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Microstructure and properties of squeeze cast Cu-carbon fibre metal matrix composite

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There have been reported attempts of producing Cu based MMCs employing solid phase routes. In this work, copper was reinforced with short carbon fibres by pressure infiltration (squeeze casting) of molten metal through dry-separated carbon fibres. The resulting MMC's microstructure revealed uniform distribution of fibres with minimum amount of clustering. Hardness values are considerably higher than that for the unreinforced matrix. Addition of carbon fibres has brought in strain in the crystal lattice of the matrix, resulting in higher microhardness of MMCs and improved wear resistance. Tensile strength values of MMCs at elevated temperatures are considerably higher than that of the unreinforced matrix processed under identical conditions. © *1999 Kluwer Academic Publishers*

1. Introduction

Metal matrix composites (MMC) provide a relatively novel way of strengthening metals. During the past years, successful attempts have been made to reinforce some of the metals/alloys with ceramic reinforcements—particles, whiskers, discontinuous fibres or continuous fibres, through solid phase bonding or liquid phase bonding. Solid phase bonding methods depend on the powder metallurgy route (PM) which requires hot pressing to obtain dense, pore-free products. This processing route is associated with increased cycle time and lower productivity.

The near-net-shape process "squeeze casting" [1] on the other hand, overcomes the above by its ability to produce MMC components in a single step. Aluminium and zinc based MMCs have been produced through squeeze casting, incorporating different ceramic reinforcements [2].

2. Present investigation

Copper is one of the most suitable engineering materials for applications that call for high thermal and electrical conductivities. Like any other metal, copper softens at elevated temperatures. Alloying is one of the solutions to overcome this problem, but beyond 500 °C, some of the Cu alloys (e.g. Cu-Cr and Cu-Ti) get overaged. At this juncture, it was thought worthwhile to attempt to reinforce copper by carbon fibres, for enhancing the thermal stability. Details of the efforts in producing copper based MMCs reinforced with alumina particles [3, 4], silicon carbide whiskers [5], carbon fibres [6, 7] and particles of SiC [8] through different routes have already been reported.

A critical review reveals that there has been no reported attempt wherein (a) molten copper was infiltrated through a preform of carbon fibre and (b) uniform distribution of other fibres (tried) without channelling/clustering. It is to be noted that clustering of fibres has been a perennial problem in processing of all the MMCs [9, 10].

Uniform distribution of fibres is an important factor which determines the useful properties and satisfactory performance of the MMCs. With the objective of producing Cu-based MMCs with uniformly distributed carbon fibres, and studying their properties, a series of trials was carried out and the findings are reported in this paper.

3. Experimental Details

The first step in producing MMCs is making the fibres suitable for infiltration of molten metal. This mandates the separation of individual filaments to avoid segregation and to ensure uniform distribution. As-received fibres were separated using a centrifuge in dry condition by subjecting the fibres to rotation for 2–3 min. This method proved to be very effective, as indicated by the wide variation in SEM photographs of as-received fibres and dry-separated fibres shown in Fig. 1. The properties of carbon fibres used are listed in Table I.

Calculated amount of fibres separated as above was placed inside a metallic die and heated to 300 °C. In the fibre producing factories, for ease of handling of the fibres and for making the product compact, resin binders are added during manufacture. To separate the filaments, removal of this resin binder is essential. This can be achieved either by treating the fibres with a chemical reagent (like ethyl methyl ketone) or by burning the resin. Treatment with chemical solvent is not very promising as the percolation of the reagent to the full bulk of fibre is inhibited by the strong adhesive film of the resin. The second method is more appealing since fibres are not subjected to any form of surface reaction and subsequent drying is not needed. In this work,

TABLE I Chemical composition of copper investigated (% by weight)

