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The effect of short circuits and flame temperature modes on the change in the microstructure of copper in automotive wiring

Vasyl' Gudym [a], Borys Mykhalichko [b,*], Oleg Nazarovets [c], Andrii Gavryliuk [d]

[a] *Department of Electrical Engineering Systems, L'viv National University of Nature Management, Dubliany UA-80381, Ukraine*
[b] *Department of Physics and Chemistry of Combustion, L'viv State University of Life Safety, L'viv UA-79007, Ukraine*
[c] *Department of Supervision and Prevention Activity and Fire Automatics, L'viv State University of Life Safety, L'viv UA-79007, Ukraine*
[d] *Department of Vehicles Operation and Fire Rescue Machinery, L'viv State University of Life Safety, L'viv UA-79007, Ukraine*

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ABSTRACT

The purpose of the work is to investigate the causes of vehicle ignition by analyzing the microstructure of copper conductive elements of automotive wiring. This study considers the three most likely vehicle fire scenarios. According to the first scenario, a fire occurs due to overheating of the automotive wiring by short circuit currents. In the second scenario, car fires result from direct exposure to an open flame. In the third scenario, vehicle fires are due to the combined effects of short circuits and open flames. These three scenarios affect the microstructure of copper conductive automotive wiring elements in different ways. Microstructural analysis of copper wires exposed to the temperature conditions of these three fire scenarios was carried out using an optical microscope (OM) and a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) spectrometer. It has been disclosed that when exposed to an open flame on a copper wire, the fine-grained microstructure of the original copper wire turns into a coarse-grained one. The impact of an electric arc caused by a short circuit can instantly melt copper wires. As a result, local spherical inclusions (beads and pits) appear on the surface of the copper wire, and grains of the dendritic structure are formed in its surface layer. The impact of an open flame on already short-circuited copper wires transforms their fine-grained microstructure containing local spherical inclusions into a kind of coarse-grained microstructure with clear boundaries between grains consisting of copper(II) oxide. The study of the microstructure of copper wires taken from a burned-out car should form the basis for studying the causes of car fires.

1. Introduction

Studying the relationship between the microstructure and properties of metals and their alloys exposed to high temperatures and an oxidizing environment is of great importance not only for solving various engineering problems [1], but also for the development of modern fire protection technologies in many industries [2,3]. In addition, from the point of view of ensuring fire safety, this kind of research is of particular interest, since information on the microstructure of copper wires removed from a burned-out car can be very useful in determining the true causes of vehicle fires. It should be noted that the number of car fires in the world has increased dramatically in recent years. According to statistics [4], car fires occur twice as often as fires in residential buildings. Moreover, fires

* Corresponding author.
E-mail address: mykhalitchko@email.ua (B. Mykhalichko).

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can occur on various types of vehicles, from private cars [5] to commercial buses [6–9], trucks [10], construction and agricultural machinery, etc.

Analysis of the causes of fires in cars shows that fires in cars often occur either due to a malfunction of the system of conductive elements, or due to arson, or due to fuel leakage in combination with an electric arc [11], or due to overheating bearings and brake pads [12], or exhaust pipe overheating in combination with mechanical and electrical sparks [13]. But the most common causes of fires in cars are faulty electrical wiring in the car and leaks in the fuel system. Practice shows that electrical faults can occur in vehicles, which often arise due to overcurrent, short circuit and increased resistance of electrical contacts. In order to minimize accidental fires in vehicles, it is necessary to take timely measures to ensure fire safety. To do this, it is necessary to carefully investigate the exact causes of the fire. To elucidate these reasons, a large number of theoretical [14–16] and experimental [17] studies have been carried out. In particular, the authors of [15] have developed a mathematical model of the processes of heating the conductors of the internal electrical networks of residential and public buildings. In [16], the influence of non-stationary heating of insulated conductors in the electrical system of vehicles by instantaneous thermal impulses was studied. The authors of [17] have studied the microstructure of copper wires in household electrical appliances and electrical networks under various heating modes and current loads. Everything above suggests that the most effective way to investigate the causes of car fires is a thorough examination of the electrical wiring removed from the burned-out car, and, in particular, the study of the copper microstructure of car wiring.

This paper reports on the development of new approaches to studying the causes of car fires by analyzing changes in the microstructure of copper in conductive elements of a car exposed to various external factors (short circuit/flame) using an optical microscope (OM) and a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) spectrometer.

2. Materials and methods

To carry out required tests, the following materials and equipment were needed: copper current-conducting elements of vehicular wiring – copper multicore wires covered with polyvinylchloride, cross-section area – 2.5 mm^2 and 4 mm^2, and length – 20 cm; the seat of fire of B class for generating flame temperature modes – diesel fuel ($M = 204$ g·mol^{-1}, $\rho = 0.824(1)$ g·cm^{-3}, $T_{boiling} = 246$ °C, $T_{flash} = 65$ °C, $T_{self\text{-}ignition} = 210$ °C, $T_{flame} = 1100$ °C, $r_{burn\text{-}out} = 18$–20 cm·h^{-1}); etching components for making microsections – ferrum(III) chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), concentrated hydrochloric acid (HCl), distilled water.

