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SPECIFIC FEATURES OF SHORT CIRCUIT IN AUTOMOBILE ELECTRICAL SYSTEM

It is shown that fires on vehicles refer to particularly severe accidents, so the problem of increasing their fire safety is extremely important. It is experimentally illustrated that in a number of cases, when a short circuit happens in an electrical circuit containing 51AH/280A and 60AH/330A batteries, a spherical fusion is not formed in a copper conductor with a cross-section of 0.75 mm^2, but there is a burn-out of separate conductor wires, their adhesion to the steel surface and destruction in the immediate vicinity of the contact point. The results of a study with JSM-6390LV scanning electron microscope of copper multiwire conductors samples and steel band exposed to short circuits at a voltage of 12 and 24 V are given. There are shown photographs of the copper multiwire conductors' fused surfaces, as well as of the steel band exposed to short circuits. Characteristic diagnostic factors are found out that allow to identify the cause of the damage in the event of a fire (high-temperature exposure, short circuit, current overload) of a copper conductor in an electrical circuit with a voltage of 12 V using the method of scanning microscopy. It is found out that the detected factors are stable and are not prone to changes in the natural storage conditions of a vehicle, which was damaged as a result of thermal exposure.

Keywords: fire; scanning electron microscopy; diagnostic feature; ultratrace; forensic fire and technical expertise; primary short circuit; secondary short circuit; current overload; copper conductor.

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Introduction

Fires cause significant material damage, in particular, destroy or damage property, as well they cause deaths and injuries. The damage from fires exceeds 1 % of the national income in industrialized countries and tends to constant growth [1–3]. Motor vehicle fires are among the most severe accidents.

It was shown in a number of works [4–8] that the vehicle electrical system fire hazard is determined by the fact that its individual elements can serve as an ignition source in the event of an emergency operation in any functional circuit. It should be noted that according to Fire Safety Research Institute in the Russian Federation, there has been a trend of increasing the number of fires in vehicles due to technical malfunction. In particular, the number of car fires due to technical malfunction increased from 15.7 % in 2001 to 34.0 % in 2010. And in 2012, the total number of fires resulting from malfunctioning of systems, mechanisms and components of the vehicle and the failure of the vehicle wiring, amounted to 7,718 (40.0 %) in the Russian Federation. It is noted in the work [8] that the proportion of car fire examinations reaches 40–50 % of the total number of received materials in some Forensic Expert Institutions of the Federal Fire Service (FEI FFS) of the Ministry of Emergencies of Russia. It should be recalled that a program for automating vehicles has been launched on a worldwide scale since 2013, and it is currently being implemented. For example, a Mercedes-Benz S 500 of 2016 production year has only about 80 various electrical devices control units. According to this program, vehicles automation should reach a high level by 2020, and there is no driver's control of the vehicle in these conditions and he/she only occasionally takes over the control. By 2025, vehicles should become fully automated and in conditions a driver does not need to drive the vehicle. Nevertheless, practice shows that fires happen even in cars with a high level of automation, in particular, we know that there was an accident when Tesla Model S burst into flames.

Thus, the development of measures aimed at preventing fires in motor vehicles is important [4–9]. One of the types of preventive measures is a fire investigation.

It is the author's opinion that [10] fire investigation is based on a complex of special knowledge being necessary for the investigation of a fire site, individual structures, materials, products and their scorched residues in order to obtain information, which is necessary for establishing initial fire, its cause, scorched residues, as well as to solve some other problems arising in the analysis of the causes of the fire.

It should be noted that the overwhelming number of forensic experts' conclusions on the technical causes of fires in motor vehicles has a presumptive (probabilistic) nature that does not allow the development and implementation of specific engineering solutions [11]. This can be explained by many reasons, including the lack of modern scientifically grounded techniques that make it possible to unequivocally determine, for example, the primary or secondary nature of a short circuit. This fact is confirmed indirectly by I. D. Cheshko and G. I. Smelkov in the framework of the work [9], pointing out to the need to improve the existing methods.

As shown by the authors [9, 10, 12], if the characteristic features of the destruction of current-carrying wires are found in the fire zone, the question of the mechanism of damage (arc or thermal one) and, in particular, of the primary or secondary nature of the short-circuit is inevitably raised. According to many authors, this issue is far from being a simple one. Attempts to solve it with the help of instrumental methods were made by criminologists in the fifties of the last century [9, 10, 12]. Unfortunately, an approved and scientifically based universal technique is not available at the moment, despite the existence of a number of solved particular problems [4–22].

