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Characteristics of an Aluminium Alloy/Alumina Metal Matrix Composite

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ABSTRACT

A metal matrix composite, consisting of a dispersion of Saffil alumina fibres in an aluminium alloy casting (Al–6Si–2Cu) has been produced using a flow-cast semi-liquid metal matrix. The microstructure obtained shows the typical features of a flow-cast alloy, characterized by the presence of rounded dendrites surrounded by a eutectic phase containing the reinforcement. The reinforcement is therefore non-uniformly distributed in the metal matrix. Mechanical characterization shows that the presence of 10 vol.% of fibres improve the specific modulus and specific strength, while the elongation remains low, probably as a result of the high local concentration of fibres around dendrites. Examination of fracture surfaces and the measured values of Young's modulus and UTS, allow us to conclude that good wetting between metal matrix and reinforcement has been established during the semi-liquid state production of the MMC.

INTRODUCTION

Metal matrix composites (MMC) obtained by incorporating ceramic fibres into an aluminium alloy have recently been receiving considerable attention. The favourable combination of technological properties, arising from proper mixing of reinforcement and metal matrix, makes these materials very interesting for a wide range of applications both in the aerospace

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industry, where they were first developed, and in other industrial fields such as for automotive components or sporting goods.

Nevertheless aluminium-based MMCs have until now not been widely utilized. There are essentially two main reasons for this:

(i) the high cost of reinforcement;
(ii) the high cost and low spread of production technologies.

The first problem will probably be resolved when larger quantities of reinforcements are produced in response to market requirements. The second problem has been faced by many researchers trying to discover ways to produce MMCs at low cost. Hitherto, in fact, most MMCs have been expensively produced by diffusion bonding or by vacuum infiltration, for continuous fibres, or by squeeze casting or powder metallurgy routes when using discontinuous reinforcements (particles and whiskers or chopped fibres).

An alternative method, based on the use of a semi-liquid metal matrix (slush or stir casting), was proposed in 1974.[1] In this technique, the reinforcement is added to a metal matrix during stirring at a temperature within the solid + liquid range, when a significant fraction of solid metal is dispersed in the molten bath.

This method has several advantages:

(a) it can be performed at temperatures lower than those which are conventionally used in foundry practice during pouring, resulting in reduced thermochemical degradation of the reinforcement surface;
(b) the material exhibits thixotropic behaviour typical of stir-cast alloys; it therefore offers near-net-shape forming at low pressure in the semi-solid state, resulting in a defect-free product;
(c) production can be carried out by conventional foundry methods.

Moreover several static stirrers have recently been developed allowing production of semi-solid alloys at low cost, without the need for expensive and troublesome plant. Preliminary results obtained by stir-casting for the production of MMCs have suggested that good results can be obtained in terms of the wetting[2] of fibres and ease of production. Furthermore, the MMCs can be produced at very attractive cost.[3]

In this paper the production of an Al–6Si–2Cu/Al_2O_3 MMC is described. The composite has been produced starting from a stir-cast (flow-cast) alloy obtained with recently developed low-cost equipment;[4] a semi-solid shaping was then performed in a metallic die. Microstructural and mechanical characterization of the finished composite product has also been carried out.

PRODUCTION OF THE METAL MATRIX COMPOSITE

As pointed out above there is considerable advantage in the use of stircast alloys in MMC production, in the low processing temperature during the addition of reinforcements, in order to avoid as far as possible a thermochemical reaction at the fibre surface. Addition of fibres has therefore to be performed during low-temperature stirring when a semi-solid metal matrix is already present. The production process can therefore be divided into the following steps:

(i) flow-casting of a semi-solid alloy at a temperature just above the solidus;
(ii) adding fibres during slow stirring at constant temperature just above the solidus of the metal matrix; and
(iii) semi-solid shaping in a metallic die.

If necessary, because of the thixotropic character of semi-solid alloys (i.e. a reversible sol/gel transition at the solidus temperature) the resulting semi-solid alloy can be solidified and remelted after step (i). Step (i) was carried out by a method, described elsewhere, based on the use of a static stirrer.[4] A typical die-casting foundry alloy, of nominal composition Al–6Si–2Cu, was flow-cast at a temperature of 585°C, to give a metallic slurry that was held at the same temperature in a temperature-controlled furnace. The chemical analysis of the alloy gave results reported in Table 1.