A short circuit was generated by applying a current load to the copper wires using the FORSAGE charging and starting device with the technical characteristics of the mode “Start” 12 V – 250 A (Figure S1, Supp. Info).

The microstructure of copper wires was studied using a METAM PB–1 optical microscope (OM) (Figure S2, Supp. info), a ZEISS EVO 40XVP scanning electron microscope (SEM) equipped with a INCA energy dispersive X-ray (EDX) spectrometer (the accelerating voltage $U_a = 10$ kV) (Figure S3, Supp. info).

2.1. Short circuit effect

The heat generated by short circuit currents can produce various temperature modes [15] (Table 1). Calculations [16] showed that short-circuit currents arising in copper wires of automotive electrical wiring can reach values from 80 to 200 A at a current density of 30–60 A·mm^{-2}.

Automotive wiring tests with FORSAGE charging have shown that when current loads up to 200 A are applied to copper wires, those quickly heat up to very high temperatures. In this case, the melting point of copper (1083.4 °C) is reached instantly. In addition, the short circuit is a common cause of wire breakage due to the occurrence of an electric arc, which, in turn, results in copper boiling ($t_{boiling}$ of copper is 2567 °C), after which the ends of the broken wire are melted. At that, the current density can reach 60 A·mm^{-2}, which exceeds the nominal current value by more than 10 times.

2.2. Open flame exposure

The temperature characteristics of fires in vehicles can vary greatly. These depend primarily on the class, purpose, weight, fuel system, manufacturer and age of the vehicle. Thus, if a fire occurs on a passenger car, the heat release rate (HRR) can reach 3 MW [18,19]. The time to reach the HRR peak varies from 10 to 55 min [20]. The flame temperature of such fires varies from 800 °C to 1100 °C, depending on the flame zone [21]. In the oxidation zone, the temperature is the highest (about 1100 °C), while the temperature in the luminous zone is slightly lower (about 800 °C) due to the scattering of heat energy and heated combustion products into

Table 1
Temperature modes of different current loads [15].

***I*, A**	***T*, °C**	
	$S_{cross\text{-}section} = 2.5$ mm^2	$S_{cross\text{-}section} = 4.0$ mm^2
50	191	98
100	703	331
150	1557	720
200	–	1260

Note: Calculations were carried out for a copper wire with a current load time of 200 s.

the environment. It is not excluded that the copper wires of the vehicle's electrical system may even melt under the influence of an open flame. Obviously, the said flame temperature modes will also facilitate a change in the microstructure of copper wires. To confirm it, we carried out a series of open-flame experiments, for this a seat of fire of class 8B was prepared. This is a round steel pan (height, diameter and lip thickness are 0.23, 0.56 and 0.002 m, respectively; burning area is 0.25 m^2), which was first filled with tap water (16 L), and then with a combustible liquid (8 L). Combustible liquid (diesel fuel or A–76 (A–80) gasoline) corresponded to all-Union State Standard 4063.

The test samples of both the original copper wires (previously not exposed to any impact) and the wires that had previously been exposed to a short circuit are placed above the flame (Fig. 1).

The flame temperature in the area of the copper wires was measured by thermocouples, the signals from which were transmitted to the personal computer. The experimental dependence of changes in the temperature modes of the flame on time is shown in Fig. 2. The temperature characteristics generated by the seat of fire of the class 8B were used to study the effect of open flame on copper current-conducting systems of cars

2.2 Preparation of microsections for microstructural analysis

Microsections were prepared both from the original copper wire and from copper wires exposed to an open flame, a short circuit, and the combined action of a short circuit and flame. The corresponding copper wire samples were placed in aluminum cylindrical shapes, which were then filled with Wood's alloy. The prepared samples were polished with sandpaper (350–2500 grain size) and then polished with diamond paste (60/40–0.25/0 grain size) applied to the felt. Then, the microsections were etched using the etching solution [22] prepared by dissolving 10 g of $FeCl_3{\cdot}6H_2O$, 25 cm^3 of concentrated HCl in 100 cm^3 of water (Figure S4, Supp. info).

Etched microsections were first examined using the optical microscope and then the scanning electron microscope. The necessity of metallographic studies is due, first of all, to the ability of copper to change its microstructure under the effect of temperature factors of fire [23], the influence of which on the growth rate and, consequently, on the shape and size of grains becomes dominant. As for copper wire, the shape of the grains in different axial sections may differ from each other (Fig. 3). Here everything depends on the technology of wire making, for example, when drawing wire [24]. It is important to note that the grains elongated along the direction of wire drawing (Fig. 3, *b*), will be easier to undergo thermal oxidation due to their strain state [25]. That is why, in order to obtain comprehensive information about the microstructure of copper wires exposed to different temperature modes, it is necessary to examine both crosswise and lengthwise microsections.

3. Results and discussion

3.1. Microstructure of the original copper wire

OM images of crosswise and lengthwise surfaces of the copper wire in its original state are shown in Fig. 4. It can be seen that the samples consist of polycrystalline grains elongated along a line, coinciding with the direction of wire-drawing [24,25]. It is noteworthy that in the crosswise microsection (Fig. 4, *a*) grains of the original copper are almost invisible, while in the lengthwise microsection (Fig. 4, *b*) those are quite clearly visible. The reason for this is the threadlike shape of the grains obtained by wire-drawing.

