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Fabrication and characterisation of graphite/alumina reinforced copper composites

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The infiltration of graphite/alumina preforms with a bronze alloy has been investigated taking into account the influence of the binder type, the graphite/alumina content in the preform and the percentage of binder in water. The preforms showing an acceptable rigidity have been infiltrated with a CuSn12 bronze alloy by squeeze casting considering two different pouring temperatures. The composite produced has been characterised in terms of density, Brinell hardness, coefficient of thermal expansion, as well as friction and wear behaviour. The coefficient of friction for the bronze matrix composite is around 0.17, being three times lower than that shown by the unreinforced copper alloy. Given the contact geometry (ball of steel against a planar sample) and testing conditions (20°C, dry sliding, 40% humidity), the composite wear rate is around twenty times lower that of the bronze, being 10^{-6}mm^2/kg for the composite and 2×10^{-5} mm^2/kg for the bronze.

1. Introduction

The development of new materials offering a high thermal conductivity, a low coefficient of friction [1] with respect to the counterpart material, and, the ability to withstand high surface temperatures [2] is of great interest in the field of sliding components such as bearings.

The paper is dedicated to the development and characterisation of a low-cost bronze matrix composite for sliding bearing applications. Copper is a high thermal conductive material able to withstand high temperatures, but showing poor frictional and mechanical properties [3, 4]. Frictional properties are likely to be significantly improved by introducing graphite particles to copper [5]. Low cost short oxide fibres have also been added to copper in order to increase the copper mechanical properties. Squeeze casting has been employed to produce the bronze matrix composite. The process involves the manufacturing of a rigid porous graphite/alumina preform able to withstand the extreme infiltrating conditions required by copper alloys. The strength and stiffness of the preform is achieved through the use of a binder able to support the pressure and temperature to be applied in the squeeze casting process. The first part of the paper gives the main informations related to the fabrication and infiltration of graphite/alumina preforms. Details of the procedure and results are given elsewhere [6]. The characterisation of the composite in terms of hardness, CTE, friction and wear behaviour is presented in the second part.

2. Fabrication and squeeze casting infiltration of graphite alumina preforms

Graphite/alumina preforms has been prepared by mixing "Saffil" short alumina fibres with graphite flakes. Different binders have been investigated for the preparation of suitable rigid porous preforms. Table I gives the main characteristics of the binders selected in the study. For each binder, three different graphite/alumina volume fractions, i.e. 30/70, 50/50 and 70/30 and two percentages of binder dilution in water have been investigated. Depending on the graphite/alumina content, the final volume fraction of reinforcement ranges from 12 vol% to 15 vol%. The quality of the preforms after heat-treating has been estimated by different standards [6]. The preforms with a standard of quality no. 1 and 2 have not been considered strong enough to be

TABLE I Characteristics of the binders used

Binder name	Binder type	Perform Heat Treatment
Carsil 2000™ [7, 8]	sodium silicate	1000°C - 15 min-inert atmosphere
Syton X30™ [7, 8]	silica binder	1000°C - 30 min - inert atmosphere
Fabutit 705™ [7, 8]	ortophosphoric acid	900°C - 60 min - inert atmosphere
Silubit FB10™ [7, 8]	alumina/silica	900°C - 60 min - inert atmosphere

TABLE II Summary of the preform infiltration experiments with the four binders selected

