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Summary of abnormal wear status of pantograph-catenary system in metro

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Abstract: In view of the frequent occurrence of abnormal wear of the pantograph/catenary system in domestic urban rail transit in recent years, this paper summarizes the abnormal wear events of the pantograph/catenary contact pairs on nearly 10 subway lines from the aspects of contact pair structural characteristics, fault phenomena, their temporal and spatial attributes, and handling measures. The main research results at home and abroad on the influence of factors such as normal load, current, and arc on the wear of pantograph-catenary system are analyzed; The research progress of the wear mechanism of the pantograph-catenary system is discussed; The research process of foreign research teams on the wear model of the pantograph catenary system is introduced. Based on the analysis results of engineering and scientific research status, a root cause analysis method for abnormal wear of the pantograph and catenary system is developed with reference to the wear model of the pantograph and catenary system; The verification and confirmation methods for the cause of abnormal wear are summarized from the perspectives of ground test, line test, simulation analysis, and data processing technology. Based on the research and analysis results and the prevention framework for abnormal wear issues, the potential exploration space for scientific and engineering issues is prospected. The research results can provide technical and management references for relevant units of urban rail transit to deal with abnormal wear events of the pantograph catenary system.

Keywords: Urban rail transit; pantograph; rigid catenary; abnormal wear; root cause analysis

1. Introduction

The contact line of flexible catenary of trunk railway is suspended to the designated space position through load-bearing cables and hanging strings. However, the contact line of the overhead rigid catenary of urban rail transit is directly clamped to the lower surface of the bus through the dovetail slot (Figure 1), which realizes the conductive function during the sliding contact with the pantograph. It has the advantages of simple structure, small installation space, no hidden danger of disconnection, long service life and less operation and maintenance workload.

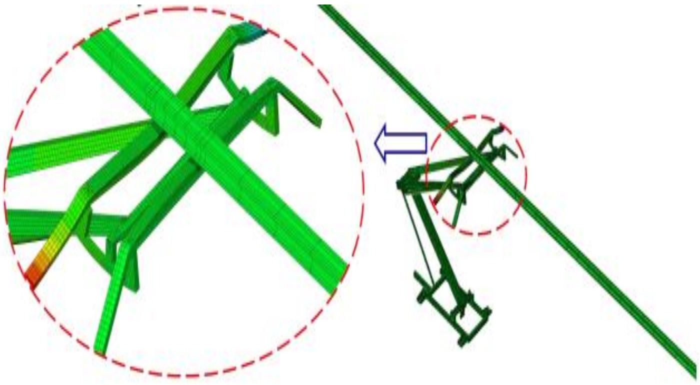

Figure 1. Rigid catenary of urban rail transit.

Since Guangzhou Metro Line 2 started the application of overhead rigid catenary technology in China in 1998, the development of rigid catenary technology in China has experienced many milestones. In 2005, Guangzhou Metro Line 1 will increase the application speed of overhead rigid catenary to 120 km/h for the first time. In September 2019, Beijing Daxing International Airport Line became the first 160 km/h high-speed overhead rigid catenary in China. The DC 1500V power supply system is replaced by AC 25 kV direct power supply with streamline. Subsequently, the first sections of Guangzhou Metro Lines 18 and 22 were opened for operation in September 2021 and March 2022, respectively. They are the first time that AC is fully adopted on 160 km/h high-speed subway in China.

Pantograph catenary transmits electric energy through sliding contact. Under the traction of vehicles, pantograph continuously excites catenary, which arouses the change of catenary motion. The motion of catenary propagates in a certain range before and after the contact point of pantograph and catenary in the form of elastic wave, which in turn affects the motion of pantograph, thus forming the dynamic interaction of pantograph and catenary system. In fact, due to the functional positioning of pantograph-catenary system, there is not only the transmission of mechanical energy, but also the transmission and conversion of electric energy and heat energy on the contact interface between pantograph and catenary. Pantograph-catenary dynamic interaction is a typical multi-physical field coupling situation, so the matching design, application and maintenance of pantograph-catenary system is a very complex system engineering.

When the rigid catenary was first applied to Guangzhou Metro Line 2, it experienced a complicated treatment process of abnormal wear of contact pairs in pantograph-catenary system. Since 2013, the abnormal wear of Line 2 has obviously increased, and the number of line changes and wear degree exceed the average value of previous years [2]. In recent years, with the increasing mileage of subway operation, abnormal wear events of pantograph-catenary system have appeared in Beijing, Shanghai, Shenzhen, Tianjin, Zhengzhou, Xi’an, Shijiazhuang and other cities.

Abnormal wear reduces the service life of equipment, increases the investment of people and property related to maintenance activities, and affects the normal operation of trains in serious cases. Due to the complexity of the pantograph-catenary system itself and the asymmetry between current carrying friction and wear research progress and engineering requirements, subway operating companies often lack effective countermeasures after abnormal wear occurs. Therefore, this paper focuses on the following issues, in order to provide an analytical framework and technical guidance for the prevention before and treatment after the abnormal wear of pantograph-catenary system:

(1) When abnormal wear occurs, researches the external performance and time-space law of pantograph-catenary contact pair.

