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Wear and mechanical properties of short carbon fiber reinforced copper matrix composites

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Abstract: The mechanical properties and wear behavior of short carbon fiber reinforced copper matrix composites was studied. In order to avoid any interfacial pronlems in the carbon fibre reinforced composites, the carbon fibers were coated with copper. The fibers were coated by electroless coating method and then characterized. Composites containing different amounts of carbon fibers were prepared by hot pressing technique. The results show that Carbon fiber/Cu–Ni–Fe composites showed higher hardness, higher wear resistance and bending strength than the common copper alloy when carbon fibers content is less than 15 vol.%. The predominant wear mechanisms were identified as adhesive wear in the alloy and adhesive wear accompanied with oxidative wear in the 12 vol.% carbon fiber/Cu–Ni–Fe composites.

Introduction

Carbon fiber reinforced metal matrix composites have been extensively used in a wide range of industrial applications because of their outstanding mechanical and/or physical properties [1-4] Carbon fibers have high specific strength, specific modulus, high thermal and electric conductivity, low expansion coefficient and good self-lubricant properties[5-8]. It is a good candidate as an additive in copper matrix composites. Zhu et al. [9] investigated the effects of processing parameters on the properties of carbon fiber/Cu composites, the relatively optimum production parameters were suggested. Xu et al. [10] studied the wear behavior of Cu/short carbon fiber under low load. Xia et al. [11] studied the wear and mechanical properties of carbon fiber reinforced copper alloy composites, they pointed out that the addition of Sn and Zn significantly improved the wear resistance. However, few works have systemically studied the effect of other alloy element Ni ,Fe and carbon fiber on tribological properties of carbon fiber/Cu composites .

Experimental

Raw materials

The copper (− 200mesh), nickel (− 200mesh) , ferrum (− 200mesh) powder were selected as matrix and carbon fibers (XA-S grade, Grafil Inc., USA) in the form of chopped fibers (4–8 mm length and 6 μm diameter) were used as reinforcements for making the composites.

Electroless coating of carbon fibre

The size and finish coatings present on the surface of the fibers were removed by ultrasonic cleaning in acetone at room temperature for 45 min. Subsequently they were coated with copper using the electroless process. A two-step pre-treatment, sensitisation and activation, was used for catalysing the carbon fibers. The cleaned fibers were activated using stannous chloride followed by

palladium chloride treatment. The fibers were coated in copper sulphate bath with sodium potassium tartarate as chelating agent, and formaldehyde as the reducing agent.

Preparation of composites by hot pressing process

The composite samples were produced using a hot pressing technique. A copper alloy was chosen as the matrix (the chemical composition is shown in Table 1). Carbon fibers were coated with a layer of copper to improve the wettability between carbon fibers and matrix. The coated fibers were cut to 0.6–1 mm in length and mixed with copper, nickel and ferrum powder. Two composites, carbon fiber/Cu–6Ni–1Fe (1) and carbon fiber/Cu–6Ni–2Fe (2) were mixed. The The mixture was then sintered for 30min at 1123Kand 100MPa under N_2 gas protection. For comparison, the copper alloy (Cu-6wt.%Ni-6wt.%Fe) alloy was also preparedunder the same conditions. Vickers hardness, bulk density, and bending strength were measured and are summarized in Table 2.

Table 1. Composition of the materials

Name of specimen	Composition (wt.%)
specimen 1	Carbon/Cu–6Ni–1Fe
specimen 2	Carbon/Cu–4Ni–2Fe
specimen 3	Cu–6Ni—2Fe

Wear Test

Wear properties of the designed composites and the copper alloy were measured by pin-on-plate wear test as shown in Fig. 1. A rotating plate specimen was rubbed against a fixed pin specimen under dry sliding conditions. All experiments were carried out at an air humidity of 55 ± 5RH% and a temperature of 293 ± 2 °K. A 30 mm diameter plate was machined out of the alloy, or designed composites, and the cylindrical pin specimen with the dimension of 4 mm in diameter was made of was made of GCr15-type bearing steel with a hardness of HRC 62 ± 2. No lubrication was used during wear tests. Prior to wear tests, all the contact surfaces were mechanically polished with 1000 grit emery papers. The weight loss of composites was calculated by measuring the disk weight before and after each wear test in an electrical balance with 0.1 mg accuracy. From the wear loss data, the value of wear rate, k, was estimated by using the Eq. (1):

$$k=m/t \quad (1)$$

Where m is the wear mass loss, t is the wear time.

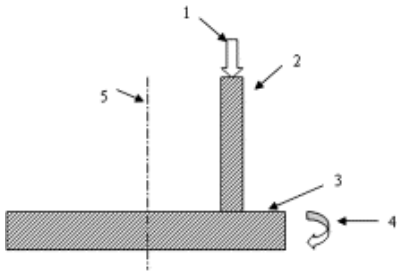

Fig. 1. Schematic view of wear test apparatus: (1) pressure direction; (2) fixed pin sample; (3) plate sample; (4) rotating direction; (5) rotating axis

The friction coefficient was also measured in the experiment under the following conditions: friction distance12mm; sliding speed 2m s^{-1}, and a period of 200 turns. The tester recorded the coefficient automatically. Five specimens were tested in each experiment and an average of the experimental data was taken as the result.

