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Research Article

From sparks to nanostructures: How arcing induces C/Cu wear and microstructural evolution

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Abstract: Most electric locomotives currently draw power from overhead contact lines. As train speeds continue to increase, irregularities in the contact wire cause system vibrations, leading to frequent pantograph-catenary arc discharges. The presence of arcing imparts distinctive friction, wear, and erosion product characteristics to the current-carrying friction process. Carbon/copper materials subjected to arc erosion exhibit significant differences in surface morphology and physicochemical properties compared to those resulting from pure mechanical wear. In this study, the phenomenon of arcing due to contact wire irregularities under simulated service conditions was investigated to examine the effects of arcing on the current-carrying wear behavior of carbon strips in pantograph-catenary systems and the resulting erosion products. The results indicate that current magnitude is positively correlated with the friction coefficient, temperature, arc ignition rate, and arc energy. Increased current shifts the

dominant wear mechanism from abrasive wear to arc-induced erosion. Moreover, higher current levels promote the emission of particles, especially small-sized ones, while the proportion of medium and large-sized particles also increases. However, sustained intense arcing slightly reduces the total particle count due to material sublimation. The microscopic morphology of the particles is predominantly characterized by onion-like carbon spheres encapsulated with copper nanoparticles and multi-walled carbon nanotubes. Additionally, arc erosion significantly enhances the crystallinity and graphitization degree of the carbon material. This study provides an in-depth analysis of arc-induced erosion products and contributes to the theoretical understanding of the microstructural evolution and graphitization behavior of carbon materials under arcing conditions.

Keywords: Current-carrying friction and wear, C/Cu, arc erosion, erosion products, onion-like carbon, graphitization

1 Introduction

In recent years, to alleviate urban traffic pressure, subways have become a key focus in urban rail transit construction. As of 2024, the operational mileage of subways in mainland China has reached 11,232 kilometers ^[1]. Among these, the rigid catenary system has become the primary method for subway power supply due to its simple structure, minimal tunnel space occupation, cost-effectiveness, and conductive capabilities ^[2].

As the primary power source for trains, the pantograph-catenary contact pair undergoes high-speed sliding friction under electrified conditions, inevitably leading to the occurrence of electric arcs ^[3]. Arcs can alter the current-carrying performance and wear mechanism of the contact pair ^[4]. Firstly, electric arcs significantly affect the system's electrical conductivity ^[5]. Arcs caused by system vibrations lead to fluctuations in current and voltage, and may even result in current interruption ^[6-7]. Yang et al. ^[8] found that arc sparks cause minor current distortion, while prolonged arc discharges lead to significant current distortion. Consequently, the occurrence of arcs alters the overall current-carrying efficiency and stability of the system ^[2, 9]. Furthermore, electric arcs severely impact the friction characteristics and wear mechanisms of materials. Mei et al. ^[10] concluded that the wear mechanisms of carbon strips against contact wire sliding electrical contacts mainly include arc erosion, heat-enhanced wear, and adhesive wear. The degree of surface damage and the temperature of the contact pair exhibit a strong positive correlation with arc intensity. Additionally, arc discharge substantially exacerbates the transfer of Cu material on the friction surface ^[11], while prolonged arc erosion duration also leads to an increase in the friction coefficient of carbon strips ^[11]. Ren et al. ^[2] suggested that the energy of arc discharge

is proportional to the sliding speed. High sliding speeds intensify arc discharge phenomena, and the energy generated by strong arc discharges can cause instantaneous flash temperatures on the contact surface to reach as high as 6,000 K ^[12], resulting in the immediate vaporization of carbon material into the surrounding air environment.

Moreover, particulate matter generated by the friction in pantograph-catenary systems represents one of the three primary sources of particulate emissions in railway systems. Research by Vânia Martins et al. ^[13] identified barium, copper, manganese, zinc, chromium, antimony, strontium, nickel, tin, cobalt, zirconium, and molybdenum as the trace elements most highly enriched in subway PM_{2.5}. According to an investigation by Keith Van Ryswyk et al. ^[14], subway commuting in Montreal contributes up to 97% of the daily exposure to copper in PM_{2.5}, with a portion of the copper in subway particulate matter believed to originate from the pantograph-catenary system ^[15]. The high temperatures induced by arcing in pantograph-catenary systems can lead to the sulfidation or oxidation of metal particles ^[16]. In fact, beyond mechanical friction, the particulate matter generated by the friction pairs in these systems is largely attributed to the increased friction products resulting from arcing during operation ^[17,18], thereby exacerbating particulate emissions. Simultaneously, arc erosion can significantly alter material properties. Zhou et al. ^[19] suggested that the high temperatures generated by arcing can cause the formation and rupture of graphite lubricating films on the surface of carbon materials. The instantaneous high temperatures from arc discharge may also lead to the melting and sublimation of graphite on material surfaces ^[20], adversely affecting system performance. Gao et al. ^[21] found that increased current induces more internal defects in carbon materials, resulting in a highly disordered structure and consequently deteriorating friction and wear performance. Conversely, Yu et al. ^[22] discovered that after current-carrying friction, a T-shaped crystal structure forms in the wear scars of hydrogenated amorphous carbon films, which enhances electrical conductivity.

While substantial research has been conducted on the current-carrying friction-wear characteristics of pantograph-catenary systems under arc erosion and the macroscopic changes in material surface morphology, few studies have explored the correlation between the erosive wear characteristics of carbon contact strips and particulate matter emissions, or examined the microstructural evolution of carbon materials under different electrical current conditions. To address this gap, this paper systematically investigates the impact of electric arcs on particulate emissions and erosion products by varying current intensity under conditions of contact wire irregularity. In rail transit systems, the irregularity of the contact wire is almost inevitable, which is essentially a stochastic process formed by the superposition of random irregularities with diverse wavelengths, phases and amplitudes ^[23]. Nevertheless, for an infinitely long catenary system, such irregularity can be approximated as a stationary and ergodic stochastic process and can generally be

represented by an ideal sinusoidal function ^[24–25]. Accordingly, in this paper, the periodic irregularity conditions of the contact wire are simulated by setting the irregularity of the copper disc with the aid of a pin-on-disc tribometer. The study establishes a link between the friction-wear properties of carbon strips and particulate emission levels, and identifies characteristic transformations in arc erosion products. This work contributes to a deeper understanding of arc erosion mechanisms in pantograph-catenary systems, providing a theoretical basis for reducing particulate emissions and enhancing operational reliability.

2 Test equipment and methodology

2.1 Test materials

The carbon strips used in this test are consistent with those currently employed in high-speed railway systems. The carbon strips were removed from the pantograph and processed into multiple cylindrical specimens, each with a diameter of 10 mm and a height of 30 mm. The material has a bulk density of 1.66 g/cm³, with a chemical composition of 85% carbon, and the remainder consisting of oxygen, sulfur, nitrogen, chlorine, phosphorus, and calcium. The friction counterpart disk was made of red copper with a purity of 99.9%, and the disk radius was 98 mm.

2.2 Test equipment

The test was conducted on an electrical friction wear test rig, with the experimental setup illustrated in Fig. 1(a). The test system mainly consists of a pin-on-disc electrical friction wear tester, a photodiode, a particulate sampler, and a particle counter (CLJ-A3016, Deans Instrument Technology Co. LTD, China). Prior to testing, the carbon pin was installed in the upper fixture and brought into contact with the copper disc. The electrical circuit, as schematically shown in Fig. 1(b), includes a DC regulated power supply, a variable resistor, the carbon pin, the copper disc, a current sensor, a voltage sensor, a data acquisition card, and connecting wires. A mechanical sensor continuously measures the normal load and shear force between the friction pairs in real time. A Hall current sensor and a voltage sensor monitor the circuit current and the voltage across the friction pairs, respectively. A high-precision photodiode (S5971, Hamamatsu Photonics K.K., Japan) with a wavelength response range of 300–1100 nm is used to detect arc intensity. All measured digital signals are recorded and stored in real time by a data acquisition module.

