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Resistance of fibrous reinforced silver matrix composites to repeated make-break arc erosion

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The resistance of fibrous reinforced silver matrix composites to repeated make-break arc erosion has been investigated in this study. Three different types of short fibers were used as reinforcements, including graphite short fibers, Saffil short fibers, and silicon carbide whiskers. The weight losses of eroded composites increase with fiber content, applied current, and test number due to the worse thermal conductivity of the composites and the higher remained temperatures on contact surfaces. The composites reinforced with Saffil short fibers exhibit the best erosion resistance of all reinforcements in the study because of the small spacings between Saffil short fibers and the strengthening of strong short-fiber skeletons. The effective contribution of short fibers to arc erosion resistance depends on their sizes to construct small-spacing and deeply-embedded skeletons.

1. Introduction

For the electrical contact materials widely used in electronic industry, a high strength and good wear resistance, high electrical and thermal conductivity, and good chemical stability are typically required properties to resist the severe arc erosion during operation [1–5]. Silver-based materials with high electrical and thermal conductivity have been well developed and applied as electrical contacts because of their good resistance to the damages caused by either single spark or repeated arc erosion [4–10]. Among them, particulate reinforced silver matrix composites, including CdO/Ag, SnO_2/Ag, TiO_2/Ag, TiB_2/Ag, and Al_2O_3/Ag etc., with further improved mechanical properties at only a small expense of electrical and thermal conductivity are especially used as up-graded electrical contact materials [11–14]. However, for high-power make-break contacts or brushes, contact materials must stand for much stronger mechanical collision beside to repeated arc erosion under sustained high temperatures during continuous arc formation [7–9]. Therefore, the composites with fibrous reinforcements, which provide a much stronger mechanical strengthening effect to the composites than particulate reinforcements, have been developed recently [14–16].

Because of the geometry effect and high viscosity to molten composites contributed by short fibers, silver matrix composites reinforced by short fibers positively exhibit a better resistance to static-gap, single spark erosion than those reinforced by particles [15, 16]. However, their resistance to repeated make-break arc erosion still needs to be systematically studied for evaluating their application suitability to up-graded high-power electrical contacts. In addition, the short fibers with larger aspect ratios and smaller sizes provide the composites better mechanical properties [14, 17], but, with increasing aspect ratio but decreasing size of short fibers, the effective strengthening depth might become smaller than the arc-affected melting or softening zone during arc formation. The arc-erosion behavior of the stronger composites reinforced with finer but shorter short fibers thus also needs to be clarified before the electrical contact industry decides which size of short fibers should be properly used. Therefore, the silver matrix composites containing three different sizes of fibrous reinforcements, including graphite short fibers (GR_{sf}), Saffil short fibers (SF_{sf}), and silicon carbide whiskers (SiC_w), were tested by repeated make-break arc erosion in this research to verify their arc erosion behavior and to compare the size effect of these short

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fibers. The arc-erosion resistance of these composites under different experimental conditions was measured to investigate their suitability to practical operation.

2. Experimental procedures

Three sizes of fibrous reinforcements were selected in this investigation, including graphite short fibers (7.0 μm in diameter), Saffil short fibers (Al_2O_3-3.8 wt% SiO_2, 3.0 μm in diameter), and silicon carbide whiskers (0.4 μm in diameter). An "electroless plating and hot pressing" process was used to produce bulk GR_{sf}/Ag, SF_{sf}/Ag, and SiC_w/Ag composite with 10 to 40 volume-percent, uniformly distributed reinforcements [11]. Due to the high applied stress of 300 MPa during hot pressing, these GR_{sf}, SF_{sf}, and SiC_w short fibers were broken into lengths of about 100–200 μm, 50–100 μm, and 10–15 μm respectively. The Vickers hardness of these composites increased with the addition of short fibers, and SiC_w/Ag composites exhibited the highest hardness, SF_{sf}/Ag second, GR_{sf}/Ag the lowest because of the higher mechanical strengthening effect provided by the finer reinforcements [11].