The image of the microstructures of the original copper wires visualized by SEM and EDX results is shown in Fig. 5. It is interesting that on the crosswise microsection (Fig. 5, a) rounded grains of almost the same size (average linear intercept (L) is ~15–20 μm, equivalent ASTM grain-size number (G) is no. 8 [26]) are also barely noticeable, while grains in lengthwise microsection already are clearly visible (Fig. 5 (b)). Small dark spots on the crosswise microsection apparently belonge to copper(II) oxide. The grains in lengthwise microsection have a slightly elongated shape oriented in the direction of wire-drawing. In some areas of the surface of lengthwise microsections, there are grains whose sizes (L = ~30 μm, G = no. 7–6) exceed the average size of most grains.

Fig. 1. An experimental installation for testing copper wires with an open flame.

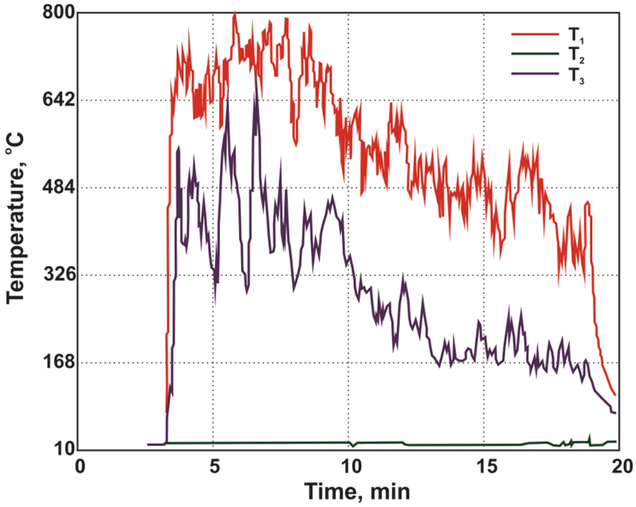


Fig. 2. Flame temperature modes versus time: $\mathbf{T_1}$ – temperature near copper wires; $\mathbf{T_2}$ – ambient temperature; $\mathbf{T_3}$ – temperature over flame (the flame is generated with a seat of fire of class 8B).

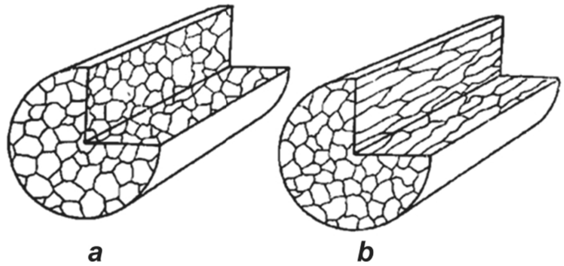


Fig. 3. Shape of grains in crosswise and lengthwise microsections: (***a***) equiaxed, (***b***) elongated along the direction of wire drawing.

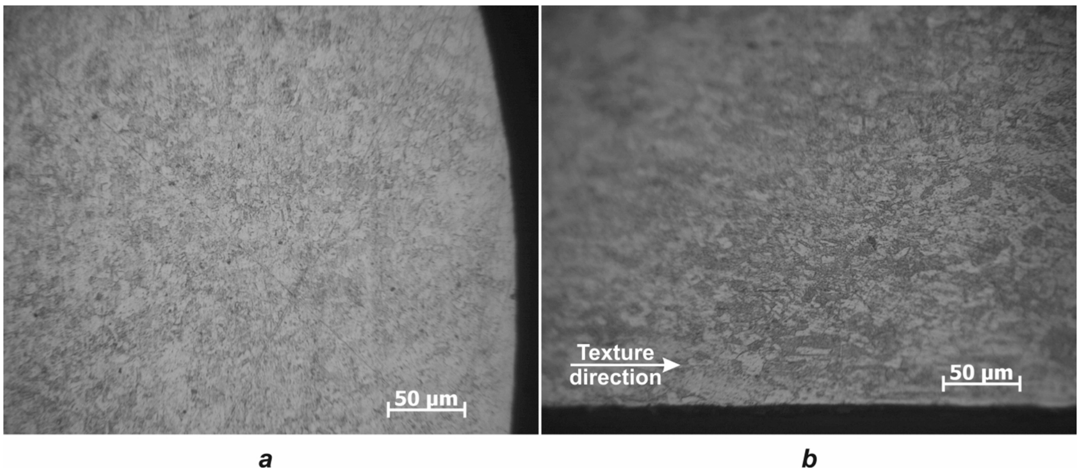


Fig. 4. OM images of the original copper wire surface: (***a***) crosswise microsection, (***b***) lengthwise microsection (the arrow indicates the direction of wire drawing).