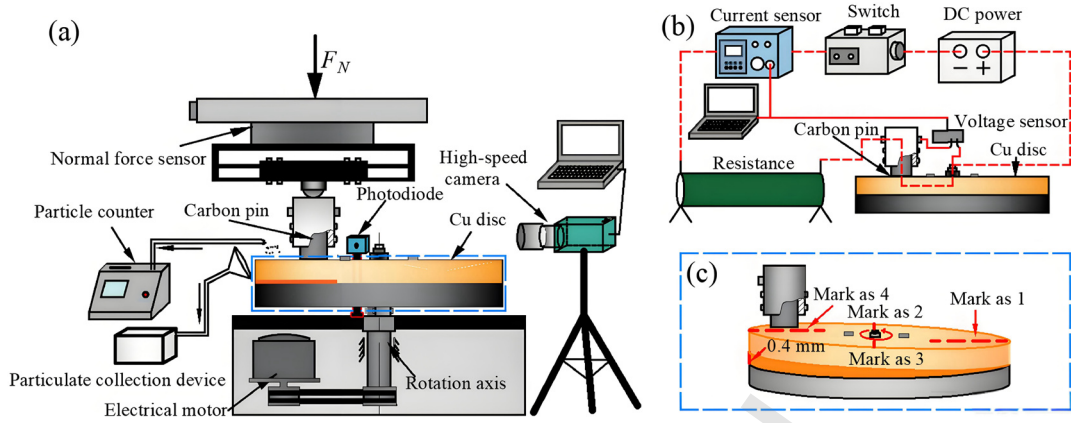


Fig. 1 Pin-on-disc current-carrying friction and wear test rig: (a) schematic diagram of the setup, (b) circuit diagram, (c) method for setting disc surface irregularities

2.3 Test procedure

Prior to formal testing, a preload was applied to ensure contact between the carbon pin and the copper disc, followed by several hours of low-speed running-in to achieve stable contact conditions. To simulate the arcing phenomenon caused by the irregularity of the contact wire, an uneven amplitude is introduced by elevating one side of the disk, as shown in Fig. 1(c). The irregularities of the contact wire are mainly classified into several types, including large irregularities, irregular suspension point positions, and minor irregularities^[23]. Among them, minor irregularities have amplitudes greater than 0.3 mm. Therefore, an irregularity amplitude of 0.4 mm is selected to study its impact on carbon strips wear. The highest point on the copper disc is marked as position 4, and the lowest as position 1. After running-in, the carbon pin was weighed and installed in the fixture to maintain tight contact with the copper disc, with a rotational radius of 82 mm. Tests were conducted under currents of 0, 25, 35, 50, 65, and 80 A, at a sliding speed of 2.06 m/s, a normal load of 25 N, and for 2400 cycles. During testing, particulate matter was continuously collected, and its concentration was monitored in real time. In addition, when the test lasted 9 min, an infrared thermometer (InfiRay M305, IRay Technology Co., Ltd., China) was used to detect instantaneous temperature in the contact area, respectively. After testing, the carbon specimen was removed and weighed, and wear debris on the copper disc was collected using conductive tape for subsequent analysis.

2.4 Data processing and characterization

Poor contact between the carbon pin and copper disc can result in arc discharge. Parameters such as current and voltage during the test were collected via a data acquisition system, and the cumulative arc energy was calculated using Equation (1):

$$E = \int U I d t \quad (1)$$

Where E is the cumulative arc energy (kJ), I is the circuit current (A), and U is the voltage drop between the copper disc and the carbon pin (V). The integration is performed over the entire duration of the test.

The arc occurrence rate is used to quantify the frequency of arc generation under irregular conditions, expressed by Equation (2):

$$K = \frac{\sum_{i=1}^n N_i \Delta t}{t} \times 100\% \quad (2)$$

Where K is the arc occurrence rate, N is the number of arc occurrences, Δt is the duration of a single arc, and t is the total duration. Arc light signals were acquired using a photodiode at a sampling frequency of 40 Hz. In the absence of arcing, the measured light intensity was zero, while the occurrence of an arc yielded a non-zero light intensity. The arcing duration throughout the test was calculated by dividing the number of data points exhibiting non-zero light intensity by 40.

Current-carrying efficiency and current-carrying stability are used to characterize the current transfer quality of the friction pair. The current-carrying efficiency, which reflects the dynamic contact state of the current-carrying system, is expressed by Equation (3). The current-carrying stability, which indicates the magnitude of current fluctuation during the conduction process, is expressed by Equation (4).

$$\eta = \frac{\bar{I}}{I_0} \times 100\% \quad (3)$$

Where η is the current-carrying efficiency, where $\bar{I}$ is the average current during the test and I_0 is the current when the friction pair is in stationary contact.

$$\delta = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (I_i - \bar{I})^2}}{\bar{I}} \times 100\% \quad (4)$$

Where δ represents the current-carrying stability, I_i is the instantaneous sampled current value (A), and n is the total number of current data points collected during the test.

Arc duration is one of the key parameters characterizing arc behavior. In the experiment, arc duration was recorded using a high-speed camera (i-SPEED 717, iX Cameras Ltd., UK). The camera captured arc images between the contact pairs at a frame rate of 1000 frames per second, and the arc duration was determined by counting the number of frames from arc initiation to extinction.

The worn surfaces and debris morphology of the materials were examined using a scanning electron microscope (SEM; HITACHI SU8010, HITACHI, Japan) and an energy dispersive spectrometer (EDS; X-Flash 6I60, Bruker, USA). A 3D profilometer (Zygo, ZeGage™ Pro HR, Zygo Corporation, USA) was employed to measure the two-dimensional profiles and three-dimensional topography of the wear scars. Additionally, the chemical composition of several typical wear scars was analyzed by X-ray photoelectron spectroscopy (XPS; Thermo Fisher Scientific, USA). Collected particles from filter papers were ultrasonically dispersed, uniformly dropped onto molybdenum

films, and then examined by transmission electron microscopy (TEM, JEM-2100plus) to observe morphological characteristics and analyze elemental distribution.

3 Results and discussion

3.1 Current-carrying friction and wear performance

Fig. 2(a) shows the evolution of the friction coefficient with the number of cycles for the C/Cu contact pair under different current levels. In the absence of electrical current, the friction coefficient remains stable without fluctuations. When current is applied, slight fluctuations in the friction coefficient emerge and become progressively more pronounced with increasing current. The most severe fluctuations occur at 80 A. Comparison reveals that the friction coefficient reaches its minimum value at 35 A. Beyond this point, the average friction coefficient increases with further increase in current. The introduction of electrical current significantly deteriorates the friction and wear performance of the materials. Moreover, as shown in Fig. 2(b), the application of current leads to a substantial increase in wear loss, with a particularly notable rise observed when the current exceeds 50 A. At 80 A, the wear loss is nearly 266 times higher than that under dry sliding conditions without current. This indicates that the material damage under current-carrying conditions is far more severe than under conventional dry friction, and this effect becomes increasingly pronounced with higher currents. Additionally, under 0 A condition, the contact pair temperature measured in the late stage of the test (at 2160 cycles) is only 29 °C. With current applied, the temperature rises continuously, reaching 365 °C at 80 A. This temperature increase is attributed not only to frictional heating but also to additional Joule heating and arc-induced heating caused by the current. Higher current levels generate more heat, resulting in a significant temperature rise on the material surface.

