EFFECT OF ROLLING ON TENSILE FLOW AND FRACTURE OF Al-4.5Cu-3.4Fe CAST COMPOSITE

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ABSTRACT
Al-4.5Cu-3.4Fe composite was cast in a heated cast iron mould to obtain a structure consisting of needles of brittle Al$_3$Fe intermetallic in a eutectic matrix of Al + Al$_3$Fe. Pieces of this as-cast composite were cut in the form of small bars and deformed to large strain by hot rolling. Tensile tests were carried out on the rolled specimens at room temperature. The associated fracture surfaces were examined under a scanning electron microscope. With an increase in the extent of rolling, the needles of the brittle Al$_3$Fe intermetallic were found to break down into progressively smaller fragments. At the same time the fragmented particles got oriented along the direction of rolling, the extent of orientation increasing with the extent of rolling. A gradual increase in ultimate tensile strength and ductility with an increase in the extent of rolling was observed. The poor mechanical properties of the as-cast composite resulted from the 'coarse crystalline' fracture which was caused by the cracking of the brittle second phase particles (Al$_3$Fe). A transition from the coarse crystalline fracture in the as-cast condition to the form of void growth and void linkage occurred as the extent of rolling increased.

1. INTRODUCTION

Metal–matrix composites (MMCs) consist of a continuous metallic phase as matrix and the second phase, either of the metal or a non-metallic compound, acts as the reinforcing phase. Optimization of combinations of properties is achieved by appropriate choice of the type, amount and the form of the constituent materials. A number of techniques are now available for the production of metal-matrix composites. The in-situ techniques of composite processing offer the advantage of intrinsic uniformity in the distribution of the reinforcing phases.

The increasing demand for light aluminium-based composites by the Aerospace and Defence industries has created a constant pressure for the development of aluminium-based composites with superior mechanical properties. The Al–Fe phase diagram shows that the structures of the alloys of aluminium and iron containing more than 1.7 per cent iron consist of Al$_3$Fe intermetallic embedded in a Al/Al$_3$Fe eutectic matrix. The Al-Fe binary system, therefore, offers a possibility of producing in-situ composite by the casting route. On the other hand, Al-Cu age hardenable alloys are well known and used extensively.

Thus the addition of iron, leading to the formation of primary Al-Fe intermetallic compounds, could lead to interesting improvements in the properties of Al-Cu age hardenable alloys and perhaps widen their applicability. Unfortunately, very little information on Al-4.5Cu-Fe alloys is available in the published literature. An earlier study has shown that Al-Cu-Fe in-situ composites can easily be made through the casting route and gives interesting properties.
This study also showed that the mechanical properties of the composite could be significantly altered by mechanical processing.

It is convenient and realistic to consider the micromechanisms of deformation important to ductility through the examination of samples subjected to uniform deformation as in the conventional tensile test. Numerous studies have shown that the second phase particles may control the initiation of intergranular and cleavage fracture process but they certainly dominate the entire ductile fracture regime. In the present work an attempt has been made to correlate the tensile properties of the Al-4.5Cu-Fe in-situ composite to the changes in the size and arrangement of second phase particles caused by rolling.

2. EXPERIMENTAL PROCEDURE

Commercially pure aluminium was melted in a graphite crucible and superheated to 850°C. Electrolytic copper in the form of wire (from discarded electric cables) was added to the superheated melt and stirred manually to homogenise the solution. The required amount of low carbon steel chips was then added to the superheated melt. The melt was again homogenised by manual stirring and cast into a preheated cast-iron mould. The melt of composition Al-4.5Cu-3.4Fe (weight percent) was thus allowed to solidify under slow cooling conditions. During solidification Al-Fe based intermetallic particles precipitated in-situ to yield a metal-matrix composite. Small pieces were cut from the cast block and rolled to different extents (17 - 73 per cent reduction in diameter), with intermediate stress relief annealing, in a manually driven two-high rolling mill. Brinell hardness values were determined on as-cast and rolled specimens. A load of 5 KN was applied for a period of 15 seconds to cause the indentations. The hardness values of the rolled specimens having diameters less than 12 mm were measured by using Rockwell-B scale and then converted into BHN values by reference to standard tables. Room temperature tensile properties (ultimate tensile strength, percentage elongation and percentage reduction in area) of as-cast and hot-rolled (17 and 73 per cent reduction) samples were determined by a laboratory type TERCO tensile testing machine with specimens measuring 4.8 mm diameter and 25 mm gauge length. The test-samples were polished and etched using standard techniques and were observed under both optical and scanning electron microscopes. Photomicrographs were taken at five different places of each sample and measurement of the size of the largest particle was made. Fracture surfaces resulting from the tension tests were also placed under the scanning electron microscope. Qualitative energy dispersive x-ray analysis (EDAX) has been carried out on the polished surfaces of the as-cast composite to characterize the chemistry of the particles.