(2) Cognitive consensus on influencing factors and wear phenomena of pantograph-catenary system.

(3) Technical framework for dealing with abnormal wear after its occurrence.

(4) Quantitative evaluation of hot spots of concern for abnormal wear of the pantograph/catenary system.

2. Research on the current situation of operation and maintenance

Through direct project participation, public literature and data investigation, the author's team combed the abnormal wear events of rigid catenary pantograph allocation in detail from the aspects of structure form, abnormal wear phenomenon, abnormal wear time and space law, operator research content and treatment measures. Table 1 is the summary statistics of abnormal wear events of pantograph-catenary system which can be queried publicly.

In terms of structural attributes, there are many pantograph manufacturers and skateboard brands affected by pantograph and abnormal wear, including pantograph such as Tianhai, CRRC Zhuji, Toyo and STEMMANNN, and skateboard such as Morgan, PANTRAC, HOFFMANN, SCHUNK, Dongnanjia, Wangao and Westinghouse. The number of pantograph slides includes both four-slide pantograph [2,3] and two-slide pantograph [4–7]. The slide plate material includes pure carbon, metal impregnated carbon and powder metallurgy carbon slide plate. For catenary, most of the abnormal wear events are related to the pull-out value arrangement of sine wave type [8], but the catenary with zigzag triangular wave arrangement also has abnormal wear events [9]. The maximum pull-out value of contact wire includes 200 mm and 250 mm at the same time, and the contact wire area covers 120 mm^2 and 150 mm^2.

From the aspect of abnormal wear phenomenon (Figure 2), for pantograph slider, pit or wave wear and the magnitude increase of wear rate occur frequently. As for the abnormal wear rate of skateboard, Guangzhou Metro Line 2 considers that it is abnormal wear exceeding 6.82 mm/10000km [8], Shenzhen Metro Line 11 believes that the wear rate exceeds 4.6 mm/10000km too high [10]. Normal wear of skateboard in Nanjing Metro Line 4 is 0.35 mm/10000km, abnormal wear 40 mm/10000 km [5]. Zhengzhou Metro Line 1Before the opening of Phase 2, the skateboard wear is 0.4 mm/10000 km, and the maximum after opening can be up to 12 mm/10000 km [6], the normal wear of Zhengzhou Metro Line

3 is 5 Mm/10000 km, and 35 mm/10000 km in case of abnormality. As far as the contact line is concerned, the main reasons are that the wear width and wear rate of the lower surface of the contact line in the same section and anchor section are too large, and the contact line, bus scratch, edge burr of the contact surface and so on. For example, Guangzhou Metro Line 2, the abrasion rate of normal section is 0.0014 mm^2/10000 bow sorties, and the abrasion is serious. The wear rate of section contact wire can reach 0.5 mm^2/10000 bow sorties [8].

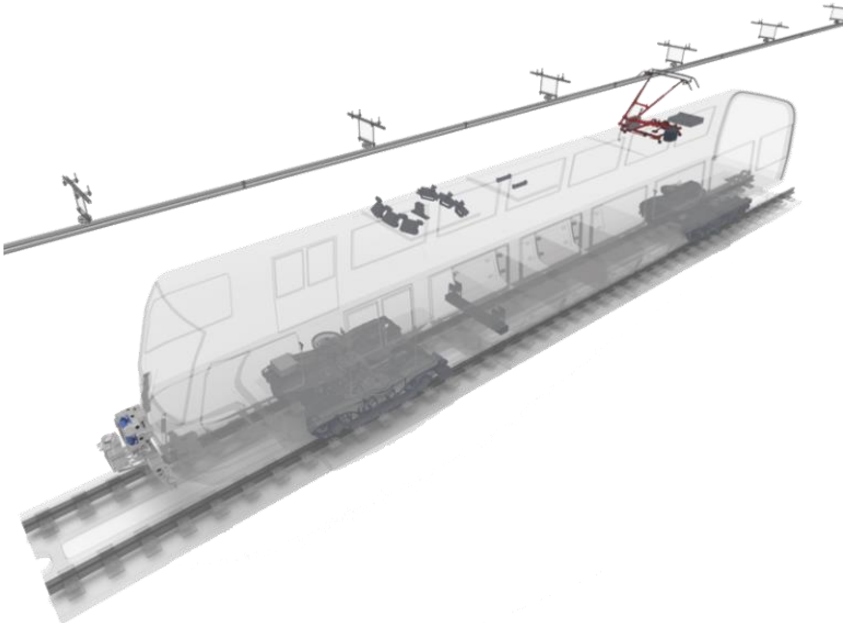

Figure 2. Abnormal wear of pantograph and catenary in metro.

According to the spatial attribute of abnormal wear, the serious wear sections of contact line are mainly concentrated in the acceleration section of outbound train, sectional insulator, anchor joint, line bifurcation, elastic ballast section, bend, ramp section and indirect head in bus [4,7,11]. However, most of the carbon slide pits appear near the maximum pull-out value, and the slide pits can also be observed at the center of the slide [10] and between the maximum pull-out and the center of the slide [6]. For the time attribute of abnormal wear, the change rate of wear width of contact line of Urumqi Line 1 in winter is slightly higher than that in non-winter [4]. The abnormal wear of Nanjing Metro Line 4 also occurred in winter, from November 2017 to February 2018 [5]. The abnormal wear of pantograph and catenary was first found in Beijing Metro Line 6 in mid-December, 2018 [12]. The abnormal wear of Zhengzhou Metro Line 3 was discovered in early December, 2020, and the operators thought that there was an obvious negative correlation between the wear amount and temperature and humidity during the abnormal wear period [13].