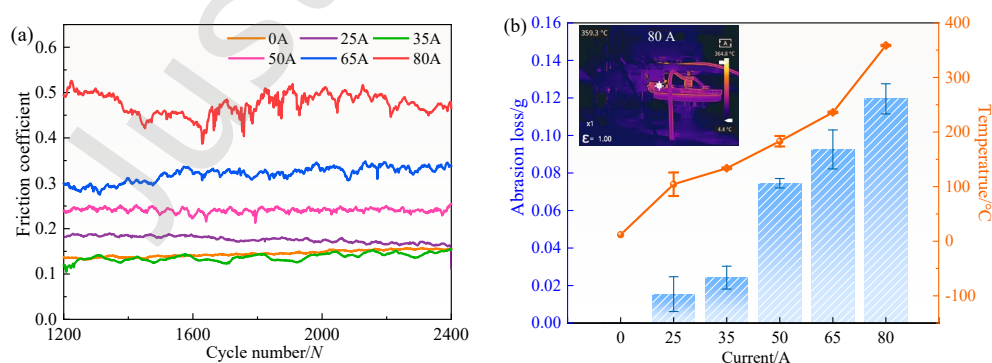


Fig. 2 Tribological performance of the contact pair under different current: (a) friction coefficient; (b) wear loss and temperature

Arc discharge occurred across all test conditions from 35 A to 80 A. However, at 35 A–50 A, the generated arcs are predominantly faint arcs, as illustrated in Fig. 3(a-1). These arcs are characterized by rapid ignition and extinction, rendering them difficult to detect reliably, as shown in the inset of Fig. 3(b). When the current increases to 65

A, strong arc (similar to Fig. 3 (a-2)) discharges are observed in the early stage of the test. As the test progresses, the arc intensity gradually weakens. This behavior can be attributed to changes in the surface condition of the contact pair during the initial running-in period. In the early stage, the contact pair undergoes a running-in process accompanied by intense arcing. After running-in, carbon wear debris fills the gaps between surface asperities and provides a certain lubricating effect, thereby reducing subsequent arc generation. When the current is increased to 80 A, arc discharge persists throughout almost the entire test cycle, with significantly higher intensity compared to other current levels. In particular, during the last 1000 cycles, the arc intensity increases markedly and remains high until the end of the test. This indicates that under high current conditions, arc discharge causes cumulative damage to the contact pair. The synergistic effect of prolonged arc erosion and mechanical wear gradually degrades the contact condition and exacerbates interface damage, leading to persistent and intensified arc discharges in the later stages. This positive feedback mechanism makes arc-induced damage more severe under high current conditions, while also revealing the complex interaction between arc discharge and the surface state of the contact pair.

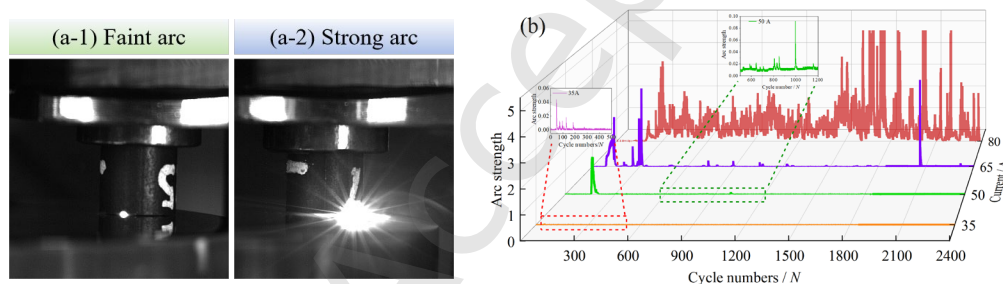


Fig. 3 Arc characteristics of the contact pair under different current: (a) high-speed camera images of arc morphology; (b) variation of arc intensity with cycle number

In high-speed current-carrying friction, arc discharge significantly influences the friction and wear performance as well as the service life of materials [1]. Fig. 4(a) shows the variation of arc occurrence rate and cumulative arc energy with current in the experiments. When the current ranges from 25 A to 50 A, the arc occurrence rate remains at a low level (below 5%). However, as the current increases to 65 A, the arc occurrence rate rises sharply. Here, 50 A serves as a critical threshold: beyond this value, the frequency of strong arc discharges increases significantly. At 80 A, the arc occurrence rate reaches 43.47%. Similarly, the cumulative arc energy exhibits a positive correlation with current. In the range of 35 – 65 A, the growth rate of arc energy remains relatively consistent. Since arc energy is proportional to both the voltage drop across the contact pair and the current, the emergence of strong arcs at 80 A transforms what would otherwise be a completely broken circuit into a sustained arc-conducting state. This leads to a slightly higher growth rate of arc energy compared to that at 65 A. Thus, cumulative arc energy can, to some extent, quantitatively represent the characteristics of arc discharge [8].

The duration of arc discharge directly influences both arc energy and material loss [26]. Fig. 4(b) shows the average arc duration of the contact pair under different current levels. It should be noted that arc ignition timing and location exhibit significant randomness, leading to variations in actual arc duration even under the same current condition, reflecting the complexity and uncertainty of arc behavior. As the current increases, both the average and maximum arc durations display an increasing trend, with a particularly pronounced rise from 65 A to 80 A. At 35 A, the average arc duration is relatively short, only 7.28 ms, indicating limited impact on energy release and material loss. When the current reaches 80 A, however, the average arc duration increases significantly to 60.66 ms, while the maximum duration reaches 239 ms. This sharp contrast highlights the intensified arcing behavior under high current conditions. The increase in both the frequency of strong arc discharges and the average arc duration collectively contributes to the rise in arc occurrence rate. This synergy is the primary reason for the sharp increase in arc occurrence rate when the current exceeds 65 A.

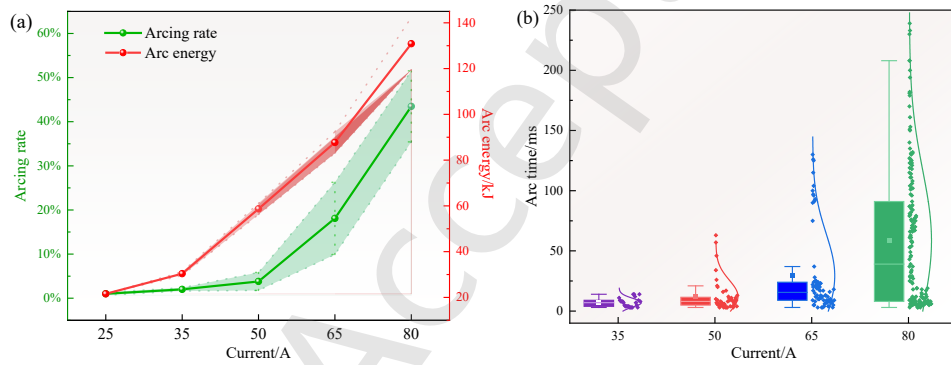


Fig. 4 Arc parameters under different current: (a) actual arc energy and arc rate; (b) arc duration

3.2 Arc erosion characteristics

Under current-carrying friction conditions, wear on the contact surface of the friction pair is complex. With increasing current, the wear mechanism evolves from mechanical wear to electrochemical wear as the dominant mode. This transition has been elaborated in detail in our previously published work [27]. Therefore, this section only compares and discusses the arc erosion morphologies of the friction pair surfaces under different current conditions. Fig. 5 shows the wear morphology of the carbon friction pair under different current levels. At 35 A, the locations and sizes of arc erosion pits appear randomly distributed (Fig. 5(a)). This randomness arises because the micro-asperities that carry the load and current during contact and relative motion change dynamically, leading to variations in both the position and intensity of individual arc discharges. Upon closer examination, the arc-eroded surface exhibits a network-like microstructure (Fig. 5(b-c)). At 50 A, the erosion pits show a powdered and porous network structure (Fig. 5(d-e)), along with patchy granular features encased in carbonaceous material (Fig. 5(f)). When the current increases to 65 A, the area of the erosion pits expands significantly (Region A in Fig. 5(g)). The high, localized

temperature generated during arcing creates substantial thermal gradients on the specimen surface, causing thermal expansion in the surrounding areas. Under the combined action of repeated thermal stress, normal stress, and friction-induced shear stress, fatigue cracks gradually form, eventually developing into a loose, crack-filled layer (Fig. 5(h)). The underlying material also exhibits nanotubes structure (Fig. 5(i)). At 80 A, the worn surface shows multiple spalling areas and cracks, with numerous pores of varying sizes at the bottom of the erosion pits (Fig. 5(j-l)). During sliding, the crack-affected zones undergo repeated impact and compressive stress, promoting crack propagation. When cracks extend and interconnect, the affected material spalls off under shear stress. The resulting uneven surface enhances electron emission, facilitating further arc ignition. Moreover, arc root movement becomes more difficult across such rough areas, intensifying local arc erosion. Throughout the wear/erosion process, these cracked regions act as preferential sites for arc attack and represent vulnerable points in the material.

