcing particles of size 100 μm. However, the general observations are also pertinent for the other conditions as well. The linear increase in flowability with the pouring temperature is obviously due to the fact that the viscosity of the melt decreases with the increase in pouring temperature resulting in increased spiral length. This finding is in agreement with the reports of other researchers (Ref 9, 10). Using a higher pouring temperature can compensate for the reduction in spiral length due to the presence of

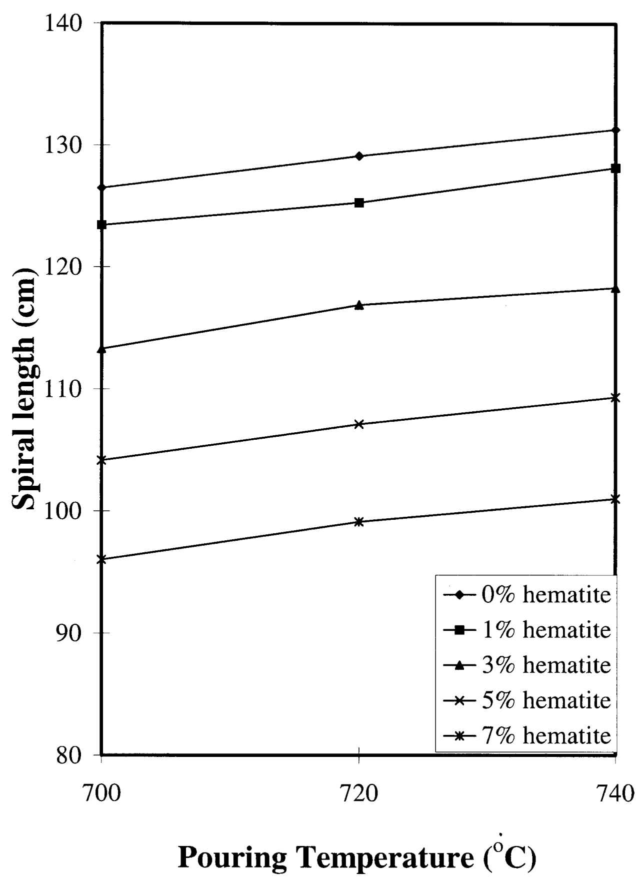

Fig. 4 Spiral length under condition of 100 μm metal mold

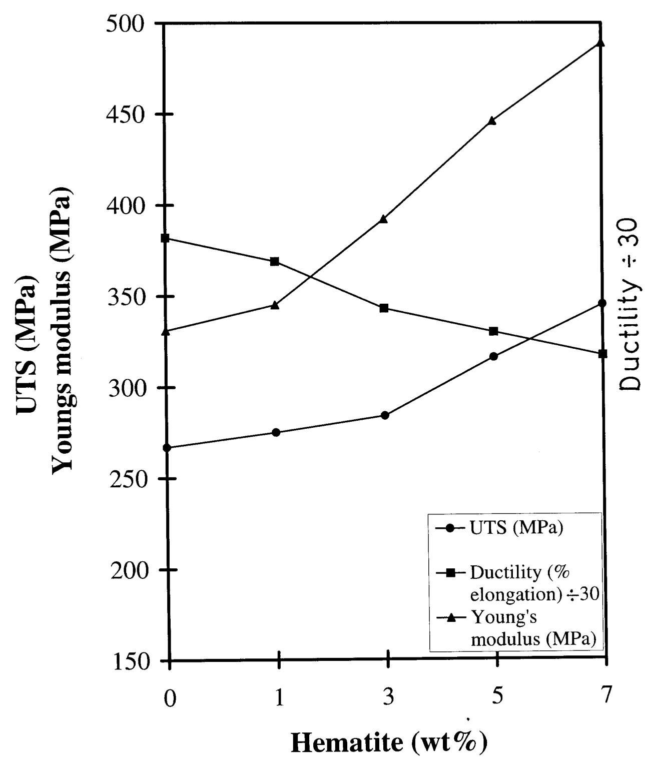

Fig. 5 Tensile properties of aluminum-hematite composites

hematite particles. A maximum increase in the casting temperature of 20 °C to compensate for the reduced spiral length is not a critical factor for aluminum composite material casting behavior, but the casting temperature cannot exceed 800 °C. Increasing the casting temperature beyond this generally is not viable due to the formation of aluminum carbide.