Composite no.	Preform no.	Binder type	B%	$V_{F\text{-}Gr/Al}$	T_M	Preform Infiltration quality
1	1	Syton	10 vol%	30/70	1200	3
2	1	Syton	10 vol%	30/70	1100	2
3	2	Syton	10 vol%	50/50	1200	1
4	2	Syton	10 vol%	50/50	1100	1
5	4	Syton	50 vol%	30/70	1200	3
6	4	Syton	50 vol%	30/70	1100	3
7	5	Syton	50 vol%	50/50	1200	2
8	5	Syton	50 vol%	50/50	1100	1
9	7	Fabutit	3 wt%	30/70	1200	3
10	7	Fabutit	3 wt%	30/70	1100	2
11	8	Fabutit	3 wt%	50/50	1200	1
12	8	Fabutit	3 wt%	50/50	1100	1
13	8	Fabutit	20 wt%	30/70	1200	3
14	10	Fabutit	20 wt%	30/70	1100	3
15	11	Fabutit	20 wt%	50/50	1200	2
16	11	Fabutit	20 wt%	50/50	1100	1
17	13	Carsil	10 vol%	30/70	1200	5
18	13	Carsil	10 vol%	30/70	1100	4
19	14	Carsil	10 vol%	50/50	1200	4
20	14	Carsil	10 vol%	50/50	1100	4
21	15	Carsil	10 vol%	70/30	1200	1
22	15	Carsil	10 vol%	70/30	1100	1
23	16	Carsil	50 vol%	30/70	1200	5
24	16	Carsil	50 vol%	30/70	1100	5
25	17	Carsil	50 vol%	50/50	1200	4
26	17	Carsil	50 vol%	50/50	1100	4
27	18	Carsil	50 vol%	70/30	1200	1
28	18	Carsil	50 vol%	70/30	1100	1
29	19	Silubit	3 wt%	30/70	1200	3
30	19	Silubit	3 wt%	30/70	1100	3
31	22	Silubit	20 wt%	30/70	1200	3
32	22	Silubit	20 wt%	30/70	1100	3
33	23	Silubit	20 wt%	50/50	1200	2
34	23	Silubit	20 wt%	50/50	1100	2
35	24	Silubit	20 wt%	70/30	1200	1
36	24	Silubit	20 wt%	70/30	1100	1

infiltrated, while those characterised by standards no. 3 or 4 have been chosen for a later infiltration by squeeze casting. The alloy used for preform infiltration is a Cu-12wt%Sn binary bronze (CuSn12), in accordance with the standards DIN 1705. A typical microstructure of the CuSn12/Graphite-Alumina composite is shown in Fig. 1. The quality of the infiltrated preform has been estimated by considering five standards (Fig. 2). Experimental results concerning the study of the preform infiltration quality with respect to the binder type, the graphite/alumina content $V_{F\text{-}Gr/Al}$ in the preform, the percentage B% of binder in water and the metal pouring temperature T_M are shown in Table II. The binder type and the graphite/alumina volume fractions are the main processing parameters which have to be carefully optimised in order to obtain a suitable preform before and after infiltration. Carsil 2000™ is the most effective binder of those considered in the study. It is also worth noting that the lower the graphite content, the better the quality of the preform whatever the binder type. The composite material with the highest level of quality (standard 5) is obtained by infiltrating a Carsil 2000™ bonded preform containing 30 V_F% of graphite. However, taking into account the objective of producing a self-lubricating copper composite, it is recommended to infiltrate a 50/50 graphite/alumina preform binded with Carsil 2000™. This composite (no. 19) featuring a standard of quality no. 4 has been considered good enough to be characterised.

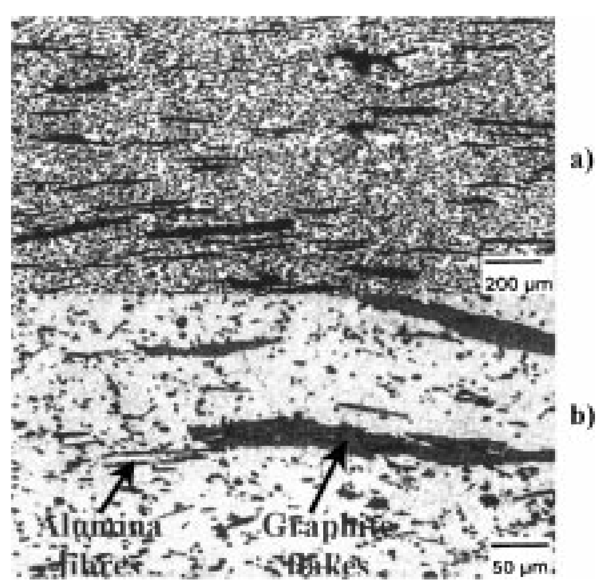

Figure 1 Microstructure of a CuSn12/graphite-alumina infiltrated composite at low (a) and high (b) magnification.