Cu	P	Zn	Bi
99.97 (min)	<0.01	0.012	<0.01

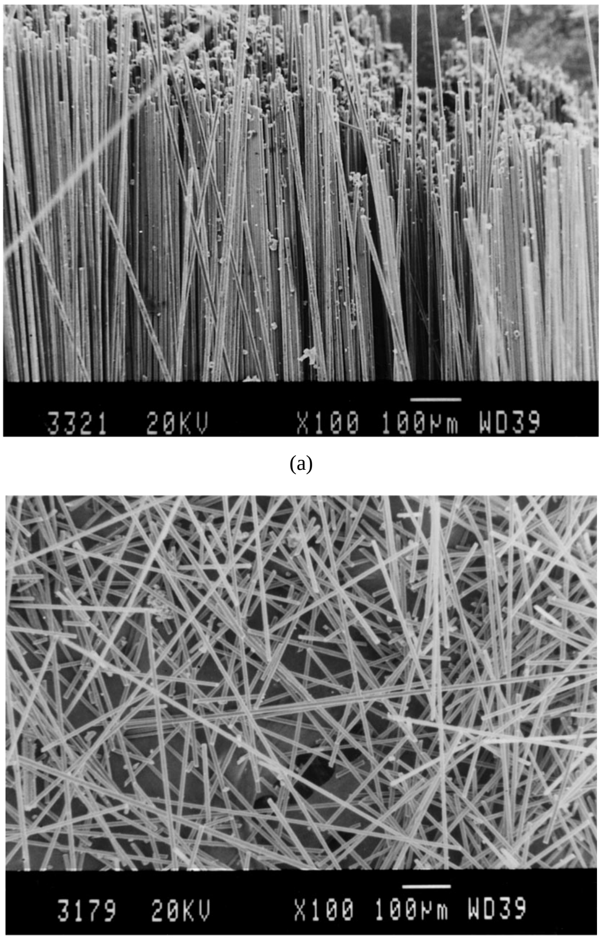
(Coefficient of thermal expansion of copper, $16.4 \times 10^{-6}\ \mathrm{K}^{-1}$)

TABLE II Properties of carbon fibre

Fibre type	Chemical composition	Density	Diameter	Coefficient of thermal expansion
Carbon	C-93%	1780 kg/m^3	6.8 μm	$8.4 \times 10^{-6}\ \mathrm{K}^{-1}$

TABLE III Optimized values of processing parameters in squeeze casting

Preform	Preform temperature	Die temperature	Super heat of melt	Squeeze pressure
Carbon fibre	300 °C	300 °C	150 °C	40 MPa



(a)

(b)

Figure 1 SEM photographs of carbon fibres: (a) as-received and (b) dry-separated.

heating to 300 °C removed all the resin binder, leaving behind only carbon fibres. Molten copper (chemical composition shown in Table II) at sufficient superheat was then poured in the die and pressure infiltrated (squeeze cast) into these fibres to result in planar random oriented metal matrix composite. The schematic of the process is shown in Fig. 2. The processing parameters adopted in the pressure infiltration are listed in Table III.

Cast MMC specimens were characterised for their microstructure, specific weight, hardness, microhardness, adhesive wear resistance and tensile strength (at room temperature and elevated temperatures of 100, 200 and 300 °C). For adhesive wear assessment, pin-on-disc configuration was made use of. Pure copper specimens (without any reinforcement) produced under identical conditions were also characterised for all the above mentioned properties, for comparison.

4. Results and discussions

4.1. Microstructure

The distribution of fibres in the matrix of copper is shown in the optical micrograph (Fig. 3) which highlights uniform distribution of fibres devoid of any clustering, confirming that the method employed has resulted in effective infiltration.

4.2. Specific weight

The variation of the specific weight of the cast MMC specimens with fibre content is shown in Fig. 4. Appreciable reduction in specific weight due to the presence of the lighter material, i.e., carbon in the matrix is obvious.

4.3. Hardness

The hardness values of the specimens are shown in Fig. 5. It is clear that the hardness of the composite is higher than that of the unreinforced copper processed under identical conditions. Further, hardness increases with increase in the fibre content.

