Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 106 **2020**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2020.106.8

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Mańka, A., Hełka, A., Ćwiek, J. Influence of copper content on pantograph contact strip material on maximum temperature of railroad wire. *Scientific Journal of Silesian University of Technology. Series Transport*. 2020, **106**, 97-105. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2020.106.8.

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INFLUENCE OF COPPER CONTENT ON PANTOGRAPH CONTACT STRIP MATERIAL ON MAXIMUM TEMPERATURE OF RAILROAD WIRE

Summary. This article presents the results of studies on the impact of the percentage of copper in the carbon composite of the railway pantograph contact strips on the maximum temperatures of the contact wire of the overhead contact line. The tests were carried out in accordance with the requirements of standards [7, 9] and TSI [4]. The obtained relationship allows for an initial assessment of the introduced materials due to the contact wire heating criterion based on the copper content of the carbon composite, which greatly facilitates the design process and the initial assessment of the pantograph slides performance. This publication also indicates the minimum value of the percentage of copper at which the standard requirements [7] for railroad wire heating are still met.

Keywords: pantograph contact strip material, carbon strips, composite material, railway pantograph, railroad wire, maximum temperature of railroad wire

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1. INTRODUCTION

The railway pantograph contact strip is an element of traction vehicles that cooperates with railroad wire during operation. The durability, reliability and safety of the pantograph and, consequently, the entire railway vehicle depend on its performance. The contact strip and contact wire used for decades were technically made of pure copper. Graphite grease was used for proper cooperation and reduction of wear of this friction pair. As technology progressed, new materials were developed that enabled the withdrawal of copper-based contact strips in favour of copper-based carbon composites. This allows:

- longer service life of carbon strips at a comparable cost,
- longer life of contact wires, which reduces the overall cost of network maintenance,
- no need to sinter strips with contact wires (carbon does not react with copper),
- no need to lubricate the contact surface of the strip-contact wire.

The listed advantages of the introduced contact strips, including the reduced adverse impact on the environment (reduction of copper consumption products and the lack of the use of lubricants) have contributed to the introduction of the obligatory use of composite contact strips in rail transport throughout the European Union.

In 2011, the Polish railway lines introduced the obligation to apply pantographs fitted with contact strips made of carbon composite. These strips have replaced the copper ones that were used for many years. This change resulted from the need for the Polish railways to match the requirements of the Technical Specifications for Interoperability [4]. This provision forced the carriers to install in their pantographs composite materials that previously had to undergo specific test procedures [7, 9], material and thermal testing among others.

In professional literature, many researchers take up the topic related to the analysis of pantograph dynamic cooperation with the overhead contact line [1, 8, 13]. The authors define mathematical models describing the interaction between the pantograph and the overhead contact line, including for the purposes of pantograph diagnostics [1, 8]. They also examine the impact of a number of parameters on the intensity of the contact wire wear [12]. There are also works related to thermal phenomena [10], however, they are focused mainly on testing the contact wire temperature during operation.

It is important, however, that due to the use of overhead contact lines in the EU with different rated voltages, that is, from 3 kV to 25 kV, and there are significantly different requirements for its electrical conductivity. For instance, assuming a constant power demand value for a traction vehicle, for example, 5 kW as for a Dragon locomotive, it is simplified that this power can be obtained at 3 KV supply voltage at 1667 A or 200 A at 25 kV. The presented extreme current values of 200 A and 1667 A also have their effects in the heating of the elements through which the electric current flows.

According to Joule–Lenz law, which states that the power of heating generated by an electrical conductor is proportional to the product of its resistance and the square of the current:

$$Q = R \cdot I^2 \cdot t \tag{1}$$

where:
Q [W] – power of heating generated by an electrical conductor,
R [Ω] – resistance,
I [A] – current,
t [s] – current flow time.

Therefore, it can be seen that the obvious disadvantage of using a relatively low voltage overhead contact line generates very high values of the flowing current I, which in consequence forces the use of conductors with a very low resistance R. This applies in particular to the contact strip. The limitation associated with heat release is important both from the viewpoint of minimising energy losses and the impact of heat on mating elements. In the case of copper, an increase in temperature above approx. 200°C causes its recrystallization and a significant deterioration in its performance, which is unacceptable for railroad wire. Therefore, the criterion of the amount of heat generated in the interface between the contact strip and the overhead contact line is particularly important for rail transport, and the need to verify it is also found in normative requirements [7, 9].