Table 1. Analysis on abnormal wear events of pantograph-catenary system under DC 1500 V power supply system.

Metro line	Pantograph	Catenary	Abnormal phenomenon	Temporal and spatial properties of abnormal wear	Research content	Treatment measures
Urumqi Line 1	Spring tube type, double slide plate	CTA 150	1. Wave eccentric wear and block drop of skateboard 2. The wear of contact wire in the same section and anchor section is unbalanced 3. Increased arcing	1.2019.6-2020.12 2. The contact line of curve section and elastic ballast bed is worn seriously 3. Serious arcing in the exit flow taking section 4. The change rate of contact wire wear width in winter is slightly higher than that in non-winter	1. Compared with the normal operation diagram, the arc difference is obvious when entering and leaving the station at a uniform speed 2. Adjust the static lifting force.120 N wear is the smallest.130 N is the second,and 110 N is the largest	1. Adjustment of skateboard levelness 2. Adjustment of catenary slope and pull-out value by section 3. The hanging screw is changed into an elastic screw, and the positioning clamp adopts an elastic clamp
Dalian Metro Line 1 & 2	Tianhai, four skateboards	CTA 200	1. Abrasion of slide pits 2. The catenary is seriously worn	1. 2018. 03 2. The slide plate groove is located at the maximum pullOut of position 3. The catenary is seriously wornVehicle acceleration area, damping trackBed, variable slope area	/	1. Skateboard grinding and levelness adjustment 2. Hard point of catenaryVisual inspection of prone areas; pointsSection pull-out value adjustment
Chongqing Metro Lines 1 & 6	Tianhai, double skateboard, pure carbon skateboard	/	Arc-pulling burns ADD trachea to cause bow-lowering protection; High temperature carbonization of conductive adhesive for slide plate	1.2012. 04-2013.06 2. The arc pulling of exit, bend and slope changing section is obvious 3. Burning of the bonding between carbon slide plate and aluminum alloy	1. When the static lifting force is adjusted from 110 N to 120 N, the skateboard still burns out 2. The skateboard temperature rise test shows that the skateboard current-carrying design is not rich enough 3. Double skateboards are changed to four skateboards without burning loss	1. The skateboard is re-selected as metal-impregnated carbon skateboard and replaced with four skateboards; 2. Installation and adjustment of contact wire in hard spot prone area

Table 1. *Cont.*

Metro line	Pantograph	Catenary	Abnormal phenomenon	Temporal and spatial properties of abnormal wear	Research content	Treatment measures
Nanjing Metro Line 4	Zonde Hoffman, SK1204,	CTAH 120	The wear rate of skateboard is determined by0.35 mm/10, 000 km, increased to 40mm/10, 000 km; "V"-shaped deep pit on one side of skateboard 3.Skateboard collapse	1.2017.11-2018.2 2.Some outbound speed-up areas and high-speed operation areas continue to burn arcs 3. Abnormal wear occurred after the opening of Phase II	1. The skateboard is changed to SCHUNKSK2113, still abnormal wear 2. Correlation study on out-of-round wheelset of elastic ballast bed, no correlation 3. Slide plate friction and wear test	1. Limit the peak value of interval velocity 2. Adjustment of catenary pull-out value on abnormal wear side 3. Carbon slide plate grinding 4. Sine wave changing to zigzag pull-out arrangement
Guangzhou Metro Line 2	CY280	RIS120	1. Pit wear of slide plate, accompanied by abnormal wear rate 2. The wear rate of contact line increased from normal 0.0014 mm2/10, 000 bow sorties to 0.5 mm2/10, 000 bow sorties 3. Abnormal uplift of central anchor 4. Severe pull arc	1. Abnormal wear occurred after opening in 2003, and increased after recovery with 2013 as the turning point 2. The slide plate groove is located at the position where the pull-out value is maximum 3. Abnormal wear of contact line in exit acceleration zone, damping ballast bed and variable slope zone4. Increased arc pulling at insulating joints	1. Replace the pantograph as a whole; The wear rate decreased and the pits remained the same 2. When the static lifting force is adjusted from 120 N to 110 N, the wear rate of sliding plate increases inversely 3. Comparison of different types of skateboards, some abandoned	1.Daily maintenance and adjustment of contact line and replacement of local or whole anchor section 2. Change the skateboard type 3. Move the central anchor position, and install anchor clamps and adjusting bolts on both sides. 4. Grinding the slide plate
Shenzhen Subway Line 11	STEMMAN	1/4 Flexible, 3/4 Rigid	1. The wear rate of skateboard is too high, and the profile is pitted 2. Severe arc pulling 4. 3. The skateboard is missing	1. The pit is located in the center of the slide plate and is pulled out at the corresponding expansion joint 2. The expansion joint has serious arc tension 3. Initial operation	New bow head and new spring support replace vane spring	1. Adjustment of catenary pull-out value 2. Modification of expansion elements 3. Application of new bow head 4. Manufacture and application of carbon slide plate grinding process

