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DESTRUCTION MECHANISMS OF CU-ETP COPPER GUIDES FOR SECTIONAL INSULATORS OF RAILWAY TRACTION

Summary. This article presents the results of a research on the operational damage to sectional insulator guides made of hard electrolytic copper Cu-ETP (Electrolytic Tough Pitch Copper). The guides were used on various rail routes, in real conditions, on which the trains ran at maximum speeds between 40 and 120 km/h for periods of 6 or 12 months. The microstructure of the surface, the working layer of the guide, which contacts the graphite plate of the current collector and the cross-section of the guide in the place where it was damaged was examined using the Olympus light microscope. The analysis of the chemical composition in the EDS micro-regions was performed using the Zeiss Supra 53 scanning electron microscope (SEM), while the qualitative X-ray phase analysis was performed with the use of the Panalytical X'Pert diffractometer. Scratches and deformations of the surface layer characteristic of the phenomenon of friction caused by the current collector were observed in the microstructure of the damaged parts of the guides of section insulators. The effect of a very intense oxidation process was also observed, as well as the effects of an electric arc, which according to the author, is the factor that has the most destructive effect on the condition of the guides.

Keywords: microstructure, wear mechanisms, electric traction, guide, section insulator

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1. INTRODUCTION

The guide is made of Cu-ETP copper (CW004A) and is part of the railway traction section insulator. Section insulators are the elements of the railway traction, which supply electricity to electric locomotives. The entire traction is sectioned so that, for example, it is possible to switch off a section (for example, within a railway station) to perform necessary repairs [1]. The current is received by the locomotive using a pantograph, whose current collector directly adjoins the traction (including the guide) and slides along it during the movement of the locomotive. The guide is an element, which constitutes the end of one section and is 5-10 cm away from the next one, which is the beginning of a new section. The guides stabilise the pantograph head during sliding and prevent the sliding element from catching on the insulator structure [2].

The contact of the current collector – damages the guide as a result of tribological mechanisms (abrasion, abrasive wear of the working surface). While the train is moving, a cloud of dust and fine particles of the rail bed material as well as the transported materials, for example, coal, sand and other aggregates are stirred up as a result of a blast of air generated by the fast-moving rolling stock. The excited fine particles settle on the traction lines or get between the working surfaces of the current collector and the guide and act as an additional abrasive medium. Moreover, the difference in the potentials of the two adjacent railway traction sections causes an electric arc to be generated during the jump of the pantograph from one guide rail to another [3]. The temperature of an electric arc in its centre can be as high as 20,000°C [4, 5]. The initiation of an arc and the generated temperature causes the metal elements close to the arc to become plasticised or even melted. The guide material is copper Cu-ETP (Table 1), the melting point of which is 1,083°C [6]. The plasticised guide deforms under the pressure of the pantograph, leading to its further destruction. In an electric arc, small local discharges are generated, resulting in small craters burned in the guide.

This publication presents damage to the guides of section insulators which is the result of their operation in real conditions.

2. MATERIALS AND METHODS

The chemical composition of Cu-ETP copper, from which the guides of the section insulators subject to the tests were made, is presented in Table 1.

Tab. 1

Approximate chemical composition of copper Cu-ETP (based on standards [7, 8])

Type of copper	The maximum concentration of elements, %					
	Cu	Ag	O	Bi	Pb	Other, in total
Cu-ETP	99.9	0.015	0.04	0.0005	0.005	0.03 (without Ag, O)

An X-ray phase analysis was performed using the Panalytical X'Pert diffractometer using filtered radiation from a cobalt anode lamp. The measurement step was 0.05, and the impulse counting time was 10 s.

The samples cut out from the used guides were incorporated in epoxy resin, then sanded with sandpaper of progressively finer grit. The previously prepared specimens were polished with the Al_2O_3 suspension, which was replaced with a diamond suspension with a grain size of 1 μm. The specimens were then etched in a solution of: 2 g of potassium chromate $K_2Cr_2O_7$, 100 cm^3 of distilled water, 4 cm^3 of sodium chloride NaCl solution, 8 cm^3 of sulfuric acid H_2SO_4. The specimens were subjected to multiple alternating polishing and etching to obtain the proper images of the microstructure.

The metallographic specimens were examined using the Olympus light microscope with magnifications of 50, 100, 200, 500, 1000, 2000x.

The Zeiss Supra 25 scanning electron microscope (SEM) was used to perform the microstructure examination employing the EDS method.