4.4. Microhardness

In order to assess the influence of the reinforcement on the hardening of the matrix at a microscopic level, microhardness assessment was made at selected locations. The results are shown in Fig. 6. With increasing addition of reinforcement, microhardness increases. This is due to the difference in the coefficient of thermal expansion of carbon fibres and pure copper (Table II). Such difference between coefficient of thermal expansion of the matrix and the reinforcement causes generation of dislocations which in turn will bring in strain in the crystal lattice of the matrix leading to increased microhardness values. These dislocations are generated *in situ* and cannot be removed by heat treatment.

4.5. Wear

The variation of wear (adhesive wear) of the specimens for different volume fractions of the reinforcements is shown in Fig. 7. The wear of unreinforced matrix processed under identical conditions is also shown for comparison.

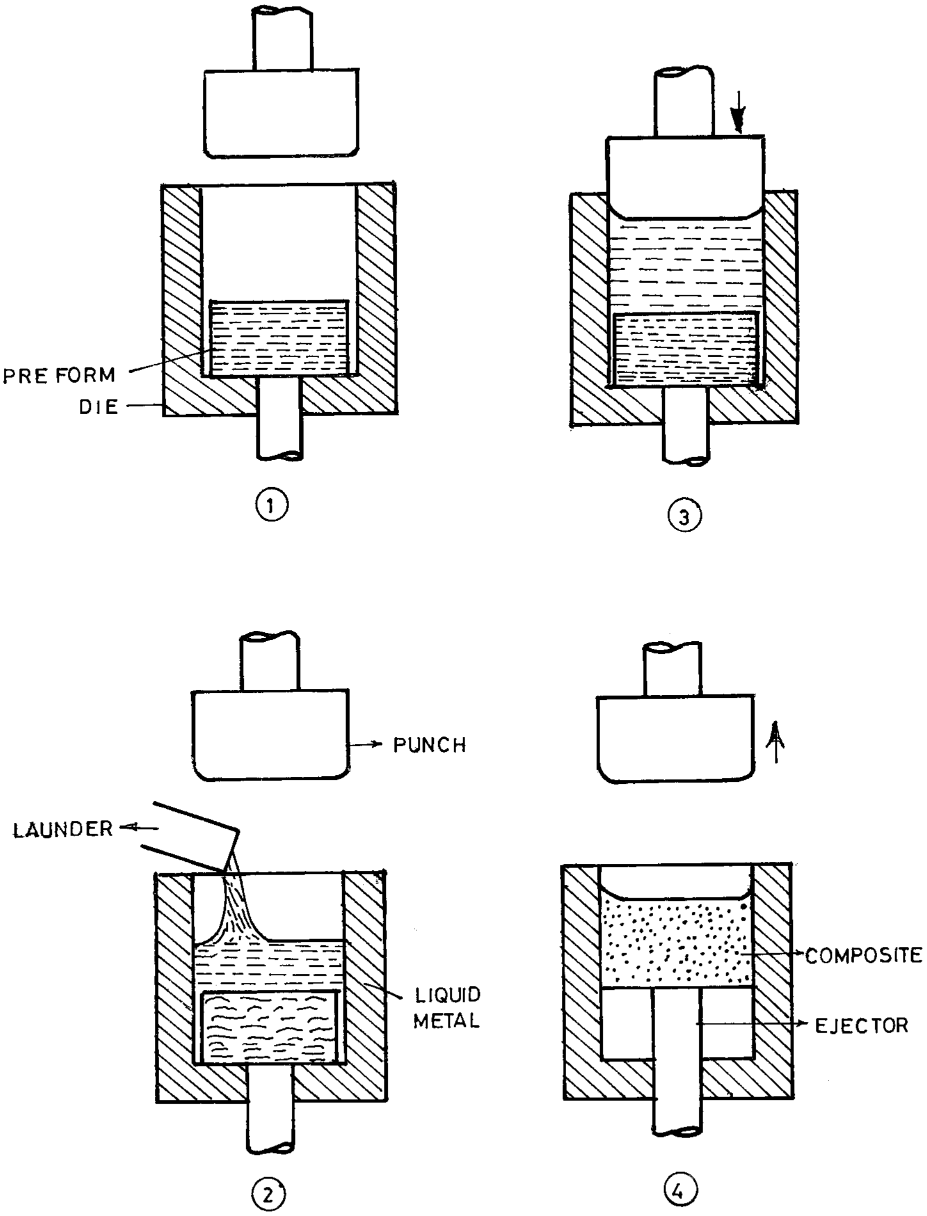


Figure 2 MMC production by pressure infiltration.