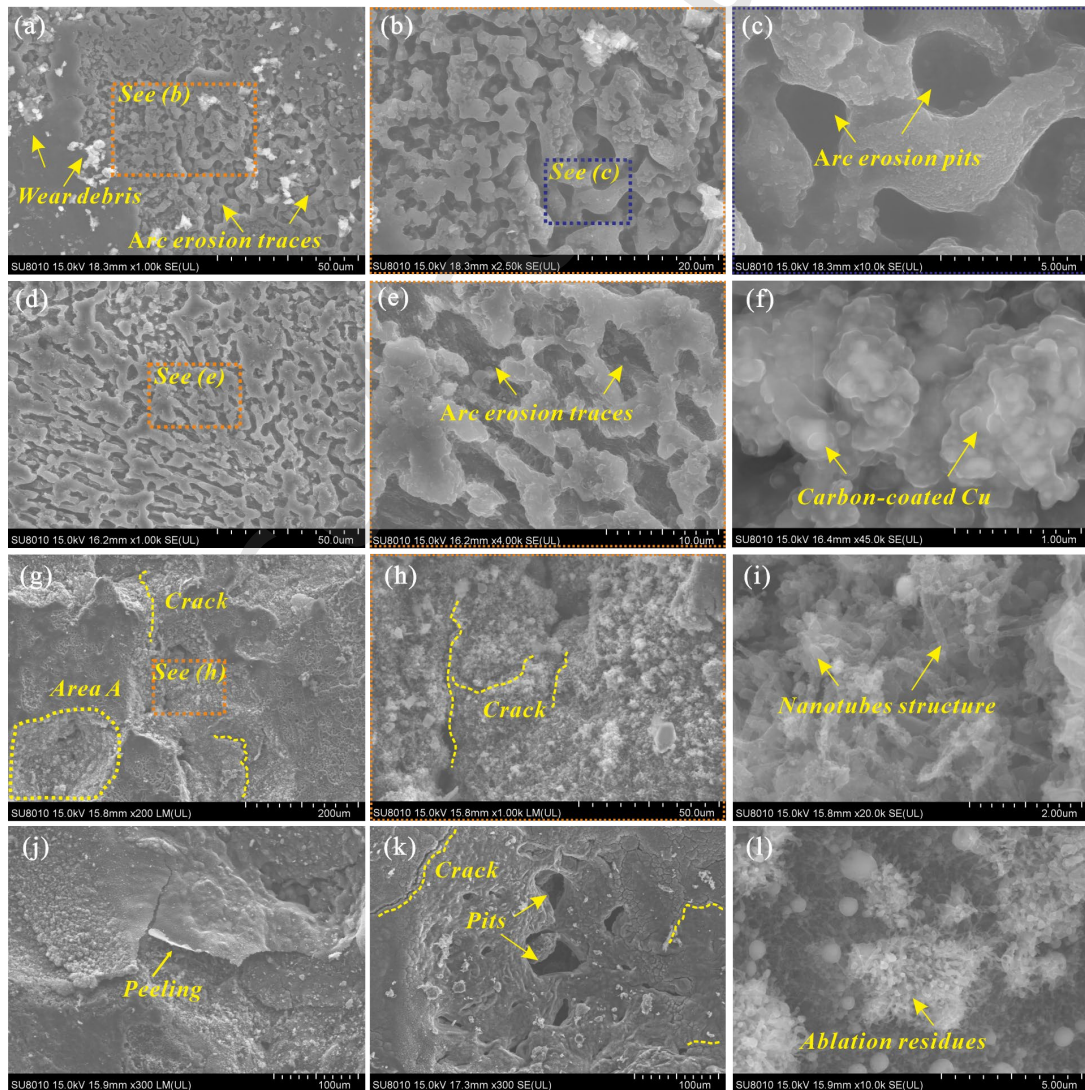
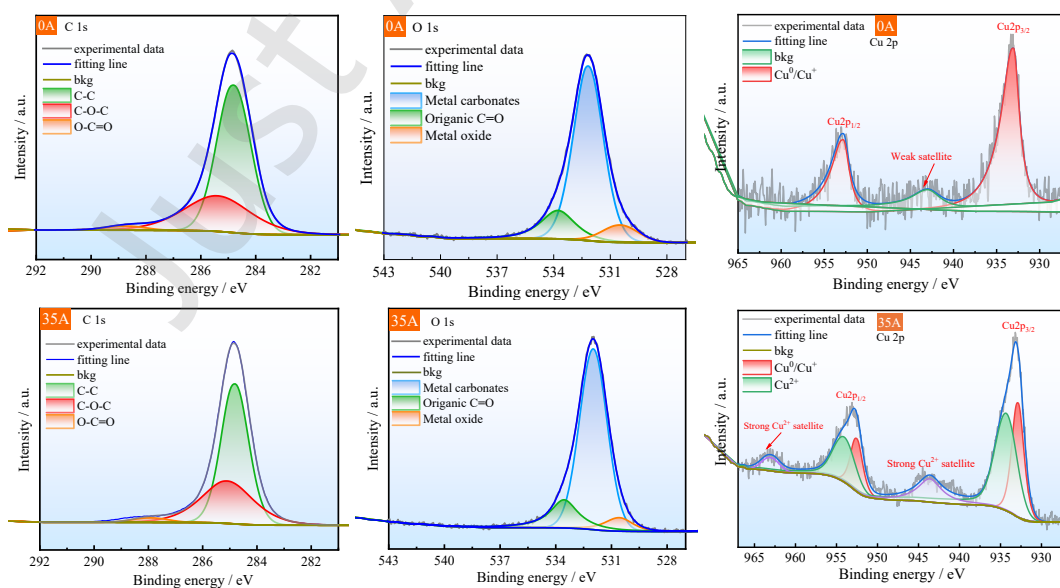


Fig. 5 Microscopic morphology of worn carbon surfaces under different current: (a-c) 35A; (d-f) 50A; (g-i) 65A; (j-l) 80A

To analyze the elemental composition and atomic valence states on the carbon material surface, XPS tests were conducted on specimens after current-carrying tests at 0 A, 35 A, and 80 A (Fig. 6). Peaks corresponding to C 1s, O 1s, and Cu 2p were detected on the material surface under all three conditions. However, significant differences in the valence states of surface elements were observed between pure mechanical wear (0 A) and electrically dominated wear (80 A). The main C 1s peak at 80 A is noticeably asymmetric and shifts toward higher binding energy. Peak fitting reveals that the C 1s spectrum decomposes into four sub-peaks, corresponding to C-C, C-O-C, O-C=O, and sp^2 -hybridized carbon. The appearance of sp^2 carbon (284.0 eV), a characteristic hybridization state of graphitic compounds, is attributed to the persistent strong arcing and associated temperature rise at the contact surface under 80 A. To reach a more stable state, the carbon material tends to form the lower-energy sp^2 -hybridized structure, thereby increasing the degree of surface graphitization [28, 29]. Analysis of the Cu 2p spectra shows that at 0 A, only weak satellite peaks are present, indicating the dominance of Cu^0 and Cu^+ species. Under pure mechanical wear, the low interfacial temperature (Fig. 2b) allows copper material removed from the disc to transfer to the carbon surface. At 35 A, the peak observed at 934.4 eV corresponds to the $Cu^{2+} 2p^{3/2}$ state [30]. At 80 A, the area of the peak at 933.9 eV increases relative to that at 35 A, indicating the presence of Cu^{2+} oxides [31]. The elevated temperature under high current significantly promotes the oxidation of copper, transforming some Cu^0 and Cu_2O into CuO . The O 1s spectrum is deconvoluted into three peaks assigned to metal oxide (530.5 eV), metal carbonate (532.2 eV), and C=O (533.8 eV). The metal oxide peak area at 35 A is smaller than that at 80 A, further confirming that high current promotes the formation of metal oxides on the worn surface.