3. RESULTS

Given the observations on a macro scale, it was found that the greatest wear, as well as the deformation of the working surface, occurred in the immediate vicinity of the beginning of the arcing horn of the guide (Figure 1).

Given the measurement of the length of the abrasion marks on the guides of the section insulator, it was found that with the increase in vehicle speed (current collector), the length of the marks decreased. For the maximum speed of 40 km/h (the guide used for 12 months), the length of the abrasion mark is 75 mm (P1), for the speed of 120 km/h (the guide used for 12 months), it is 35 mm (P2) and for 120 km/h (the guide used for 6 months), it is only 25 mm (P3) (Figure 2).

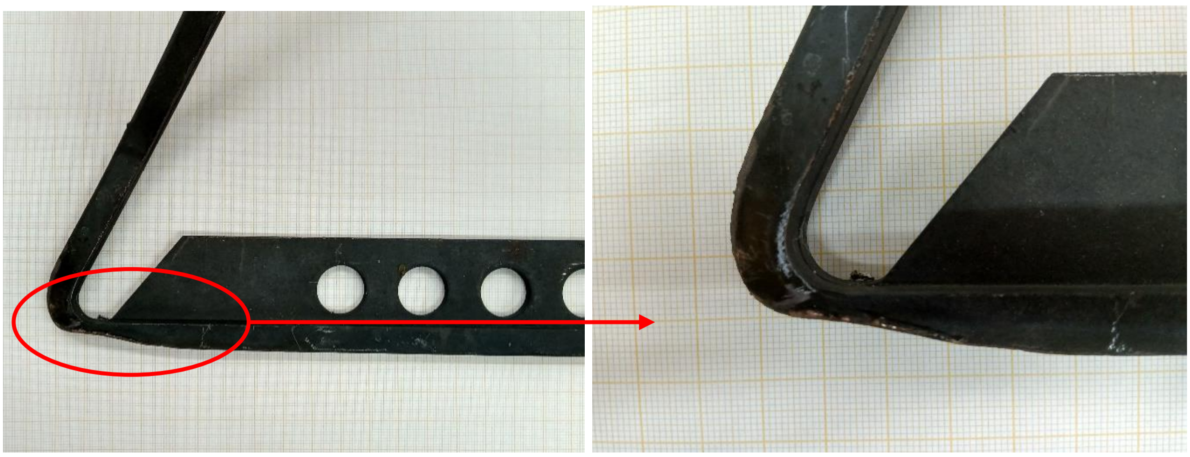


Fig. 1. Guide of the section insulator at the beginning of the horn extinguishing an electric arc. a) a new unused element; b) an element operated with a visible defect

The relation shown in Figure 2 can be explained by the fact that the sliding speed is an important parameter influencing the process, which takes place between the copper-graphite elements. As it results from the research [9], both the friction coefficient and the degree of wear increase at low speeds. Increasing the sliding speed to moderate speeds reduces the friction, and consequently, the wear decreases.

The article [10] investigated the mechanisms of premature tribological wear between the contact strip made of copper and the copper wire used as a railway line with the use of a graphite layer on the wire. It was noticed that because of exploitation, wear debris was present between the mating elements (copper oxides Cu_2O and hardened copper). Additionally, the presence of hard abrasive particles such as SiO_2 and Al_2O_3 was found. These particles, which most likely got between the mating elements from the outside, intensify the abrasion process. In all investigated regions without apparent wear, with moderate wear and severe wear, based on the nature of the cracks of the surface, it was found that they were caused either by work hardening or thermal cycle. A material detachment and production of hard abrasives were also frequently noticed. A material detachment (on a macro scale) was also found in this article. The presence of a copper oxide layer, which was formed in the copper wire and acid-resistant steel type 18-8 couple, was also found in the article [11].