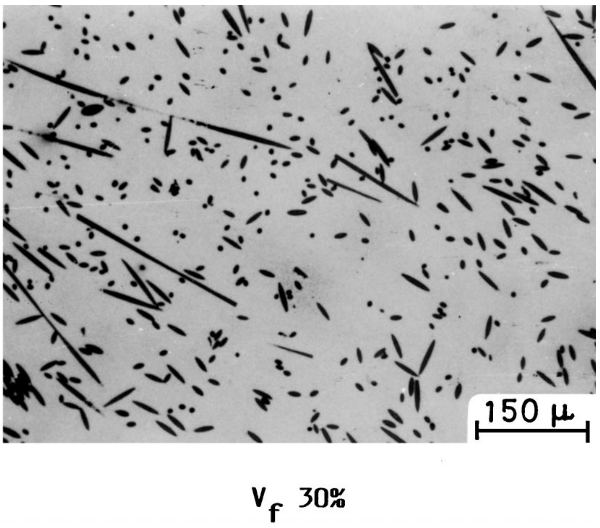


Figure 3 Distribution of fibres in the matrix (fibre volume fraction 30%).

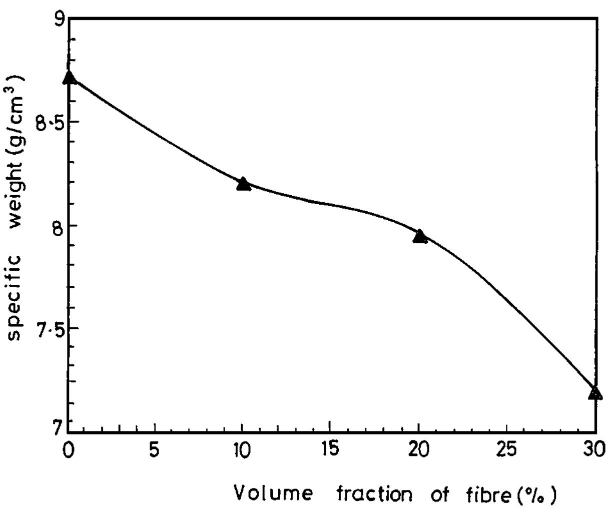


Figure 4 Variation of specific weight with fibre content.

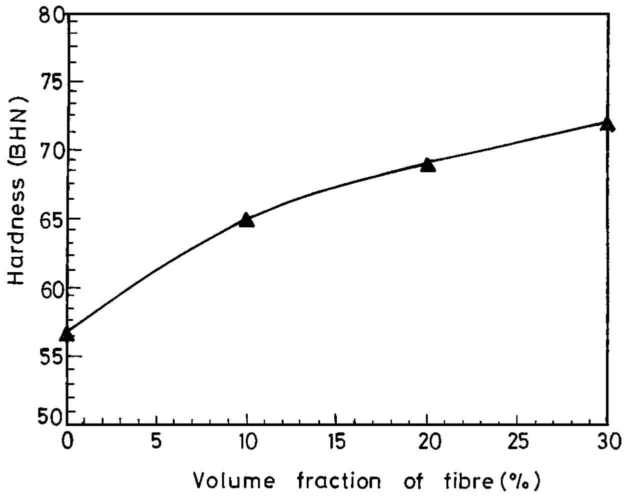


Figure 5 Variation of hardness with fibre content.