In order to analyze the causes of abnormal wear of pantograph-catenary system, various subway operators have used various verification and confirmation methods. It mainly includes: changing pantograph with normal wear line [2], adjusting nominal static lifting force of pantograph [2,4,13–15], comparing different types of skateboards [16], comparing normal operation diagram of trains entering and leaving stations at a constant speed without stopping [4], skateboard temperature rise test [14], skateboard friction and wear test [17], wheel set out-of-circle correlation analysis [5], bow head structure transformation, *etc.*

For the treatment measures after abnormal wear, except for appearance inspection and increasing the frequency of daily maintenance operations such as grid rail inspection, other aspects mainly focus on the adjustment of catenary geometric parameters, sliding plate grinding, bow head levelness adjustment, local or whole anchor section line change of catenary, expansion element rectification [10], central anchor position adjustment and installation of anchor clamp and adjustment bolt [8], catenary suspension screw changed to elastic screw, positioning clamp adopted elastic clamp [4], pantograph bow head parts [10] and slide plate replacement, *etc.*

From the survey results, there are two phenomena worthy of attention. Firstly, almost all abnormal wear events are accompanied by obvious increase of pantograph-catenary arc; Secondly, in Zhengzhou Metro Line 1 and Guangzhou Metro Line 2, wave wear similar to rail wave wear appeared in the contact line [15]. Among them, the abnormal wear events of pantograph and catenary are accompanied by the increase of arc phenomenon, which provides a starting point for exploring wear laws. On the one hand, the research results of wave wear of rigid catenary in Japan can be used for reference [18], and the exploration of friction and wear of pantograph-catenary system can learn from the research methods related to rail wave wear [19,20].

The investigation results also show that the abnormal wear phenomenon of pantograph-catenary system in urban rail transit has not been fundamentally solved. Especially for lines with periodic abnormal wear, subway operators often need to prepare in advance and increase investment in spare parts and maintenance frequency. There are still the following problems to be further solved in the scientific response to abnormal wear:

(1) The operating parameters affecting the wear of contact pairs and their interrelationships are not clear, and the research test lacks scientific working condition design, so it is impossible to accurately orient the root causes of abnormal wear. For example, the pantograph lifting force affects the test, and the test results cannot support the operation and maintenance decision because it does not match other application parameters to design the test conditions together.

(2) The temporal and spatial law of abnormal wear of contact pairs is complex, and the operation and maintenance activities of pantograph-catenary system are related to vehicles, power supply and other specialties. The abnormal wear control measures lack unified and standardized process management, and the effectiveness of rectification measures cannot be verified, so it is difficult to form abnormal wear response experience that can be popularized and replicated.

(3) The special standards and specifications of rigid catenary and pantograph in urban rail transit need to be improved. For example, the quantitative parameter management of rigid catenary layout, the construction of contact pair grinding standard and so on. Each subway operator completes its own pantograph-catenary system maintenance work by experience, and the maintenance efficiency is uneven and the trial and error cost is too high.

3. Analysis of research status of wear influencing factors

Pantograph-catenary system is in a multi-physical field interaction environment, and there are many energy conversion forms including thermal energy, mechanical energy and electrical energy in its contact interface (Figure 3). The friction and wear performance of pantograph-catenary system under the action of multiple physical fields is the result of the interaction of general mechanical properties, hydrodynamic aerodynamic effects, electrical effects and thermal effects. The application parameters of pantograph-catenary connection system include sliding speed, normal load, current intensity and so on; The state characterization parameters include contact resistance, temperature rise of contact pair, wear rate, friction coefficient, arc rate and so on. Considering the lack of complete theoretical solution of pantograph-catenary friction and wear phenomenon under multiple physical fields, this section introduces the objective experimental results of current-carrying friction and wear of pantograph-catenary system under the influence of normal load, friction velocity, current, arc rate, temperature and other factors, so as to establish an intuitive cognition of the correlation between various application parameters or characterization parameters and current-carrying friction and wear of pantograph-catenary system.

Figure 3. Wave film of contact line between Guangzhou Metro Line 2 and Zhengzhou Metro Line 1.

3.1. Normal load

Under AC system, Zhang Saidan *et al.* [21] studied the contact characteristics of carbon slide plate/copper contact wire when the sliding current was 250 A, the sliding speed was 160 km/h, and the normal loads were 50 N, 70 N, 90 N, 110 N and 130 N. The results show that the wear rate of sliding plate is high at the beginning stage, and it enters a stable stage after 20 min, and the wear rate of sliding plate decreases and continues to be stable until the end of 80 min test. During the stable period, the wear rate of sliding plate decreases first and then increases with the increase of normal load, showing a “U” shape distribution, the wear rate is in the range of 0.025 mg/s~0.13 mg/s, and the wear rate is the smallest at 90 N. Chen Zhonghua *et al.* [22] set the normal load to change in the range of 40 N~120 N under the running speed of 150 km/h. It is also found that the wear rate of slide plate changes in a U shape with the increase of normal load, and the wear rate varies from 0 g/10000 km to 150 g/10000 km. At the same time, he used multi-objective particle swarm optimization to solve the Pareto optimal solution of current relative stability coefficient (current range is 100 A~300 A) and wear rate, and the calculated optimal normal load is 58.1 N. The overall rigid contact network system model is shown in Figure 4.