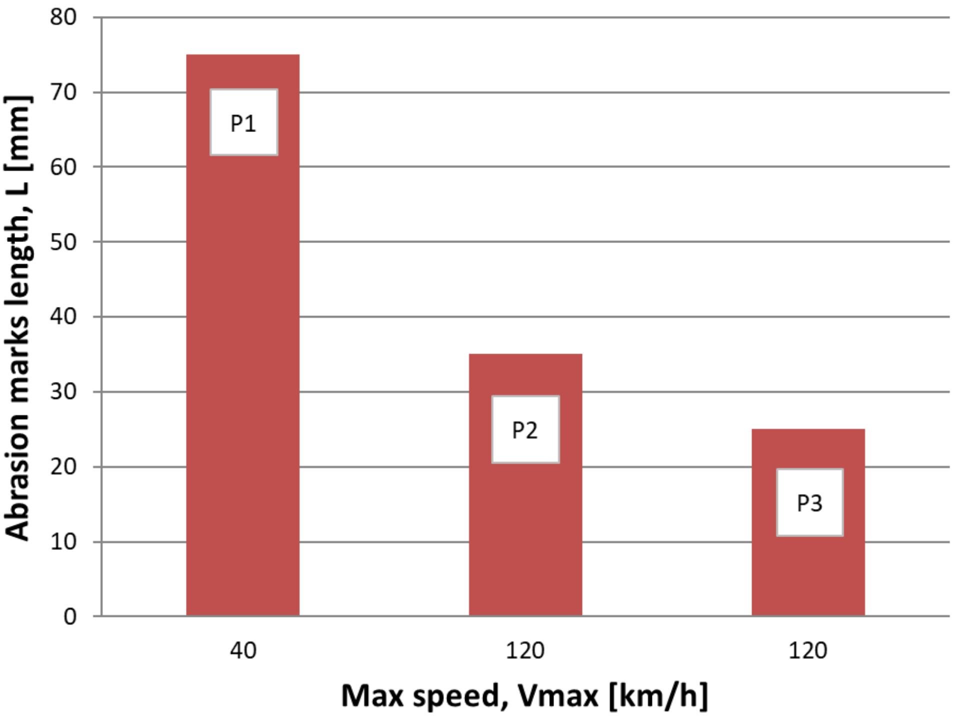


Fig. 2. Change in the length of the abrasion marks on the guide depending on the maximum speed of the locomotive, P1 - 40 km/h, 12 months, P2 - 120 km/h, 12 months, P3 - 120 km/h, 6 months

The guide which had been damaged as a result of operation was cut and a cross-section was mounted in the epoxy resin (Figure 3). Considering the macroscopic observations, it was found that the working surface of the guide, due to exploitation, was worn and formed in a shape of a so-called 'cradle' (1). On both sides are visible 'whiskers' (2) – made by plasticised material of the guide and then by the pressure of the current collector.

The microstructure in the area of the geometric centre of the cross-section (3) and the deformed 'whiskers' (2) are shown in Figure 4. Figure 4a shows the microstructure of copper, which is characteristic of a non-plastically deformed material with a predominant amount of equiaxed grains, with a shape similar to a sphere. Figure 4b shows the microstructure grains with an elongated shape close to axial, showing the mechanism and direction of the deformation. The average grain size (diameter) of the microstructure shown in Figure 4a is 14.9 μm with a standard deviation of 6.2 μm (41.6% of the average value), whereas, for the microstructure shown in Figure 4b, it is 7.1 μm with a standard deviation of 4.3 μm (60.5% of the average value). The presented data show that the plastic deformation in the 'whiskers' (2) resulted in a reduction of the grain size by over 50%, and the increase in the value of the standard deviation indicates an increasing difference in grain size.

