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Dynamic variation of arc discharge during current-carrying sliding and its effect on directional erosion

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ABSTRACT

Current-carrying sliding tests of sintered Cu/Graphite composite were conducted at 80 A and 20 m/s. The dynamic variation of arc discharge captured by a high speed camera revealed a migrating behavior of arc discharges along the sliding direction, and this, in turn, caused an aggravated erosion of worn surface, as consistently proved by SEM, EDS and 3D characterizations. Based on the erosion mechanism, arc discharge induced material erosion could be alleviated by various means, including inhibiting migration of arcs by proper surface modification and employing functionally gradient materials (from mechanical wear resistant to arc discharge erosion resistant) in current-carrying sliding conditions.

1. Introduction

The erosion and wear issues of contact wire under electrical operation have attracted researcher's attention as early as the 1920s [1]. In this early study, the contribution of arc discharge to the wear of contact wire was not as significant as that of the mechanical and chemical factors like weight, flexibility and lubrication. However, with the rapid technological development of electric railways over the past decades, the increased collecting current density of the strip and the increased frequency of contact break between strip and wire [2,3] have made the arc discharge more responsible for wear than other wear modes like mechanical wear and chemical attack. Considerable efforts [2,4–17] have been made to study the wear mechanism of materials under electrical sliding conditions in order to improve wear resistance and thus prolong the service life of facilities and reduce the maintenance cost. Nagasawa et al. [18] conducted laboratory wear tests with three types of wire materials sliding against an iron-base sintered alloy strip under electric current flow condition. They proposed a wear map for wear rate of trolley wire expressed with two parameters (normalized contact pressure and accumulated thermal energy). For a specific wire/strip pair, the wear rate of wire was related to heat generated at contact surfaces, including frictional heat, joule heat and arc induced heat. From the map it could be deducted that the increased current would lead to increased wear, which has been demonstrated repeatedly. However, this conclusion was drawn under a relatively mild condition (sliding velocity 1.1–5.6 m/s, load 10–40 N, current 10–30 A). For sliding tests carried out under a more severe circumstance (27.8 m/s and 200 A) [2], heat generated by arc discharge was enormous compared to that generated by friction and contact resistance, so the wear of the Cu-impregnated carbon strip was mainly caused by thermal effects of arc discharge, including melting, evaporation and dropping-out of impregnated Cu particles and oxidation of carbon. A proportional relationship was found between wear rate and the accumulated energy of arc discharge [2]. The greatly aggravated wear of materials caused by arc discharge as a result of contact break has also been reported by other studies [10,14,15]. In addition, the arc discharge could also lead to the formation of hard particles on the contact interface and thus gives rise to a severe wear [12].

Effects of arc discharge on wear of materials have been extensively investigated and consistent conclusions have been drawn, but most of the wear mechanisms were put forward from thermal perspective, which means they are mainly considered from an accumulated effect of thermal energy. This might neglect the serious material erosion caused by the transient high-intensity arc discharges. As a result, some inconsistent or even controversial measures have been proposed to suppress arc discharge and reduce wear. For instance, Nagasawa et al. [18] suggested decreasing heat generation on sliding surface and reducing contact pressure on the premise of not increasing contact loss to decrease wear rate of wire. But Chen [15] proposed to suppress arc discharge and decrease wear by increasing the normal force. Moreover, Yasar et al. [16] pointed out that arc erosion was the dominant wear mechanism only at lower pressure (30 kPa) and if the contact pressure was above 120 kPa the dominant wear mechanism would be abrasion wear which could be even worse than the arc erosion.

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A possible method to clarify the controversy and make the arc discharge (and the wear) more controllable lies in the clarification of arc discharge variation process and its effect on material erosion. However, to the best of our knowledge, few studies have been reported on the dynamic variation of arc discharge and its effect on material erosion during current-carrying sliding conditions. To this end, we employed a high speed camera to try to capture the dynamic process of arc discharge, and then characterized the worn surfaces to examine the effect of arc discharge on erosion of materials, followed by the discussion of erosion mechanisms.

2. Experimental

Electrical sliding tests were carried out on a current-carrying pin-on-disk tribometer. The schematic diagram is shown in Fig. 1. A constant-current power supply was employed to output a 125 Hz single-phase AC electric current up to 300 A with a trapezoidal waveform. The maximum sliding speed is 100 m/s. A photodiode array was employed to measure the intensity of arc light. Sintered Cu/Graphite composite and commercial QCr0.5 were used as the pin and the disk materials, respectively. Sliding tests were carried out at a speed of 20 m/s and a load of 60 N under both 0 A and 80 A. A JSM-5610LV SEM was employed to observe the worn surfaces. A μSurf (Nanofocus AG, Germany) device was employed to measure the 3D morphology of the worn surfaces. A NAC H-5 (Japan) high speed camera with a frame rate of 10,000 fps/s was used to observe and record the arc discharge process. The collecting frequency is 3000 Hz for both electrical and light parameters. Prior to each electrical sliding test, the friction pairs (pins and disks) were first polished by #1200 sandpaper and then pre-worn without electric current for 10 min to ensure a conformal contact, thus minimizing the arc discharge caused by unflatness of samples.