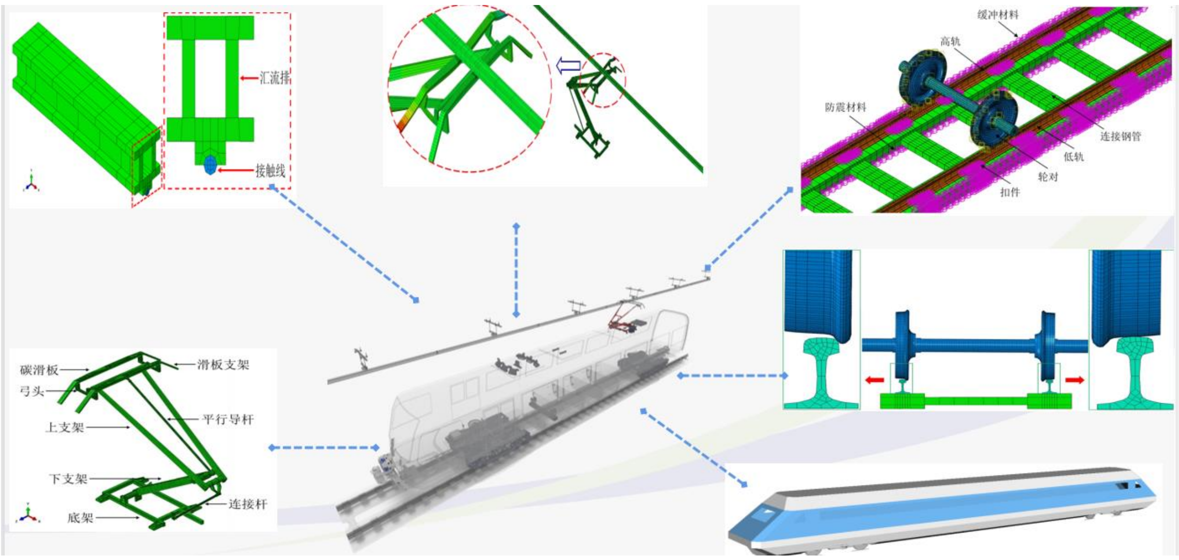

Figure 4. Interdisciplinary study of pantograph-catenary system.

3.2. Running speed

Chen Zhonghua *et al.* [22] used pure copper contact wire with metal-impregnated slide plate, and set the normal load at 80 N. From the current-carrying friction wear test results, it was found that the wear rate of slide plate decreased with the increase of speed under various current conditions (100 A~300 A), and the wear rate was the highest at the speed of 50 km/h, which was close to 700 g/10000 km. Yang Zhenghai *et al.* [23] studied the wear rate of slide plate when the normal load is 70 N, the current is 60 A and 120 A respectively, and the sliding speed varies from 10 m/s to 40 m/s. It was found that the wear rate increased monotonously with the speed, with 30 m/s as the boundary, and the wear rate increased sharply with the increase of speed, and the wear rate ranged from 0.25 mg/m to 2.25 mg/m. Yang Guangying *et al.* [24] tested the wear performance of CTS150 copper-tin alloy contact wire with DSA380 carbon slide plate at a mileage of 6000 km at the speeds of 250 km/h, 300 km/h and 350 km/h respectively, and the current intensity was 500 A of power frequency AC. The results show that the weight-to-wear ratios of the sliding plates at three speeds are 30 g/10000 km, 16 g/10000 km and 25 g/10000 km respectively. At the same time, in the range of 6000 km test mileage, the curves of contact line wear ratio with velocity are interlaced with each other, and there is no specific monotone increasing or decreasing law.

3.3. Current

Mei Guiming *et al.* [25] adopts copper-silver alloy contact wire with metal-impregnated carbon slide plate, and the sliding speed is set at 60 km/h, and each slide plate is in contact withThe normal load between the lines is 30 N and the sliding distance is 150 km. The wear rate of slide plate under 0 A and 400 A DC was compared. The results show that the wear ratio of slide plate is 0.096 mm3/km without current.When the current 400A, the lower wear rate is 53 times higher than non-current carrying condition. Guo Fengyi *et al.* [26] used120 mm2 copper-tin alloy wire was matched with copper-based powder metallurgy slide plate and copper-impregnated carbon slide plate. The effect of current on the wear rate of slide plate was studied. It is found that the wear rate of the two materials increases with the increase of current when the current varies from 150 A to 500 A, and the increase of wear rate varies with the change of current in different current ranges.