The grains within the selected area of the crosswise microsection contain 96.93 wt% copper and 3.07 wt% oxygen (Fig. 5 (a) (at the right)), and the grains of the lengthwise microsection consist only copper (Fig. 5 (b) (at the right)). The actual absence of traces of oxygen in the lengthwise microsection is due to the presence of insulation, which hermetically covers the surface of the initial copper wire and thus protects it from oxidation by air oxygen.

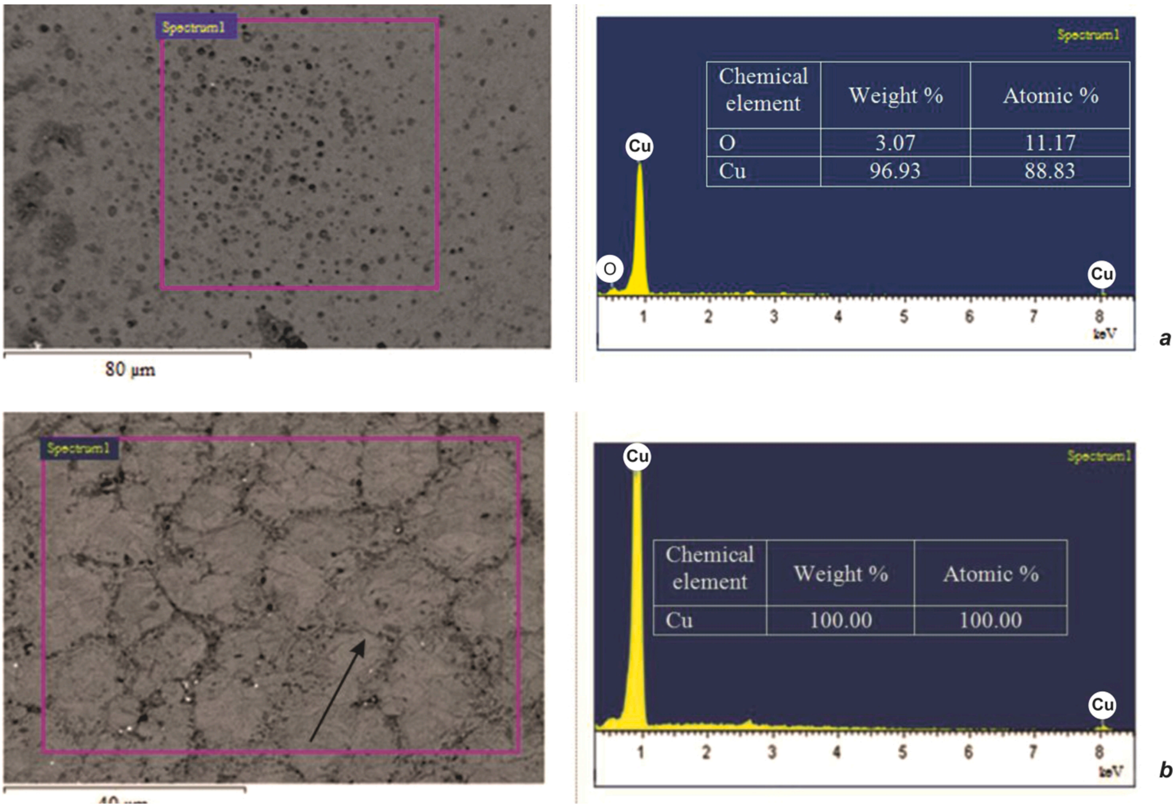
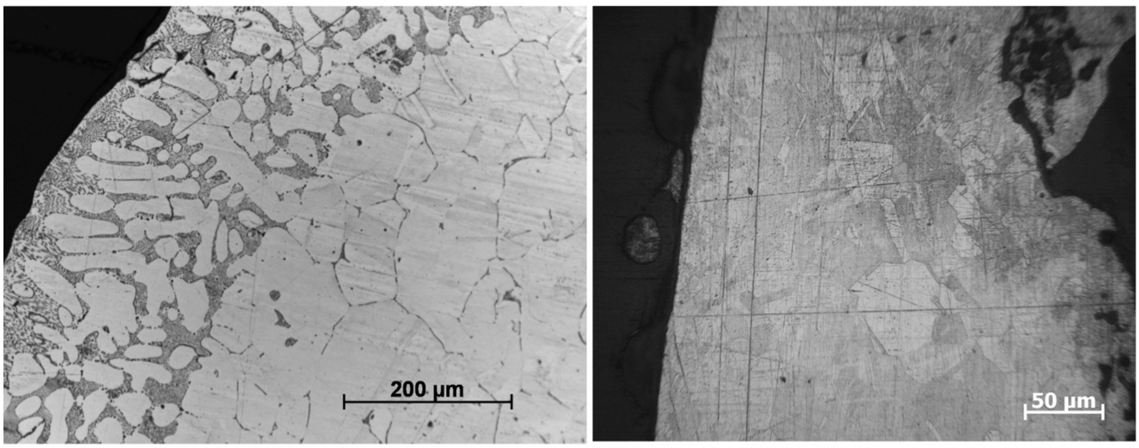


Fig. 5. SEM images showing the areas where the EDX analysis was applied on samples of the original copper wire: (***a***) crosswise microsection, (***b***) lengthwise microsection (the arrow indicates the direction of wire drawing). To the right of the SEM images, the relative signals of copper and oxygen are shown.