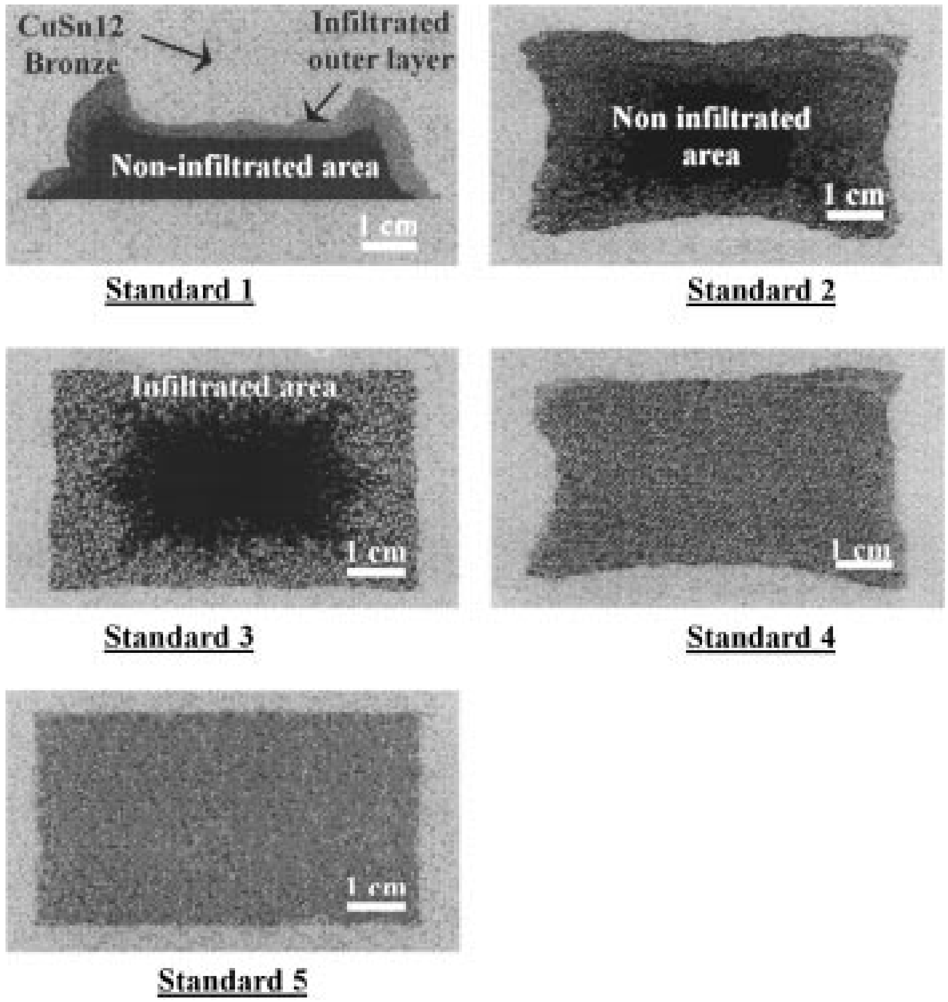

Figure 2 Standards for the preform infiltration quality. *standard 1*: partially infiltrated preform (infiltration of an outer layer of 3-4 mm); *standard 2*: nearly fully infiltrated preform with great deformation (20% of the sample is not infiltrated in a central zone, deformation of the sample greater than 30% in the infiltration direction); *standard 3*: nearly fully infiltrated preform with some deformation (less than 10% of the sample is not infiltrated, deformation less than 20% in the infiltration direction); *standard 4*: fully infiltrated preform with some deformation (less than 1% of the sample is not infiltrated, deformation less than 20% in the infiltration direction); *standard 5*: fully infiltrated preform without deformation (less than 1% of the sample is not infiltrated, deformation less than 10% in the infiltration direction).

TABLE III Density, Brinell hardness, and coefficient of thermal expansion of both the CuSn12 bronze and the CuSn12/graphite-alumina composite

			CTE (10^{-6} °C^{-1})			
Material	Density (kg/m^3)	Brinell Hardness	100°C	200°C	300°C	400°C
CuSn12 Bronze	8700	102	15.65	16	16.36	16.88
Composite No. 19	7600	102	15.24	15.4	15.65	16.07

3. Characterisation of the composite

3.1. Hardness and CTE testing

Table III shows the density, the hardness and the coefficient of thermal expansion measured for both the unreinforced CuSn12 bronze alloy and the composite number 19. The hardness of the composite is similar to that of the unreinforced matrix. The hardness of metal matrix composites reinforced with ceramic particles or fibres is often higher than that shown by the unreinforced matrix, but, in this study, the presence of the soft graphite flakes in the composite (hardness of 0.5–1 Mohs) is responsible for the relatively low hardness value obtained for the copper matrix composite. As observed in Table III, the composite CTE value is slighty lower with respect to the unreinforced bronze in the range of temperatures running from 100°C to 400°C. This is mainly due to the reinforcements incorporated which have low CTE values around 6×10^{-6} K^{-1} for "Saffil" fibres, and 5×10^{-6} K^{-1} for graphite flakes.