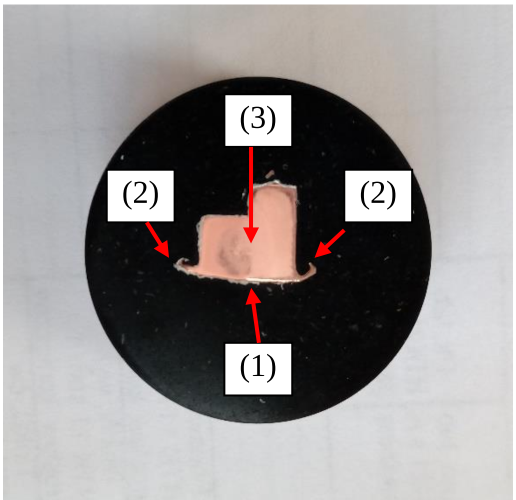


Fig. 3. Cross-section of the guide in the area marked in Figure 1B

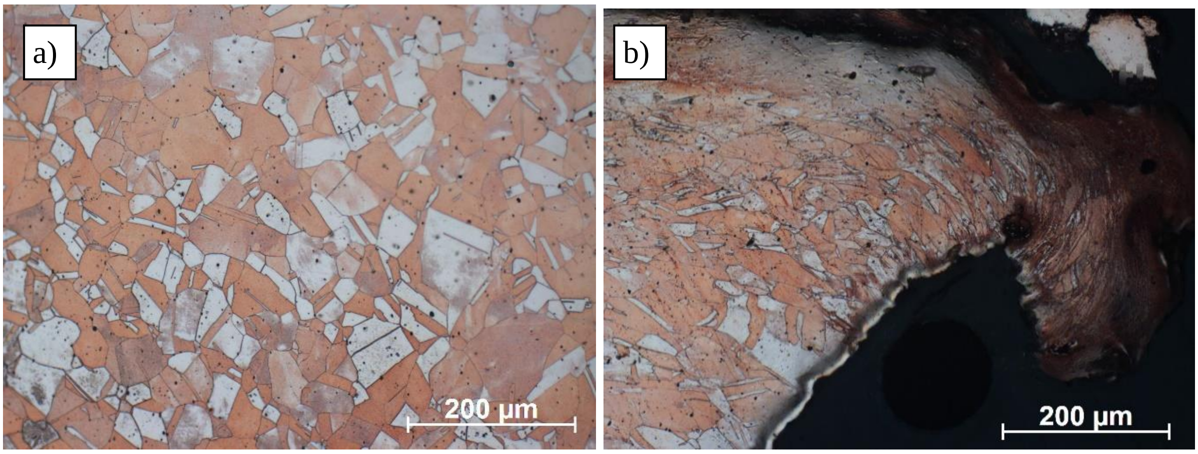


Fig. 4. Microstructure of the cross-section of the Cu-ETP copper guide; a) central area of the section; b) deformed 'whiskers'

In the next stage of the research, it was verified whether the working surface of the guide, apart from the deformation of its shape, was not permanently contaminated, as that could reduce the electrical conductivity in the contact between the guide and the current collector and also enhance corrosion processes. Thus, a qualitative X-ray phase analysis was applied.

In the structure of the material of a new guide of the section insulator made of Cu-ETP copper (Figure 5), only the presence of copper was confirmed based on the qualitative X-ray phase analysis, which was expected. However, in the case of a guide that had been used for 12 months on a railway line, where the trains travelled at the maximum speed of 120 km/h, apart from copper, the presence of copper oxide Cu_2O was found (Figure 6), which was confirmed by the reflections from the planes (111), (002), (022) and (113) of this phase. These results prove that during the operation of the guide, copper oxide was released on its surface. This is because the flow of electric current produces a thin layer of oxides, which may also play a positive role as a lubricant on the contact surface [9, 12]. The thin oxide layer formed on the contact surface excludes direct contact and reduces the adhesion between the elements. According to some scientists [13, 14], the oxide layer formed by the electric current on the contact surface of mating elements plays a major role in reducing the coefficient of friction. However, the authors [10, 15, 16] suggest that the flowing electric current works as a lubricant in the pulling process at constant parameters.

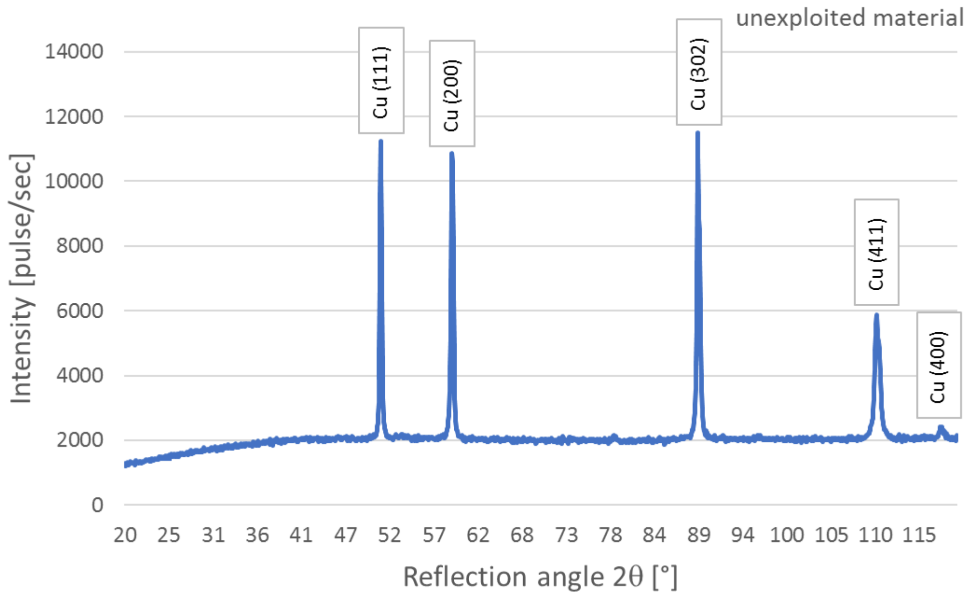


Fig. 5. Diffractogram of a new guide

The thickness of the oxide layer which is released as a result of the flowing electric current can be determined using the following equation [17]:

$$R_c = \frac{q_c}{2a} + \frac{q_0 X}{\pi a^2} \tag{1}$$

Rc – contact resistance,
qc – electrical resistance of copper,
q0 – electrical resistance of a thin layer of copper oxide,
X – thickness of the copper oxide layer,
a – radius of the circle corresponding to the total contact area.