3.2. *Microstructure of copper wire after a short circuit (I fire scenario)*

OM images of crosswise and lengthwise microsections demonstrating changes of microstructure for copper wire samples that experienced short circuit current, with a density of 30–60 A·mm^{-2} is presented in Fig. 6. Under conditions of short-term high-temperature exposure (short-circuit effect), the microstructure of copper wire undergoes significant changes. These changes are mainly related to the grain morphology and are determined by the cooling rate of the samples. Thus, Fig. 6, *a* shows a peculiar dendritic grain structure that has arisen in the surface layer of copper wire, where fast and efficient heat removal is possible. Darker areas belonging to



a ***b***

Fig. 6. OM images of copper wire samples having been undergone the short circuit impact: (***a***) crosswise microsection, (***b***) lengthwise microsection.

copper(II) oxide are also visible between the dendritic formations. On the contrary, the inside of the copper wire does not cool as quickly as the outside. Under these conditions, the threadlike grains, which previously belonged to the copper wire in the original state, are significantly enlarged (see Fig. 6, *a*). On the other hand, copper wires can instantly melt under the action of short-circuit currents with a density of >30 A·mm^{-2}. As a result of this, peculiar beads and pits may appear on the surface of the copper wire (Fig. 6, *b*). These local spherical formations (beads and pits) are especially clearly visible on SEM images (see Fig. 7). At that, these formations occur both in crosswise and lengthwise microsections (Fig. 7, *a* and *b*). It should be noted that due to a short circuit, these formations are localized in the places where an electric arc occurred, which caused melting and even partial boiling of copper. Moreover, when a direct current of a higher density is passed, the number of such surface defects, as well as their sizes (L = 30–50 μm), increase noticeably.

Under the action of high-density direct current, the elemental composition of grains on the surface of the copper wire changes compared to the original copper wire. The grains on the crosswise microsection contain 95.61 wt% copper and 4.39 wt% oxygen. But in the spots where copper melts and even boils, the oxygen content increases to 27.18 wt%, and the copper content accordingly decreases to 72.82 wt%. However, the grains of the lengthwise microsection contain 97.75 wt% copper and 2.25 wt% oxygen.

3.3. *Microstructure of copper wire after a flame exposure (II fire scenario)*

OM images of copper wire samples exposed to an open flame are shown in Fig. 8. In the case of a long-time stay of copper wires in a high-temperature oxidizing medium (flame exposure), the pattern change of the microstructure will differ from that at a short circuit. In this regard, a microphotograph of the crosswise microsection of copper wires which had been in flame for a long time turned out to be very indicative. Thus, the dendritic structure of grains is completely absent on the outer surface of such a wire (Fig. 8, *a*). Instead, we see oxidized copper that penetrates from the outside into the inside of the wire (darker surface layer). This is the result of a long-time exposure to the copper wire of a very aggressive oxidizing agent – air oxygen. At the same time, the inner part of the copper wire, from which heat removal is difficult, consists mainly of coarse grains. Apparently, the observed grain growth is the result of diffusion processes, which increase with elevating temperature. Such a coarse-grained microstructure is especially clearly visible on the lengthwise microsection (see Fig. 8, *b*).

SEM images of crosswise and lengthwise microsections of copper wire samples exposed to an open flame are shown in Fig. 9. The images demonstrate the transformation of the fine-grained microstructure of original copper wires into a coarse-grained one during