3.2. Friction and wear testing

Friction and wear testing were carried out in air (around 40% humidity) at room temperature (20°C) under unlubricated conditions in a BICERI universal wear test machine following the standard ASTM G99-90. The equipment was used in the pin-on-disk mode for friction tests and in the pin-on-reciprocating-plate mode for wear testing. In both tests, the counterpart material was a 10 mm bearing ball made of AISI-54100 steel.

3.2.1. Friction behaviour

Fig. 3 shows the measured coefficient of sliding friction as a function of the sliding time for the bronze alloy and the composite no. 19. The evolution of the

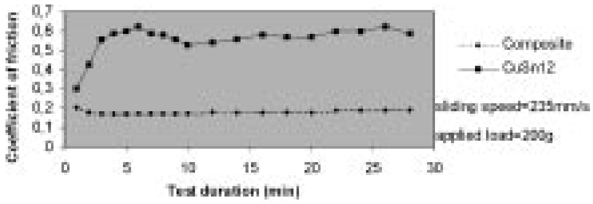

Figure 3 Coefficient of friction of CuSn12 bronze and composite versus test duration.

friction coefficient versus time usually shows two different states. The transient state 1 is developed at the beginning of the friction test, until a permanent steady state (state 2) is reached. In Fig. 3, the state 1 is clearly observed for the matrix, but not for the composite. In steady state, the coefficient of friction for the bronze matrix composite is close to 0.17, being about three times lower than the one of the unreinforced alloy ($\mu = 0.6$). The low friction coefficient of the composite should be explained considering the fine discontinuous graphite layer (Fig. 6) dispersed on the surface of the track and avoiding the metal-to-metal contact. nevertheless, given the nature of the friction mechanism which is dissipative, the reduction in plastic deformation due to the presence of δ-Al_2O_3 is also likely to contribute to the decrease in the friction coefficient.

3.2.2. Wear behaviour and mechanisms

The wear behaviour was studied for the bronze alloy and the number 19 composite. A constant sliding time of 30 minutes was chosen. The wear rate was studied by varying both the load applied and the sliding speed. Experimental results are given in Table IV for both the bronze and the composite. The wear rate WR, expressed in relation 1, was used to estimate the wear behaviour of both the composite and the bronze alloy.

$$\mathrm{WR} = \frac{\text{volume loss}}{\text{load} \times \text{sliding distance}} \tag{1}$$

The plot of the volume loss as a function of load× sliding distance is given in Fig. 4. The wear rate for the composite is far smaller than that suffered by the bronze alloy. The bronze wear rate is around twenty times higher that of the composite, being respectively

TABLE IV Wear testing conditions and results

Material	Sample no.	Load (kg)	Sliding speed (mm/s)	Weight loss (g)
Bronze	1	10.53	67	0.22
	2	10.53	100	0.323
	3	10.53	133	0.401
	4	7.02	67	0.141
	5	7.02	100	0.195
	6	7.02	133	0.253
	7	2.34	67	0.04
	8	2.34	100	0.054
	9	2.34	133	0.067
Composite no. 19	10	2.34	100	0.003
	11	7.02	133	0.017

2×10^{-5} mm^2/kg and 10^{-6} mm^2/kg for the bronze and the composite.

Wear of the bronze seems to be controlled by an adhesion mechanism. Adhesive wear occurs when two metallic components slide against each other under a given applied load, and no abrasive is present [9, 10]. The sliding of bronze against the steel ball results in "severe wear". The oxide film at the surface of the bronze is continuously dispersed at the point of contact of each material as a result of the tangential motion at the interface. Thus, the oxide film can not act as a lubricant but lead to a mechanism of severe wear. During the wear test against steel, bronze particles are produced giving rise to a great amount of debris. Some of the debris are not ejected from the track but spread again on the surface. Few bronze particles have also transferred to the steel counterpart where they remain attached. The wear track resulting from the sliding wear of the composite against steel under a load and speed of 2 34 kg and 67 mm/s respectively, is shown in Fig. 5. The composite shows almost no wear loss and grooves, and the plastic deformation is low whatever the wear conditions. A fine discontinuous graphite layer is dispersed on the surface of the track avoiding metal-to-metal contact. The lubricant properties of the graphite particles are mainly attributed to its anisotropic structure. During the wear event, shear stresses lead to a shear process of the graphite flakes. Afterwards, the graphite forms a film on the surface of the wear track which is able to protect the bulk material from adhesion wear. A few grooves are present on the surface of the steel balls with