So, for example, the authors of the work [22] came to the conclusion on the basis of numerous experimental data that round copper globules with distinct delineation lines, which are traditionally defined as "overlaps", were formed on the wires not only under voltage, but also with no voltage as well. An arc appeared on some wires under voltage leading to the formation of such globules. At the same time, some wires with no voltage did not have an arc, but these characteristic overlaps were observed [22]. The overlaps of some wires under voltage had a porous structure under the microscope and contained a large number of internal pore volumes, while there were no pore volumes in other overlaps. The authors [22] note that the same tendency was characteristic for wires with no voltage.

It is clearly shown in the work [22] that it was determined when studying samples under a scanning electron microscope, the samples have no tendency to change the grain structure or chemical compositions. The internal grain structures of the overlaps were studied with respect to the dimensions of the micro structure elements, porosity and major changes. None of the studied physical aspects of the overlaps revealed any distinctive features for the samples of wires under voltage and with no voltage [22]. This opinion is supported by such researchers as V. Babrauskas, Kuan-Heng Liu, Yung-Hui Shih, Guo-Ju Chen and others, who point to the inability of the scientific community to differentiate the primary and secondary fusion of copper conductors at the present stage [16, 18]. In particular, V. Babrauskas, using the coordinates of the fire, critically analyzes the results obtained by N. J. Carey [21] in relation to the primary or secondary short circuit in work [16].

At the same time, it should be noted that the work [6] contains actual data that allows one to differentiate the cause of failure caused by the electric arc or thermal process by the nature of the fracture in the copper conductor in the fusion zone. The present work is also concerned with the establishment of features that allow one to identify the cause of the destruction of a copper conductor.

The aim of the work is the development of a scientifically grounded method for studying copper conductors of an automobile electrical system destroyed as a result of a short circuit, in order to establish the cause of their damage during the fire investigation.

Based on this goal, the following research objectives are set:

- to conduct experimental studies on the electrical arc destruction of copper conductors at a voltage of 12 and 24 V;
- to confirm the conditions for the occurrence of a primary short circuit in the automobile electrical system experimentally;
- to prove that there may be traces that allow to identify the electric arc process on the destroyed surface of the copper conductor, which has been short-circuited;
- to establish that the traces revealed on the destroyed surface the of copper conductors that have been short-circuited are stable and are not prone to changes in the natural storage conditions (unless the traces are destroyed deliberately);
- to show that scanning microscopy can be applied in the study of fusible elements of vehicle fuses as the main method.

Actual examples of the research of copper conductors' fusion exposed to short-circuiting at a voltage of 12 and 24 V are considered in this article.

Materials and methods

The researches were carried out at the Regional University Engineering Laboratory "IRGETAS" of Serikbaev East Kazakhstan State Technical University with the application of JSM-6390LV scanning electron microscope with energy-dispersive microanalysis attachment. The destroyed surfaces of copper conductors were analyzed without preliminary sample preparation. The testing chart is shown in Fig. 1.

By analogy with the work [7], a multiconductor copper wire with 0.75 mm^2 cross-section was used to imitate the short-circuit state, as being the most common in automobile electrical systems. The direct current source at a voltage of 12 V was 51AH/280A and 60AH/330A rechargeable batteries, which are the most popular for modern passenger cars, 6ST190 rechargeable batteries were used at a voltage of 24 V. The starting current of 51AH/280A and 60AH/330A recharge-