3.4. Combustion arc

Wangxin *et al.* [27] used pure carbon slide plate and pure copper contact wire to match the pair, set the current to 100 A, and affected the average arc discharge time of the contact pair by changing the normal load, thus indirectly controlling the arc energy. In the range of 20N~90 N, the larger the normal load, the shorter the discharge time and the smaller the arc energy, it is confirmed that the arc energy is approximately proportional to the wear amount. Hu Daochun *et al.* [28] designed the test conditions of three factors (force, current and speed) and four levels, and obtained that the wear volume per unit load and per unit friction stroke has a power function relationship with arc energy when the normal load is 50 N~80 N, the sliding speed is 30 m/s~60 m/s and the current is 70A~160 A. KUBO *et al.* [29,30] completed the test of impregnated carbon slide plate and pure copper contact wire under the action of direct current, and the relative sliding speed was set to 100 km/h, and the current varied from 0A to 200 A. The results show that the wear rate is affected by the intensity and duration of arc discharge. It is considered that the surface thermal effect caused by arc discharge plays a leading role in the wear rate of slide plate, and it is also considered that the wear rate is proportional to the arc energy. KUBOTA *et al.* [31] set the friction velocity of 55.6 m/s, the normal load of 59 N and the DC current of 100A~500A. It is also found that the wear of copper-impregnated C/C composite slide plate is positive with the arc discharge energy. The research results of MEI *et al.* [32−34] also show that the wear rate of slide plate is proportional to the arc energy under laboratory conditions, whether it is AC or DC.

3.5. Temperature

In terms of the correlation between the application parameters and characterization parameters of pantograph- catenary system, the team of Southwest Jiaotong University [32–36] made a preliminary exploration based on its current-carrying friction and wear test-bed, studied the changes of current, normal load, arc amount and temperature, and established the relationship between various physical quantities and the temperature distribution of sliding plate. The results show that the temperature rise is inversely proportional to the normal load in the normal load range of 20 N~140 N when the pure carbon slide plate with copper-silver contact wire carries current; In the range of 0 A~200 A, the temperature rise is proportional to the current; In the range of 50 km/h~300 km/h, the temperature rise is proportional to the velocity, and the correlation coefficient between temperature rise and arc energy is 0.903. The final results show that the higher the sliding plate temperature, the greater the wear rate.

From a macro scale, the main sources of temperature rise energy of contact pair areIncluding mechanical friction heat, current joule heat and arc heat. In this regard, The calculation methods of friction power q_F, and current joule thermal power q_I and arc thermal power q_A are established respectively in literature[37], as shown in Equation (1).

$$q_{\mathrm{F}} = \frac{\mu F v}{A}, q_{\mathrm{I}} = \frac{pl}{A_{\mathrm{r}}} * \frac{I^2}{A}, q_{\mathrm{A}} = \Psi \frac{UI}{A} \tag{1}$$

On this basis, Zhou Yue *et al.* [38] further studied the influence of three heat sources when RIM120 copper-magnesium contact wire is matched with pure carbon slide plate based on pin-on-disk test bench. In the static contact state, the current Joule heat can raise the slide plate to 170 ℃ at room temperature within 15 min. Under pure rolling friction without current, the sliding plate temperature only rises by 1 ℃ when the friction heat is within 15 min. Under current-carrying rolling friction condition, the temperature of sliding plate is stable between 130 ℃ and 140 ℃ within 15 min under the combined action of current joule heat, friction heat and arc heat. According to the above experimental results, the known laws of current-carrying friction and wear of pantograph-catenary include:

(A) Contact resistance of contact pair includes surface shrinkage resistance and film resistance, which is equal to the resistivity of contact element divided by the diameter of conductive spot. The more conductive spot number, the larger radius, the smaller the resistance.

(B) When the normal load changes, the wear amount changes in U shape.

(C) When the friction speed changes, the wear of pantograph-catenary contact pair does not change monotonously with the speed.

(D) The greater the current is, the greater the wear rate is, and the increase of wear rate is different in different current intervals.

(E) The greater the arc energy, the greater the wear rate.

(F) The temperature rise of pantograph-catenary contact pair is inversely proportional to normal load and directly proportional to current friction velocity and arc energy.

The research results also show that the application parameters and characterization parameters of pantograph-catenary contact pair, such as contact resistance, normal load, running speed, current and arc energy, are closely related to each other, but the coupling mechanism among the variables and the decoupling verification of their influence on the wear law of contact pair still lack the support of research results.

3.6. Wear mechanism

From the perspective of friction and wear, under the joint action of pantograph lifting force and train traction, pantograph slide plate is lifted to contact with contact line stably and slides at high speed to realize electric energy transmission. Because the real contact surface has different scales of roughness, the contact behavior of contact pairs is actually the comprehensive effect of a large number of surface bulge peaks. Under current-carrying condition, the bulge peak, which accounts for about 1% of the nominal area, bears all the functions of contact force, current and heat conduction. Therefore, the real contact stress, current density and heat flux are much higher than the nominal stress, current and heat flux. The concentration effect of thermal, electrical and mechanical loads on the protruding peaks in the contact area has become the key feature of current-carrying friction and wear of pantograph-catenary [39,40]. In addition, due to the different materials of pantograph-catenary contact pairs, the typical asymmetric contact behavior caused by the same application parameters, and the diffusion and transfer of abnormal wear phenomena between different friction pairs on the same line are also the main characteristics of pantograph-catenary current-carrying friction and wear.

