Features of structure changing of copper wires in terms of the complex action of current and high temperature

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Abstract. The article presents the results of researches changing the structure of copper wires internal electric networks under the action of electric and thermal loads. Described metallographic signs of short circuits in terms of the complex action of current and high temperature. On the basis of researches the features of the structure of electrical wires at different temperatures.

Key words: *short circuit, fire, internal electric networks, microstructure wire*

Introduction. According to the statistics of fires in Ukraine in recent years, almost 80% of all fires are occurred in residential sector. Among the main reasons of their occurrence, almost 20% of fires, depending on the year, are breach of fire safety rules while constructing and operating electrical installations [1].

However, in some cases conclusions about the involvement of elements of internal electrical networks to fires are not justified enough. This is due to different ways of laying wires and their ability to ignite the combustible elements of structure. Fire occurs when the flame appears after heating, which will be supported by the presence of a sufficient amount of oxidizer and combustible environment [2-3].

During the operation of electric networks, overheating of wires insulation is dangerous, which significantly accelerates the process of aging. [4].

Problem. The possible involvement of a short circuit (SC) to fire usually occurs when electrical wires with traces of melting are in burned areas. However, melting wires along with current of SC can also be caused by external heat influence. The form of melting and its location along the length of the wire are usually chosen like the criterion of difference between these types of melting by visual inspection.

Purpose is to develop and to propose methods to identify the implication of electrical installations to fires by identifying patterns of microstructure change of copper wires of internal electrical grids of residential and public buildings that were in the fire conditions.

Materials and methods. For achievement of the purpose of work, the researches of wires structures were made in cases when their temperature was 19, 250, 300, 400, 600, 800, 950°C till the SC occurs. Researches of the wires structure were also made after the SC occurred in model fire.

Copper wires with rubber and PVC insulation are used as part of internal electric networks in cross-sectional area of 1,5 and 2,5 mm^2. Wires were at voltage of 220 V at different temperatures of environment. Heating was performed by using a muffle furnace and in open flame of model fire.

Performing experiments were conducted in the furnace for regimes that are listed in the Table 1.

Table 1. Terms of experiments in a muffle furnace

№	The temperature in the furnace T, °C	The residence time of the wire in the furnace before SC, τ min	The residence time of the wire in the furnace after SC τ, min
1.	19	15	–
2.	250	15	–
3.	250	15	20 and 60
4.	300	15	–
5.	300	15	20
6.	400	15	–
7.	400	15	20 and 60
8.	600	15	–
9.	600	15	20 and 60
10.	800	15	–
11.	800	15	20 and 60
12.	950	15	–
13.	950	15	20

The Class A model fire was created to study the patterns of wires after SC in open flame [5]. Insulated wires

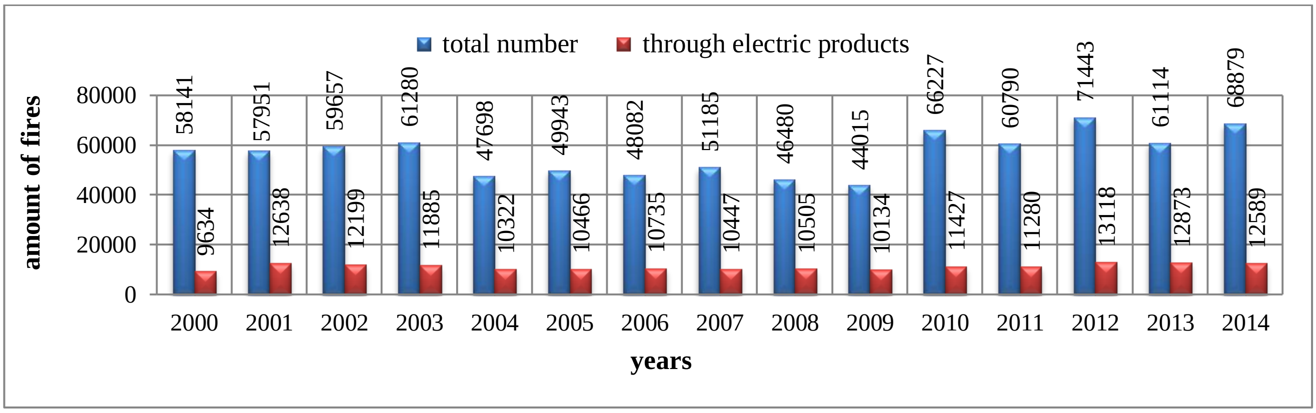


Fig. 1. Statistics of fires from 2000 to 2014

energized 220 V laid crosswise, SC arose at the time of combustion of isolation and contact wires. The temperature of the flame ranged 580-800°C in the combustion zone.