3.2 Mechanical Behavior

The properties of discontinuously reinforced composites are strongly dependent on many variables including distribution of the particles in the matrix, the mechanical properties of the matrix and the reinforcing particles, and the interfacial bond between the matrix and the reinforcement. Figure 5 is the graph of UTS of as-cast composite specimens. Each point is an average of eight values. Each individual value did not vary more than 4% from the mean value. It follows from the graph that the as-cast specimens show an increase in UTS by about 29% as the percentage of hematite in the composite is increased from 0 to 7. The increase in UTS of the specimens is probably due to the presence of hard hematite particles that impart strength to the aluminum matrix by way of dispersion strengthening. The increase in UTS is similar to that observed by Humphreys et al. (Ref 11), who report that the strength of the particle reinforced composites is most strongly dependent on the volume fraction of the reinforcement with a somewhat weaker dependence on the particle size. McDanels (Ref 12) has reported up to 60% increase in the UTS for SiC reinforced alloys, depending on the type of the alloy and the volume fraction of reinforcement. There is a decrease in the interparticle distance between the hard hematite particles, which causes increased resistance to dislocation motion as the hematite content is increased. This restriction to the plastic flow due to the dispersion of the hard particles in the matrix provides enhanced tensile strength to the composite.

It follows from Fig. 5 that the specimens show a reduction in ductility by about 64% as the particle content is increased from 0 to 7 wt%. The ductility of a discontinuously reinforced MMC generally is low compared with the base alloy (Ref 13). This is seen as a major limitation in the mechanical properties of the composites. This is quite interesting since the fracture process occurs in a ductile manner (Ref 14). The results and the behavior trends observed in this research are similar to others (Ref 5, 6). The loss in ductility can be attributed to an embrittlement effect due to the presence of the hard hematite particles, which cause increased local stress concentration sites.

Mummery et al. (Ref 14) are of the opinion that this behavior can be due to void nucleation during plastic straining at the reinforcement, either by reinforcement fracture or by the decohesion of the matrix-reinforcement interface. Nucleation of the voids begins during early stages of straining and continues until the final fracture. The voids grow and coalesce exactly as

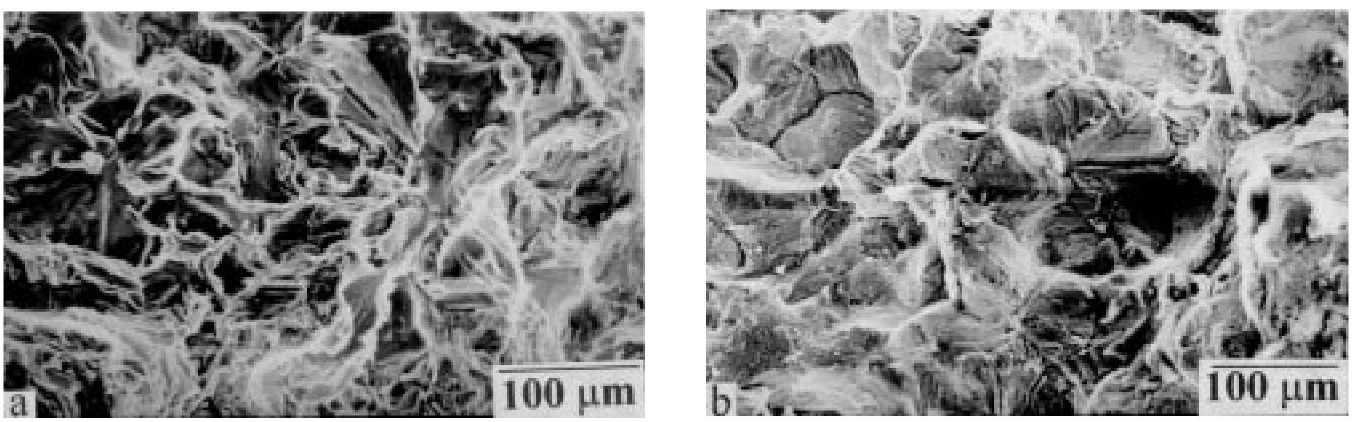

Fig. 6 SEM of tensile specimens showing tear ridges and dimple patches in (a) 5 wt% and (b) 7 wt% hematite reinforced composites