An unfavourable effect of the current flow through the railway line during the friction process is the increase in the contact temperature of the copper-graphite couple.

In the experiment performed by [18], the contact temperature of the materials increased sharply at the beginning of the experiment and became stable after about 20 minutes for the current of 0, 10, 20 or 30 A. The stabilisation of the temperature is slower when the current increases and for 50 A it takes place only after 50 minutes. The contact temperature of the tribological couple increased with the increase in the applied electric current. The contact temperature of the friction couple without the applied electric current was about 40°C, and for the maximum value of the applied electric current (I = 50A), the temperature was much higher and was about 115-120°C. Similar results were described in the article [16]. Further, It was found that the synergistic interaction of Joule's heat, the heat caused by friction and arc discharge, leads to a rapid increase in the contact temperature [19]. Hence, it follows that a locomotive, which moves with a heavy freight train, due to the intense consumption of electricity from the railway line, makes such line most vulnerable to damage.

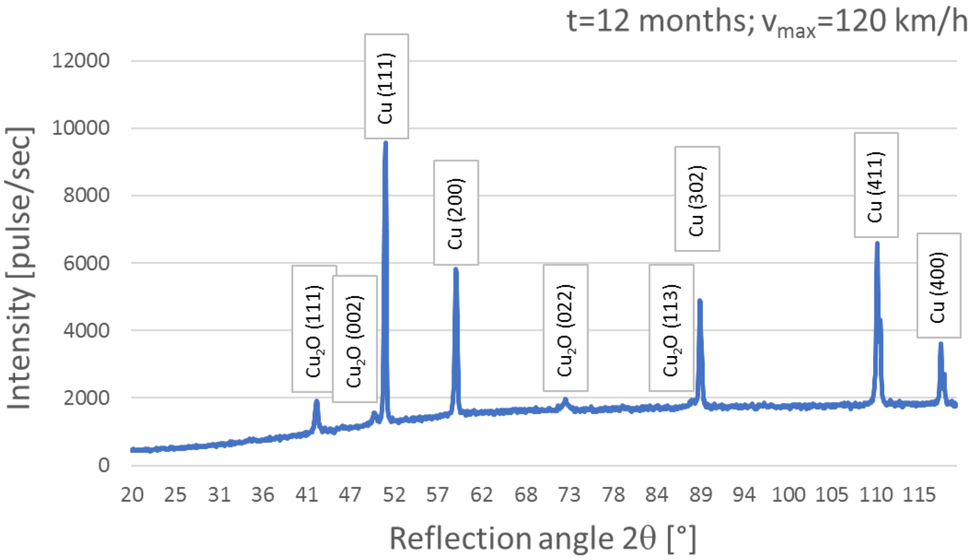


Fig. 6. Diffraction pattern of the guide after 12 months of operation on the route with a maximum train speed of 120 km/h

The increase in temperature on the surface adversely affects the properties of copper. It is conducive to oxidation [6]. Figure 7 shows the dependence of the increase in the volume of copper oxides on its surface with the time and temperature of exposure. With the increase in temperature to 70°C, the volume of oxides increases more than four times compared with the temperature of 20°C after 600 minutes of exposure and five times after 1000 minutes. Moreover, the composition, size and nature of the debris consisting of oxides formed on the contact surface affect the friction between the friction elements, and thus, the nature of the couple's operation [20].

Oxidation occurs by diffusion of oxygen ions into the interior of the metal and sometimes by metal ions, which diffuse out of the rough surfaces. When the oxide layer reaches a critical thickness, it becomes unstable and disintegrates. Such exposed unoxidised surface may re-oxidise [21].

Thereafter, the microstructure of the guide's working surface was examined using a scanning electron microscope. The examination revealed abrasion marks visible on the surface caused by sliding and friction of the current collector on the surface of the guide during operation. The scratch lines are visible in the photo and run from left to right (Figure 8) following the working direction of the pantograph. An area of the base material was also noticed, which was torn off as a result of exploitation, and then, due to successive slides of the pantograph (current collector), glued/pressed with the guide base material in the contact place. A detachment of the base material due to friction was also observed in [10].