Experimental Results

Characterization of copper-coated fibre

Fig. 2 shows the photographs of un-coated and coated carbon fiberes. It can be seen that the fiber coated uniformly and the copper coating is continuous over the fiber. Optical micrograph of transverse cross-section of copper-coated carbon fibers is shown in Fig. 3. The coating thickness is uniform throughout the circumferences of the fibers.

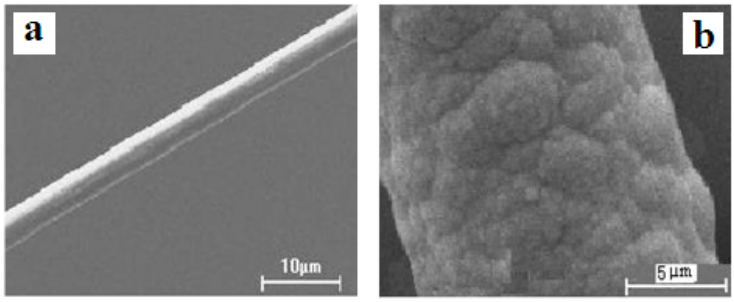

Fig. 2. Photographs of (a) un-coated carbon fibers and (b) coated carbon fibers

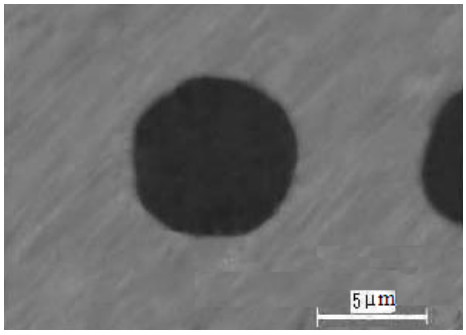

Fig. 3. Optical micrograph of transverse section of copper-coated carbon fibers

Mechanical Properties

The effects of volume fraction of carbon fibers on hardness, density, and bending strength of the sintered composites were studied. Results are shown in Table 2.

Table 2.Density, hardness, bending strength and friction coefficient of copper alloy and composites

Materials	Volume fraction of carbon fiber [%]	Density [g cm^{-3}]	Hardness, [HV]	Bending strength [Mpa]	Friction coefficient
copper alloy	0	8.80	84.1	113	0.38
Cf/ Cu–6Ni–1Fe	2	8.56	80.3	125	0.48
	5	8.23	83.6	152	0.26
	10	7.06	87.4	174	0.11
	15	6.56	96.4	180	0.09
	20	6.01	60.6	160	0.12
Cf/ Cu–6Ni–2Fe	2	8.59	90.3	129	0.52
	5	8.26	93.6	159	0.30
	10	7.12	106.5	180	0.15
	15	6.59	118.0	187	0.10
	20	6.21	80.6	162	0.16

The densities of composites are found to decrease with increasing carbon fibers addition, which is caused by the relatively lower density of the carbon fibers compared to that of the matrix. It is shown that the hardness and the bending strength of composites are higher than that of the copper alloy. The maximum hardness occurs in the composites with 15 vol.% fibers. The hardness and the bending strength of specimen 2 are slightly higher than that of specimen 1 with the same volume fraction of carbon fibers.

Tribological Properties

The variation in wear rate of the composites with volume fraction of carbon fibers is shown in Fig. 4. The carbon fibers zero point in the figure represents the wear rate for the copper alloy. It is seen that the wear rate of specimen 2 was reduced by incorporating of 10 vol.% carbon fibers, and remains unchanged with the increase of the content of carbon fiber. For specimen 1, the wear rate decreases with increasing content of carbon fibers to 10 vol.%. At carbon fiber content up to 10%, the wear rate increases slightly and remains constant.

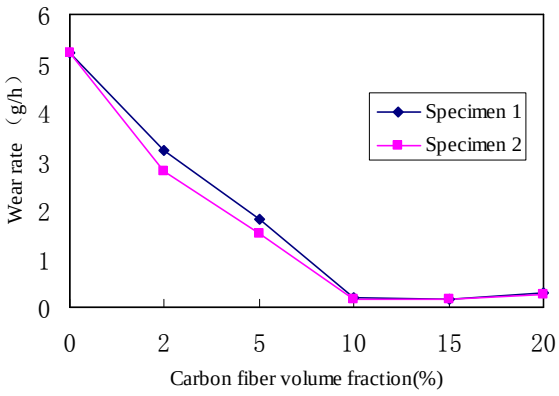

Fig. 4. Effect of carbon fiber volume fraction on the wear rate

The friction coefficient of composites as function of volume fraction of carbon fibers is shown in Fig. 5. The friction coefficient of specimens 1 and 2 decreases with increasing the content of carbon fibers from 5 vol.% to 20 vol.%. The addition of carbon fibers reduces the friction coefficient significantly(friction coefficient 0.09), in comparison with the alloy. The friction coefficient of specimen 1 is slightly higher than that of specimen 2. showed in Fig. 5. The value of wear rate increases initially with increasing sliding time, but then decreases with sliding time.