TABLE 1
Chemical Analysis of Flow-Cast Al–6Si–2Cu Alloy (weight percentages)

Si	*Cu*	*Mg*	*Ti*	*Fe*	*Others*	*Al*
5·97	1·95	0·43	0·11	0·03	<0·02	Rem.

A volume fraction $V_f = 0{\cdot}10$ of δ-Al_2O_3 Saffil fibre (trade mark of ICI plc) was then added during slow stirring of the slurry in the same temperature-controlled furnace, as described in Fig. 1. The Saffil fibres were pretreated at a temperature of 380°C in air. Fibre incorporation was completed in about five minutes. A subsequent shaping was then performed at very low pressure ($\approx 0{\cdot}1$ MPa), transferring given amounts of MMC to the die shown in Fig. 2, preheated to a temperature of 300°C, to give discs 20 mm thick suitable for characterization. Shaping operations were completed in about 20 minutes. A different route was also followed which involved solidification and subsequent remelting after each step before shaping. There were no significant differences in results.

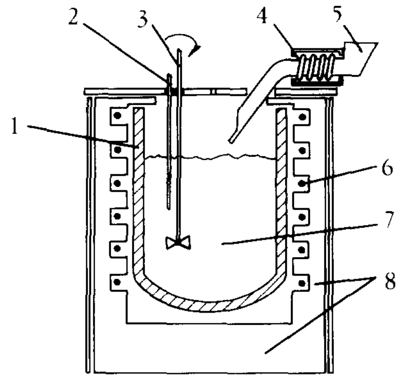


Fig. 1. Experimental facility used in producing the MMC. Fibres are added during slow stirring of the semi-liquid slurry in a temperature-controlled furnace: (1) crucible; (2) thermocouple; (3) stirrer; (4) heater; (5) fibre feeder; (6) electrical resistances; (7) semi-solid bath; (8) insulating refractory.

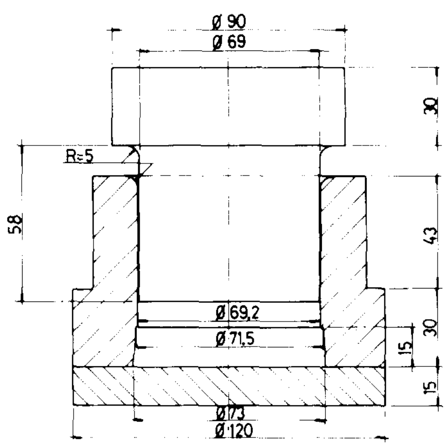
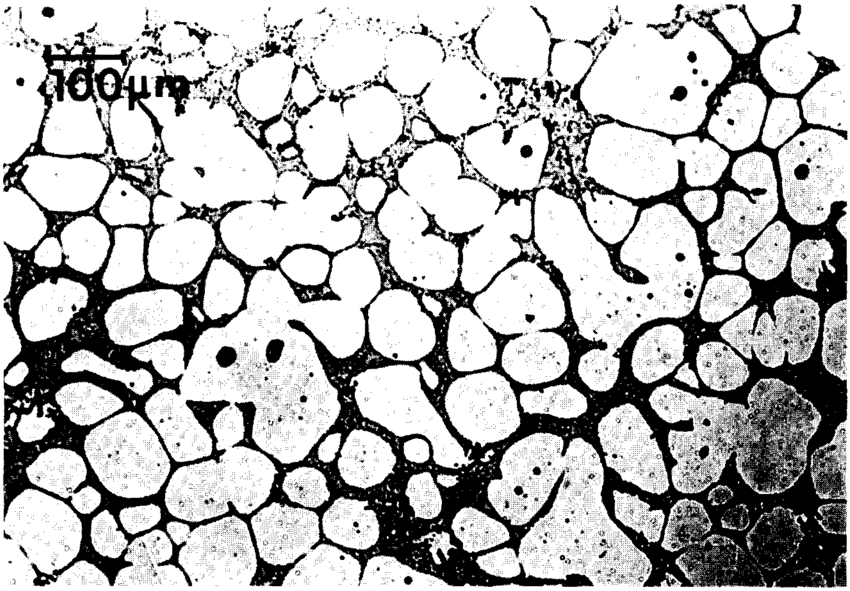


Fig. 2. Metallic die used in shaping the semi-solid MMC; the die was pre-treated at 300°C for operations.