3. Results and discussion

3.1. *High-speed camara observation and light intensity measurement of arc discharges*

Fig. 2(a) gives the snapshots taken by high speed vedio camera, which shows the typical dynamic variation process of arc discharge during electrical sliding at 80 A. This process lasted ~2.8 ms. As shown, a small bright point, corresponding to the arc discharge, shows up at the middle part of the contact area (the second image). Then it moves down (namely the sliding direction) and becomes more easily visible due to increased intensity. Once it moves out of the contact area, a sudden increase in size and intensity of the light spot can be seen. However, it is noteworthy that the arc does not extinguish immediately after moving out of the contact interface. Instead, it reaches its maximum intensity and spot size after about 0.5 ms. It should also be noted that another bright point emerges in the contact area before the first arc completely vanishes. Then a repeated process as described above was observed. This dynamic variation process for arc discharge is also reflected by the light intensity signal, Fig. 2(b). As shown, the slowly increased light intensity at the begining corresponds to the arc discharge evolution within the contact interface. Then the light intensity increases drastically to the peak value, corresponding to the moment the arc discharge just moves out of interface. Then the gradually weaked arc discharge out of the contact interface leads to the decline of light intensity signal. However, the emerging of the subsequent arc discharge within the contact interface before the complete extinction of the frist one causes the overlapping of light intensity and thus gives rise to an increase in the light intensity signal at the end of this observed process, as seen in Fig. 2(b).

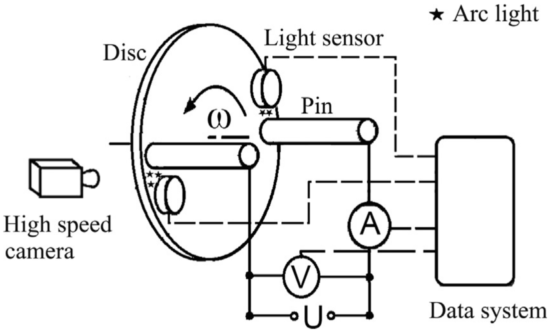

Fig. 1. Schematic diagram of test apparatus.

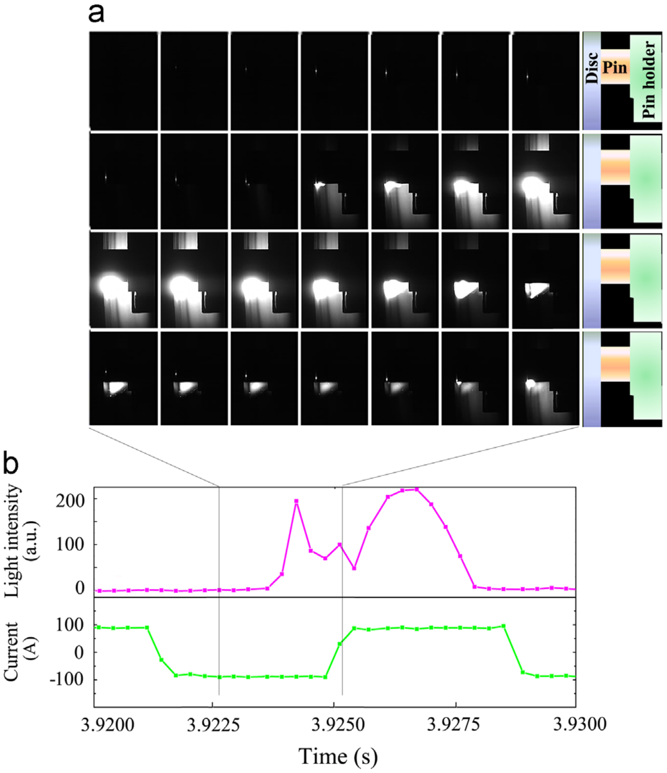

Fig. 2. (a) Snapshots of arc discharge process and (b) the corresponding arc light intensity signal. The rightmost schematic illustration shows the relative position of pin and disc.

Due to the unexpected high intensity and length of life, as well as the probably neglected destruction to sliding pairs, the arc discharge out of the contact area was further examined, Fig. 3. As seen, once being pulled out of the contact interface by the relative motion of the counting disc (sliding from top to bottom in Fig. 2), the arc drasitcally grows into a bright spot which further expands in volume and then a curved arc column could be identified after about 0.4 ms (the fourth image). This curved arc column has one end on the disc surface and the other at the side of the pin. Then, with the further increase in column length as a result of sliding, the arc column quickly narrows at the middle and then breaks after about 0.5 ms.

3.2. *Characterization of worn surfaces under current-carrying sliding*

Fig. 4 shows the optical images of worn surface of pin before and after sliding test under 80 A. As clearly seen, the arc discharge leads to a non-uniform worn surface and a large amount of black substance