Repeated make-break arc erosion tests were applied to investigate the erosion behavior of GR_{sf}/Ag, SF_{sf}/Ag, and SiC_w/Ag composites. Fig. 1 schematically illustrates the experimental setup for these tests [16]. These hot-pressed composite specimens were cut to a size of $2.8 \times 4 \times 10$ mm^3, polished before tests, and set as both anode and cathode. The tests were performed at room temperature under a voltage of DC 24 Volts and circuit currents of 1.5, 2.5, and 3.5 Amp. The specimens were tested under a contact pressure of 500 g/cm^2 and a frequency of 2 times/sec for different times of arc operation up to 10,000 times. The weight losses of these composites after arc erosion tests were measured to analyze the erosion resistance of the composites reinforced by different types and contents of short fibers. Scanning electron microscopy (SEM, JEOL 5410) was used to investigate the surface morphologies and cross-sectional microstructures of the eroded composite specimens. The samples for the observation of SEM cross-sectional microstructures were prepared firstly by mounting, grinding, and then polishing.

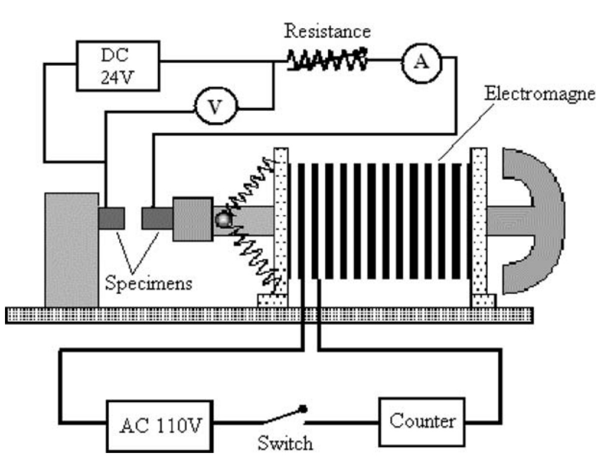


Figure 1 Schematic illustration of the experimental setup for repeated make-break arc erosion tests.

3. Results and discussion

Fig. 2 shows the weight losses of arc eroded GR_{sf}/Ag, SF_{sf}/Ag, and SiC_w/Ag composites after 10,000 times of arc operation under different circuit currents. It was obviously found that the weight losses of all composites increased with increasing applied currents. Due to higher arc energy provided by larger currents, more heats accumulating and higher temperatures remaining on the contact surfaces resulted in more materials molten and thus more serious damages occurred. The composites containing 40 vol% short fibers exhibited much more severe damages than those containing 20 vol% due to their worse thermal dissipation [15, 16]. With circuit currents larger than 2.5 Amp, the weight losses of the composites began to saturate at limited high values because of the gradual equilibrium between heat energy accumulation and dissipation by thermal conductivity through these composites. The differences in weight losses between 3.5 and 1.5 Amp-eroded composites with 40 vol% short fibers were much larger than those with 20 vol% short fibers due to the later heat equilibrium of the composites containing more low-conductivity reinforcements. In addition, by curve prediction using first-order exponential decay, there seemed almost no weight loss occurring with applied currents under 1.0 Amp. Under the arc erosion