The detachment of a part (volume) of the material may also be caused by the plastification of the material due to a sudden increase in temperature from an electric arc. Because the pressure force of the current collector is not big enough to cause the effect shown in Figure 8 without the influence of temperature.

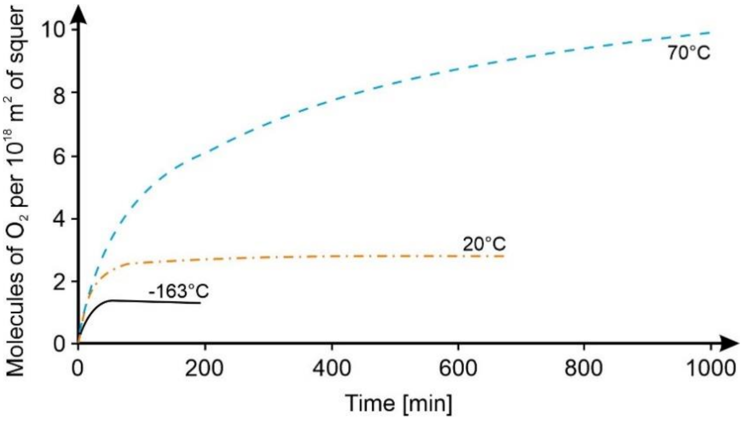


Fig. 7. Effects of temperature on oxidation of copper [6]

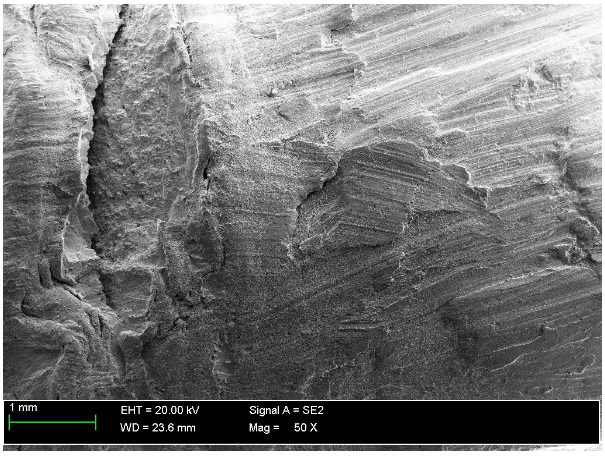
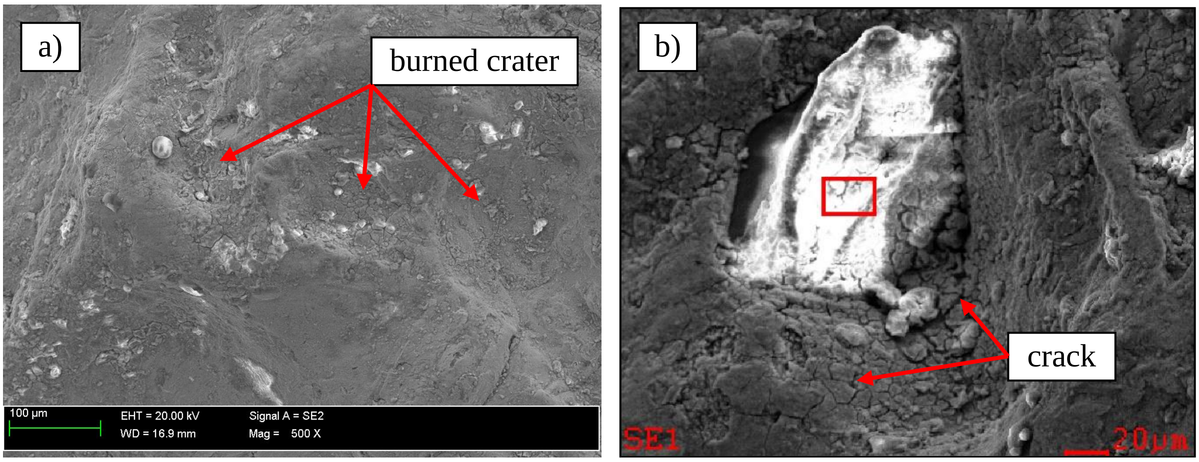


Fig. 8. Microstructure of the working surface of P2 sample (120 kph for 12 months)