After the experiment, the areas wires with melting size of 50-100 mm were withdrawn, which were produced thin sections for research on optical microscope.

Results and discussion. An analysis of wires after the study (Table. 1) showed that SC at 19°C does not cause metal spraying (fig. 2).

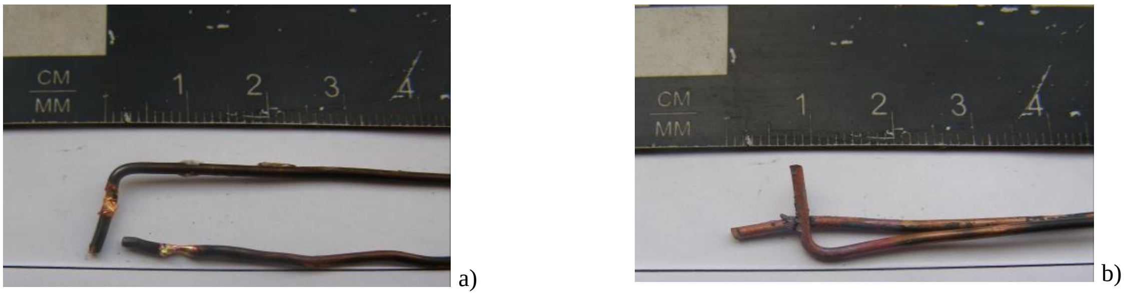


Fig. 2. Samples in which SC occurred at temperature 19°C: a) without conglutination; b) with conglutination

At the same time, the SC leads to metal spraying of wires at temperatures of 250 and 300°C (fig. 3).

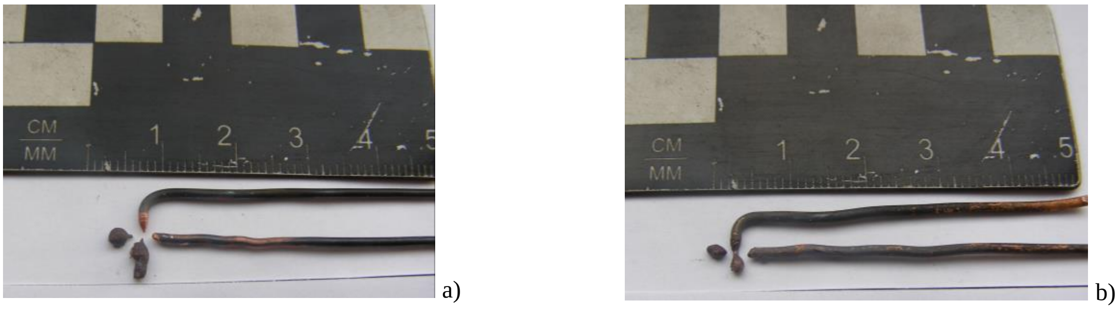


Fig. 3. Samples in which SC occurred at temperature: a) 250°C, 15 minutes to SC and removal from the furnace; b) 300°C, 15 minutes to SC and endurance of 20 minutes in the furnace

Studies of wires in which SC was set at 400 °C showed the absence of metal spraying after SC (fig. 4).

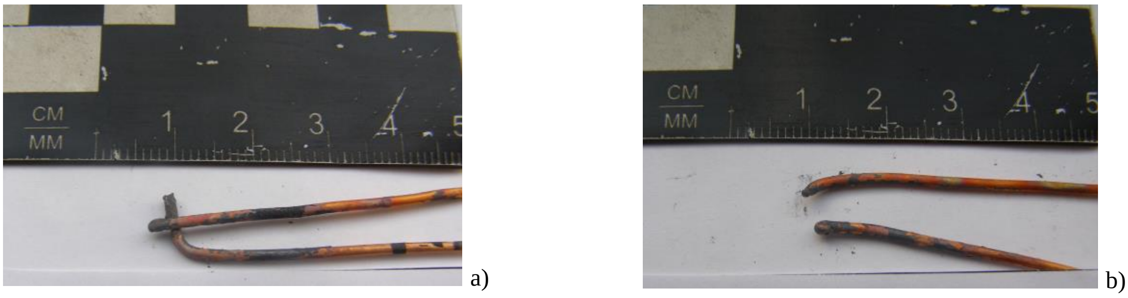


Fig. 4. Samples in which SC occurred at temperature 400°C: a) endurance of 20 minutes in the furnace; b) endurance of 60 minutes in the furnace;.