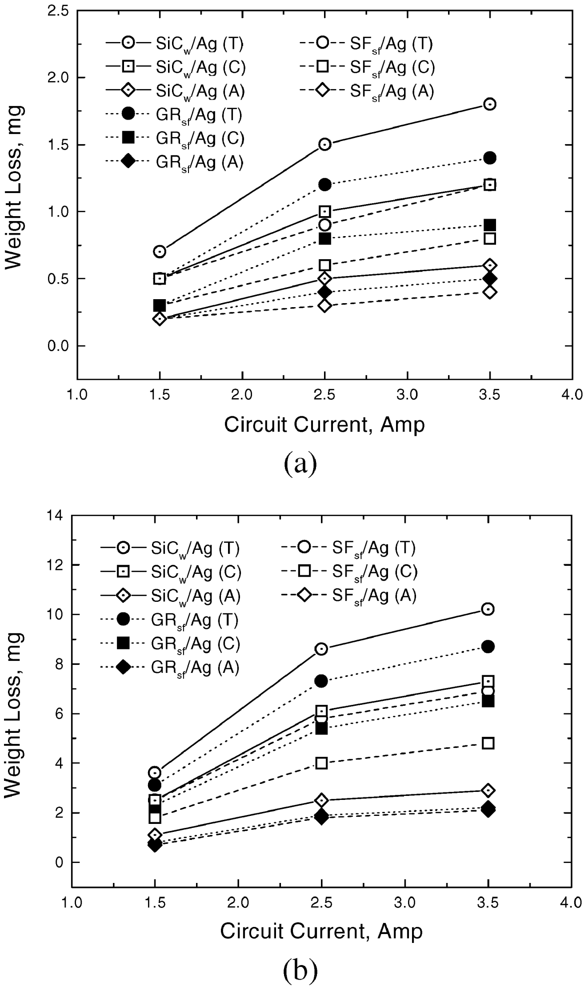
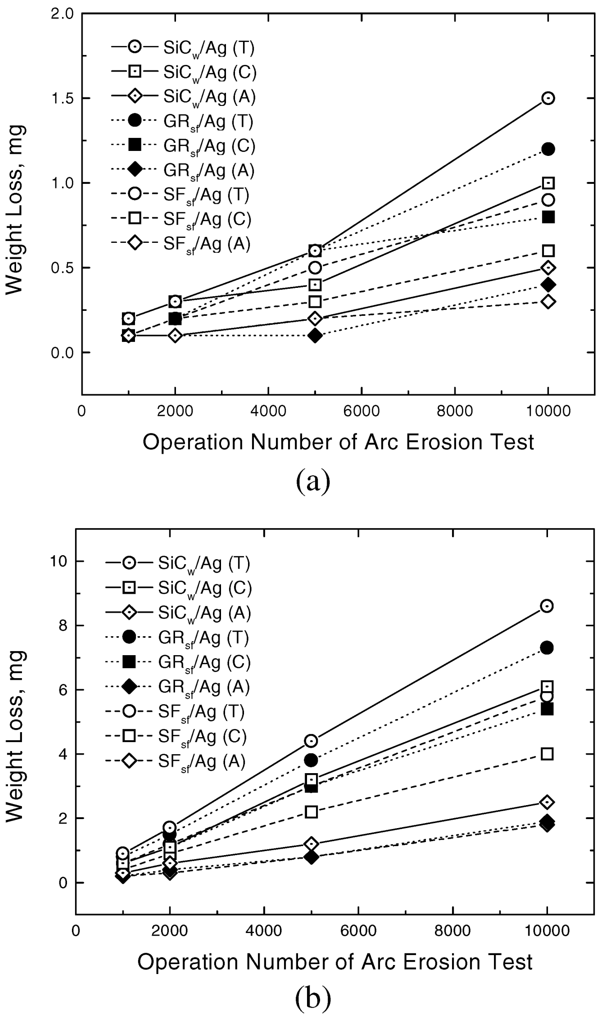


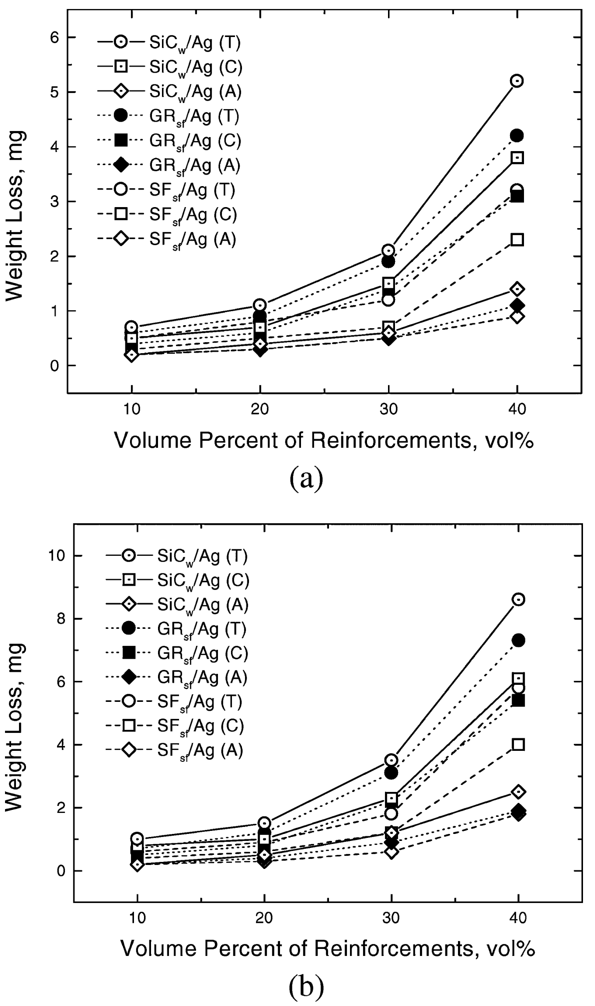
Figure 2 Weight losses of arc eroded (a) 20 and (b) 40 vol% GR_{sf}/Ag, SF_{sf}/Ag, and SiC_w/Ag composites after 10,000 times of arc operation under different currents (T: total weight loss, C: weight loss of cathode, A: weight loss of anode).