As for the wear mechanism of pantograph-catenary contact pairs, due to the differences in test conditions, equipment conditions and environmental factors, the interpretation of current-carrying friction and wear test results of pantograph-catenary is different, and there are different views on the main mechanism of current-carrying friction and wear of pantograph-catenary in scientific research fields. Among them, Zhang Yongzhen *et al.* [39] think that the load concentration effect will cause the melting of conductive spots, so the adhesive wear is dominant. Hu Yan *et al.* [35] used pin-and-disc test bench and pure carbon slide plate with copper-silver contact wire to explore the evolution law of wear mechanism of pantograph-catenary contact pair under temperature change. The results show that when the temperature rises about 50 ℃, the mechanical wear of carbon slide plate surface is mainly caused by sheet peeling; When the temperature rises about 90 ℃, the surface of carbon slide plate is mainly worn by machinery, and a small number of ablation areas appear; When the temperature rise is about 180 ℃–200 ℃, a large number of ablation areas appear on the surface of carbon slide plate, and arc ablation is the main wear area; When the temperature rise is about 300 ℃, the carbon slide plate is prone to fatigue cracks, which are mainly worn by arc ablation. Li Hanxin *et al.* [41] studied the change law of wear mechanism of pantograph-catenary contact pair when humidity changed based on reciprocating friction and wear tester. The contact pairs are pure copper contact rod and pure carbon rod. The normal load applied in the test is 4 N, and the sliding displacement amplitude is 4 NIs 6 mm, and the currents are 0 A and 5 A, respectively. The results show that in low humidity (10% RH) environment, the main wear mechanisms are adhesive wear and abrasive wear; In medium wet environment (35% RH–55% RH), water film acts as lubricating film to reduce adhesive wear and abrasive wear, but electric current induces electrochemical oxidation reaction, and the wear mechanism is slight adhesive wear, abrasive wear and oxidative wear; Under high humidity environment (80% RH), the main wear mechanism is oxidation wear, accompanied by adhesive wear.

Currently, according to reference [42], adhesive wear, abrasive wear, corrosive wear, and surface fatigue wear are listed as the main types of wear, while surface erosion and erosion are listed as secondary types of wear.Various methods of describing and naming these wear mechanisms can be found in the literature. However, in the real service environment, the temporal and spatial law of wear phenomenon of pantograph-catenary system is complex and changeable, and the interaction mechanism among wear influencing factors is still unclear. Up to now, the current-carrying friction and wear mechanism of pantograph-catenary contact pair is not very clear, and there is no uniform quantitative law.

4. Countermeasures for abnormal wear

Due to the lack of closed solution to the multi-physical field problem corresponding to abnormal wear of pantograph-catenary system, artificial assumptions and empirical formulas need to be introduced to simplify the simulation process. There is a certain deviation between the simulation scene and the real physical process, so it is the main means in the current scientific research field to complete the current-carrying friction and wear of pantograph-catenary based on bench test.

However, urban rail transit is not fit 25 kV power supply system.The subway train completed the operation cycle of outbound acceleration between adjacent stations with a length of one kilometer to several kilometers. The length of an anchor section of the catenary in the interval was between 200 m and 300 m, and the relative sliding speed range of the contact pair could reach 44.44 m/s. The average contact force of a single pantograph ranged from 60 N to 300 N, and the dynamic contact force could reach 500 N. The current intensity of a single pantograph in DC 1500 V power supply system did not exceed 3000 A, and it was about 400 A to 500 A in AC 25 kV power supply system. Such actual scene parameters are difficult to be realized simultaneously in laboratory environment, especially limited by the length of indoor contact line. Most of the experimental studies on current-carrying friction and wear of pantograph-catenary are based on ring-block or pin-disk test rig. From the electrical parameters, there are some differences between the power supply of the test-bed and the actual scene of pantograph and catenary; From the mechanical interaction point of view, because the laboratory can not simulate the spatial arrangement of straight contact lines, the coupling relationship between transverse and vertical vibration of the real pantograph-catenary system changes, which further affects the heat distribution law of the pantograph-catenary system. In a word, the deviation between the mechanical vibration coupling relationship, heat dissipation period and power parameter setting of the contact pair of the test bench and the real scene of pantograph-catenary system leads to great uncertainty when the test results are extrapolated to the real scene. As the analysis of research status shows, different bench tests for the same wear influencing factors may get different test results.

At the same time, the results of current situation analysis also show that the wear of pantograph-catenary system includes electrical wear and mechanical wear; The wear mechanism involves different types such as adhesive wear, abrasive wear, arc erosion and oxidation wear. The heat sources of pantograph-catenary contact pair include friction heat, current joule heat and arc heat. In a word, the mapping relationship between different operating parameters and performance indexes of pantograph-catenary system at thermal, electrical and mechanical levels is complex, and they influence and even interfere with each other. Researchers have not formed a unified conclusion on the causes of abnormal wear of the system, and there is still a lot of room for exploration on the cognition of abnormal wear of pantograph-catenary system. In fact, it is impossible and unnecessary to completely solve the wear problem of pantograph and catenary. When the abnormal wear of pantograph and catenary is confirmed, the relevant parties should follow a unified and standardized problem analysis framework, scientifically investigate the root causes of abnormal wear, verify and confirm the related control variables of abnormal wear as soon as possible, and restrain and alleviate the development trend of abnormal wear through reasonable maintenance means, which is a preferable strategy to deal with abnormal wear events at present.