From the above considerations, it is clear that not all contact strips that work properly in pantographs operated on 25 kV networks can be used on 3 kV networks. In practice, based on many years of research experience of the authors, it is found that hardly any material used for contact strips meets all normative requirements related to current carrying capacity. The basic feature that affects the applicability of a given contact strip is its specific conductivity, which results directly from the copper content of the carbon composite. Based on previous experience in testing the compliance of materials for contact strips, the authors first took into account the results of testing the percentage of metals and then performed tests on the thermal resistance of the contact wire, as these tests were the most demanding and indicated the desirability of performing further tests provided for in the standard [7].

It can therefore be assumed that it is possible to determine the value of the percentage of copper that will ensure that the maximum temperature requirement is met when trying to heat with electricity.

2. RESEARCH METHODOLOGY

PN-K-91001: 1997 on page 12 defines the requirements of 2.15.3. “Contact wire temperature increase”, which posits that the maximum contact wire temperature increase over the design ambient temperature, that is, 40°C, cannot be greater than 80°C. This gives a maximum contact wire temperature of 120 °C. Tested system: contact strip – contact wire, should be loaded with the maximum current received from the contact system during the current, that is, 200 A within 30 min.

The test stand was made in accordance with the normative requirements presented above, with the provision that the wire was used without significant wear and tear. Stand 1 Fig. 1 is equipped with a current circuit with one conductive type Djp100 made of copper in CuETP grade with the required current value of 200 A. The current value was measured with an indicator ammeter with an accuracy of ± 5 A and a clamp meter ammeter type CM-9930 from Lutron with serial number 04011 and measurement uncertainty ± 2% A.

During the tests, pressure 102 N within the normative range of 100^{+20}_{-10} N was applied. The contact wire temperature was measured by placing thermocouples in the contact wire slots located above the contact strips according to the diagram in Figure 2.

Materials for contact strips being the subject of tests for placing in service in Poland that is operated at the rated voltage of the traction network 3 kV were used for the tests. These materials were given letter markings in the order of the smallest percentage of copper in the carbon composite. Due to similar results obtained for a group of materials with a copper content in the range of 30%, the mean values from 3 materials with a share of 29.3; 31.2 and 31.7% Cu were used for further development.

Fig. 1. Laboratory stand for pantograph and contact strip material testing

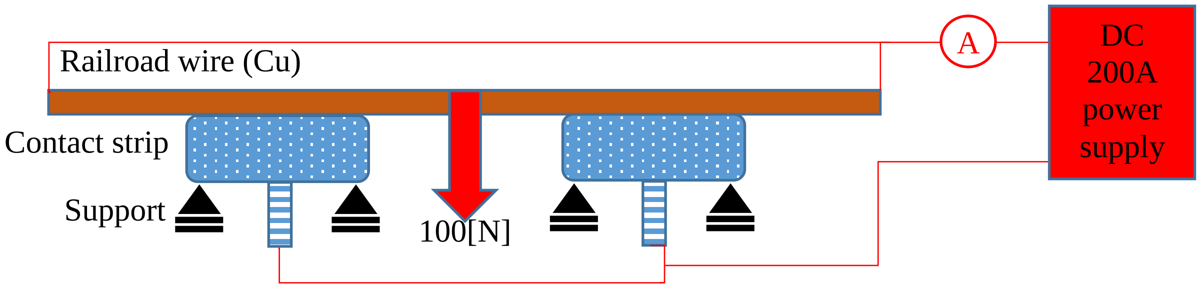

Fig. 2. Diagram of the measuring system

Tab. 1

The percentage of copper in the carbon-copper composite

Material designation	Copper percentage in composite [%]	Carbon percentage in composite [%]	Binder percentage in composite [%]
A	0,2	94,5	5,3
B	20,1	76,4	3,5
C	30,7	63,5	4,8
D	40,4	48,6	11,0

It should be noted that, according to the standard [2], the weight of metals may not exceed 40% of the weight of the overlay material.