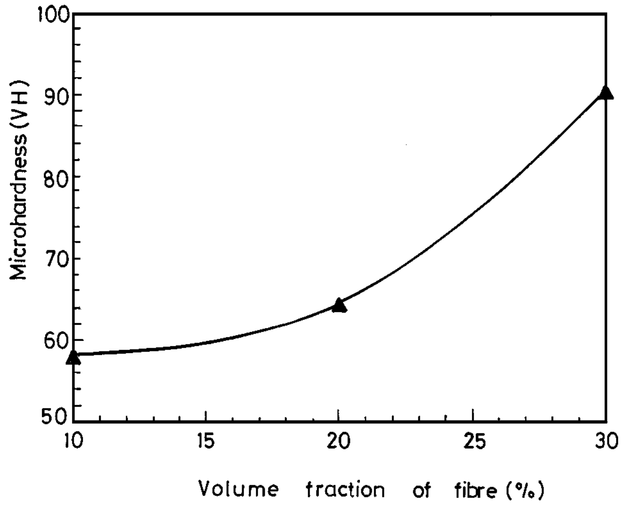


Figure 6 Variation of microhardness with fibre content.

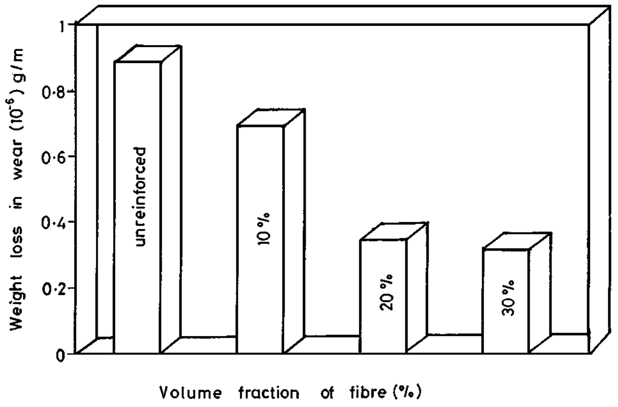


Figure 7 Variation of weight loss in wear with fibre content.

It is clear that wear is less for the composites compared to the unreinforced metal. Further, wear resistance keeps improving with increasing additions of reinforcement. In Cu-Carbon fibre MMC, reduction in wear is due to the enhanced hardness and due to the contribution of carbon as a lubricant. SEM photograph of worn surface (Fig. 8) shows the participation of fibres in wear.

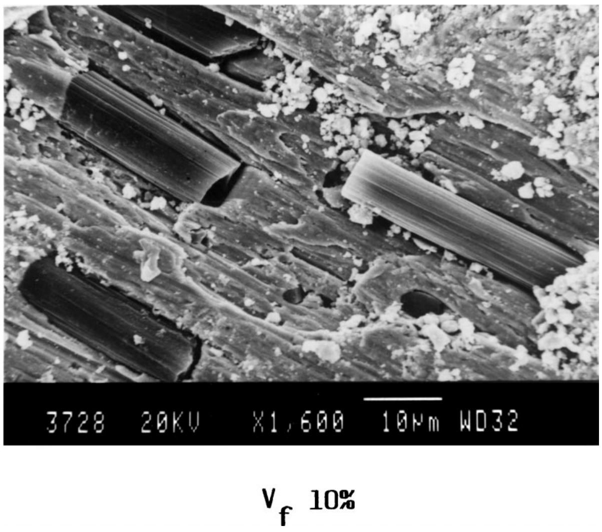
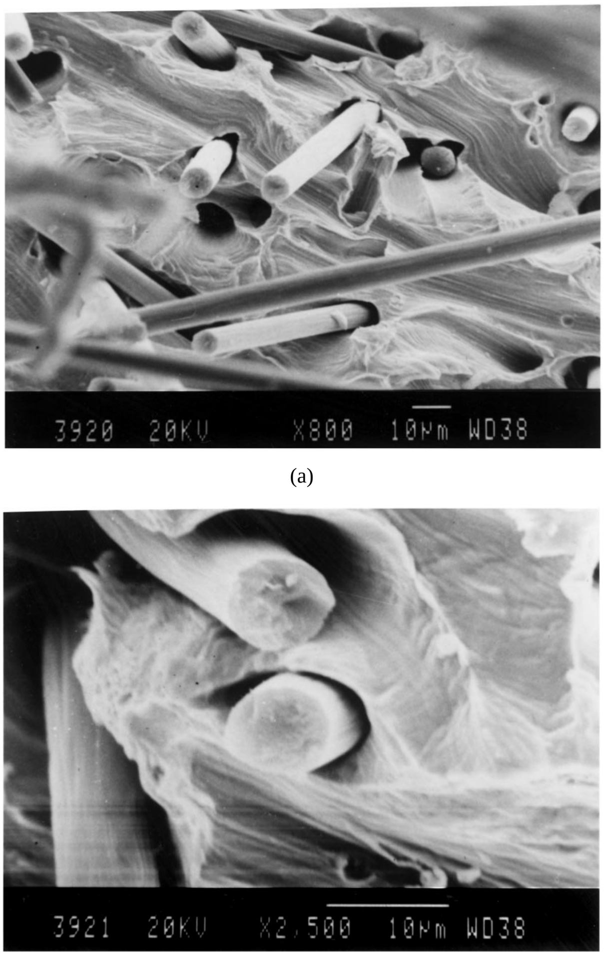