The next step in the analysis of the failure mechanisms of the section insulator guide was the analysis of intensity as a function of energy-dispersive X-ray spectroscopy (Figure 9). Burned craters were noticed in the microstructure of the surface of the guide. The analysis of the chemical composition in the micro-areas confirmed the presence of carbon, oxygen, silicon and copper as well as small amounts of iron, sulfur, aluminium, phosphorus and chlorine (Figure 9c). A large amount of oxygen indicates the presence of oxides. The reason for such a large increase in oxides is most likely the phenomenon of an electric arc generated during the jump of the current collector between the guides of neighbouring sections of the railway traction. An arc usually occurs as a result of the distinct potential differences between the neighbouring sections. The temperature in the centre of an arc may rise to several thousand degrees Celsius [22]. The presence of oxides on the examined surface is evidenced by numerous bright areas in the photo (Figure 9a, b) caused by the lack of electrical conductivity of the electron beam forming the image in the electron microscope. The particle shown in Figure 9b can also be a grain of sand, which was pulled in the gust of the moving train, then got between the surfaces of the current collector, softened by the high temperature of the electric arc of the guide and finally pressed into the guide. The large increase in temperature also generated local melting of the basic material and its subsequent rapid cooling caused numerous stresses, leading to local cracks in the material of the guide (Figure 9b).



Element	Wt%	At%
CK	19.58	35.48
OK	25.98	35.35
AlK	00.76	00.61
SiK	20.86	16.17
PK	00.88	00.62
SK	01.74	01.18
ClK	00.74	00.46
FeK	01.00	00.39
CuK	28.46	09.75

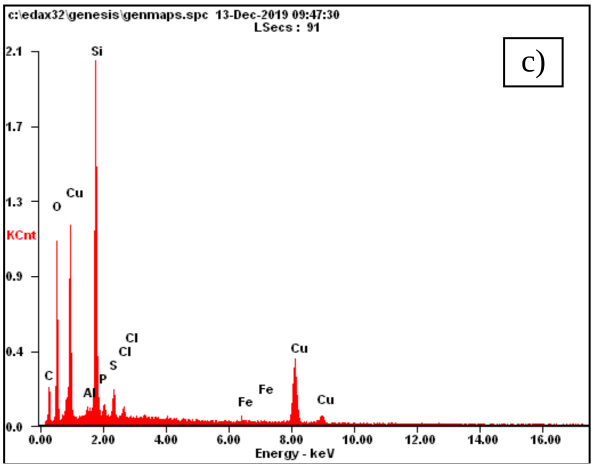


Fig. 9. Microstructure of surface of P2 sample (120 km/h for 12 months) (a, b) and analysis of the chemical composition of the marked area (c)

The effect of an electric arc on the copper guide is shown in Figure 10. In the upper part of the guide's cross-section (Figure 10a), a melted area of the material is visible, whereas, below there is a transition zone and then the microstructure of the Cu-ETP guide. Some grains are visible in the microstructure.

Figure 10b, which is a top view of the guide's working surface, on the left can be seen a melted area and on the right side, there is a groove carved by the current collector. The geometrical features of the groove indicate that it could have been carved by foreign particles, that is, sand grains that got between the working surface of the guide and the current collector. The melted layer of the vitrified material of the guide is interspersed with holes from which gases escaped during melting. The nature of these damages clearly indicates surface erosion caused by an electric arc. A negative effect, which an electric arc has on the elements of the railway traction, is the significant porosity of the melted metal. The pores can be penetrated by pollutants or water from precipitation, which may constitute local corrosion centres. Moreover, the metal melted in such conditions is characterised by unfavourable mechanical properties and reduced resistance to frictional wear. As earlier indicated, the oxide layer grows to a critical thickness, and then separates from the base material, revealing a non-corroded material layer, which may oxidise again [21].

Depending on the parameters of the current, an electric arc consists of many separate, simultaneous discharges. Because the typical spot size is within the sub-micron range, local melting causes characteristic craters. The arc jumps from one place to another with a greater likelihood of ignition near the craters of previous arcs. Eventually, macroscopically visible traces are formed, consisting of many craters with a micron range [23, 24].