A material with a copper percentage of 40.4% was not taken for further analysis due to a much larger proportion of binders, that is, 11.0%, which significantly affected the deterioration of the thermal and electrical properties of the contact strip material. At the same time, exceeding the threshold of 40% discriminates against this material from further normative studies.

Importantly, according to the authors, the mandatory examination of the content of the inclusions of metals required by the standard [7] can also be an indication for the initial determination of the thermal resistance of the material to the pantograph contact strips.

3. RESULTS AND DISCUSSION

As a result of the set current load in the contact strip – contact wire system, and due to the contact wire temperature measurement, it was possible to determine in the first minutes of the test whether the material meets the required condition of not exceeding the temperature of 120°C. However, the tests were conducted for a period of 30 min set in the standard. The obtained results are presented in Table 2.

Tab. 2

Summary of final temperatures (30 min) of contact wire for various copper percentages in the carbon composite of contact strips

Material designation	Copper percentage in composite [%]	Average contact wire temperature [°C]
A	0,2	**230,7**
B	20,1	**138,4**
C	30,7	**111,7**

It should be noted that material A (material used in the 15 kV network) was tested last and as expected, material with such low copper content does not meet the requirements of the standard [7]. It should also be noted that for material A, already in the 2nd minute of the test, the contact wire temperature exceeded the permissible value, that is 120°C. In addition, as bench tests showed, the use of such an overlay in operating conditions would recrystallize the contact wire copper after approx. 9 min of co-operation at standstill, that is, damage to its physical properties after exceeding 200°C – Fig. 3.

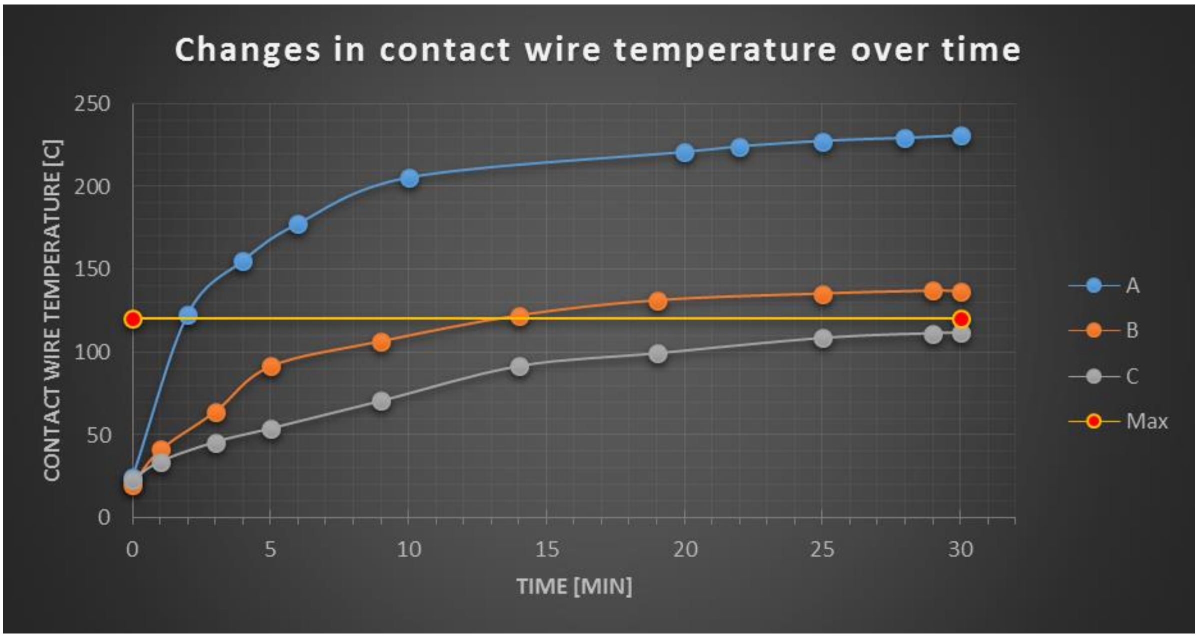

Fig. 3. Summary of test results of the influence of the percentage of copper strip on the contact wire temperature (heating 200 A for 30 min)

From the waveforms of temperature changes presented in Figs. 3 and 4 during the current flow 200 A corresponding to the values taken by the traction vehicle with the heating switched on, it can be seen that the material A and B does not meet the heating temperature criterion, that is 120°C (assuming the initial design temperature of 40°C).