(a)

(b)

Figure 3 Weight losses of arc eroded (a) 20 and (b) 40 vol% GR_{sf}/Ag, SF_{sf}/Ag, and SiC_W/Ag composites after different times of arc operation under a current of 2.5 Amp (T: total weight loss, C: weight loss of cathode, A: weight loss of anode).



(a)

(b)

Figure 4 Weight losses of arc eroded GR_{sf}/Ag, SF_{sf}/Ag, and SiC_W/Ag composites with different volume percents of reinforcements, (a) after 5,000 times of arc operation under a current of 3.5 Amp and (b) after 10,000 times of arc operation under a current of 2.5 Amp (T: total weight loss, C: weight loss of cathode, A: weight loss of anode).

with very low currents, heat accumulation might be too small and too slow to result in high temperatures for the melting of the composites, and thus only few materials would lose because the high mechanical strengths of these composites at solid state [6, 11].

Fig. 3 shows the weight losses of arc eroded composites after different times of arc operation under a current of 2.5 Amp. The weight losses of the composites linearly increased with increasing operation times of erosion tests, especially for the composites containing high volume percents of short fibers shown in Fig. 3b. The linearly increased weight losses revealed that high temperatures and same erosion situation stabilized on contact surfaces since the early stage, i.e. equilibrium of heat accumulation and thermal dissipation at the beginning of erosion tests. While for the composites with small contents of short fibers, their weight losses remained low and did not stabilize until 5,000 times of arc operation, indicating the slower heat accumulation on the composites with better thermal conductivity. Therefore, for the application of these composites to high-power electrical contacts, a short period of interruption time after continuous operation of 5,000 times to cool the composites could be designed to highly extend the lifetime of the composites.

Fig. 4 shows the weight losses of arc eroded GR_{sf}/Ag, SF_{sf}/Ag, and SiC_W/Ag composites reinforced with different volume percents of short fibers. It was clearly found that these composite specimens were more severely damaged as the contents of short fibers increased, under an exponential tendency, whenever they were tested for different times of arc operation or under different applied currents. Especially for specimens reinforced with larger contents of short fibers than 30 vol%, the weight losses were relatively high due to their worse thermal conductivity [15, 16]. Although the larger contents of reinforcements contributed the composites higher mechanical properties [14], they resulted in lower thermal conductivity according to the following theoretical calculation [15–18].

$$k_{\mathrm{CL}} = V_{\mathrm{f}}k_{\mathrm{f}} + V_{\mathrm{m}}k_{\mathrm{m}} \tag{1}$$

$$k_{\mathrm{CT}} = (1 - \sqrt{V_{\mathrm{f}}})k_{\mathrm{m}} + \frac{\sqrt{V_{\mathrm{f}}}k_{\mathrm{m}}}{1 - \sqrt{V_{\mathrm{f}}}\left(1 - \frac{k_{\mathrm{m}}}{k_{\mathrm{f}}}\right)} \tag{2}$$