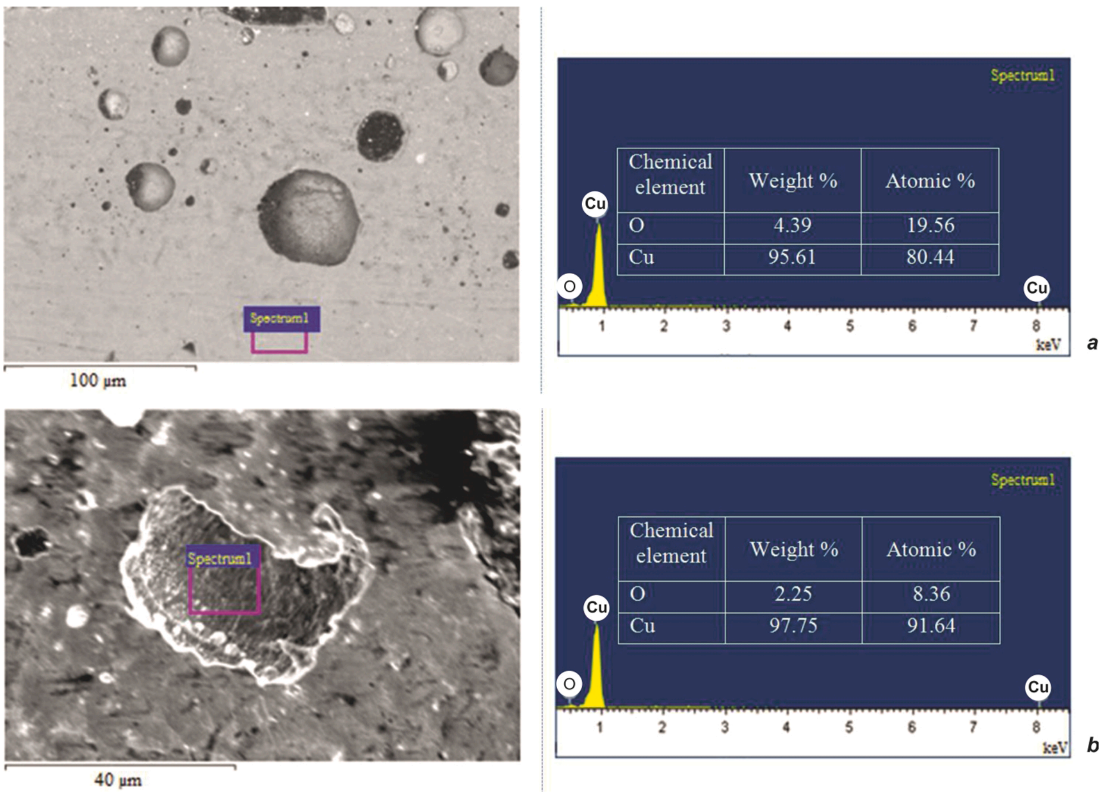


Fig. 7. SEM images showing the areas where the EDX analysis was applied on the sample of copper wires having been undergone the short circuit impact: (***a***) crosswise microsection, (***b***) lengthwise microsection. To the right of the SEM images, the relative signals of copper and oxygen are shown.

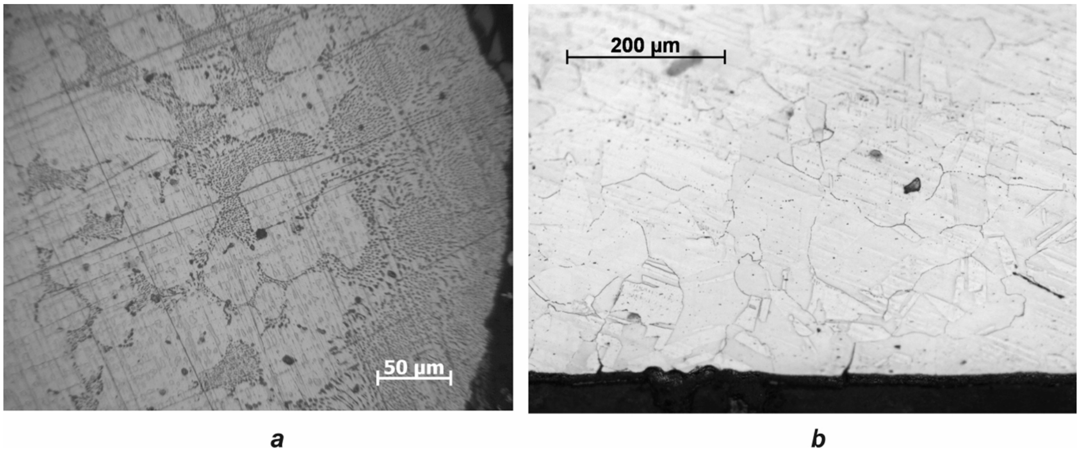


Fig. 8. OM images of copper wire samples having been exposed to an open flame: (***a***) crosswise microsection, (***b***) lengthwise microsection.

exposure to a flame. In this process, the linear sizes of the grain increase by about 10 times (L = 150–200 μm; G = no. 2). This applies equally to both the crosswise (Fig. 9, *a*) and the lengthwise (Fig. 9, *b*) microsections.

The Cu and O content in the grains of the crosswise microsections is 96.94 and 3.06 wt%, respectively (Fig. 9, a (right)), and in the grains of lengthwise microsections it is somewhat lower and amounts 2.86 wt% and 97.14 wt% for O and Cu, respectively (Fig. 9, *b* (right)).

3.4. Microstructure of copper wire after the combined effect (III fire scenario)

OM images of crosswise and lengthwise microsections of copper wire samples after the combined effect of a short circuit and flame are shown in Fig. 10. It is easy to see that the microstructure of copper wires, previously short-circuited and then exposed to an open flame, has an extremely interesting structure of grains. Under conditions of first short-term high-temperature exposure (short-circuit effect), and then long-term exposure to copper wires of a high-temperature oxidizing environment (flame exposure), the fine-grained microstructure of the original copper wire is transformed in a characteristic coarse-grained microstructure is formed, within which the formed grains are separated by dark boundaries of copper(II) oxide. Moreover, the closer the grains are to the surface layer of the wire, the brighter their oxidized boundaries appear. This is especially well seen in the crosswise microsection (see Fig. 10, a). Such a microstructure pattern results from of coarsening the dendritic formations that appear in the surface layer of copper wire after a short-term high-temperature exposure (see Section 3.2). Thereupon, the temperature mode of flame, which was applied to copper wires after a short circuit effect, should be considered as a kind of recrystallization annealing, resulting in full recovery of the equilibrium coarse-grained microstructure of copper. It should be noted that the linear dimensions of the grains formed both under the action of fire only and under the combined action of short circuit and fire are practically the same (compare Fig. 8, b and 10, b). Apparently, the oxidation of grains at their boundaries occurs much more efficiently under combined action.