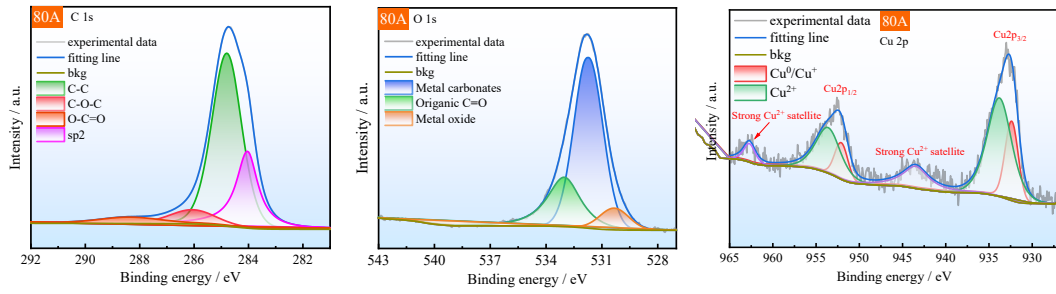
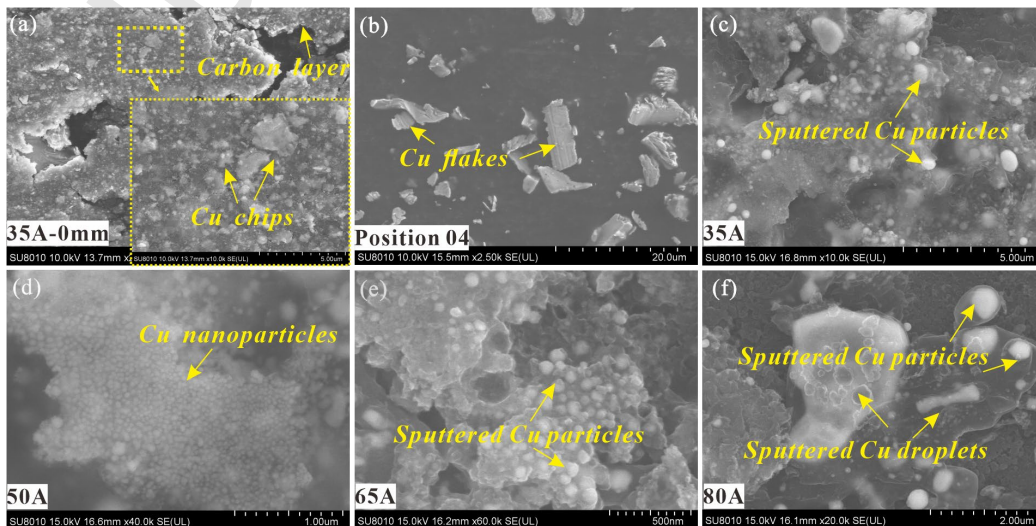


Fig. 6 XPS spectra of the carbon material surface under different current levels

To better understand the arc erosion characteristics of the contact pair materials, wear debris from different locations on the copper disc under various current levels was examined (Fig. 7). Under smooth operating conditions at 35 A (Fig. 7(a)), the contact between the carbon pin and copper disc remains stable with no arc occurrence. The wear debris mainly consists of copper or carbon fragments sheared or peeled from the contact surfaces, with copper appearing as chips or flakes. When the copper disc exhibits irregular surface conditions, debris at the highest point (Position 4) shows flake- or block-shaped morphology due to severe interfacial shearing (Fig. 7(b)), indicating the dominance of mechanical wear [32]. Observation of debris from Position 3 of Cu disc reveals distinct morphological variations under different currents (Fig. 7(c-f)). Combining the results from Fig. 5(l) and Fig. 7(g), the white spherical particles in the debris are identified as copper [17], and most arc-eroded debris exhibits a carbon-encapsulated-copper structure (Fig. 7(g-h)). At 35 A, the carbon layer encapsulates copper nanoparticles with sizes ranging from 10 to 40 nm (Fig. 7(c)). Under 50-65 A conditions, the copper particles within the debris are notably smaller, mostly below 10 nm (Fig. 7(d-e)). At 80 A, the graphite tends to reach a molten state (Fig. 7(f)), as local temperatures induced by arc erosion exceed the sublimation temperature of graphite. The high temperature vaporizes carbon from the graphite into the arc, forming various compounds. When the arc extinguishes or moves, these compounds may deposit on the friction surface if conditions permit. Consequently, under prolonged and intense arc erosion, both friction pairs suffer severe damage.



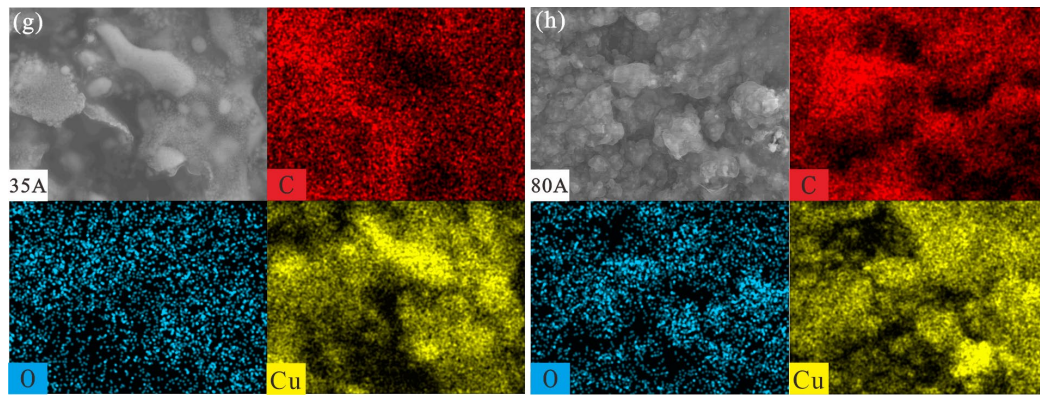


Fig. 7 Micromorphology and elemental analysis of wear debris under different current

3.3 Particulate matter emissions and characteristics

The fine copper-rich particles generated during the pantograph–catenary current-carrying friction process pose significant risks to human health^[33]. Therefore, this study investigates and analyzes the particle size distribution and morphological characteristics of particle emissions under various operating conditions. Based on particle size ranges, particles of 0.3 μm and 0.5 μm are classified as small-sized, those of 1.0 μm and 3.0 μm as medium-sized, and particles of 5.0 μm and 10.0 μm as large-sized. The total number and concentration distribution of particles during the stable phase (i.e., the last 480 cycles before the end of the test) are presented in the line chart and bar graph in Fig. 8. Clearly, the total particle emissions under low-current conditions are significantly lower than those under high-current conditions. At 35 A, the surface properties of the carbon material deteriorate, leading to a sharp increase in particles released into the air. The total particle count rises from 4.23×10^5 at 0 A to 1.57×10^6 at 35 A. As the current continues to increase, the total number of particles also rises, with a notable increase in small-sized particles. The total particle count reaches its maximum at 65 A. However, at 80 A, the total number of particles decreases slightly. The pie chart in Fig. 8 shows the statistical analysis of the proportion of particles of different sizes over the entire cycle. The proportion of small-sized particles gradually decreases as the current increases, while the proportion of medium-sized particles increases (only 3% at 25 A, stabilizing at around 25% at 50 A and above). Similarly, the proportion of large-sized particles also increases significantly. These findings indicate that particle emissions are current-dependent. An increase in current promotes the emission of particles, particularly small-sized ones, while the proportions of medium and large-sized particles also rise. However, the continuous generation of strong arcs leads to a slight reduction in the total number of particles due to material sublimation.