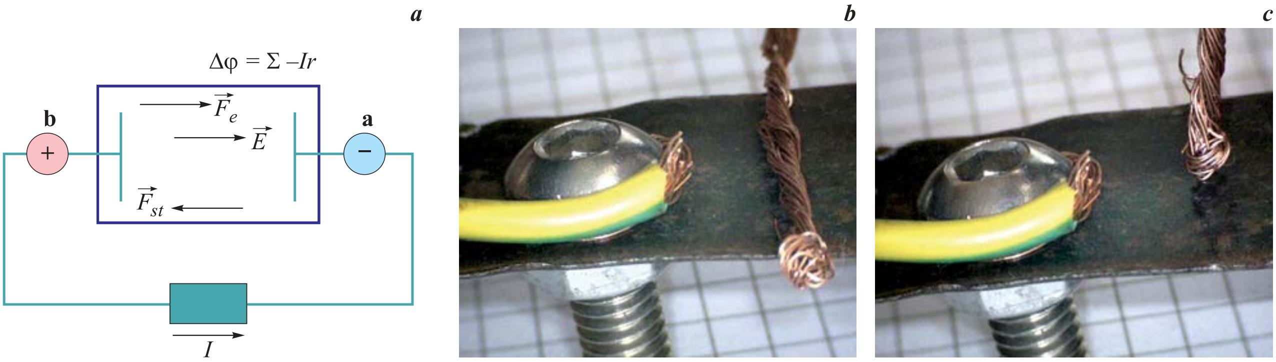


Fig. 1. Testing chart: *a* — fundamental chart (**a** — negative conclusion of storage battery; **b** — positive conclusion of storage battery; Σ — size of electromotive force of storage battery; *I* — strength of current; *r* — internal resistance of storage battery; Δφ — difference of potentials; $\vec{E}$ — tension of electric-field into a storage battery; $\vec{E}_e$ — electric force; $\vec{E}_{st}$ — strange force); *b* — a copper wire is arranged along the tangent to the surface of the steel band; *c* — a copper wire is arranged perpendicular to the surface of the steel band

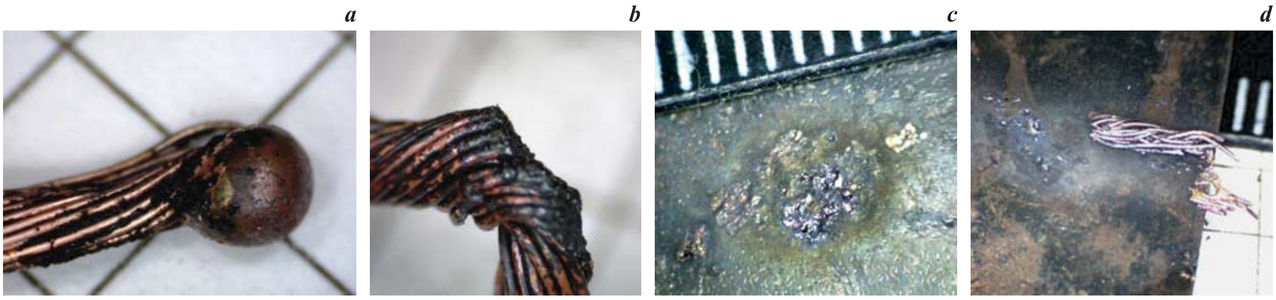


Fig. 2. General view of fragments of the copper conductor and steel band which has been exposed to a short circuit: *a* — fusion of the conductor with a voltage of 24 V; *b* — the destruction of the conductor with a voltage of 12 V; *c* — the damage to the steel band with the perpendicular location of the conductor to its surface; *d* — the damage to the steel band with the tangent location of the conductor to its surface

able batteries is 280 and 330 A, respectively, as well as the starting current of 6ST190 rechargeable battery is 1150 A. A steel band with the dimension of 52×20×0.8 mm imitated the car body part. A steel band was connected by means of the multiconductor copper wire to the negative terminal of the battery, and an electric bulb as a load was connected to the positive terminal. To imitate a short circuit, the conductor was arranged along the tangent to the surface of the band (See Fig. 1*b*) and perpendicular to it (See Fig. 1*c*).

Results and discussion

The results of the short circuit imitation are shown in Fig. 2. Classical spherical fusion was obtained only in the case of the arrangement of a copper wire perpendicular to the steel band at a voltage of 24 V received from 6ST190 battery (See Fig. 2*a*). When using 51AH/280A and 60AH/330A batteries and the voltage of 12 V, the copper conductors destruction occurred without forming spherical fusion (See Fig. 2*b* and 2*d*). When applying perpendicular arrangement of the multifilament wire relative to the surface of the band, the wires were fused with complete burn-out of their fragments (See Fig. 2*b*).

When applying tangential arrangement of the multifilament conductor relative to the surface of the band, the separate wires were fused to each other and to a steel plate. This effect was described in the work [7] and is called sticking. At the same time, the copper conductor wires were destroyed with characteristic signs of current overload in the immediate vicinity of the place of sticking. The craters and drops of molten metal on the surface of the steel band occur both in the case of a perpendicular and tangential arrangement of the conductor (See Fig. 2*c* and 2*d*). It should also be noted that at the moment of a short circuit, the filament of the electric lamp, which acted as a load, ceased to emit light. This fact in-

Fig. 3. Air gap that is equal to the thickness of the wire insulation and prevents the occurrence of a short circuit in the automobile electrical system

dicates that the consumer does not have enough power for functioning at the moment of short circuit.

It should also be noted that the air gap between the bare copper conductor and the steel band that is equal to the thickness of the conductor insulation (in this case its thickness is about 0.4 mm), prevents short-circuit, in spite of the fact that according to the scheme in Fig. 1*a*, the voltage is maintained in the circuit by means of 51AH/280A battery and the filament of the electric bulb emits light (Fig. 3).