3. RESULTS AND DISCUSSION

3.1 Microstructure

The scanning electron micrographs of the as-cast composite [Fig. 1(a)] showed well-developed and randomly oriented needles of the Al3Fe intermetallic compound on the polished plane along the tensile axis. Rolling to an extent of 17 per cent (per cent reduction in diameter of the sample) caused fragmentation of the particles of Al3Fe intermetallic compound located near the surface. With such an extent of rolling, the particles of the intermetallic compound located at greater depths below the surface showed the initiation of cracks only [Fig. 1(b)]. Energy dispersive x-ray has shown that these particles are compounds of aluminium and iron. An increase in the extent of rolling caused fragmentation of the particles of the intermetallic compound located at progressively greater depths of the sample. At the same time particles near the surface became finer through further fragmentation [Figs. 1(c)-(d)].
Rolling also caused the fragmented particles to get progressively more completely oriented along the direction of rolling. Fig. 1(c) shows scanning electron micrograph recorded on longitudinal sections of samples rolled to 45 per cent. It can be seen that fragmented particles, even at the center of the sample, have become completely oriented in the direction of rolling.

With more than about 59 per cent reduction, the extent of fragmentation, even at the center of the samples, was very high and there was virtually no difference in the size of the fragmented particles at the surface or at the center of the rolled specimens [Fig. 1(d)]. The intermetallic compounds are brittle and therefore, during rolling they get fragmented by the applied load and became dispersed. Severe rolling caused the intermetallic particles to get oriented along the rolling direction. This is to be the expected as the matrix is ductile.

3.2 Hardness

The hardness of Al-4.5Cu-3.4Fe in-situ composite was found to increase gradually with an increase in the extent of reduction (Fig. 2). The gradual increase in hardness with an increase in the extent of rolling may be attributed to the progressively finer dispersion of the fragmented particles.
3.3 Tensile Properties

Fig. 3 shows the variations in ultimate tensile strength (UTS) and per cent reduction in area (RA) as a function of the extent of rolling. It can be seen that both the UTS and RA of the composite are progressively raised by the extent of rolling. Appearance of tensile fracture surfaces has often been used to appraise the degree of ductility of unnotched cylindrical tensile test specimen. Fig 4 shows the macroscopic appearance of fracture surfaces of the as-cast and the rolled samples, where fibrous zone resulting from slow and stable crack propagation predominates the fracture surface. Usually crack propagation in a fibrous zone occurs by fracture resulting from microvoid coalescence and these microvoids are initiated at interfaces between the matrix and particles. Voids may nucleate by cracking of the second phase particles or by decohesion at the interface.

The role played by particles varying in size on the formation of fibrous tears is clearly shown in the fractographs of as-cast composite in Fig 5(a). Major features of the fracture surface suggest that particle size, shape and distribution are important factors in determining the properties of the materials. Figure 5(a) shows the ductile-fracture surface with initiation sites differing from dimple to dimple. Region marked by 'A' shows the dimples that were initiated at spherical precipitates or inclusions, but at 'B' in Fig 5(a) fracture of particles at plane
Fig. 5. Scanning electron micrographs of fracture surfaces of (a) as-cast, (b) 17% rolled, (c) 39% rolled, (d) 45% rolled, (e) 59% rolled and (f) 73% rolled samples.

perpendicular to tensile axis or separation of precipitates from matrix occurred. Usually initiation of voids around these facets seldom take place; rather particles may crack and the localised stress concentrations can initiate and produce cleavage in the particle and later voids may nucleate and grow by decohesion at the interface between the cracked particles and the matrix. Subsequently these faceted or cleaved surfaces are bridged by microvoid coalescence of small particles. As a result, large area occupied by needles may cause the sudden separation of their faces through fast crack propagation that in turn reduces the strength and ductility of the cast sample.

Fragmentation of particles due to gradual increase in the extent of rolling was found to change the appearance of fracture surface of the tensile test samples as illustrated in Figs. 5(b) - (f) representing extents of rolling of 17, 35, 45, 59 and 73 per cent respectively. Faceted
appearance from precipitates were observed on the fracture surface of samples rolled to the extent of 17 per cent, but both the size and the number of facets observed were less compared to those on the as-cast samples. The number of dimples increased and the facet features diminished on the fracture surface as the extent of rolling increased. Pure microvoid coalescence was observed on samples rolled to 73 per cent.

Therefore, microstructural damage resulting from tension test in rolled sample is less than that in as-cast sample and this may lead to improve strength and ductility of sample with increased rolling. The relationship between the longest inclusion observed on metallographic sections and the mean RA values from adjacent tensile specimens is shown in Fig. 6. It is clearly evident form the Fig. 6 that shape and size of the second phase particles are important in controlling ductility i.e. larger the particles lesser the ductility. This hyperbolic curve shown in figure has a similar trend for the experimental points obtained by previous researcher [5].

4. CONCLUSIONS

From this study on Al-4.5Cu-3.4Fe in-situ composite it may be concluded that:

(1) The major features of the micrographs and the fracture surfaces suggest that the large size of the particles and their distribution might have led to the poor mechanical properties of the composite.

(2) The hardness and the ultimate tensile strength of the composite gradually increased with an increase in the extent of rolling. This has been attributed to the fragmentation and dispersion of the Al3Fe intermetallic particles throughout the matrix.

(3) In tensile test, mainly the cracking of particles controls the ductility of the as-cast composite but for rolled samples void nucleation, growth and linkage control the ductility.

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REFERENCES