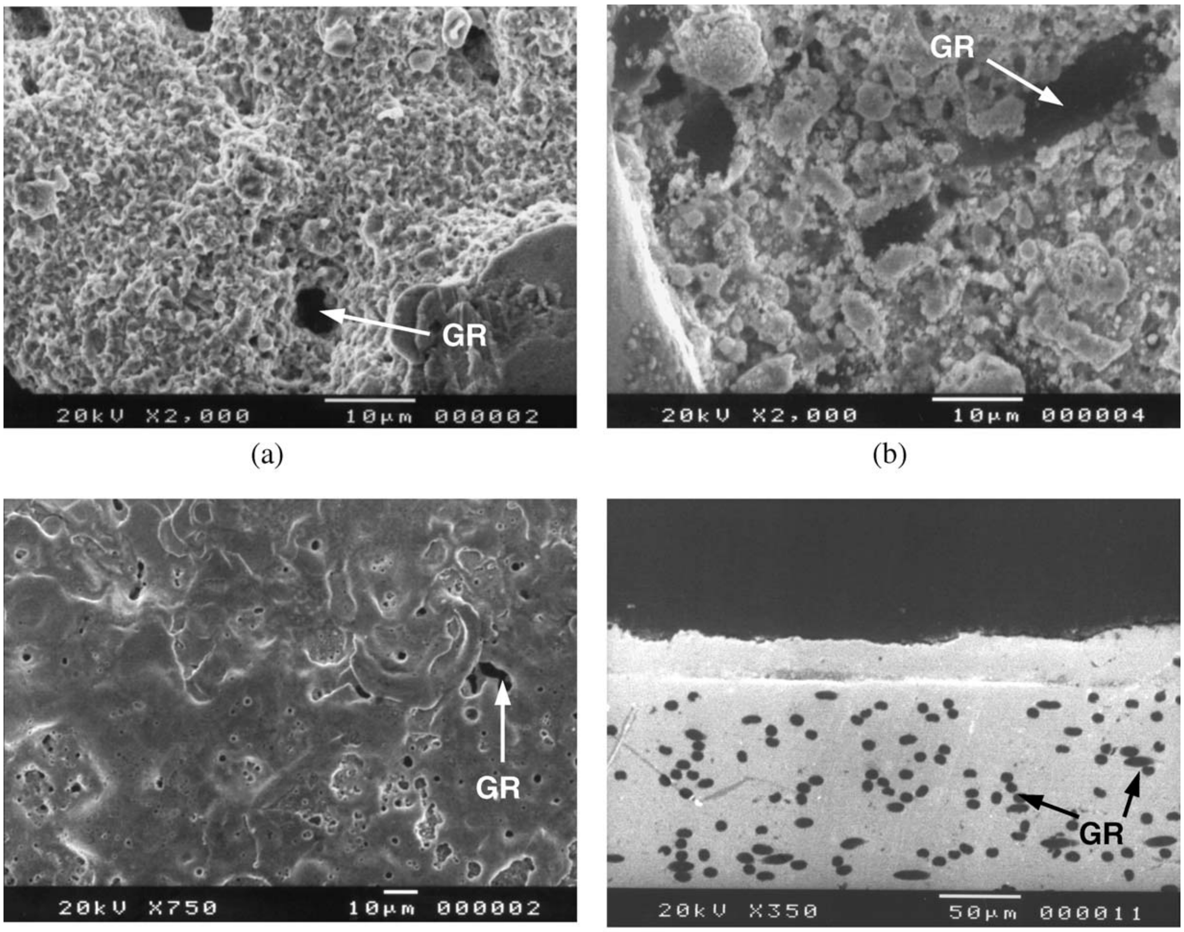
$$k_{\mathrm{C}} = \frac{3k_{\mathrm{CL}} + 5k_{\mathrm{CT}}}{8} \tag{3}$$

in which k_{f}, k_{m}, and k_{C} are the thermal conductivity of short fiber, matrix, and composite respectively. The symbol V_f is the volume percent of short fiber, and the subscripts L and T denote the anisotropic thermal conductivity of the composite in longitudinal and transverse directions, respectively. Obviously known from the above equations, the composites containing higher volume percents of short fibers resulted in lower thermal conductivity. More heat energy remained and accumulated on the contact surfaces of the composites containing more short fibers during repeated arc operation, thus leading to much larger amounts of silver softened and molten to splash under collision.

It was particularly found from the above Figs 2 to 4 that SiC_w/Ag composites always exhibited the largest weight losses among these three types of composites although the SiC_w/Ag composites had the highest mechanical properties provided by the strongest and largest aspect-ratio SiC whiskers [14]. It was realizable that, due to the softening and melting of silver matrix at high temperatures, the mechanical properties of the composites no longer played the dominant factor in the resistance to repeated arc erosion but did the thermal properties of the composites [15, 16]. However, these three composites presented similar thermal properties, and the SiC whiskers even had the highest thermal conductivity [15–18]. Unexpectedly, the SF_{sf}/Ag composites showed the best arc erosion resistance with a difference of about 1.5 times to that of SiC_w/Ag composites even though the SF_{sf}/Ag composites had the worst thermal conductivity. Moreover, the erosion behavior of short-fiber reinforced composites was reported to relate to the competition of their thermal conductivity and viscosity in previous study [16], but the difference in the viscosity of these three molten composites was still not identifiable from the following modified function given by Hsu *et al.* because the same geometry shape of these three short fibers [16].

