Research Square

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Study on friction and wear properties of copper-impregnated carbon slide plate under different humidity conditions

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Research Article

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Abstract

The pantograph–catenary system is one of the most commonly used power-receiving modes of metro trains. Its friction and wear performances are related to the safety and stability of train operation. In this study, a copper-impregnated carbon slide plate material, widely used in numerous metro lines in China, is considered as the research object. The problem of abnormal wear of pantograph slide plates caused by the decrease in relative humidity in the autumn and winter in tunnels is studied. Current-carrying friction and wear tests under humidity conditions of 20%, 30%, and 40% relative humidity(RH) are performed to reveal the mechanism of seasonal abnormal wear of slide plates and provide a reference for the service of pantograph slide plates under low-humidity conditions. The results reveal that relative humidity significantly influences the wear process of slide plates; further, the wear rate and friction coefficient decrease with an increase in relative humidity. As observed by electron microscopy and laser scanning confocal microscopy, with an increase in the relative humidity, the mechanical wear of the slide surface is weakened, arc erosion is enhanced, and surface roughness is increased. Scanning electron microscopy(SEM) and energy dispersive spectrometry(EDS) analysis reveal that under high humidity conditions, a relatively complete oxide film forms on the slide plate and plays a role in lubrication and protection. Under low humidity conditions, a large number of fine abrasive particles are distributed on the surface, and an insufficient oxide film is formed; consequently, the wear rate and friction coefficient are maintained at a high level.

1 Introduction

The metro in China has undergone rapid and comprehensive development since the late 1990s owing to its large capacity, high efficiency, and low energy consumption [1]. The power of subway vehicles is relatively low, and the operational safety requirements are high. Therefore, some subway lines in China have adopted pantograph–catenary DC power supply systems [2, 3]. With the continuous improvement in metro traction power and running speed, the problem of abnormal wear of the pantograph–catenary is gradually exposed. Research has revealed that metro lines in numerous cities in China have different degrees of abnormal pantograph-slide seasonal wear. After entering the autumn and winter seasons, the wear rate of slide plates abnormally increases and the surface morphology is unusually rough. Thus, Mei [4, 5] studied the wear mechanisms of rigid catenary and pantograph slide plate systems to solve the wear problem of pantograph slide plates and found that the wear rate and temperature of slide plates with a current of 400 A were 53.0 times and 7.4 times greater than that of slide plates without current, respectively. The leading causes of severe wear of the slide plates are arc ablation and adhesive wear. Li et al. [6] studied the effects of friction speed and current density on the friction and wear properties of copper matrix composites. Reportedly, with an increase in friction speed and current density, the wear rate of the material increased. Xu et al. [7] found that with an increase in current, the wear of alloy-impregnated carbon slide plates increased significantly. Kubota et al. [8] studied the wear properties of copper-alloy-impregnated carbon-fibre-reinforced carbon composites and reported that under high-voltage and high-current conditions, arc ablation energy increases, thus resulting in increased slide plate wear.

Researchers have found an optimal contact pressure value between the pantograph and catenary. Contact pressures that are too large or too small aggravate arc erosion or mechanical wear [9–11]. Numerous scholars have studied the effect of pantograph–catenary related parameters, such as reciprocating distance [12], catenary sag [13], and slope [14], on the contact stability between a pantograph and catenary and their effect on pantograph–catenary wear. These above studies report that the factors affecting the wear of pantograph slide plates are complicated and primarily focus on the pantograph–catenary materials and operating parameters.

Metro lines with seasonal abnormal wear have relatively stable working conditions during train service. After a series of tracking and monitoring steps, key parameters, such as contact pressure, current, and running speed, did not change significantly during operation. Owing to the significant seasonal characteristics of abnormal wear, the temperature and humidity in a tunnel were monitored and revealed a strong correlation between slide plate wear and the air humidity in a subway running tunnel.

Therefore, this study investigated the influence of humidity on the current-carrying friction and wear performance of copper-impregnated carbon slide plates under different humidity conditions. It is compared with the pantograph slide plates after service in different environments, and the mechanism of seasonal humidity change on the wear of pantograph slide plates was analysed to provide a reference for solving wear problems in engineering practice.

2 Equipment And Materials

2.1 Equipment

The test was performed using the current-carrying friction tester of the State Key Laboratory of Traction Power, Southwest Jiaotong University. The tester consisted of a block-on-ring friction testing machine, DC power supply device, and data acquisition system. The main components included the frame, rotary disc, plate-fixing device, and plate-lifting mechanism. The rotary disc was driven by a central motor and had an external fixed contact wire to provide a relative sliding speed of 0–400 km/h. The processed block slide material achieved reciprocating motion through the slide fixing device and lifting mechanism to simulate a Z-shaped sliding contact form between the pantograph and catenary. The slider surface contact pressure adjustment depended primarily on the weight and pulley device, as shown in Fig. 1 The temperature and humidity sensors and dehumidification and humidification equipment were arranged in the test environment to control the ambient humidity at ± 1% RH during the test process.

2.2 Test materials

The test was based on a copper-impregnated carbon slide plate used in a typical metro system. The slide plate was primarily composed of coke, graphite, and copper impregnated into pores. The mass fractions of carbon and copper were 70 and 30%, respectively. According to the requirements of the test machine, a 122 mm × 34 mm × 22 mm block sample was fabricated by machining. The contact wire was a copper–

silver alloy wire with mass fractions of copper and silver of 99% and 0.08–0.12%, respectively, which is consistent with that of the contact wire used in a typical metro. The relevant physical parameters of the contact pairs are presented in Table 1.

Table 1
Relevant physical parameters of contact pairs

Material	Mass fraction	Density	Hardness
Copper-impregnated carbon slide plate	C wt. 70%, Cu wt. 30%	2.7 g/cm^3	85 HS
Cu–Ag alloy contact wire	Cu wt. 99%, Ag wt. 0.08–0.12%	8.96 g/cm^3	60 HRBW

The test sample was compared with the actual service state of a slide plate used in a previous study [15]. For this, the samples of the carbon slide plate were obtained under the normal wear state (when the actual operation line was not in the autumn or winter seasons (Fig. 2a)) and under the abnormal wear state (after entering the autumn and winter seasons (Fig. 2b)). These are hereafter referred to as the normal and abnormal wear plates, respectively.