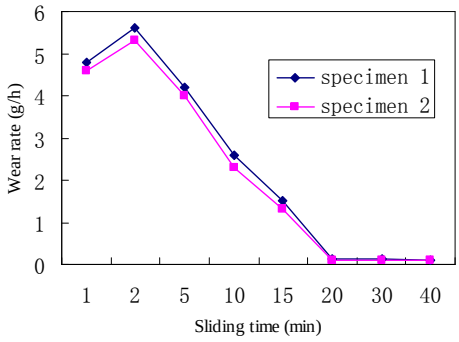

Fig. 5. The relationship between sliding time and wear rate for the 15vol.%Carbon fiber/Cu–4Ni–Fe and the 15vol.%Carbon fiber/Cu–4Ni–2Fe

Morphologies of the Worn Surfaces

The worn surface of the copper alloy disk after tribotesting against the pin with applied load of 50 N and sliding time of 40min is shown in Fig. 5. The wear tracks show evidence of plastic flow in the form of grooves parallel to the sliding direction, which indicates that severe deformation and ductile fracture occurred in the subsurface region far from the surface. The EDS conducted on the worn surface of the alloy shows that the surface is composed of Cu, Ni, and Fe. This suggests that the chemical compositions are the same as the alloy matrix

The worn surface of the copper alloy and composite disks after tribotesting against the pin at applied load of 50 N with the sliding distance of 60m is shown in Fig.6 (a) , (b)and (c) respectively. Wear steps are observed on the surfaces of specimens 1 and 2 with the 15 vol.% fibers, especially on the surface of specimen 1. EDS analysis reveals that the surfaces of the two composites is mainly composed of Cu and C, and the existence of Ni and Fe suggests that the transfer from pin to disk occurred, which is characteristic of adhesive wear. A certain quantity of oxygen is also observed, indicating that the fresh surface oxidized immediately under high interfacial temperature after the materials detached from the contact surface. Therefore, it is reasonable to conclude that the surface is the mixture of Cu, Ni and Fe oxides. The oxides of Ni are easily detached from the surface owing to their higher hardness and brittleness compared with the other kind of oxides. This leads to the formation of worn steps on the wear surface.

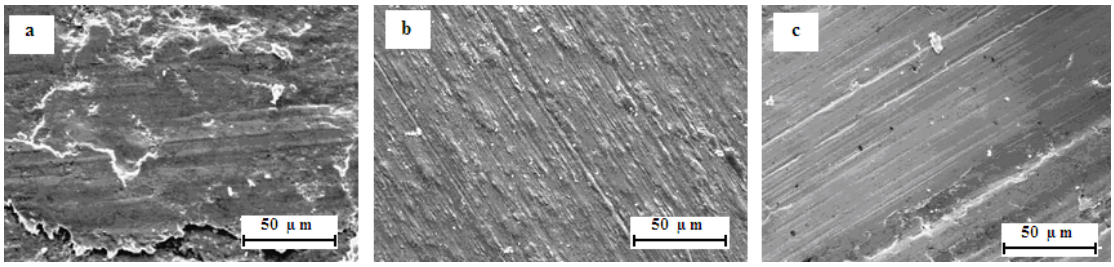

Fig. 6. The morphology of the worn surfaces (A) copper alloy (B) 15 vol.% Carbon fiber/ Cu–6Ni–Fe composite and (C) 15 vol.% Carbon fiber/ Cu–6Ni–2Fe composite

The wear properties of the carbon fiber reinforced Cu–Ni–Fe composites were carefully examined. The results indicate that the addition of carbon fibers significantly decreases the friction coefficient and wear rate of the alloy. The low hardness and strength of the alloy result in fracture of the matrix at a relatively deep location below the surface as seen in Fig. 6(a). The hardness of specimen 2 is higher than that of specimen 1, which leads to increase in wear resistance of specimen 2, showed in Fig. 6 (b) and 6 (c) .In the case of composite, the addition of carbon fibers hinders the movement of dislocations and formation of micro-cracks, resulting in an increase of the hardness and strength of the Cu–Ni–Fe alloy. The carbon film on the wear surface has the effect of lubrication and impedance to oxidation. Carbon fiber provided excellent self-lubricating ability at low temperature [12-14]. When the worn surfaces of composites are covered entirely by graphite powder, there is no significant change in wear rate. Therefore the wear mechanism of carbon fiber/Cu–Ni–Fe composite is mainly adhesive wear accompanied by oxidative wear.

Conclusions

Carbon fiber was very effective in reducing the wear and frictions of composites, particularly, the composites with 10-15 vol.% carbon fibers. The bending strength of carbon fiber/Cu–Ni–Fe composites increases with increasing content of carbon fibers. The maximum bending strength occurs when the content of carbon fibers is 15 vol.%.The friction coefficient of carbon

fiber/Cu–Ni–Fe was much lower than that of the alloy. The predominant wear mechanisms were identified as: adhesive wear in the alloy and adhesive wear accompanied with oxidative wear in the 12 vol.% carbon fiber/Cu–Ni–Fe composites.

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