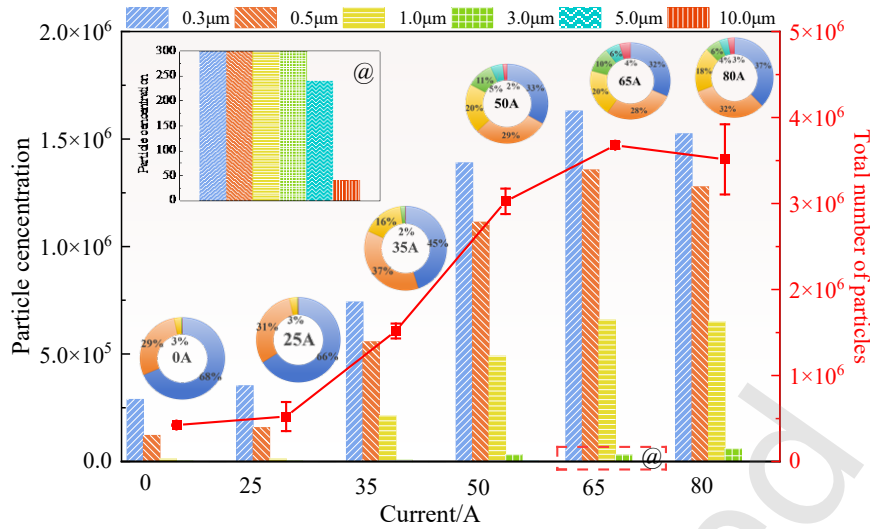


Fig. 8 Statistical data on particle emissions under different current: total particle concentration, quantity, and size distribution

The microstructure and elemental distribution of particulate matter in the air surrounding the contact pair were analyzed using TEM and elemental mapping (at 0 A and 65 A), as shown in Fig. 9. Under 0 A (Fig. 9(a-c)), the particles primarily consist of amorphous carbon spheres and carbon clusters with relatively large dimensions, where individual carbon spheres have diameters of approximately 200 nm. These carbon materials are sheared and detached from the surface by the micro-asperities of the copper counterpart under mechanical action, subsequently being emitted into the air. In contrast, under 65 A (Fig. 9(d-f)), the morphology and composition of the particles change significantly. The particles contain a substantial number of large carbon sheets exhibiting layered or flake-like structures. More notably, these carbon sheets are uniformly embedded with extremely fine particles approximately 2-4 nm in diameter. Elemental analysis confirms that these fine particles are copper nanoparticles (Fig. 9(g)). The formation of this structure is closely related to arcing. The high temperature generated by the electric arc causes localized melting and splashing of the copper material. The splashed copper nanoparticles combine with the softened carbon sheets under high-temperature conditions, ultimately forming a composite structure in which carbon sheets encapsulate copper nanoparticles. These composite particles are then released into the air ^[16], becoming a significant component of the particulate matter around the contact pair.

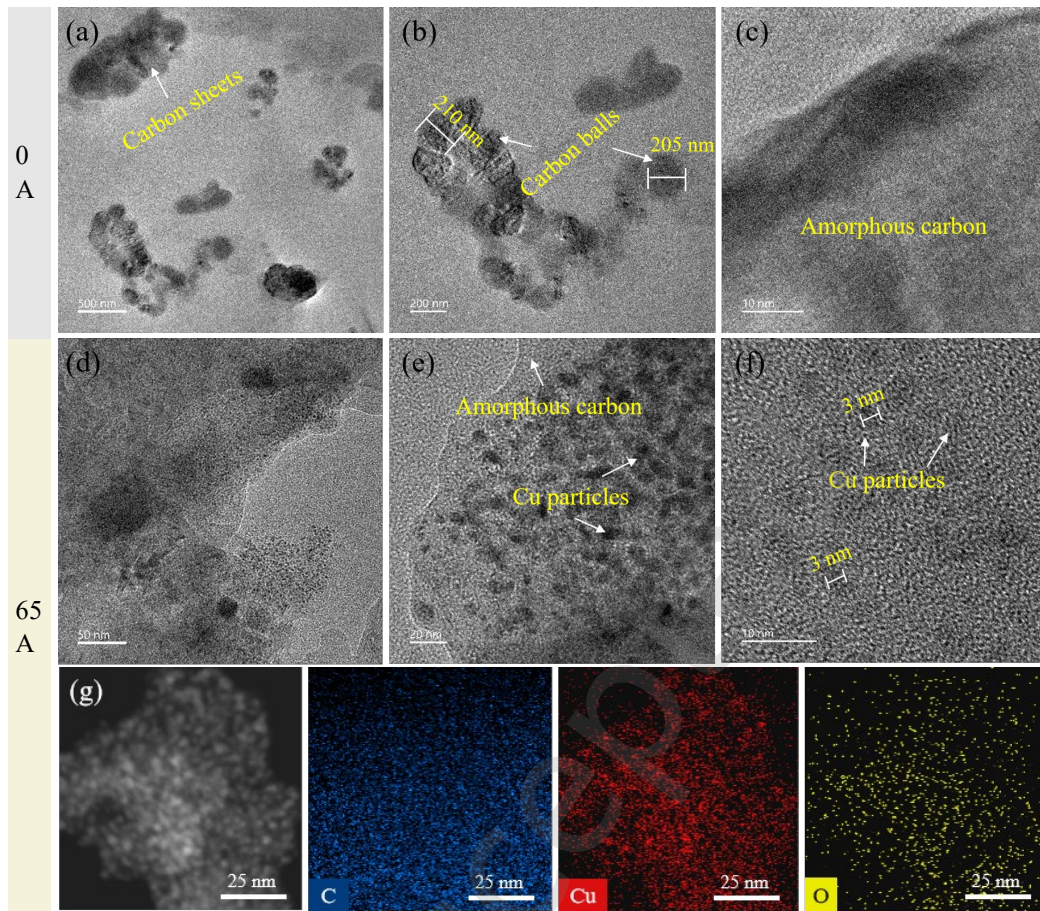
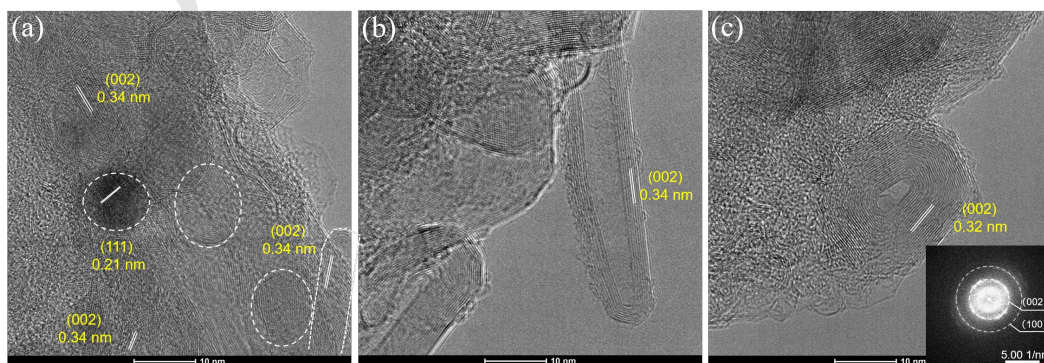


Fig. 9 Microstructure and element distribution of particulate matter

Fig. 10 presents TEM images and EDS elemental distribution of particles captured around the friction pair under the 80 A condition. At this elevated current, the particles exhibit a high carbon content, primarily existing in the form of layered carbon sheets. These layers are predominantly composed of carbon spheres and multi-walled carbon nanotubes (Fig. 10(a, b)). Copper nanoparticles are either attached to the carbon layers or encapsulated within them, with their distribution consistent with that of sulfur and oxygen (Fig. 10(d, e)). This suggests that during arc ablation, volatilized substances from the carbon material chemically react with copper vapor from the copper friction pair, forming composites. The carbon nanotubes observed are mostly closed-ended, with outer diameters ranging from approximately 100 to 150 nm (Fig. 10(b)). These findings also confirm that the tubular structures observed in the ablation pits of the carbon friction pair under the 65 A condition in Fig. 5(i) are indeed carbon nanotubes. These carbon nanotubes are generated by the arc discharge method. Traditionally, this method involves high-voltage discharge in an inert gas environment to generate high-temperature plasma from graphite electrodes, leading to the formation of carbon atom clusters and subsequent growth of carbon nanotubes. In this experiment, although the surrounding environment is air, However, the continuous combustion of the electric arc consumes most of the air in the narrow space between the contact surfaces, thus favoring the formation of carbon nanotubes. Compared to those produced by methods