It was found out with the help of JSM-6390LV scanning microscope in the course of the morphological study of a fused fragment of copper conductor exposed to the short circuit with the voltage of 24 V received from 6ST190 battery (See Fig. 2*a*) that, in addition to the microporosity, there are chemical elements relating to the composition of the steel band on the surface of the spherical fusion (Fig. 4, Table 1).

As can be seen from Table 1, there are chemical elements such as Fe, Zn, Mn, inherent in steel band on the surface of spherical fusion. And iron on the surface

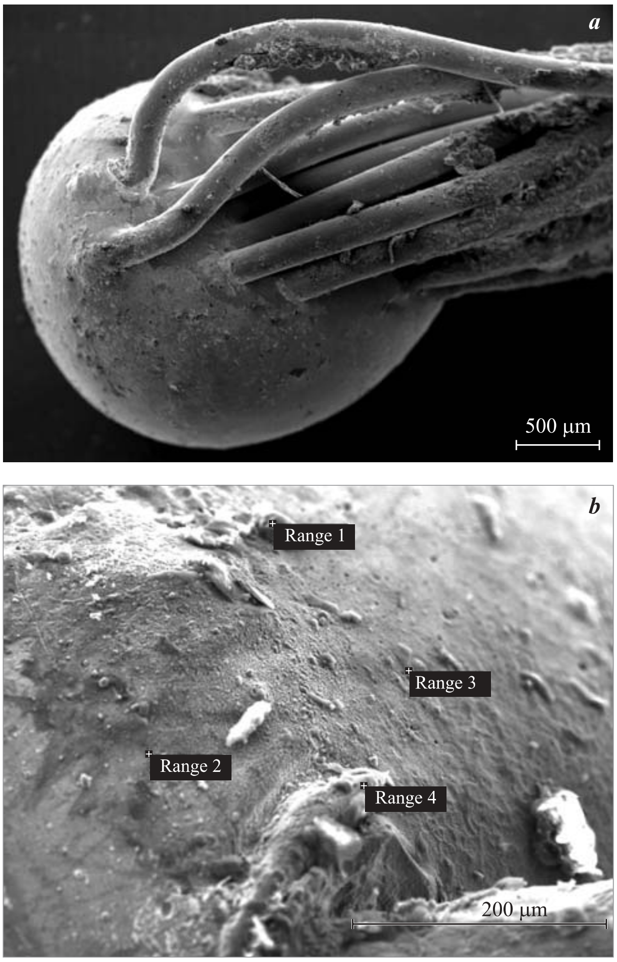


Fig. 4. The surface of a copper conductor destroyed in the process of a short circuit at a voltage of 24 V (See Fig. 2*a*), at the increase of 35$^{\times}$ (*a*) and 200$^{\times}$ (*b*)

Table 1. Results of microanalysis of the section shown in Fig. 4*b*

Measurement point number	Content of chemical element, % by mass						
	O	Mg	Al	Mn	Fe	Cu	Zn
Range 1	24.22	–	1.14	0.64	58.26	4.48	8.62
Range 2	29.64	1.17	1.92	–	6.66	21.18	37.10
Range 3	18.34	–	1.96	–	7.16	59.65	10.00
Range 4	1.96	–	2.88	–	–	95.16	–