2.3 Experimental parameters

Combined with the actual operating conditions, the relative sliding speed of the test was set to 60 km/h, current through the plate was 100 A, contact pressure was 35 N, reciprocating distance was 110 mm, frequency was 0.15 Hz, and test sliding distance was 180 km. In terms of the humidity setting, according to the tracking test results of a subway line in China (Fig. 3), the critical humidity value for a plate to wear abnormally is approximately 30% RH, and the minimum humidity value in the operation process was approximately 20% RH. Therefore, three groups of tests, corresponding to 20%, 30%, and 40% RH, were performed to reproduce the influence of humidity on an actual service process.

3 Results And Discussion

3.1 Wear rate and friction coefficient

The mass loss of the carbon slide plate before and after the test was used to evaluate the wear of the pantograph slide plate. The carbon slide plate was weighed before and after the test using an electronic balance with an accuracy of 0.1 mg. The wear rate W of the plate was calculated as follows.

$$W = \frac{m_a - m_b}{L}, \quad (1)$$

where m_a and m_b are the masses of the slide plate before and after wear (g), respectively; and L is the sliding distance of the test (km). Figure 4 shows the wear/friction coefficient–relative humidity curve of the slide plate. Under the same experimental conditions, with an increase in the relative humidity, the wear

rate decreased. When the RH increased from 20–40%, the wear rate decreased significantly from 0.0879 to 0.0197 g/km. When the humidity increased from 20–30% RH, the increase in wear rate was 0.0303 g/km; however, when the humidity further increased from 30–40% RH, the increase in wear rate was 0.0379 g/km, which is approximately 25% higher than that in the previous stage. The influence of humidity on the wear rate exhibited nonlinear characteristics.

The friction coefficient was calculated from the tangential and normal force data obtained by the data acquisition system as

$$\mu = \frac{F_t}{F_n}, \qquad (2)$$

where μ is the friction coefficient; F_t is the tangential force; and F_n is the normal force. As shown in Fig. 4, the friction coefficient decreased with an increase in humidity. After the humidity reached 30% RH, the friction coefficient stabilised at approximately 0.46, which is consistent with the experimental results of previous research [16]. This may have been the result of the formation of a layer of adsorbed water film on the contact area of the slide surface owing to an increase in relative humidity that protected the contact pairs. However, as the relative humidity increased to a certain threshold, the adsorbed water film reached saturation. As the water vapour in the air continued to increase, the friction coefficient did not change significantly [17].

3.2 Surface macrostructure analysis of different wear states

To compare the surface friction and wear morphology of the metal-impregnated carbon slide plate under different humidity conditions, macrographs of the wear surface of the pantograph slide plate under different wear conditions were obtained using a NREEOHY DZ-Y500L electron microscope, as shown in Fig. 5 The wear surface of the plate under different humidity conditions had a particular arc erosion area, and arc erosion marks gradually appeared on the surface of the plate with an increase in the relative humidity. In the process of current-carrying wear, when an off-line phenomenon between the pantograph and catenary contact pairs occurred, a voltage difference occurred between the pantograph and catenary and caused an arc [18, 19]. Arc erosion on pantograph–catenary contact pairs manifests primarily as accelerated oxidation, melting evaporation, and splashing [20]. As shown in Figs. 5a–c, the erosion marks on the slide plate surface were primarily arc ablation holes under the experimental conditions. In the macroscopic view (Fig. 5d) of the slide plate with abnormal wear in actual service, copper was present on the friction surface because the current of the slide plate was more extensive in actual service where the instantaneous current of the start-up acceleration section exceeded 700 A. At the same time, owing to the phenomenon of intensified vibration caused by aerodynamic and line conditions, the Joule heat and arc heat on the slide plate surface were significantly increased compared with those of the experimental conditions [18, 21]. At higher temperatures, copper was distributed on the slide plate surface, and the contact wire melted, spattered, and then resolidified on the slide plate surface after cooling.

Evidently from the macroscopic view of the copper–silver alloy wire surface after the wear test (Fig. 6), some differences existed on the surface after wear under different humidity conditions. Under low-humidity conditions, more apparent scratches appeared on the copper–silver alloy contact line. Further, with an increase in humidity, the phenomenon was improved and the surface became smoother, thus indicating that the mechanical wear was reduced after an increase in humidity.

3.3 Surface microstructure analysis of different wear states

To further explore the microscopic differences in the wear surface of the sliding plate under different humidity conditions, the surface of the sample was observed using an OLYMPUS OLS4100 laser confocal microscopy system. A comparison of the surfaces of the normal and abnormal wear sliding plates is shown in Fig. 7. Evidently, the 20% RH and abnormal wear state of the slide surface had more prominent mechanical wear scars, and the surface-material peeling was more distinct. When the test humidity increased to 30%, dense dark streamlines appeared on the surface of the slider, and the direction was consistent with that of the relative motion of the pantograph–catenary contact pair. As mentioned previously, when a separation exists between a pantograph and catenary, an arc is generated and it will be extinguished only when the pantograph and catenary return to contact. In this process, the arc root follows a relative sliding trajectory and leaves a black streamline on the slide plate surface [19]. When the relative humidity increased to 40%, the width of the dark streamlines on the surface increased, whereas the dark streamline traces on the surface of the pantograph slide plate were sparse but coarser under normal wear conditions.