$$\frac{\eta_C}{\eta_0} = \left(1 + \frac{6V_f}{1 - 2V_f}\right)^2 \tag{4}$$

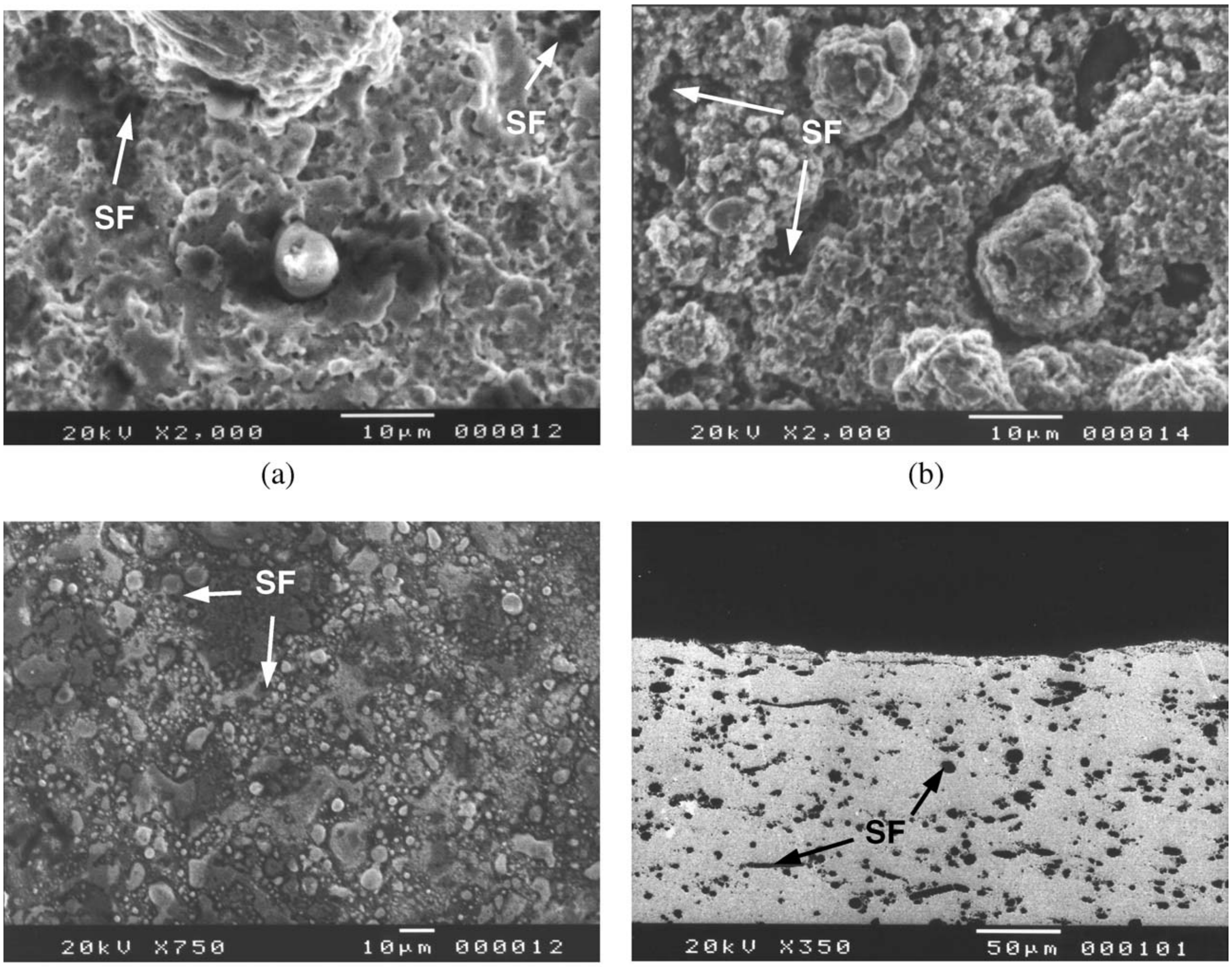
where η_C, and η_0 are the viscosity of molten composites and the intrinsic viscosity of the suspending liquids, respectively. Therefore, among these three composites reinforced by the same contents of short fibers with similar shapes and thermal conductivity, the differences in their arc erosion resistance were not just simply attributed to their thermal conductivity or viscosity as reported in reference [16]. The only differences between these fibrous reinforcements were their sizes and interface conditions with silver matrix. Thus, the following paragraphs further discuss the size and interface effects on the erosion behavior of the composites besides the thermal conductivity and viscosity mechanisms described in previous study [16].