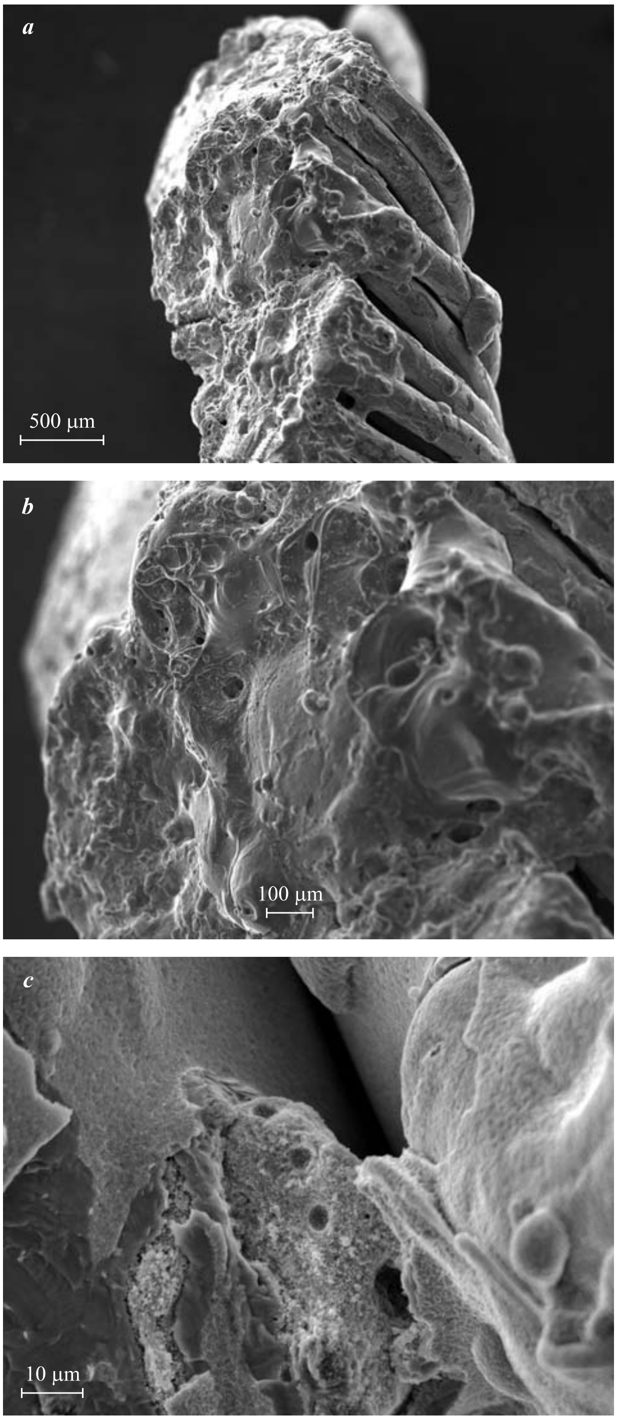
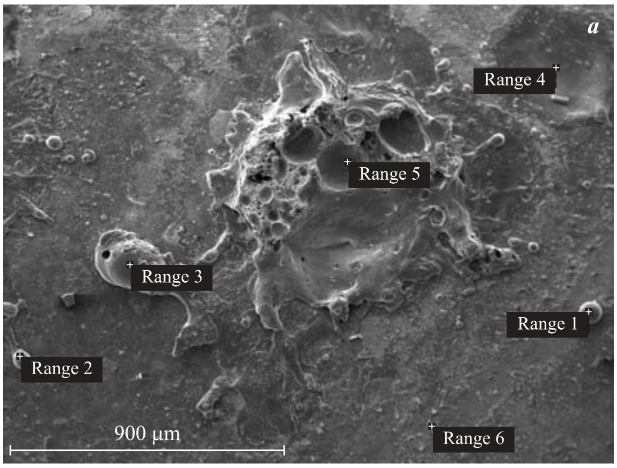


Fig. 5. The surface of a copper conductor destroyed in the process of a short circuit at a voltage of 12 V (See Fig. 2*b*), at increase of 37$^{\times}$ (*a*), 200$^{\times}$ (*b*) and 1300$^{\times}$ (*c*)



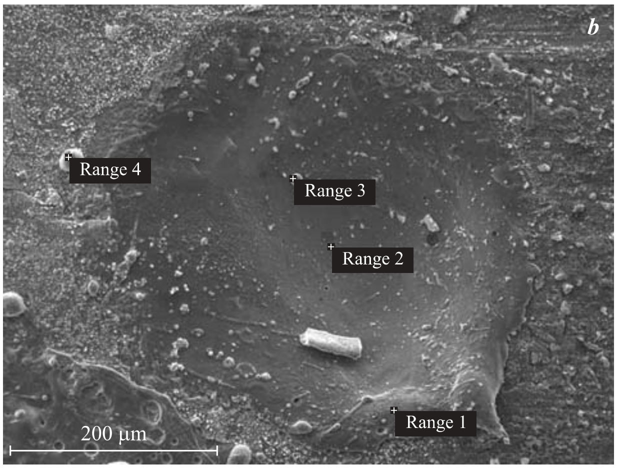


Fig. 6. The surface of a steel strip with a copper conductor after a short circuit at 12 V (See Fig. 2*c* and 2*d*) at the increase of 60$^{\times}$ (*a*) and 220$^{\times}$ (*b*)

Table 2. Results of microanalysis of the section shown in Fig. 6*a*

Measurement point number	Content of chemical element, % by mass						
	O	Mg	Al	Mn	Fe	Cu	Ca
Range 1	13.37	–	–	–	38.91	46.65	–
Range 2	28.90	–	–	–	51.70	17.26	–
Range 3	10.13	–	–	–	11.82	78.04	–
Range 4	19.20	–	–	–	69.59	9.91	–
Range 5	11.91	–	–	–	47.80	40.29	–
Range 6	27.73	0.69	0.80	0.36	59.35	7.50	0.38