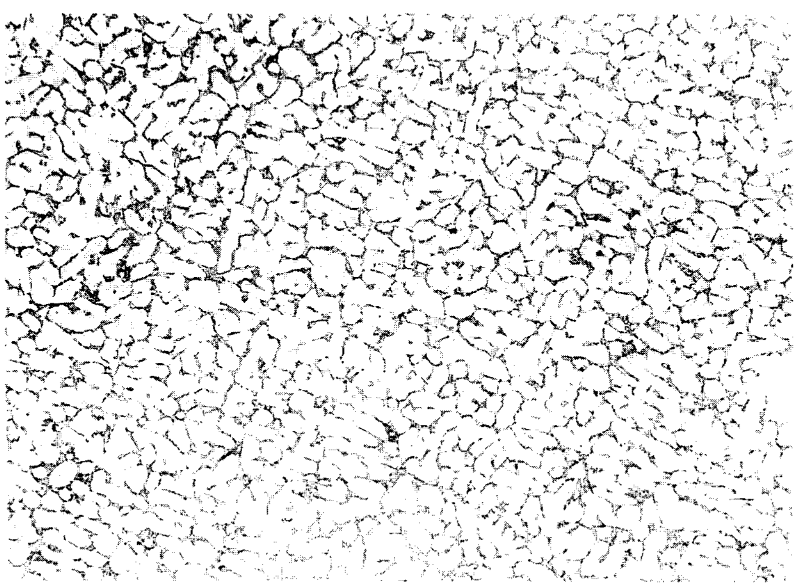
MICROSTRUCTURAL CHARACTERIZATION

The microstructure of the flow-cast alloy, seen under the optical microscope, and compared to a current die-cast alloy of the same composition, shows the typical appearance of stir-cast material (Fig. 3). The process of stirring during solidification ensures the growth of globular dendrites instead of typical tree-like ones. This implies that interconnections between dendrites are not allowed, and the melting of the low-temperature melting phase present around rounded dendrites (typically a eutectic phase) is enough to obtain a low-viscosity slurry.

Adding fibres to the slurry results in a discontinuous distribution inside the molten fraction without affecting the globular dendrites. As can be seen in the optical micrograph shown in Fig. 4 the resulting metal matrix composite thus consists of unreinforced globular dendrites surrounded by a



(a)



(b)

Fig. 3. Microstructure of the flow-cast alloy (unreinforced) (a), compared with a conventionally solidified (die-cast) alloy having the same composition (Al–6Si–2Cu) (b) (same magnification).

Fig. 4. Microstructure of the as-shaped MMC showing unreinforced rounded dendrites surrounded by fibres.

reinforced metallic phase having a local volume fraction of fibres higher than the average value of 0·10; moreover the local composition of the alloy around fibres is enriched in silicon relative to the average composition.

Because the slow stirring needed during the addition of fibres results in entrapment of air bubbles in the bulk metal, causing significant porosity, low-pressure shaping is required to obtain defect-free material. Moreover, this shaping generally causes a fibre orientation effect, depending on the metal flow and the shape of the die. It has also been reported that the presence of a globular solid phase can enhance fibre wettability during the addition of fibres, improving load transfer between the metal matrix and the reinforcement.[1]

MECHANICAL TESTING

Mechanical testing was carried out to provide engineering stress/strain curves, yield strength and ultimate tensile strength of the material as-shaped and after a thermal homogenization treatment at 480°C followed by a warm water quench at 80°C and ageing at 160°C for 18 hours, a heat treatment schedule typical of the Al–6Si–2Cu foundry alloy.

Testing was carried out in a computerized Instron machine, an electrical extensometer being placed on the sample gauge length (20 mm).