Studies have reported a correlation between the contact pair surface roughness and wear rate. The higher the roughness, the smaller the actual contact area, and the higher the offline and arcing rates [22]. To investigate the effect of slide plate surface roughness, the roughness measurement module of the Japanese OLYMPUS OLS4100 laser confocal microscopy system was used to compare the middle wear area of three slide plate samples with that of an actual service slide plate. Each piece was 5-mm long. The average roughness of the surface of the pantograph slide plate under different wear conditions was calculated and analysed, and the results are presented in Table 2. On average, the slide plate surfaces after the test and that of the actual service exhibited two trends. Under the test conditions, the roughness decreased with an increase in relative humidity. In the actual service, the humidity of the abnormal wear slide plate was lower, whereas the surface roughness of the wear surface was higher than that of the normal wear slide plate surface. Holm [23] believes that the wear between a pantograph and catenary depends primarily on three aspects: pure mechanical wear, electrical wear, and wear under the action of mechanical and electrical coupling. Electrical wear and mechanical–electrical coupling wear caused by the current on the surface of a slide plate are the primary wear mechanisms under current-carrying conditions and affect the wear of a slide plate [24]. Owing to the differences in contact pressure, running speed, and current-carrying conditions between the test and the actual service process, the arc erosion on the slide plate surface and the temperature of the contact pair during the actual service process were much higher than those of the test conditions. At this time, the slide plate surface exhibited noticeable morphological differences under the action of the arc. Because the arc erosion on the surface of the

abnormal wear slide plate was more severe and the temperature of the contact pair was higher than that during sliding, a considerable amount of copper melted. Thus, the arc erosion pits distributed on the surface increased the roughness of the surface, increased the off-line rate and burning rate of the slide plate, and further promoted the occurrence of arc erosion [25–27]. Under the experimental conditions, the electrical wear and arc ablation were lighter owing to the small loading current. According to the wear rate, the surface material removal rate of the 20% RH sample was much higher than that of the 30% and 40% RH samples. Under mechanical wear, the surface roughness of the low-humidity slide plate was minor. Compared with the other two humidity conditions, the contact relationship between the slide plate and contact wire was good, and the arc ablation was reduced. The inconsistency between test conditions and service conditions may be the reason for the differences in surface roughness.

Table 2
Surface roughness of pantograph slide plate under different wear conditions

	Test condition			Actual service	
	20% RH	30% RH	40% RH	Abnormal wear	Normal wear
Roughness *R*a (μm)	2.26	2.55	2.99	7.60	2.54

3.4 Influence of humidity on slide plate wear

The above analysis can only explain the differences in the surface morphologies of slide plates. However, humidity directly influences the surface wear of slide plates. The surface image and element distribution of the pantograph slide plate under different wear conditions were obtained using a JSM-IT500LV scanning electron microscope equipped with an energy dispersive spectrometer.

Humidity plays a crucial role in metal wear. In addition to the aforementioned water film, friction pairs can be directly protected to reduce wear. A thicker water film under high humidity can be used as an electrolyte to accelerate the corrosion and oxidation rate of metal surfaces, thereby affecting the friction and wear performance. With a gradual increase in the air water-vapour content, the surface can form a more protective oxide layer to reduce the wear between metal friction pairs [17, 28–30]. In the atmospheric environment, the water vapour attached to the metal surface can be ionised to generate H^+ and OH^- ions under current action. Thus, the hydroxide group composed of OH^- ions produced by ionisation can further promote the adsorption of water vapour molecules on the surface and accelerate surface tribochemical and electrochemical oxidation. Moreover, the H^+ ions can enhance the oxidation of O_2 in the atmosphere, thus accelerating the formation of surface copper oxides and gradually creating a more complete surface oxide film [29, 31].

Figure 8 shows the SEM and EDS scanning results of the pantograph slide plate surface under different wear conditions. Under the condition of 20% RH test and abnormal wear state, numerous arc erosion marks were produced on the slide plate surface, and copper aggregated in the area of severe arc erosion. In particular, a large amount of copper aggregated on the surface of the abnormal wear slide plate owing to intense arc erosion, whereas only a small amount was distributed in other areas. The slide plate surface did not form a complete oxide layer and could not provide good lubrication for the slide plate; thus, it exhibited a high wear rate and friction coefficient (Figs. 8a and 8d). With an increase in relative humidity, the distribution of the oxide layer on the sliding plate surface gradually became complete. Under the condition of 30% RH, a uniform dispersion of copper appeared on the sliding plate surface, and the overall colour of the SEM image deepened (Fig. 8b). Under a 40% RH and normal wear state, obvious cracks appeared on the slide plate surface; however, a relatively complete oxide film was formed. The copper element was completely dispersed, and the overall colour of the surface was considerably different from that of light grey at 20% RH. At this time, the wear rate and friction coefficient were significantly lower than th ose at 20% RH.

Humidity affects the formation of abrasive particles on a slide plate surface. Figure 9 shows the wear particle distribution on the slide plate surface under different humidity conditions. Evidently from the EDS results, the surface abrasive particles were predominantly copper particles. Under low-humidity conditions, the surface free energy of the material was high owing to the lack of water vapour in the atmosphere. Owing to the adhesion of copper and copper–silver alloy wires distributed on the slide plate surface material under high temperatures during the wear process, a large number of small abrasive particles were generated and significantly increased the wear of the contact pair. When the relative humidity was high, water vapour covered the slide plate surface, thereby reducing the surface free energy and generating fine abrasive particles. During the wear process, abrasive particles of different sizes can cooperate, and large particles provide support. Small particles play a role in repairing the surface, thereby reducing surface wear [29, 32]. This is consistent with the observed wear particle distribution on the normal and abnormal slide plate surfaces during actual service.

In general, under the condition of high humidity and repeated mechanical wear and arc ablation thermal stress, cracks are continuously initiated, thus resulting in the damage and shedding of the slide plate surface material, the surface is protected by the oxide and water films. In the case of low humidity, under the action of arc ablation and slight abrasive wear, the surface of the pantograph slide plate cannot form a surface film without sufficient water vapour and easily adheres to the copper–silver alloy wire, thus forming a large number of small copper abrasive particles and resulting in adhesive and abrasive wear. At the same time, in actual service conditions, owing to the instantaneous large current, the pantograph–catenary contact stability is poor, and arc erosion increases. Thus, the surface of the adhesive wear was more severe than that of the test conditions, and the surface smoothness was significantly damaged and caused more serious wear.