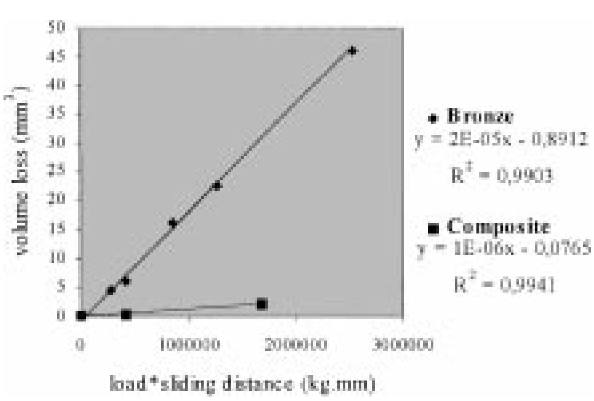

Figure 4 Volume loss versus load × sliding distance for both the composite and the bronze.

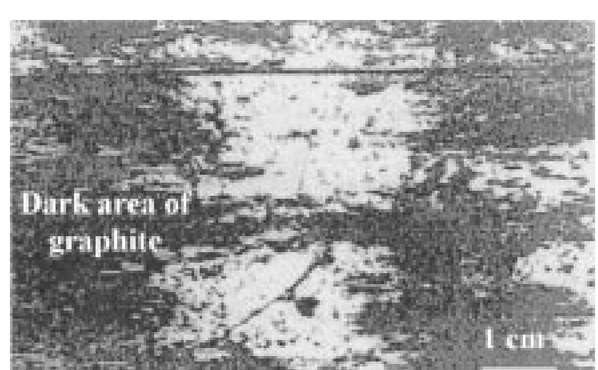

Figure 5 Micrograph of the CuSn12/graphite-alumina composite wear track.

some dispersed graphite. The wear of the ball may have resulted from an abrasive wear mechanism induced by the presence of the δ-alumina short fibres inside the matrix. Thus, mixing ceramic fibres with graphite flakes in a metal is a good way to (a) improve copper tribological properties, (b) reduce both the friction coefficient and the wear tendency of the metallic matrix.

4. Conclusions

The main conclusions obtained through the fabrication and characterisation of the bronze matrix composites are the following:

1. The binder type and the graphite volume fraction are the main processing parameters which have to be carefully optimised to obtain a completely infiltrated preform with no or few deformation. Carsil 2000™ is the most effective binder for producing a suitable preform. Moreover, the lower the graphite content, the better the quality of the preform whatever the binder type.
2. The hardness of the bronze matrix composite is similar to that measured for the matrix. The soft graphite flakes employed and the low reinforcement volume fraction are responsible for the relatively low hardness values obtained for the composites.
3. The coefficient of thermal expansion shown by the CuSn12 composite is slightly reduced with respect to the unreinforced bronze over the range of temperatures tested (100°C to 400°C).
4. The coefficient of friction for the bronze composite is around 0.17, being three times lower than that shown by the unreinforced copper alloy. This great reduction is likely to be consecutive to the presence of both the graphite flakes, acting as a solid lubricant and δ-Al_2O_3 fibres reducing the plastic deformation of the material.
5. Given the testing configuration and conditions, the composite exhibits an excellent wear resistance in comparison with that shown by the unreinforced bronze. The composite wear rate is twenty times higher that of the bronze alloy.
6. The excellent tribological properties obtained for the composite are attributed, for one part, to a thin graphite layer at the wear track surface. It impedes metal-to-metal contact which is responsible for the adhesion wear process suffered by the unreinforced alloy. δ-alumina short fibres are also supposed to play a significant role, reducing the plastic deformation of the composite. Mixing ceramic fibres with lubricant graphite in a metal is a good way of improving the composite tribological properties, reducing both the coefficient of friction and the wear tendency of the metallic matrix.

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