The results of SEM microphotography of crosswise and lengthwise microsections of copper wire samples after combined exposure are shown in Fig. 11. Like the OM data, the SEM results confirm that the initial microstructure of the copper wire, due to the combined action of short circuit and fire, is transformed into a special coarse-grained microstructure, in which oxidized copper is formed at the grain boundary (see Fig. 11, *a*). Also in the Fig. 11, *b*, local spherical inclusions (beads and pits) formed during a short circuit are visible. The EDX analysis showed that grains of crosswise microsections contain 98.03 wt% of copper and 1.97 wt% of oxygen. The O content in grains of lengthwise microsections is some higher and is 3.46 wt%, and the Cu content is 96.54 wt%.

5. Conclusions

Microstructural analysis of copper wires of automotive electrical wiring, which were exposed to various external factors simulating three different scenarios of a fire in a vehicle, made it possible to identify a number of distinctive features of the structure of their microstructures. The microstructure of copper wires was studied using both OM and SEM equipped with an EDX spectrometer. It was shown that when the automotive wiring is overheated by short-circuit currents and, as a result, an electric arc occurs (the first scenario of a fire), local spherical formations (beads and pits) appear on the surface of the copper wire, resulting from instantaneous melting and even boiling of copper, and in the surface layer of copper wires a peculiar dendritic structure of grains is formed. The second fire scenario involves direct exposure to an open flame on the wires. At the same time, the fine-grained microstructure, which was inherent in the copper wire in its original state, turns into a coarse-grained one. In the case of the combined influence of a short circuit and a flame (the third scenario of a fire), copper wires containing local spherical inclusions are transformed into a kind of coarse-grained microstructure with clear boundaries between grains, which consist of oxidized copper.

The information obtained from studying the microstructure of copper wires taken from a burned-out car can be very useful in solving problems related to determining the true causes of vehicle fires.

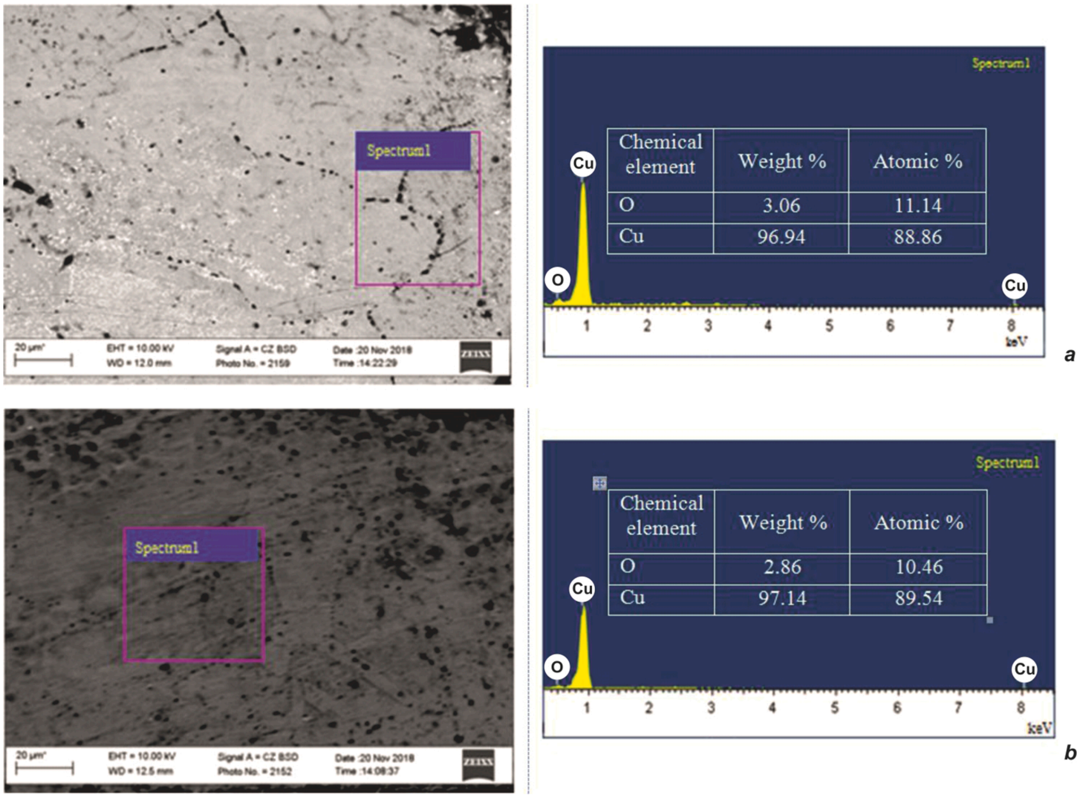


Fig. 9. SEM images showing the areas where the EDX analysis was applied on the sample of copper wires having been exposed to an open flame: (***a***) crosswise microsection, (***b***) lengthwise microsection. To the right of the SEM images, the relative signals of copper and oxygen are shown.