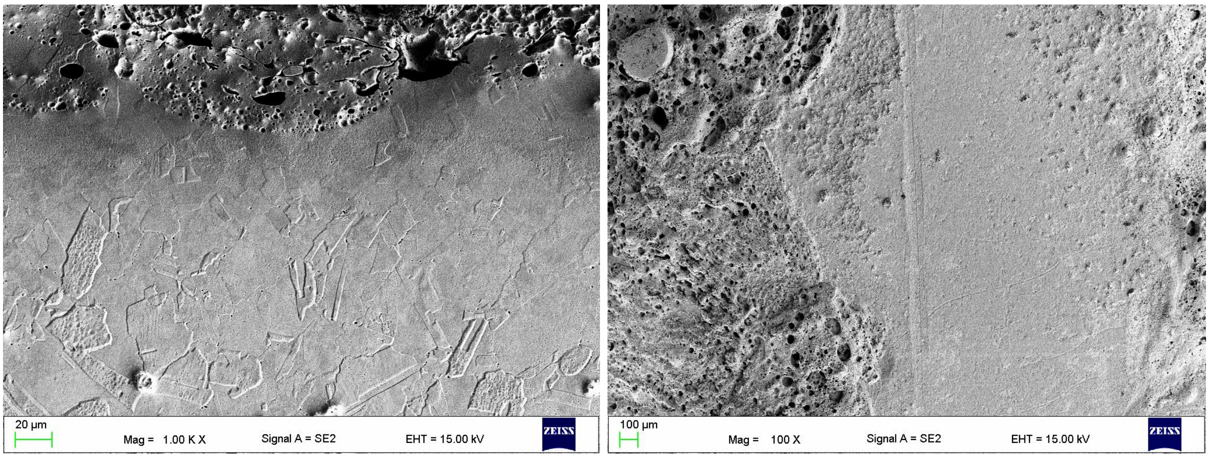


Fig. 10. Microstructure: (a) of the cross-section of the guide, (b) of the working surface of the guide

Arc erosion also depends on the cleanliness of the surface [24]. An electric arc can move quickly and remove only the surface layer of the material or cause erosion of the material. Erosion is the result of an arc plasma that consists, among others, of ions of the material and due to high temperature causes melting or even evaporation of the surface material [25]. The melted material can only move a few microns. In this way, craters are formed or the material is scattered by the pressure of droplets, which form the arc plasma [26].

The ignition of an electric arc occurs when the actual local electric field strength exceeds the critical field strength. This value, characteristic for a given place, depends, among others, on the material of the cathode, the surface geometry in nano- and microscale, as well as on dielectric layers and solid particles. The ignition is much easier when dielectric layers and 'contaminants' are present on the surface so that more spots can ignite and operate in parallel, electrically competing for available power. In the absence of field enhancing dielectrics, ignition is less likely, and the power is concentrated in a small number of fragments [24].

The article [27] states that the normal load is one of the main controlling factors for the generation of an electric arc during the friction process of the copper/graphite coupled with the electric current applied. The strength of an electric arc is enhanced with the decrease of normal loads and the increase of electric currents. At lower normal loads ($F_n \leq 1.0$ N) during tests with applied electric current, the friction process is unstable, and the friction coefficient fluctuates quite strongly due to the appearance of an electric arc.

An electric arc burning in the air is characterised by high temperature [5, 22], high current density and a small voltage drop along its length. An electric arc in the air does not limit its length only to the space between the electrodes, but it elongates under the influence of the force generated by its own electromagnetic field. One of the effects of an electric arc is an accompanying pressure shock wave, which rapidly heats the air along the arc axis. Consequently, a hot stream of gases lifts melted metal particles from the surface of the conductor [4].

4. CONCLUSIONS

The guides of section insulators are made of Cu-ETP copper, and during operation, they wear out because of several mechanisms. Based on the analysis of the presented research results, it can be concluded that:

- friction, corrosion (oxidation of copper) and an electric arc constitute the mechanisms responsible for damage of the guides;
- corrosion depends on the process of diffusion, which is thermally activated, and its intensity increases with the increase of energy, the presence of an electric arc will significantly accelerate it;
- the results of microscopic examinations clearly show that the dominant wear/destruction mechanism of the guides is an electric arc, and the damages are its consequences. The increase in temperature in the centre of an electric arc, which according to the literature data, can reach even 20,000°C [5, 22], is the factor responsible for the greatest damage to the guide. Since the action of this factor is very short (a few hundredths of a second), the damage to the guide may not be visible in a short time;
- the increase in temperature at the interface between the guide and the current collector caused by both friction and Joule heating adversely affect the properties of the copper. It is conducive to the oxidation phenomenon, and the composition, size and nature of the oxidation products have an impact on the friction phenomenon, and thus, on the nature of the mating of the guide-current collector couple [20];
- thermal wear, arc erosion and abrasive wear are the dominant wear mechanisms, which take place in the process of sliding friction in the flow of electric current that accompanies the transfer of material [13];
- contamination on the contact surface of the guide with the current collector and changing the guide geometry may facilitate the ignition of an electric arc [24].

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