Figure 8 SEM photograph of worn surface (fibre volume fraction 10%).

4.6. Tensile strength

Assessment of tensile strength was carried out at room temperature and at selected elevated temperatures. On reinforcement, there is not much gain in room temperature strength. This is due to the fact that yielding of the matrix is not appreciable at room temperature [as revealed by SEM photograph, Fig. 9a]. Load



(a)

(b)

Figure 9 SEM photographs of fractured surfaces: (a) at room temperature (volume fraction 20%) and (b) at 200 °C (volume fraction 20%).

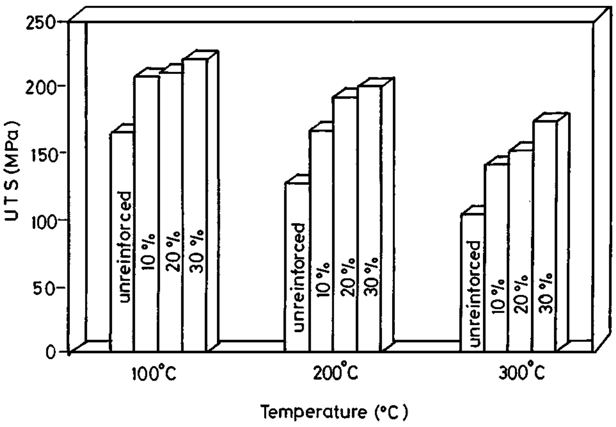


Figure 10 Variation of UTS with temperature for different volume fractions of fibre.

transfer to the fibres is more effective only if the matrix yields which takes place at higher temperatures as in Fig. 9b.

The results of high temperature strength tests are shown in Fig. 10. Yielding of the matrix and breakage of fibres are observed for specimens tested at elevated temperatures, indicating the increased participation of the reinforcement to oppose fracture. Thus, at temperature of 100, 200 and 300 °C, the ultimate tensile strength of the composite is much higher than that of the unreinforced material processed under identical conditions.

5. Conclusions

The above investigation has lead to the following salient inferences:

(a) By adopting the technique of dry separation of fibres, it has been possible to produce Cu based MMCs with uniform distribution, without any clustering.

(b) Hardness values of MMCs thus produced (Cu matrix-carbon fibre reinforcement) are significantly higher than that of the unreinforced matrix. Wear resistance too increases and is attributed to the lubricating nature of carbon fibre and the local work hardening of the matrix by increased dislocation densities arising from the presence of the reinforcement.

(c) Although the ambient strength is not benefitted by fibre reinforcement, there is significant improvement in UTS at elevated temperatures due to enhanced load transfer with the yielding of the matrix.

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