Table 3. Results of microanalysis of the section shown in Fig. 6*b*

Measurement point number	Content of chemical element, % by mass				
	O	Cl	Mn	Fe	Cu
Range 1	27.10	1.47	–	48.84	22.59
Range 2	15.96	1.96	–	72.17	9.92
Range 3	28.38	–	–	50.42	21.20
Range 4	23.37	2.18	0.52	48.27	25.66

of copper is present fragmentarily, in the form of particles of a spherical shape. It should also be noted that the temperature of the electric arc process is higher than the peak firing temperature of a car, which is about 950 °C. Thus, the presence of chemical elements on the surface of the fused copper conductor, which previously was not in its composition, can be only explained by the electric arc process.

It was established in the process of the study of the copper conductor destroyed by short-circuiting at a voltage of 12 V (See Fig. 2*b*, Fig. 5) that separate conductors are fused together, micropores are observed on the fused surface (See Fig. 5*b*), as well as micro craters (See Fig. 5*c*).

Fig. 6 shows the results of the study of the destroyed surface of the steel band after a short circuit at a voltage of 12 V (See Table 2).

As can be seen from Fig. 6*a* and Table 2, there are observed spherical and drop-shaped particles of copper, as well as a fragment of irregular shape with craters, consisting of copper in the short-circuit area. There is a “crater” with flat floor on the surface of steel band (See Fig. 6*b*). The floor of the “crater” consists of iron by 50–72 % (Table 3), and there are spherical and drop-shaped particles of copper along its edges.

In the terminology of microtracology, the factors listed above are microscopic traces that clearly demonstrate that the cause of the damage to both the steel band and the copper multifilament conductor was the electric arc process in the form of a short circuit.

In Fig. 2*d* it is shown the destruction of the copper conductor adhered to the steel band. If one side of the conductor is damaged as a result of a short circuit, the other side has been destroyed by current overload.

A stream pattern can be seen on the surface of the copper conductor, as the result of the current overload. According to RD 50-672–88 “Guidelines. Strength Calculations and Tests. Classification of Types of Metals Fractures”, the stream pattern is an element of the structure of the cleavage facets surface, which is a system of convergent steps formed in the cleavage face as a result of the destruction of the bridges between fragile microcracks propagating along parallel, closely located crystallographic planes. The direction of merging of the cleavage steps in the stream pattern corresponds to the crack propagation direction. A particular case of a stream pattern is a fan-shaped pattern that occurs if the cleavage steps converge within the facet. It should be emphasized that the stream pattern is a sign of a fragile fracture.

The studied samples of copper multifilament conductors, as well the steel band were stored for 3 months (which exceeds the average time for investigating fires), in different conditions (indoors in the open air, indoors

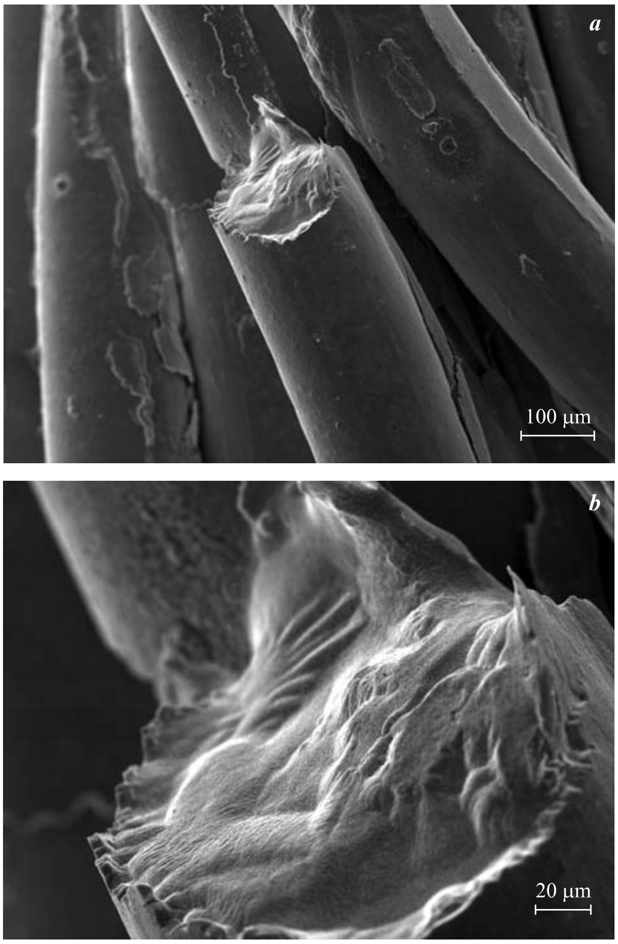


Fig. 7. The nature of the fracture in the wire of a copper conductor with current overload at the increase of $160^{\times}$ (*a*) and $600^{\times}$ (*b*)

in a sealed package, in street conditions without water access in a liquid aggregate state (without immersion in water)). When comparing the samples, it is established that the identified traces are stable and are not prone to changes in the natural storage conditions (unless the traces are destroyed deliberately).