such as chemical vapor deposition (CVD), the carbon nanotubes generated here exhibit relatively larger diameters. High-magnification observation of the carbon spheres reveals that they consist of multiple graphite-like layers with a hollow center (Fig. 10(c)), indicating a relatively ordered onion-like carbon structure [34]. This structure is similar in morphology and size to the onion-like carbon obtained through 100 cycles of vacuum arc deposition as reported in Ref. [35]. Onion-like carbon consists of quasi-spherical particles with closed concentric shells, with diameters ranging from 10 to 20 nm. The selected area electron diffraction (SAED) pattern shows distinct diffraction rings (inset in Fig. 10(c)), further confirming that the onion-like carbon is composed of well-graphitized carbon layers. The inter-shell spacing is approximately 0.34 nm, which closely matches the lattice parameter d_{002} (0.336 nm) of bulk graphite. According to Fig. 10, the carbon collected under the 65 A condition is amorphous, whereas onion-like carbon is formed under the 80 A condition. This structural evolution can be attributed to two main factors. On one hand, the transformation of carbon into nanocrystalline carbon at high temperatures is closely related to its crystal structure and thermodynamic properties. Elevated temperatures increase the kinetic energy of carbon atoms and their average interatomic distance, weakening interatomic interactions and driving the carbon source toward thermal equilibrium, leading to inward contraction. Under specific thermodynamic conditions, carbon contracts along relevant crystallographic directions, eventually forming a stable graphite structure. On the other hand, the duration of high-temperature exposure significantly influences the degree of graphitization. During arc erosion, amorphous carbon first transitions from a disordered sp^3 structure to a graphene-like sp^2 structure, forming two-dimensional graphite nanolayers. These graphene sheets aggregate with copper nanoparticles—formed from cooled copper vapor—and engulf them (as indicated by the matching lattice parameter d_{111} (0.21 nm) of the copper nanoparticles in the central part of Fig. 10(a)). Driven by extreme temperatures, the carbon further graphitizes and transforms into a relatively ordered, layered onion-like structure [36], as illustrated in Fig. 10(f). Consequently, the carbon at this stage exists in a multi-structural coexistence state, including amorphous carbon, graphite-like structures, and curled graphene configurations.



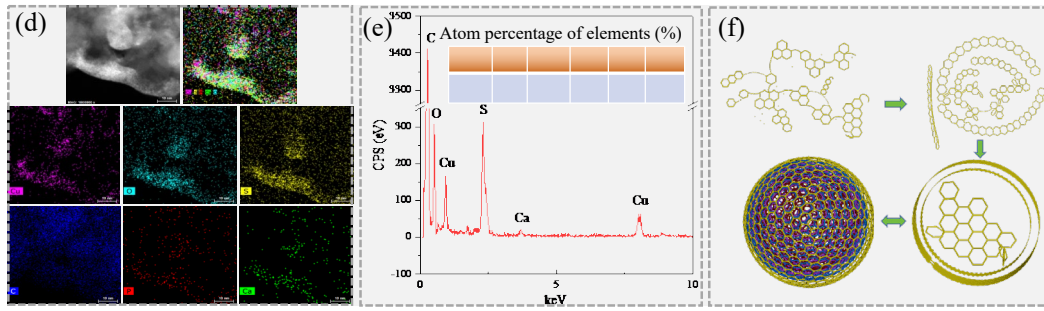


Fig.10 TEM image and EDS elemental mapping of particles at 80 A

During the current-carrying friction process between carbon and copper, two typical carbon nanostructures—onion-like carbon and carbon nanotubes—are formed due to arc discharge. Based on analytical results, a formation mechanism model is proposed, as illustrated in Fig. 11. The process can be described in detail as follows: When carbon and copper form a pair of electrodes, a high-energy plasma zone is generated between them during discharge (Fig. 11(a)). The arc burning process between contact pairs consumes oxygen molecules rapidly, creating a low-oxygen atmosphere within the narrow gap. The temperature in the arc core region reaches approximately 4000 K, which is close to the sublimation temperature of carbon (the melting and boiling points of graphite are 3823 K and 4203 K, respectively) ^[37]. Under such high temperatures, the carbon material vaporizes, and when the gaseous carbon encounters the relatively low-temperature surrounding environment, it undergoes rapid solidification. From a thermodynamic perspective, this process involves the diffusion of carbon vapor from the high-temperature plasma zone to lower-temperature regions. It is worth noting that the intense gas flow generated during arc discharge significantly accelerates the diffusion rate of carbon vapor. Based on temperature gradients and ion distribution characteristics, the cooling zone outside the arc can be divided into two characteristic regions: Region I is adjacent to the plasma zone and is an area with active ion flow and significant ion current. In this region, carbon vapor undergoes a rapid quenching process (Fig. 11(b)). Driven by the directional influence of the ion flow, carbon atoms tend to undergo epitaxial growth along specific orientations, leading to the formation of one-dimensional elongated structures such as carbon nanotubes. The ion flow here provides the necessary kinetic conditions for the directional alignment of carbon atoms. Region II, located outside the influence of ion flow, is an isotropic zone free from directional ion current (Fig. 11(c)). In this region, the growth of carbon nanoparticles is not constrained by any specific direction, exhibiting three-dimensional isotropic growth characteristics. This growth mode leads to the layered wrapping of carbon atoms in concentric shells, ultimately forming typical onion-like carbon structures. Such onion-like carbon features complete concentric spherical shells, and its formation mechanism resembles a self-assembly process similar to that in chemical vapor deposition.

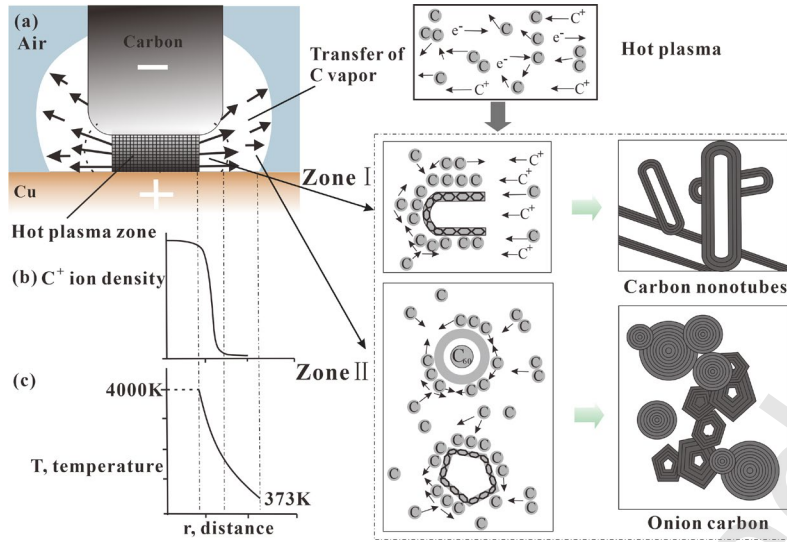


Fig. 11 The formation mechanism of onion carbon and nanotubes in electric arc

3.4 Microstructural changes in carbon materials induced by arcing

To investigate the relationship between material structure and electrical conditions, SEM-Raman analysis was performed on the worn carbon surfaces under 0 A and 80 A conditions, with the results shown in Fig. 12. Under the current-free condition (Fig. 12(a)), the Raman spectrum of the carbon material exhibits broad D, G, and 2D bands, with an I_D/I_G ratio of 0.91. The broadening of the D band indicates a high density of structural defects and disordered regions, while the relatively high I_D/I_G value further confirms the low degree of atomic ordering and crystallinity in the carbon material. In contrast, under the 80 A condition (Fig. 12(b)), all characteristic bands (D, G, and 2D) become significantly narrower and sharper, and the I_D/I_G ratio decreases to 0.86 or lower. This change suggests that under intense arcing, the carbon material at the edges and bottom of the ablation crater develops a more ordered structure with fewer defects, higher crystallinity, and an enhanced degree of graphitization. The sharpening of the 2D band further supports the improvement in graphitic ordering, which is closely associated with the high-temperature effects induced by arcing. The elevated temperature promotes atomic rearrangement and graphitization, thereby increasing the structural order and crystallinity of the material. These observations align with previously reported behavior of incompletely graphitized carbon, in which higher temperatures lead to a more ordered structure [38]. Furthermore, comparative analysis of Raman spectra from different locations within the ablation crater reveals that the material at the bottom exhibits even fewer defects and a lower I_D/I_G ratio than the edges. This indicates that the crater bottom experienced more intense high-temperature exposure, resulting in a higher degree of crystallinity and structural order compared to the outer regions of the ablation crater.