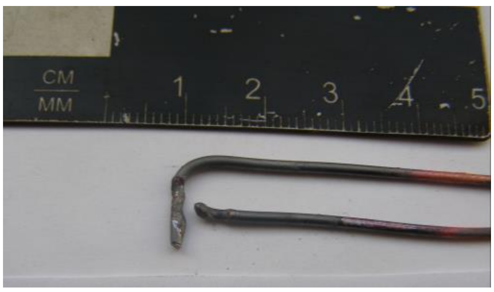


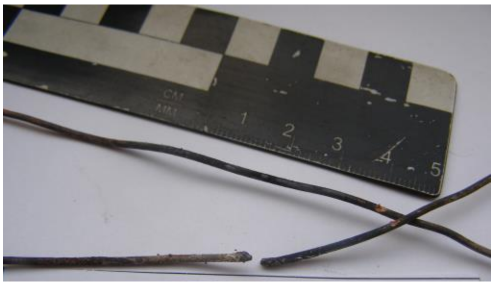
Fig. 5. Sample in which SC occurred at temperature 950°C 15 minutes to occurrence SC and removal from the furnace

After heating of wires to a temperature of 600, 800 and 950°C, SC is not accompanied by spraying, but it leads to substantial melting of the surface layers, as the presence of pits and areas indicates in which geometric parameters significantly different from the original form of wires (fig. 5).

This change of parameters of SC zone is connected with the dynamics of oxidation of the surface layers and with change of the mechanical properties of the wires material at increased temperature. Heating above 400°C leads to softening of metal (modulus of elasticity (E) and ultimate tensile strength ($\sigma_в$) are reduced) so spraying does not occur.

Thus studies have shown that the nature of SC zones can judge the temperature at which the destruction occurred. Short circuit at 19°C does not cause metal spraying of wires. Significant metal spraying was found during heating up to 250 and 300°C. When the temperature rises above 600°C, the fluidity of the metal is in terms of SC, as growth of change of the geometrical parameters of wires indicates.

Analysis of the samples in which the SC took place under conditions close to real (using the model fire) showed that burnout of wire is possible not only in the area of contact of wires but also beyond its bounds. This is due to the higher resistance in the SC zone due to the action of flame, as the formation of a layer of dark color indicates on the surface fracture (fig. 6).


a)

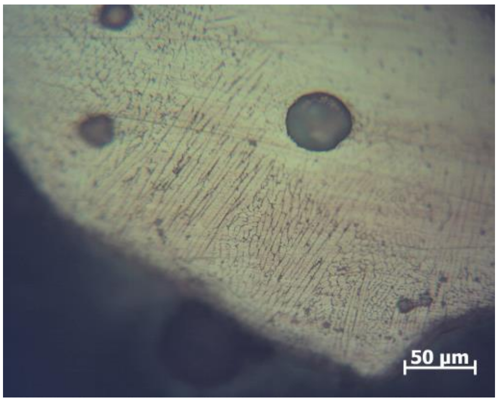
b)

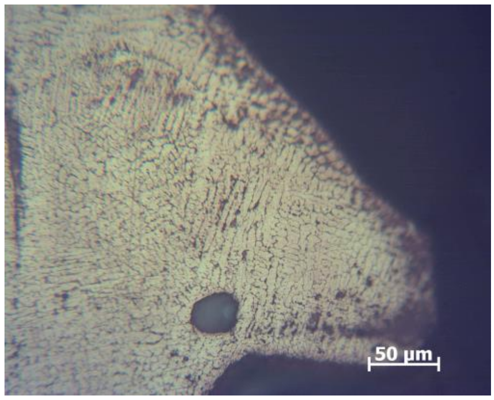
Fig. 6. Samples in which SC occurred as the result of damage of the insulation by flame

The study of micro sections confirms the results of macro analysis. The difference in geometrical characteristics of wiring increases with increasing temperature of SC.

Analysis of the microstructure of the material of wires that were studied in the SC zone at 19°C showed the formation of pores with a diameter of 50-200 microns. Moreover, the pores are formed at the surface of destruction of wire in the area of maximum overheating.