4 Conclusions

The influence of relative humidity on the friction and wear properties of a pantograph copper-impregnated carbon slide plate was investigated. The influence of the surface macro and micro morphology and element distribution on the wear process of slide plates was analysed under different test humidity and service conditions and compared. The root cause of seasonal abnormal wear of pantograph slides was revealed. The following conclusions can be drawn.

1. As the relative humidity increased from 20–40% RH, the wear rate decreased significantly. The friction coefficient first decreased and did not change significantly between 30% and 40% RH.

2. The change trends between the surface morphology of the slide plate under the test and actual service conditions differed primarily because of the inconsistency of the operating parameters, thus resulting in arc ablation and surface temperature differences.
3. The influence of humidity on the wear of a sliding plate was reflected primarily in the formation of the surface oxide film and abrasive particles. With a gradual increase in the number of water vapour molecules in the environment, the surface oxide film became more complete, thus lubricating and protecting the surface, reducing the adhesion between friction pairs, and reducing the formation of small abrasive particles on the surface.

The humidity test range setting was based primarily on the tracking test results of an actual operation line. Owing to the difference between the test conditions and actual service process, further research is required to determine if a slide plate will provide better friction and wear performance under higher humidity conditions.

Declarations

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Author Contributions

All authors contributed to the study conception and design. MH and BY designed and performed the experiments, conducted the Observations and analysed the data. YR and LZ contributed to sample

preparation. MH and BY wrote the manuscript in consultation with YR, LZ and SX. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Figures

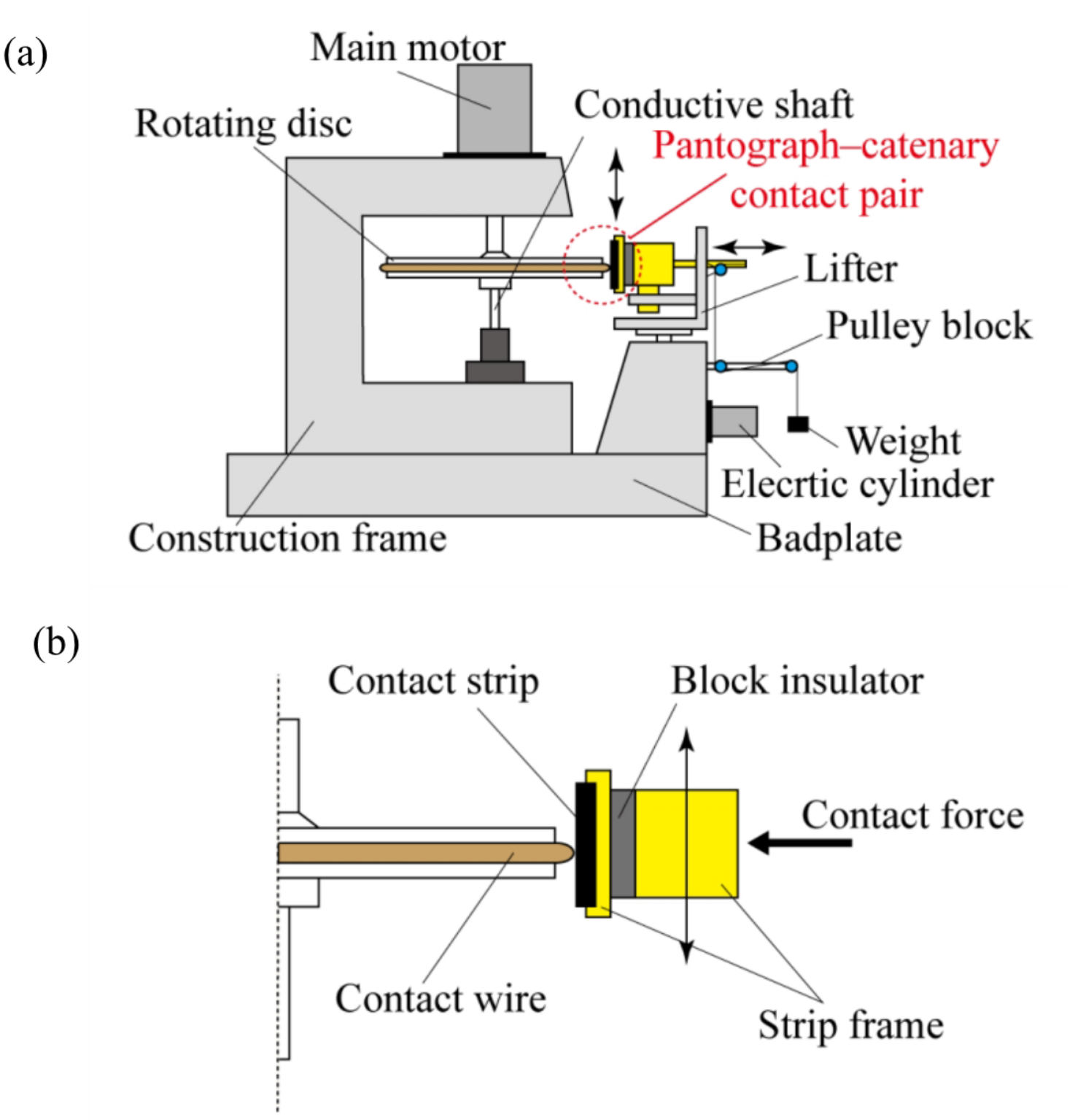


Figure 1

Current-carrying friction tester: (a) block-on-ring friction testing machine and (b) simulated pantograph–catenary contact