(a)

(b)

Fig. 5. Comparison between microstructure of shaped samples before (a) and after (b) heat treatment.

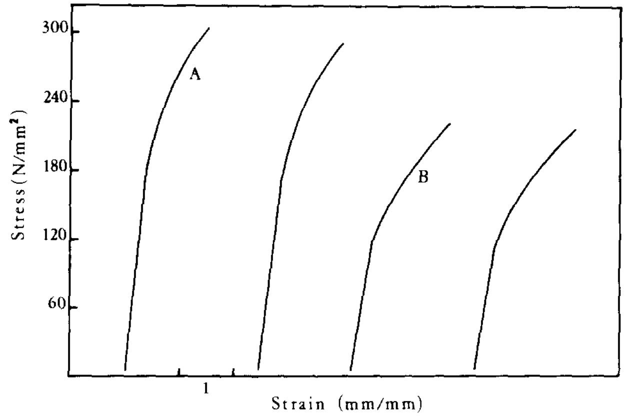


Fig. 6. Stress/strain curves obtained from as-shaped (A) and heat-treated (B) specimens (duplicate test).

Microstructures of the as-shaped and aged materials are shown in Fig. 5. Before heat treatment the lamellar eutectic is clearly visible around Al_2O_3 fibres (Fig. 5(a)) while after homogenization and ageing the eutectic appears reduced (Fig. 5(b)). It is interesting to note that the aspect ratio of the fibres is not reduced by breakage during processing because shaping occurs while fibres are surrounded by a molten phase.

A computerized Instron 1543 testing machine was used at a constant cross-head speed of a 1 mm/min in standard conditions, to obtain stress/strain curves. Typical curves are shown in Fig. 6. Heat treatment enhances both the UTS and YS, while values of elongation remain fairly low. Values of the YS, UTS, elongation and Young's modulus are given in Table 2.

The fracture surfaces of broken specimens have been examined in the scanning electron microscope. The metal matrix appears well bonded to the fibres (Fig. 7); both the metal matrix and the metal layer on the

TABLE 2
Mechanical Characteristics Obtained for As-shaped and Treated Material

	YS (MPa)	*UTS (MPa)*	*Elongation (mm/mm)*	*E (GPa)*
As-shaped	141	219	0·7	90
Heat-treated	250	300	0·5	92
Metal matrix (shaped and treated)[4]	190	255	10	68

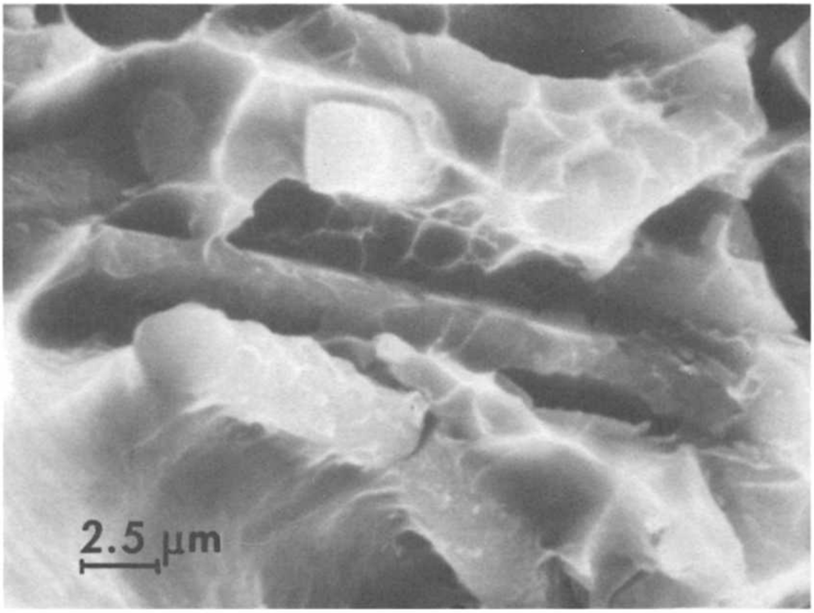


Fig. 7. Scanning electron micrograph of the fracture surface. The structure of dimples is clearly visible.

reinforcement exhibit a dimpled structure, showing that the mechanism of fracture is essentially microductile; pull-out of fibres or debonding of the metal matrix has not been detected.