Thus, as a result of study by means of scanning microscopy method of fragments of the multifilament copper conductor and steel band exposed to a short circuit, the characteristic features are established that allow one to identify the process that led to their destruction.

In conclusion, it should be noted that, in I. D. Cheshko's opinion [10] the use of the results of instrumental research as an "intermediate product" in an expert fire investigation does not reduce their value as the most important source of objective information without which the conclusions about the cause of the fire will be unconvincing.

Conclusion

It has been proved that some features can be fixed on the fracture surfaces, including mass transfer that allow to identify the electric arc mechanism of damages formation in an electrical circuit with a voltage of 12 or 24 V in the case of a short circuit between a multifilament copper conductor and a steel band imitating a car body part.

In particular, such traces as a "crater" with a flat floor and spherical and drop-shaped copper particles located on its edges on the surface of the steel body part are micro-traces of the electric arc process.

On the other hand, such features as microporosity, micro craters, spherical iron particles on the destruction surface of the destruction of a multifilament copper conductor are also traces of short circuit.

Thus, unlike the current overload in case of a short circuit in the automobile electrical system, the microscopic traces are paired and are displayed both on the copper conductor and on the car body part. This fact makes it possible to quite easily differentiate the copper conductor destruction mechanism. A short circuit is identified by mass transfer, i. e., by the presence of iron droplets on the fused surface of the copper conductor. The external high-temperature exposure is determined by the viscous nature of the fracture. In this case, the surface of the fracture in the wires of the copper conductor near the fusion has a cellular structure. Current overload is characterized by such features as the lack of mass transfer and the fragile nature of the fracture. At the same time, a stream pattern is observed on the surface of the fracture in the wires of the copper conductor near the fusion area.

It is shown that scanning microscopy can be used in studying fusions of copper conductors not only as an auxiliary method, but also as the main one in some cases.

Examples are given that a short circuit in an automobile electrical system with 51AH/280A and 60AH/330A rechargeable batteries often causes a sticking, fusing and burning out of separate wires of a copper multifilament conductor instead of a classical spherical fusion.

The following facts are clearly illustrated:

- there is not enough capacity for work continuation for any consumer (including an electric bulb) at the moment of a short circuit in an automobile electric circuit;
- the air gap between the bare copper conductor and the car body part without a paint coating equal to the thickness of the insulation coating is sufficient for preventing a short circuit in the automobile electric system.

The present study found that the traces revealed on the destroyed surfaces of copper multifilament conductors exposed to short circuit at a voltage of 12 or 24 V in the electrical system, are stable and are not prone to changes in natural storage conditions (unless the traces are destroyed deliberately).

The obtained results can be used for expert examination of multifilament copper conductors taken from fire sites, as well as for establishing the mechanism of their damage and, ultimately, the causes of the vehicle's fire. In its turn, the knowledge of the technical cause of the fire will make it possible to develop preventive measures and technical solutions aimed at its elimination.