Figure 2

Pantograph slide plates with different wear states: (a) normal and (b) abnormal

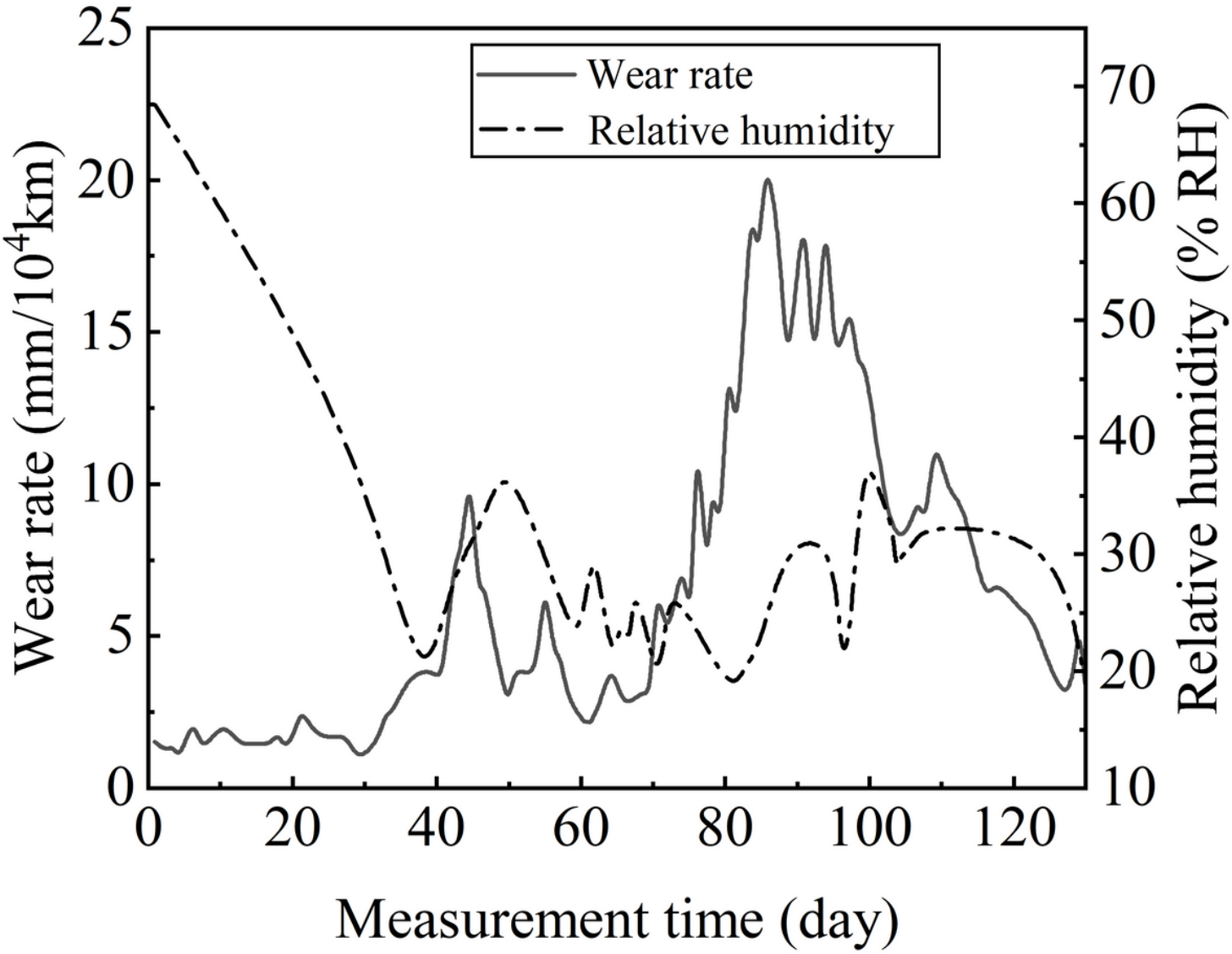


Figure 3

Variation in metro pantograph slide plate wear in autumn and winter

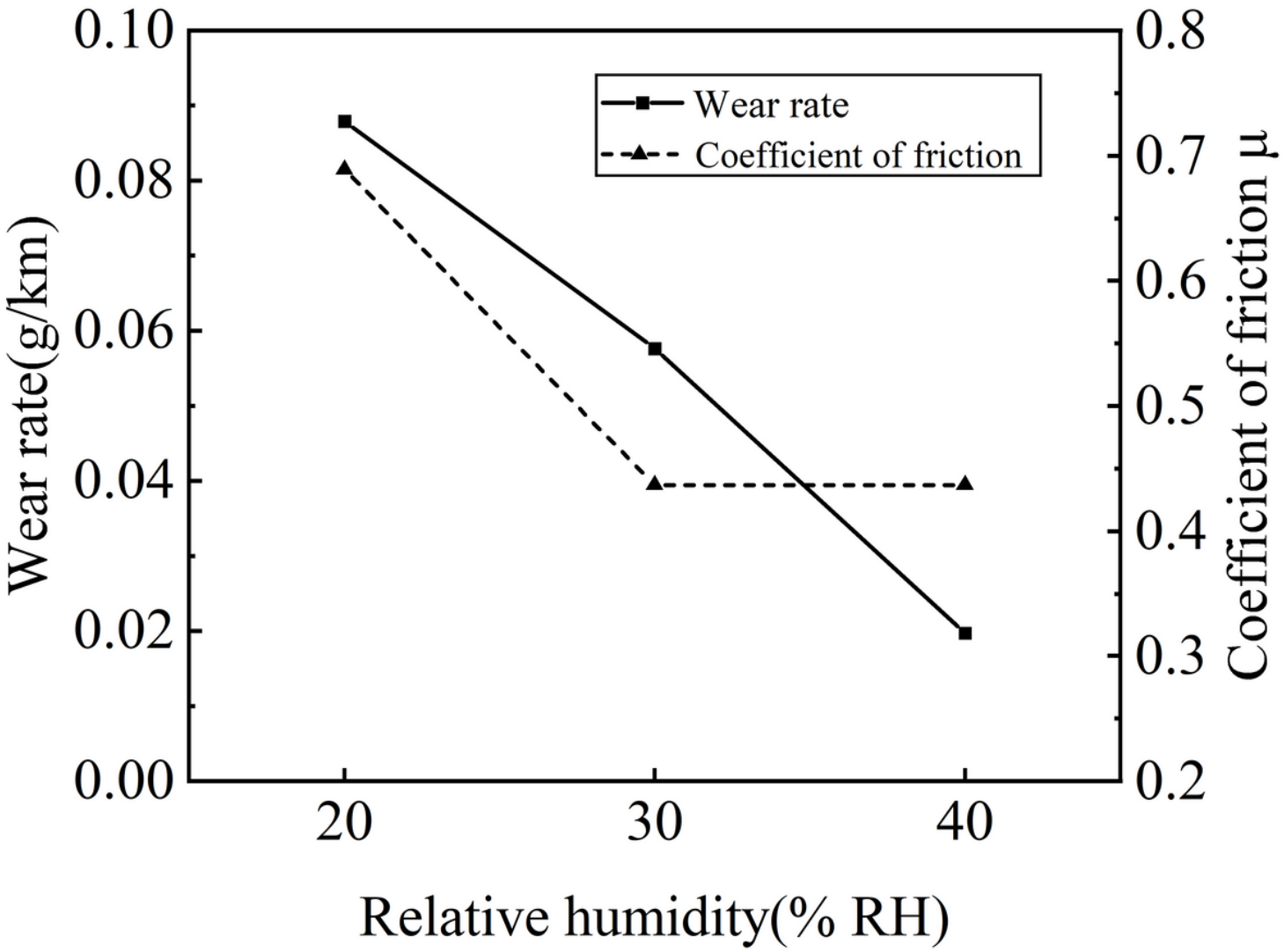