In wires that are heated to a temperature of 250°C areas of different colors are, including blue indicating the oxidation that occurs not only on the surface but also in the inner layers of the material. During the SC pores are formed, mainly in the oxidation zone or on its border. It should be noted that cast structure appears after the SC at 250°C and endurance of 20 minutes in the furnace, characteristic of which is crystallites that grow in the direction inverse heat dissipation. And after endurance of 60 minutes in the furnace the crystallite size is bigger than the crystallites formed during endurance of 20 min (fig. 7). During the destruction of SC zone it is observed the exit of pores on the outer surface of the wire that shows up well after endurance of 60 minutes at a temperature of 250°C.



a)


b)

Fig. 7. Microstructure of wire in which SC was at temperature 250 °C:
a) endurance of 20 minutes in the furnace;; b) endurance of 60 minutes in the furnace;.

Researches of samples after heating to a temperature of 300°C confirmed the getting result. Number of pore by size of 10-200 microns dramatically increases during SC. And they come to the surface destruction. Short circuit at temperature 300°C is accompanied by destruction of material which mainly occurs in crystal boundaries of polycrystalline copper (fig. 8). So metal spraying are connected during SC with the fact that the destruction passes by crystal boundary.

Researches after heating to a temperature of 400°C showed that a cast structure also is formed in the SC zone. During the destruction of wires, crystal damage and cracks are not observed as well as metal spraying does not occur. Size of dendrites is higher after endurance of 60 minutes in the furnace than after endurance of 20 minutes. Lack of spraying at 400°C is connected with the fact that the destruction does not pass by crystal boundaries during the SC but in the area of formation of the biggest thermal tension, and the cracks are between voids that are formed during melting of material (fig. 9).

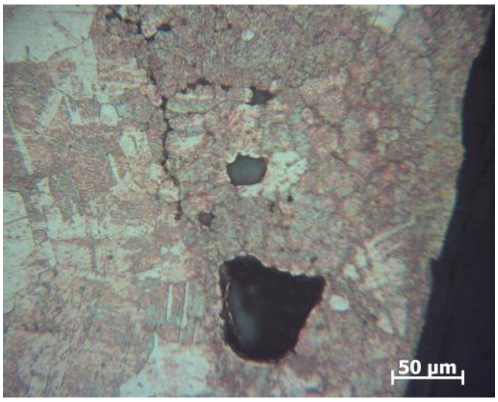


Fig. 8. Microstructure of wire in which SC was at temperature 300 °C

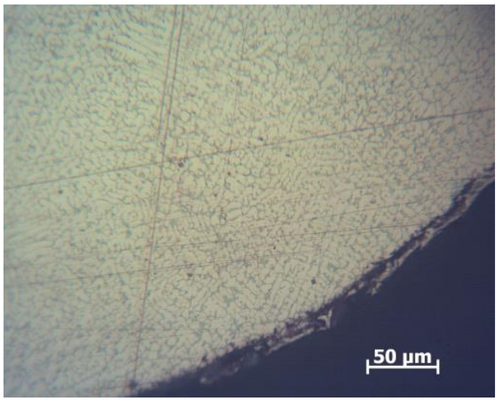


Fig. 9. Microstructure of wire in which SC was at 400 °C and endurance of 60 minutes in the furnace

In the samples, pores and cracks are formed after SCs heated to a temperature of 600°C in the areas of the biggest thermal tensions. And the cracks are mainly on the maximum size of pores (fig. 10).

Heating to a temperature of 800°C is accompanied by significant oxidation of the metal as the presence of a component containing Cu_2O indicates. The formation of cracks occurs in large pores in the area of thermal tensions on the boundaries of separation of melted and not melted metal. It should be noted that metal spraying does not occur during the SC, but it is flowing. The zone of cracks formation is oxidized as its color indicates which is significantly different from the color of the base metal (fig. 11). Additional endurance of 20 min in the furnace after SC leads to significant oxidation of zones of melted and not melted metal.