REFERENCES

1. Brushlinskiy N. N., Sokolov S. V., Wagner P. *Chelovechestvo i pozhary* [Humaniti and fires]. Moscow, IPTs Maska Publ., 2007. 142 p. (in Russian).
2. Quintiere J. G. *Fundamentals of fire phenomena*. England, Chichester, John Wiley and Sons Ltd, 2006. DOI: 10.1002/0470091150.fmatter.
3. Beyler C., Carpenter D., Dinenno P. *Introduction to fire modeling. Fire Protection Handbook*. 20^{th} ed. Quincy, National Fire Protection Association, 2008.
4. Severy D., Blaisdell D., Kerkhoff J. Automotive Collision Fires. *SAE Technical Paper 741180*, 1974. DOI: 10.4271/741180.
5. Katsuhiro Okamoto, Norimichi Watanabe, Yasuaki Hagimoto, Tadaomi Chigira, Ryoji Masano, Hitoshi Miura, Satoshi Ochiai, Hideki Satoh, Yohsuke Tamura, Kimio Hayano, Yasumasa Maeda, Jinji Suzuki. Burning behavior of sedan passenger cars. *Fire Safety Journal*, 2009, vol. 44, no. 3, pp. 301–310. DOI: 10.1016/j.firesaf.2008.07.001.
6. Nedobitkov A. I. Fractography of car electric circuit copper conductor fractures. *Pozharovzryvobezopasnost / Fire and Explosion Safety*, 2016, vol. 25, no. 2, pp. 21–27. DOI 10.18322/PVB.2016.25.02.21-27 (in Russian).
7. Bogatishchev A. I. *Comprehensive research of fire hazardous modes in mains of electrical equipment of vehicles*. Cand. tech. sci. diss. Moscow, State Fire Academy of Emercom of Russia Publ., 2002. 269 p. (in Russian).
8. Cheshko I. D., Skodtaev S. V. Formation of electronic database expert researches of car fires. *Vestnik Sankt-Peterburgskogo universiteta Gosudarstvennoy protivopozharnoy sluzhby MChS Rossii / Herald of Saint Petersburg University of State Fire Service of Emercom of Russia*, 2016, no. 2, pp. 61–65 (in Russian).
9. Smelkov G. I., Czeshko I. D., Plotnikov V. G. Experimental modeling of fire-alarm emergency modes in electrical wires. *Vestnik Sankt-Peterburgskogo universiteta Gosudarstvennoy protivopozharnoy sluzhby MChS Rossii / Herald of Saint Petersburg University of State Fire Service of Emercom of Russia*, 2017, no. 3, pp. 121–128 (in Russian).
10. Cheshko I. D. *Ekspertiza pozharov* (*obyekty, metody, metodiki issledovaniya*) [Examination of fire (objects, methods, methods of research)]. Saint Petersburg, Saint Petersburg Institute of Fire Safety of Ministry of the Interior of Russian Federation Publ., 1997. 562 p. (in Russian).
11. Rossinskaya E. R. (ed). *Sudebnaya ekspertiza: tipichnyye oshibki* [Judicial examination: typical mistakes]. Moscow, Prospekt Publ., 2014. 544 p. (in Russian).
12. Smelkov G. I. *Pozharnaya bezopasnost elektroprovodok* [Fire safety of wirings]. Moscow, Cable LLC Publ., 2009. 328 p. (in Russian).
13. Delplace M., Vos E. Electric short circuits help the investigator determine where the fire started. *Fire Technology*, 1983, vol. 19, no. 3, pp. 185–191. DOI: 10.1007/bf02378698.
14. Babrauskas V. Arc beads from fires: Can 'cause' beads be distinguished from 'victim' beads by physical or chemical testing? *Journal of Fire Protection Engineering*, 2004, vol. 14, no. 2, pp. 125–147. DOI: 10.1177/1042391504036450.
15. Wright S. A., Loud J. D., Blanchard R. A. Globules and beads: what do they indicate about small-diameter copper conductors that have been through a fire? *Fire Technology*, 2015, vol. 51, no. 5, pp. 1051–1070. DOI: 10.1007/s10694-014-0455-9.
16. Babrauskas V. Arc mapping: a critical review. *Fire Technology*, 2018, vol. 54, issue 3, pp. 749–780. DOI: 10.1007/s10694-018-0711-5.
17. Hoffmann D. J., Swonder E. M., Burr M. T. Arc faulting in household appliances subjected to a fire test. *Fire Technology*, 2016, vol. 52, issue 6, pp. 1659–1666. DOI: 10.1007/s10694-015-0556-0.
18. Kuan-Heng Liu, Yung-Hui Shih, Guo-Ju Chen, Jaw-Min Chou. Microstructural study on oxygen permeated arc beads. *Journal of Nanomaterials*, 2015, art. ID 373861. 8 p. DOI: 10.1155/2015/373861.
19. Lewis K. H., Templeton B. Morphological variation in copper arcs during post-arc fire heating. In: *Proceedings of* 3^{rd} *International Symposium on Fire Investigation Science & Technology*. Sarasota, National Association of Fire Investigators, 2008, pp. 183–195.

20. Murray I., Ajersch F. New metallurgical techniques applied to fire investigation. In: *Fire & Materials 2009*. London, Interscience Communications Ltd., 2009, pp. 857–869.
21. Carey N. J. *Developing a reliable systematic analysis for arc fault mapping.* Ph. D. diss. Strathclyde, United Kingdom, University of Strathclyde, 2009.
22. Roby R. J., McAllister J. Forensic investigation techniques for inspecting electrical conductors involved in fire. *Final Technical Report for Award No. 239052*. Columbia, Combustion Science & Engineering, Inc., 2012.

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