(a) (b)

(c) (d)

Figure 5 Surface morphologies of arc eroded (a) 20 and (b) 40 vol% GR_{sf}/Ag composites tested as anodes, (c) 20 vol% GR_{sf}/Ag composites tested as cathodes; (d) cross-sectional microstructures of arc eroded 10 vol% GR_{sf}/Ag composites tested as cathodes after 10,000 times of arc operation under a current of 3.5 Amp.



(a) (b) (c) (d)

Figure 6 Surface morphologies of arc eroded (a) 20 and (b) 40 vol% SF_{sf}/Ag composites tested as anodes, (c) 20 vol% SF_{sf}/Ag composites tested as cathodes; (d) cross-sectional microstructures of arc eroded 10 vol% SF_{sf}/Ag composites tested as cathodes after 10,000 times of arc operation under a current of 3.5 Amp.

Figs 5 and 6 shows the surface morphologies and cross-sectional microstructures of arc eroded GR_{sf}/Ag and SF_{sf}/Ag composites after 10,000 times of arc operation. Due to the different sizes and interface conditions of the reinforcements, these two composites exhibited different erosion morphologies. In GR_{sf}/Ag composites, because of the large size of graphite short fibers of about 7 μm, there existed large spacings between these fibers for molten silver to easily squeeze and splash through them under the contact collision force during arc operation. Thus, as seen in Fig. 5, the evidence of molten silver flow and spreading between short fibers was obviously found on the eroded surfaces, especially for the composites tested as cathodes with a stronger arc bombardment as shown in Fig. 5c, leading to the large weight losses of the GR_{sf}/Ag composites. Associating with poor interfacial adhesion between graphite fibers and silver matrix, silver rich zones in lack of short fibers were clearly found on the surfaces of the eroded GR_{sf}/Ag composites as shown in Fig. 5d. Large spacings and decohesion of graphite short fibers lost the composites the arc erosion resistance. In comparison, in SF_{sf}/Ag composites, the spacings between finer Saffil short fibers were much smaller, and molten silver was thus more difficult to flow through the spacings due to its surface tension. Besides, Saffil short fibers also provided better interface adhesion to silver matrix because of the slight reaction between Al_2O_3 and silver [15], resulting in the agglomeration of the Saffil short fibers and silver matrix. As shown in Figs 6a to c, the agglomeration and reaction of the fibers and silver matrix inhibited the flow and splash of molten silver, and thus the silver rich zone was not observed in Fig. 6d. The stereo skeletons constructed by these Saffil short fibers were much dense, consolidated, and deeply embedded in the solid silver matrix below the arc-affected melting zone. They were more difficult to break and erode away under the collision of two contact electrodes.

However although the finest and stiffest SiC whiskers constructed the smallest spacings and strongest skeletons, providing SiC_w/Ag composites the highest mechanical strength [14], the composites were still the most severely damaged. Unlike the Saffil short-fiber skeletons deeply embedded in the solid silver matrix, the length of SiC whiskers of only about 10–15 μm was to short to support the whole skeleton structures and to resist the erosion with an arc-affected melting depth of about 30 μm identified by the thickness of silver rich zones in Fig. 5d. The composites reinforced with SiC whiskers of small lengths would behave just like those reinforced by particles and be easily shoveled under arc erosion.

Thus conclusively, based on the thermal conductivity and viscosity mechanisms established in reference [16], the effective strengthening of short fibers to repeated make-break arc erosion resistance further depended on their sizes, i.e. fine but long enough to construct small-spacing and deeply-embedded skeletons. Moreover, beyond reference [16], this study investigates the arc-erosion resistance of silver matrix composites under various currents and different times of arc operation for a practical damage simulation during application.

4. Conclusions

The arc erosion behavior of silver matrix composites containing different sizes of fibrous reinforcements was evaluated by repeated make-break arc erosion tests. With increasing applied currents, more heats accumulated and higher temperatures remained on the contact surfaces, resulting in more serious damages of the composites. Typically the weight losses of the composites linearly increased with arc operation times, revealing the stabilized erosion situation since the early stage. The weight losses of these composite specimens increased as the contents of short fibers increased due to the worse thermal conductivity. The SF_{sf}/Ag composites exhibited the best arc erosion resistance because of the small spacings between Saffil short fibers and the strong short-fiber skeletons. The effective strengthening of short fibers to arc erosion resistance depended on their sizes to construct small-spacing and deeply-embedded skeletons.

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