DISCUSSION

The results obtained show that an MMC can be easily obtained (as already reported) using a semi-solid metal matrix. Moreover the use of static stirrers, as suggested here, reduces processing costs. When using low-cost ceramic stirrers as described in Ref. 5 MMC production can be planned in a current aluminium foundry without complex or expensive modification of existing facilities; subsequent shaping of the MMC to near-net-shape can be performed with conventional die-casting machines or low-pressure forging presses. The particular features of stir-cast semi-liquid alloys are in fact maintained in the MMC, which can be formed in the semi-solid state (by rheocasting or thixoforging) at low pressure and low temperature, obtaining all of the advantages already described.

The MMC that we have produced has a Young's modulus of about 91 GPa (average of measurements in the as-shaped and treated condition) which corresponds to the expected mixtures rule value; elastic continuity has therefore been achieved during production, resulting in a good metal/fibre interface. The specific modulus appears to be improved, from 25·2 to 33·7 GPa $cm^3 g^{-1}$; this latter value has also to be evaluated together with the obtained UTS value of 300 MPa (compared with 255 MPa for the metal matrix).

Stress/strain curves and the SEM evaluation show that a good metal-matrix/reinforcement interface has been achieved. The fracture surface in fact appears to be characterized by microdimples both in the metal matrix and in the metal layer remaining on the fibres after cracking, whereas debonding of the metal matrix from the Al_2O_3 fibres has not been observed. The dimples on the metal matrix show also that this latter contributes to yielding and cracking as also shown by the increase in UTS and YS after heat treatment.

The values of elongation obtained (less than 1%) appear to be much too low, considering the volume fraction of reinforcement and the ductile appearance of the fracture surface. This may also be linked to the non-uniform distribution of fibres inside the matrix. In fact, microstructural examination shows that the ceramic reinforcements are dispersed around the rounded dendrites produced during flow-casting. For example, a volume fraction of liquid of 0·25 during MMC production results in a local fibre volume fraction of 0·40 in material surrounding unreinforced islands of metal matrix, as seen in Fig. 4. This structure results in essentially brittle behaviour, from a macroscopic point of view, corresponding to an MMC having a higher volume fraction of reinforcement.

This trend could be avoided, in principle, by establishing suitable process parameters during production of the flow-cast metal matrix in order to achieve, if possible, a dendrite size comparable with or less than the length of the reinforcement. This can easily be achieved if the reinforcing fibres are long enough (as for the δ-Al_2O_3 used here) but could be troublesome for other kinds of smaller reinforcements.

CONCLUDING REMARKS

Results obtained in the preparation and characterization of an aluminium-alloy-based MMC allow us to draw several conclusions:

(i) Production of MMCs starting from a semi-solid matrix may be regarded as a suitable route for obtaining a low-cost, well-wetted composite of Al_2O_3 in an aluminium alloy matrix.
(ii) The metal matrix still has an important effect in determining the yielding process, as outlined by the occurrence of a dimple structure

in the fracture surface and by the increase of the UTS and YS after heat treatment.

(iii) Mechanical characteristics at room temperature are quite good; the value of the specific modulus, E/ρ, being improved from 25·2 to 33·7 GPa cm^3 g^{-1} for a UTS of 300 MPa.

(iv) The possibility of producing near-net-shape components in the semi-solid state at low temperature and low pressure, allows the manufacture of these components cheaply, without significant fibre breakage, with reduced thermochemical degradation of the fibre surface, and with little thermal fatigue of metallic dies.

(v) If required, the MMC product can also be completely remelted in order to achieve a lower viscosity, thus allowing conventional casting operations (for instance sand casting). In this case, however, care must be taken to avoid the sedimentation of fibres having different density from the metal matrix, and casting operations must be accurately controlled (especially in relation to timing) in such a way as to reduce, as far as possible, chemical interactions between the molten metal and the reinforcement (typical pouring temperatures being of the order of 750°C). This combination of properties can be considered particularly suitable for low-cost applications of MMCs.

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