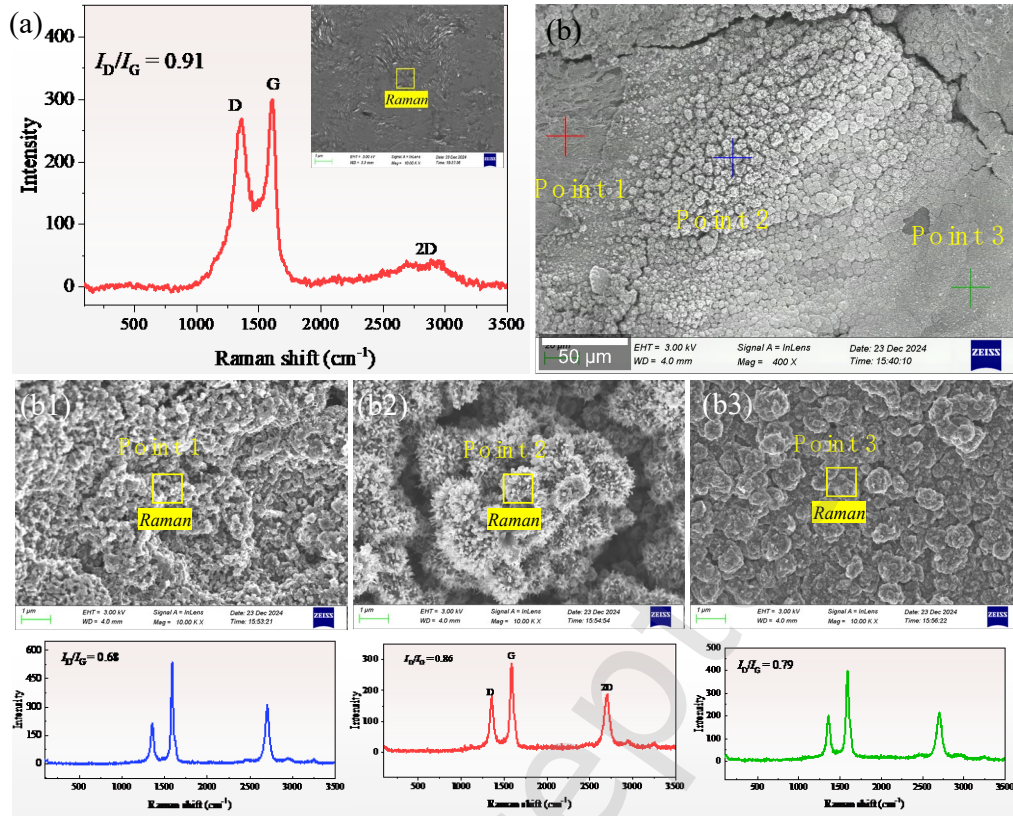


Fig. 12 SEM Raman spectra of specific locations of carbon materials (a) 0 A; (b) 80 A

Fig. 13 shows the XRD patterns of the worn carbon surfaces under 0-80 A conditions, aiming to clarify the crystalline structure characteristics of the carbon material under different operating states. For the carbon surface tested at 0 A, the marked peaks in the XRD pattern mainly correspond to characteristic diffraction peaks such as (003) and (101) of Graphite 3R (PDF card No. 26-1079), indicating the presence of a graphite phase in the material. However, the 3R phase is less stable than the 2H phase and transforms into the 2H phase at temperatures above 1000 $^{\circ}\text{C}$ [36]. In addition, characteristic diffraction peaks of calcium phosphate compounds—such as (211), (112), and (300)—are observed in the XRD pattern, attributed to the calcium phosphate additives introduced during the manufacturing process of the carbon strip. Within the current range of 35-65 A, the XRD diffraction peaks show little difference from those at 0 A, suggesting no significant change in the crystalline structure of the carbon material under these conditions. In contrast, at 80 A, the XRD pattern of the carbon material exhibits distinctly different characteristic peaks. The observed diffraction peaks at $2\theta = 26.0^{\circ}$, 42.4° , 54.7° , and 77.7° correspond, respectively, to the (002), (100), (004), and (110) characteristic peaks of standard Graphite 2H (PDF card No. 41-1487) [39]. This indicates that the carbon material under the 80 A condition possesses a highly ordered graphitic structure. In particular, the appearance of the (002) peak further confirms the layered crystal characteristics of the graphite, resulting from the phase transformation from 3R to 2H induced by high temperature. Moreover, no characteristic

peaks of calcium phosphate compounds are detected on the carbon surface at 80 A, implying that these compounds decompose under the high-current conditions due to elevated temperature or high energy input. These results demonstrate that arc ablation and high-temperature exposure significantly influence the structural evolution of the carbon material. The observed structural differences are closely related to the friction, thermal, and chemical reaction processes experienced by the material.

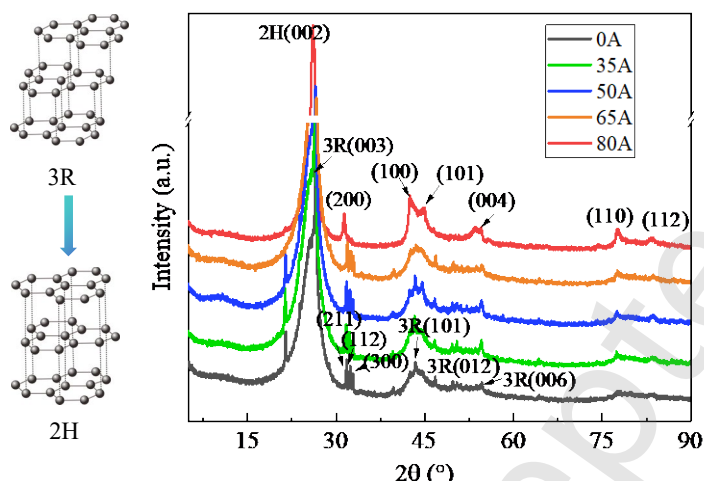


Fig. 13 XRD curves of carbon materials after wear under different current

4 Conclusions

This study systematically investigates the current-carrying friction and wear behavior of carbon strips against copper contacts under different electrical currents, along with the characteristics of erosion products. The relationship between arcing and the structural evolution of both erosion products and the carbon material has been established, leading to the following main conclusions:

- (1) The current magnitude shows a positive correlation with wear loss, temperature, arc ignition rate, and arc energy. Faint arcs dominate at 25-50 A, while strong arcs occur frequently at 65-80 A, leading to a significant increase in friction coefficient fluctuation.
- (2) Material surface damage varies considerably under different arc intensities. At low to moderate currents, the carbon surface exhibits a loose and porous network structure, whereas intense arcing at high currents causes severe pulverization, spalling, and sublimation, accompanied by thermal stress cracks. The copper counterpart undergoes melting, splashing, and resolidification, forming numerous spherical metallic particles inside ablation craters.
- (3) Intense arcing reduce defects and significantly improve the crystallinity and graphitization degree of carbon materials in ablation regions. Meanwhile, current promotes particle emission, and high-current conditions favor the formation of carbon spheres, multi-walled carbon nanotubes, and onion-like carbon structures. Such arc-induced microstructural evolution of carbon materials is rarely reported in the field of current-carrying tribology.

Nevertheless, given that current, temperature, and arcing effects coexist and are

strongly coupled throughout the experiments, it remains challenging to decouple and distinguish the individual contributions of Joule heating, flash temperature at asperities, and arc/plasma effects to the observed evolutions.

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Declaration of interests

The authors declare no competing interests.

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