Figure 4

Wear rate/friction factor–relative humidity variation

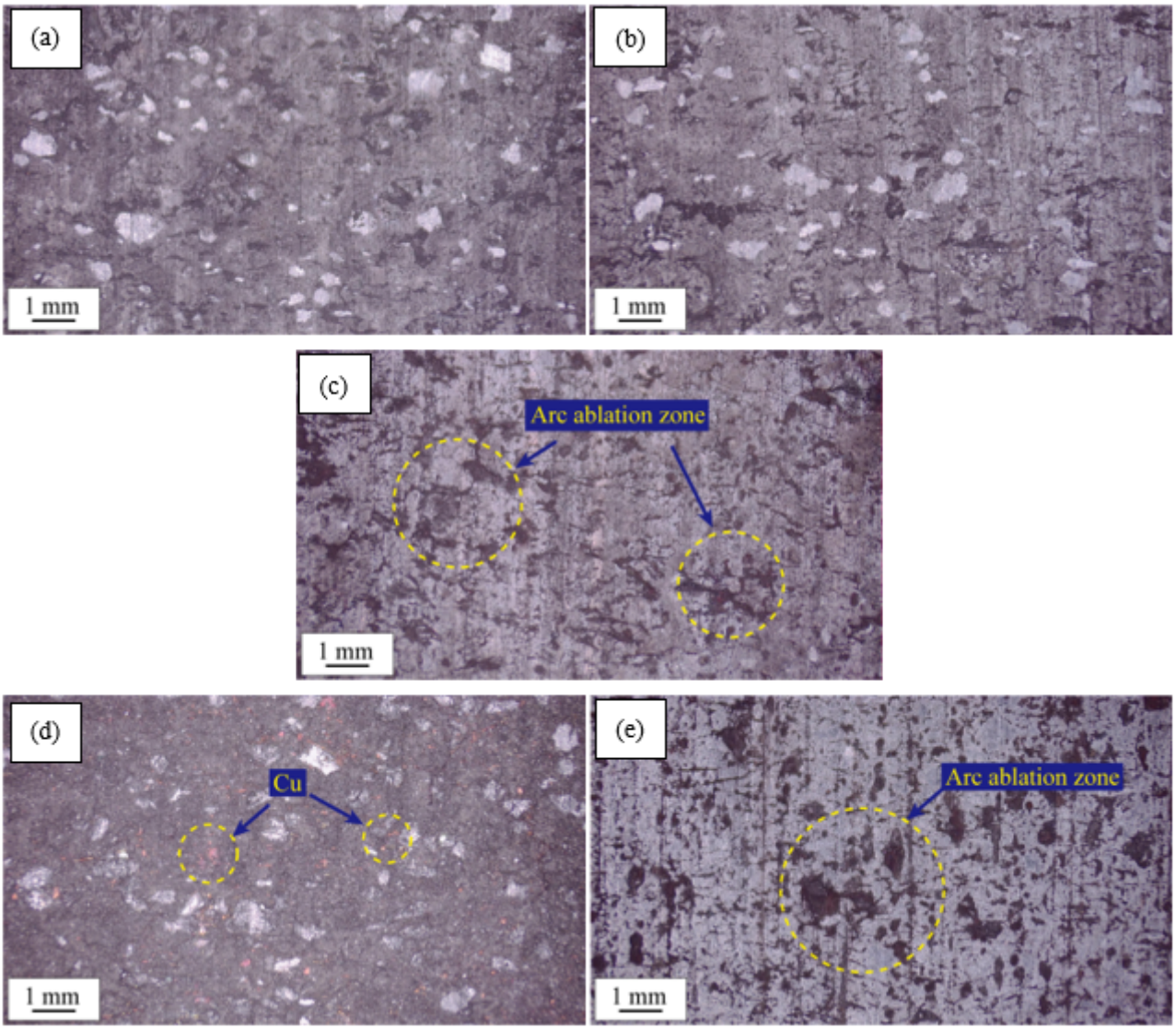


Figure 5

Macrograph of slide plate surface under different wear conditions: (a) 20 % RH, (b) 30 % RH, (c) 40 % RH, (d) abnormal wear, and (e) normal wear