To enable determination of the minimum value of the percentage of copper above which it is possible to meet the normative requirements for contact wire heating, the obtained results are shown in Fig. 4.

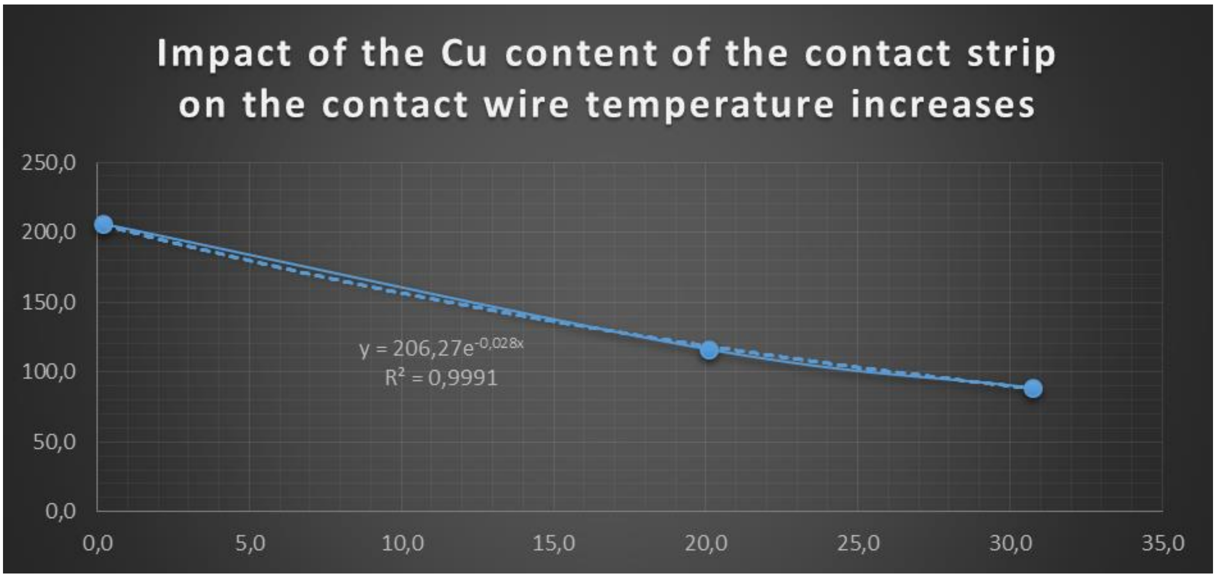

Fig. 4. Summary of contact wire temperature increase values for various materials of the contact strip relative to the ambient temperature of 20°C (heating 200 A for 30 min)

From the approximation equation for the exponential function of the relationship between the percentage of copper in the contact strip and the contact wire temperature, it follows that the maximum wire temperature will be 120°C, that is, the increase will be 100°C for a percentage of copper of 26%. Below this value, the maximum contact wire criterion is most likely not met.

The obtained relationship between the percentage of copper and the increase in contact wire temperature (at an ambient temperature of 20°C can be described by the relationship (2).

$$\Delta T_C = 206{,}27 \cdot C \cdot e^{-0{,}028 \cdot C} \tag{2}$$

where:
ΔTc [^{o}C] – contact wire temperature increment,
C [%] – the percentage of copper in the composite.

The above relationships were obtained for composites in which, apart from carbon and copper, no more than about 5% of the binder was used as the binder. It should be noted that making a composite with a binder of 11% significantly worsens its electrical and thermal properties even if the percentage of copper is within the limit value. The final temperature of 103°C was obtained for this material (D).

The graph also shows that the carbon composite alone without copper with the addition of binder up to approx. 5% will achieve a temperature increase of 206°C or 226°C, which causes damage to the contact wire (its recrystallization) in less than 9 min after starting the traction vehicle parking.