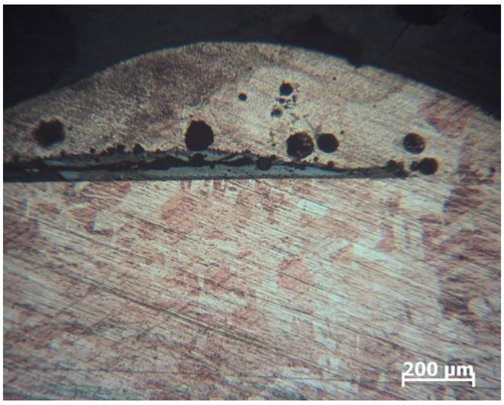


Fig. 10. Microstructure of wire in which SC was at temperature 600°C and endurance of 60 minutes in the furnace

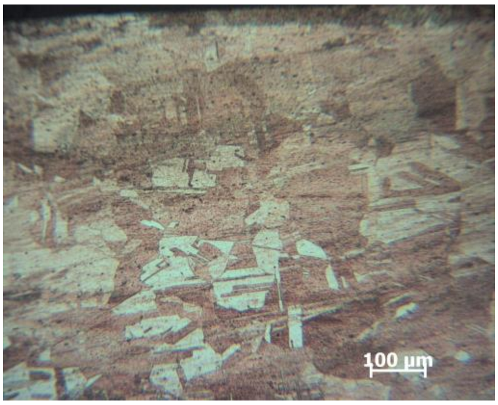


Fig. 11. Microstructure of wire in which SC was at 800°C and endurance of 20 minutes in the furnace

Zones of melted metal are formed after the SC during heating to a temperature of 950°C that is significantly different from the base metal zone (fig. 12). The selection of eutectic Cu-Cu_2O is in the area of cast metal, which is placed along the length of the surface. The presence of pores is found only in certain places, and cracks are observed only in the field of metal flow in the area of SC. The nature of the damage indicates that the SC zone formed eutectic enriched areas and areas chemical composition of which is different from the eutectic. Pores are formed in zones that significantly differ from the eutectic composition and shrinkage cracks are formed in eutectic zones. Increasing of endurance time at 950°C to 20 minutes is accompanied by increased thickness on the surface of oxidized material (fig. 13).

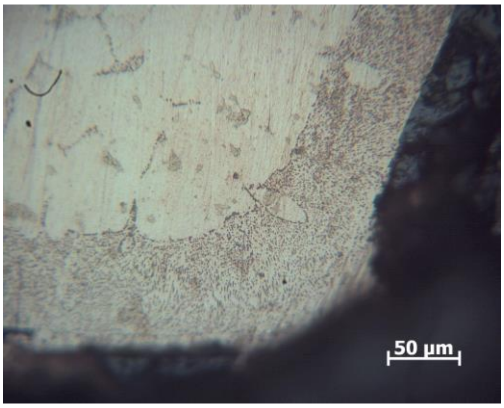


Fig. 12. Microstructure of wire in which SC was at temperature 950°C

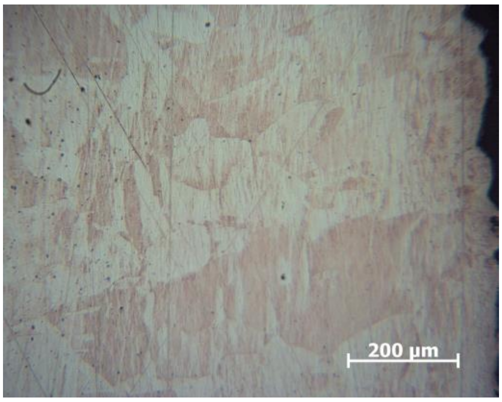


Fig. 13. Microstructure of wire in which SC was at temperature 950°C and endurance of 20 minutes in the furnace

Analysis of the microstructure of the samples after SC in model fire showed that significant differences of the microstructure due to wires that are heated in the furnace were not found.

Considering that the flame has a temperature, which varies from 300–1200°C [6] for accurate analysis of the influence of temperature on the microstructure after SC it is enough to conduct researches using a muffle furnace.

Conclusions. Based on the researches it is found:

In terms of SC of copper wires, formation of cast structure is observed over the entire range of investigated temperatures.

Fracture of the metal at the SC depends on the temperature of the wire. Spraying is observed at the temperature of 250 and 300°C, which is connected with the formation of crystal damage and cracks under the tension arising from the evaporation of material in local micro volumes.

Spraying of metal does not occur during SC at temperatures of 19°C and above 400°C. The absence of metal spraying at temperatures above 400°C is connected with its mitigating and its corresponding change elastic modulus (E) and ultimate tensile strength ($\sigma_в$). With increasing temperature of SC the difference of geometric parameters of wires becomes bigger.

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