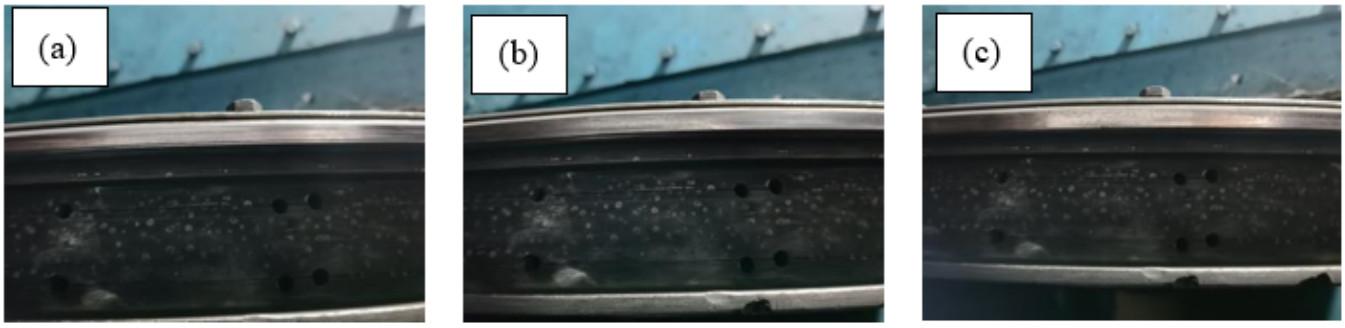
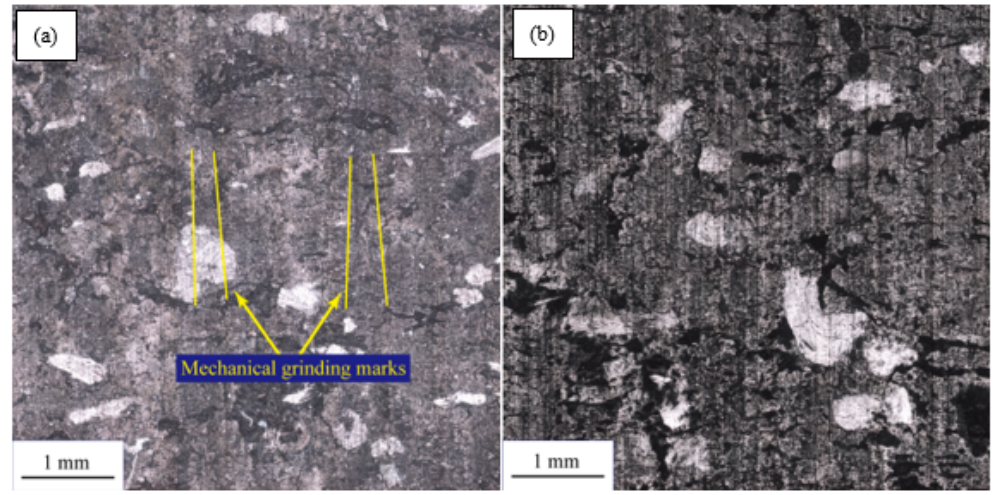
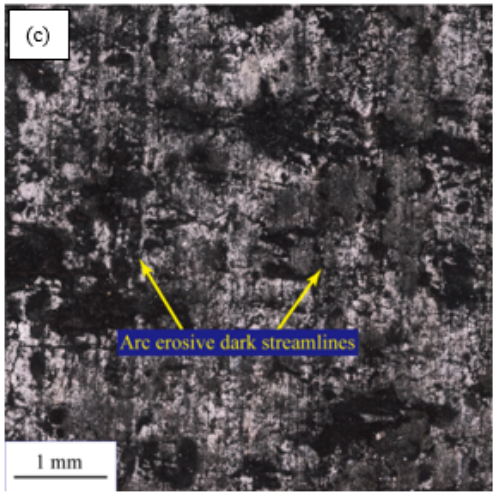


Figure 6

Macrograph of contact wire surface under different wear conditions: (a) 20 % RH, (b) 30 % RH, and (c) 40 % RH





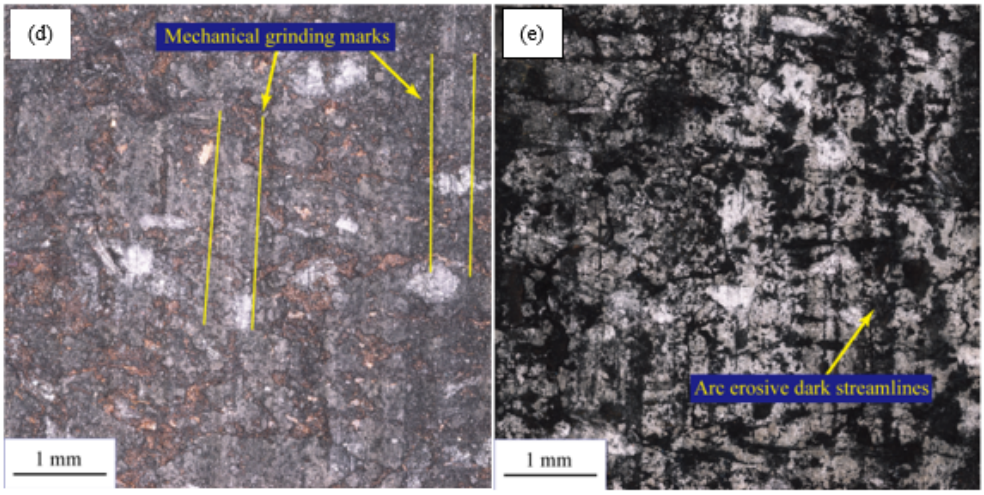


Figure 7

Surface micrograph of pantograph slide plate under different wear conditions: (a) 20 % RH, (b) 30 % RH, (c) 40 % RH, (d) abnormal wear, and (e) normal wear