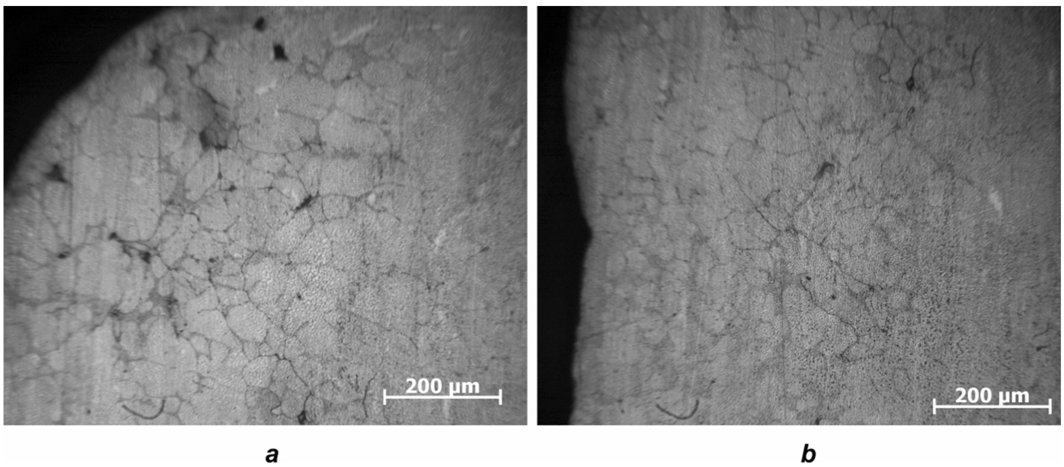


Fig. 10. OM images of copper wire samples having been undergone the combined action of the short circuit and flame: (***a***) crosswise microsection, (***b***) lengthwise microsection.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

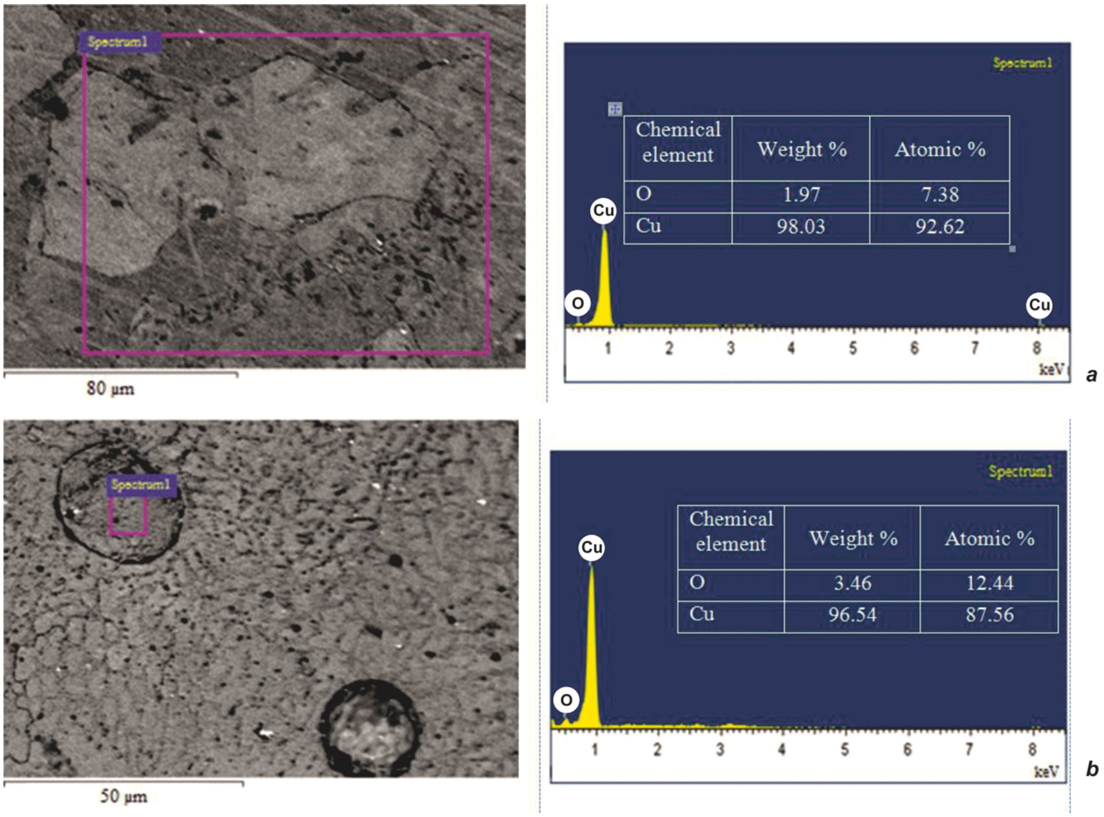


Fig. 11. SEM images showing the areas where the EDX analysis was applied on the sample of copper wires having been undergone the combined action of the short circuit and flame: (***a***) crosswise microsection, (***b***) lengthwise microsection. To the right of the SEM images, the relative signals of copper and oxygen are shown.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.engfailanal.2022.106198.

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