5. Conclusion and prospect

The characteristic attribute of pantograph-catenary relationship with multiple physical fields makes it difficult to support its operation and maintenance decision by exploring abnormal wear laws in a single physical field or specific contact pairs/specific working conditions in multiple physical fields. There is still a lack of systematic research results on multivariable correlation for cognitive coupling mechanism between physical quantities of pantograph-catenary system and decoupling verification experimental design of coupling relationship. There is still a lot of exploration space for scientific research and engineering management related to pantograph-catenary system design, manufacture and maintenance. For example, the influence of pantograph wear pit on contact force shown in Figure 5 also has the dimension of deep excavation.

Specifically, at the scientific research level:

(1) Standardize the current-carrying friction and wear bench test process of pantograph-catenary. According to the actual application environment of urban rail pantograph-catenary system, formulate standardized technical specifications for test-bed parameters; Aiming at the commonness of arc increase in abnormal wear events of pantograph-catenary, the specific gravity of arc heat, current joule heat and arc heat is strictly controlled, and the action law of pantograph-catenary electrical contact heat source and its influence on wear are studied based

on scientific test condition design and standardized test data post-processing method; Considering the differences of mechanical vibration coupling relationship, heat dissipation period and power parameter setting between the test bench and the real application scene, a standardized extrapolation algorithm from the test bench data and model to the actual scene is established.

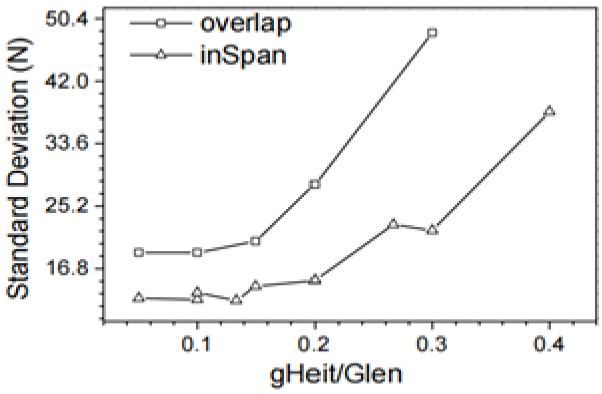

Figure 5. Wave film of contact line between Guangzhou Metro Line 2 and Zhengzhou Metro Line 1.

(2) Intensify the development of wear mechanism diagram and wear model of pantograph-catenary contact pair suitable for domestic urban rail transit. Considering the coupling effect of heat, electricity, force and other physical fields, the coupling and decoupling mechanism of wear influencing factors are studied, the wear mechanism of pantograph-catenary contact pair and its conversion conditions are confirmed, and the wear model representing the correlation between operation parameters and state parameters is further developed to guide the selection of new line products and the optimization of operation parameters of existing lines of pantograph-catenary system.

(3) Research on abnormal wear recognition algorithm based on early weak indication. Aiming at the complex relationship between the application parameters and state parameters of pantograph-catenary system, the multi-dimensional characteristic index modeling method of abnormal wear is studied in time domain, frequency domain and time-frequency domain. Guided by the existence, location, type and degree of abnormal wear and the identification demand of remaining wear life, the abnormal wear identification algorithm of pantograph-catenary contact pair is developed with the help of machine learning, pattern recognition and data mining technologies, which supports the early detection and treatment of abnormal wear events.

At the level of engineering application:

(1) Start the operation and maintenance data governance project of pantograph-catenary system as soon as possible. Metro operators should give full play to their node advantages at the source of operation and maintenance data life cycle, and establish standardized operation and maintenance data collection specifications around the design parameters, application parameters, status parameters and maintenance parameters that affect the wear of pantograph-catenary contact pairs; Study the smooth inter-departmental data sharing mechanism,

complete the construction of data analysis standards with scientific research institutions, and jointly build a demonstration project of intelligent operation and maintenance system driven by data, algorithms and scenarios. Based on data decision-making, the application parameters and maintenance regulations of pantograph-catenary system are optimized, and finally the reliability, availability, safety and economy of pantograph-catenary system are improved.

(2) Subway companies should accelerate the construction transportation, and maintenance of relevant standard systems for urban rail catenary systems. From the perspective of design, manufacture, application, inspection and maintenance of pantograph-catenary system, the applicability of relevant standards of pantograph-catenary system of trunk railway in the field of urban rail transit is comprehensively combed. According to the difference of application environment between trunk railway and urban rail transit pantograph-catenary system, revise or formulate the standard specification suitable for urban rail transit pantograph-catenary system. Aiming at the rigid catenary of urban rail transit, considering the scenes such as anchor section, line bifurcation, joint, ramp, bend and electrical subsection, the design index of contact line geometric parameters is refined to meet the current collection function requirements after skateboard wear. In the aspect of abnormal wear control of pantograph-catenary system, the coverage of technical specifications of pantograph-catenary online monitoring system is broadened, and the abnormal wear detection function is added, while focusing on the evaluation, replacement and grinding standard construction of contact line and skateboard wear.

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Conflicts of Interests

The authors declare no conflicts of interests.

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