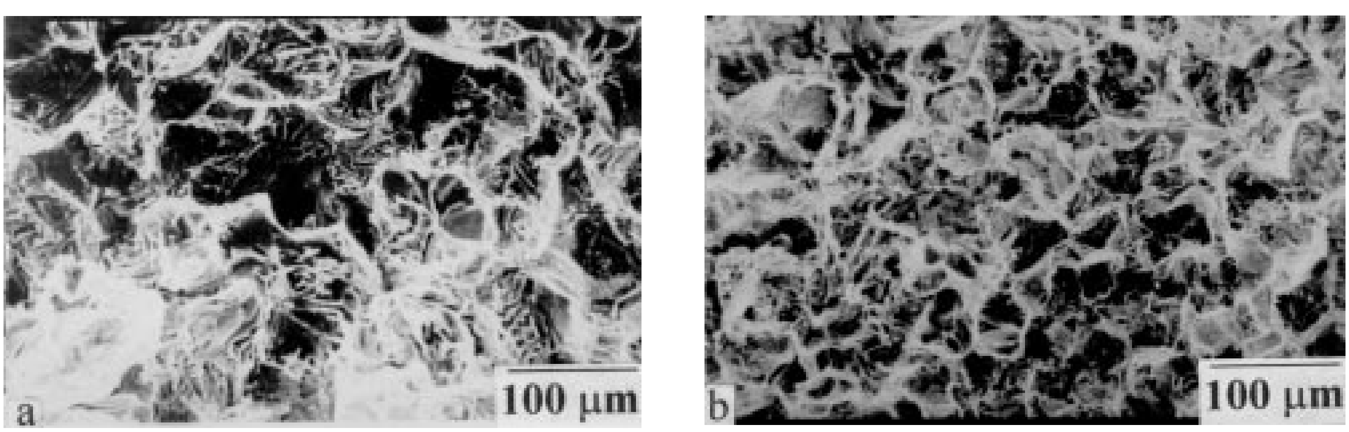

Fig. 7 SEM of tensile specimens showing microvoids in (a) 5 wt% and (b) 7 wt% hematite reinforced composites

would be expected by a ductile fracture mechanism. Other workers (Ref 17, 18) have also demonstrated that composite failure is associated with particle cracking and void formation in the matrix within the clusters of the particles.

Young's modulus is one of the important properties to be considered in designing the structural parts. Young's modulus is one of the properties that is improved in MMCs (Ref 19). Figure 5 shows that the Young's modulus increases with the increase in hematite weight fraction.

As in the cases of UTS described above, it can be seen that as the hematite content increases, the Young's modulus of the composite material increases monotonically by significant amounts. In fact, as the hematite content is increased from 0 to 7%, Young's modulus increases by about 53%. This increase in Young's modulus may be due to the hematite particles acting as barriers to dislocations in the microstructure. Similar results have been obtained in aluminum matrix composites where Young's modulus has been reported to increase with increase in the content of the reinforcing material, regardless of the type of reinforcement used (Ref 20).

4. Fractography and Fracture Analysis

The fracture surfaces of the 5 and 7 wt% hematite-particle reinforced composites have been examined in the scanning electron microscope (SEM). However, the general observations also pertain to the 1 and 3 wt% hematite reinforced composites.

Previous research on the failure mechanism in MMCs indicated that numerous factors, including the matrix/reinforcement interface, reinforcement cracking, brittle cracking of the intermetallic particles, and microstructural inhomogeneity, are associated with composite failure (Ref 21). The complexity of these materials has made it difficult to identify the contributions by each mechanism to the failure process and to identify the dominant failure mechanism. Hence, detailed fractographical examinations, which have been successful in understanding the failure behavior of monolithic metals were conducted on the tensile fractured specimens in order to determine the operative failure mechanisms in these composites.

It has been well established that the fracture of the unreinforced alloys is associated with void nucleation and growth, with the nucleation occurring at instabilities in the plastic zone, primarily at coarse constituent particles (Ref 20). It is interesting to note that the fracture surfaces at high magnifications reveal areas of ductile fracture even though the composites exhibited limited ductility on a macroscopic scale. The tensile fracture surfaces also reveal few tear ridges as shown by the fractographs in Fig. 6. The matrix of the composite was also found to be covered with large number of microvoids of a wide range of sizes as evident from the fractographs shown in Fig. 7.