At the same time, based on this relationship, it can also be pointed out that when making a 100% copper contact strip, the contact wire temperature increase will be about 12°C. Indicated in standard [7], the maximum value of the 40% copper percentage should cause a temperature increase of 67.5°C, which is to 87.5°C.

The thermogram (Fig. 5) shows the temperature distribution in the contact zone of the contact wire with contact strips.

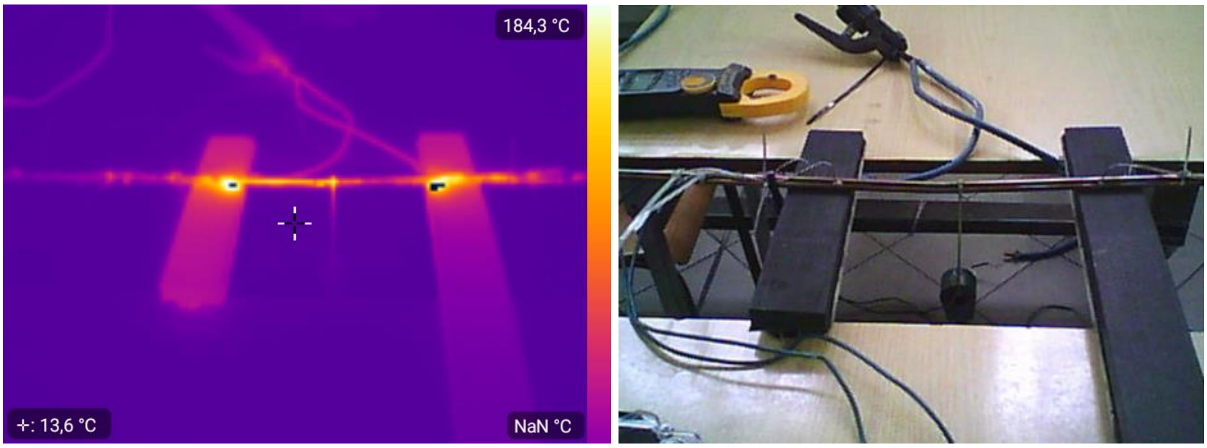

Fig. 5. Thermogram of an example contact point of contact wire and contact strip

Regardless of the demonstrated impact of the percentage of copper in the carbon overlay, it should be noted that while for networks with a supply voltage of 3 kV, it is particularly important to note the significance of such testing for the use of sliding overlays on networks with higher voltages, where current values are much lower. It is expedient to determine the normative values of current loads for vehicles used on networks with higher nominal voltages.

4. CONCLUSIONS

The research carried out on the impact of the percentage of copper in the carbon composite of the rail pantograph contact strips on the maximum contact wire temperatures of the railroad contact line showed that the increase in copper content in the contact strip material causes a reduction in the contact wire temperature. The study of the effect of current-carrying capacity on the contact wire temperature was the most common reason discriminating a given material for use in the Polish railroad contact line, therefore, the authors attempted to determine the relationship between copper content and contact wire temperature to facilitate the preliminary assessment of the operational suitability of the tested contact strip materials.

Based on the conducted research, the following conclusions can be drawn:

- it is possible to estimate the contact wire temperature based on the knowledge of the percentage of copper in the carbon composite as observed in the presented relationship (2), assuming that the percentage of binder does not exceed approx. 5.3%,

- a high percentage of binder material (adhesive) in the composite negatively affects its electrical and thermal properties. In particular, for material with 11% binder and 40% Cu, the permissible contact wire temperature was exceeded and amounted to 128°C,
- material A operated on 15 kV network did not meet the requirements for 3 kV network. At the same time, it should be noted that using such material, it is possible to "overheat" the contact wire, that is, exceeding the recrystallization temperature of 200°C after approx. 9 out of 30 min of receiving power when the vehicle is stationary.

The authors of the publication see the need to continue the presented research and extend it to include the impact of the percentage of carbon composite binders (adhesives) and to determine the impact of contact wire heat load on its strength, electrical and thermal properties.

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Received 26.10.2019; accepted in revised form 04.01.2020