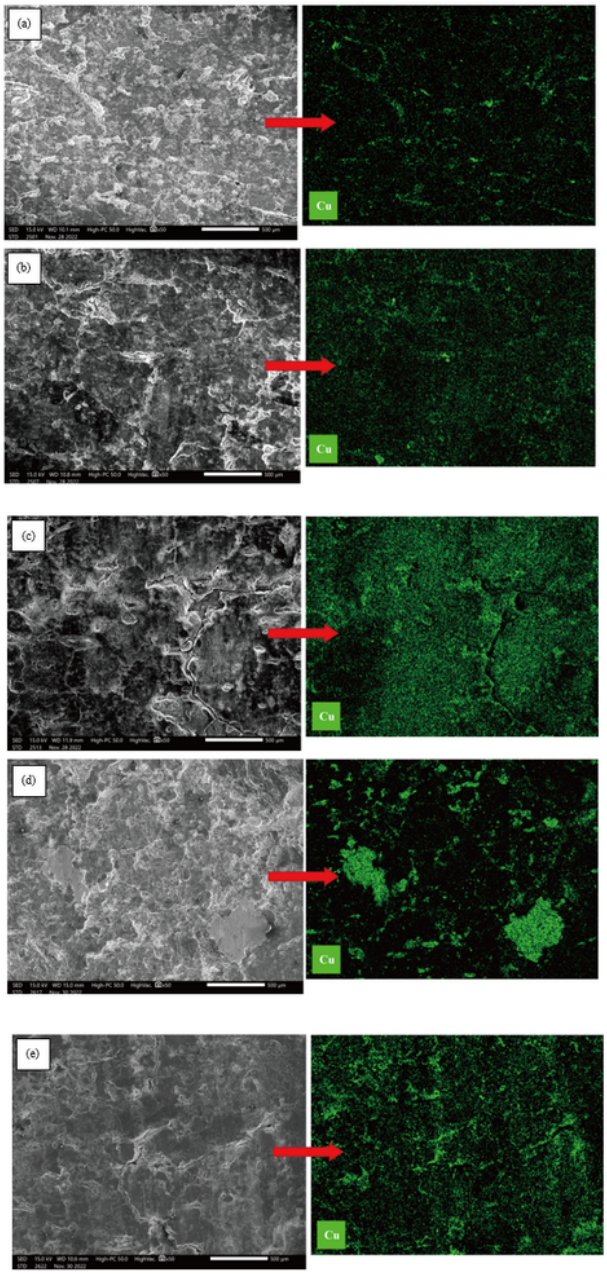


Figure 8

SEM and EDS results of different wear state surfaces: (a) 20 % RH, (b) 30 % RH, (c) 40 % RH, (d) abnormal wear, and (e) normal wear

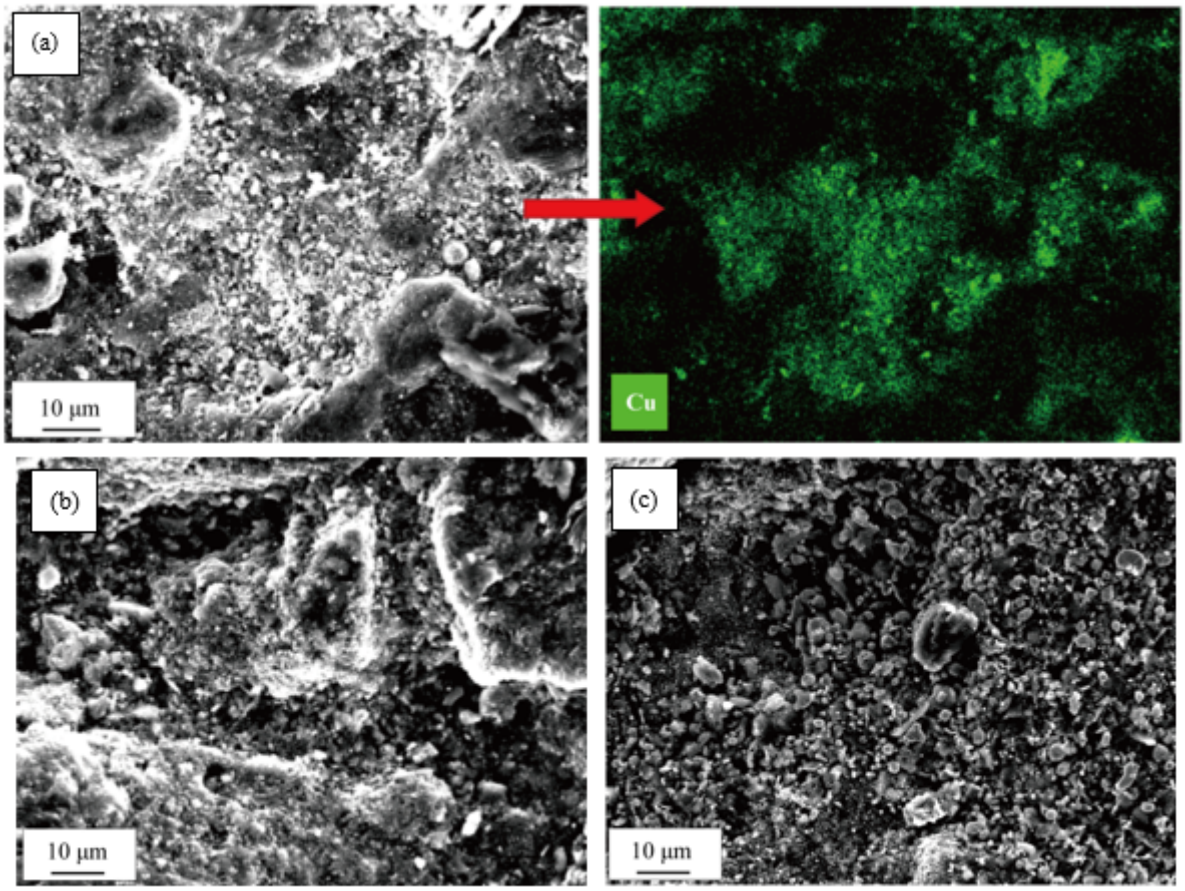


Figure 9

Distribution of surface abrasive particles in different wear states: (a) 20 % RH,

(b) 30 % RH, and (c) 40 % RH