The fracture of the reinforcing particles and the concurrent failure of the surrounding matrix results in the formation of voids. It was observed that the voids were almost homogeneously distributed throughout the fracture surfaces. The constraints induced by the reinforcing particles in the adjoining matrix and the resultant development of matrix triaxiality influences the flow stress of the composites and also the initiation and growth of the voids. It appears that under the influence of tensile loading, the voids appear to undergo limited growth, confirming a possible contribution from particle constraint-induced triaxiality on the failure of the composite matrix. Under an assumption that a strong particle-matrix interface exists, the triaxial stresses generated during the tensile loading favors limited growth of microvoids in the matrix of the composite. The observation of limited growth of the voids during tensile loading and the lack of their coalescence as a fracture mode in the present case obviously indicate that the deformation behavior of the alloy matrix is considerably altered by the presence of the reinforcing particles and that their distribution is also of prime significance because the particles can raise the hydrostatic stress component.

In the case of reinforced matrix, the majority of the damage is associated with particle clusters and exists in the form of voids generated as a result of particle cracking. The particle cracking-induced fracture coupled with decohesion of the matrix between the particles and the final fracture is achieved by the matrix fracture between the particle as is evident from Fig. 8. In the case of ductile fracture of the unreinforced matrix, the voids generated by particle cracking do not grow extensively in the tensile direction as shown in Fig. 9. Because the composites do not exhibit extensive void growth, it can concluded that the fracture strain is significantly dictated by the void nucleation strain.

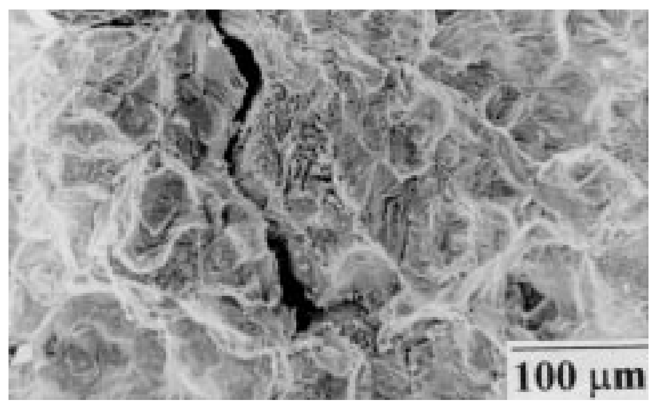

Fig. 8 SEM of composite specimens showing matrix fracture

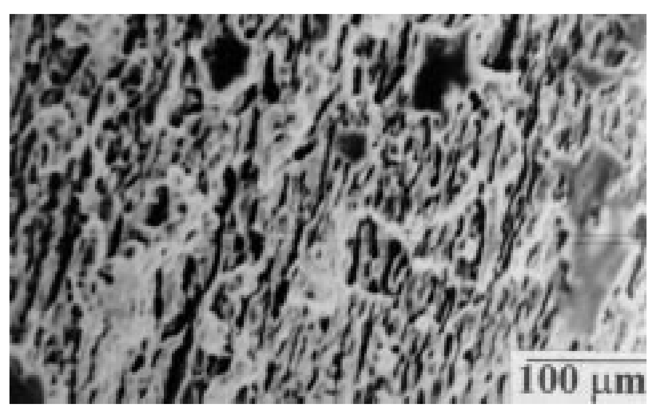

Fig. 9 SEM of the unreinforced alloy tensile fracture surface

5. Conclusions

- The incorporation of hematite particles in an aluminum matrix resulted in a decrease in the fluidity of composite. The fluidity of the composite increased with an increase in casting/pouring temperature.
- The UTS and Young's modulus of the composite increased while the ductility decreased with an increase in hematite content in the composite material.
- The presence of the reinforcing particles as well as their distribution in the matrix altered the fracture properties of the composites significantly.
- Although the composites exhibited limited ductility, the fracture mechanism examined on a microscopic scale revealed features reminiscent of ductile failure. Cracking of individual or clusters of reinforcing particles initiated fracture in the composites. Particle cracking increased with the reinforcement content in the matrix. Propagation of cracks through the matrix and the particles resulted in the final fracture of the composites.

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