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Diffusion between Cu and Cu/Ag contact materials of relays during multiple cycles under AC operation

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Abstract: Mechanisms of contact diffusion during relay-contacts operation were investigated. The contacts with the same geometry but different chemical composition were tested. The 1st relay-contact in a pair was made of copper, and the 2nd had a surface coated with a layer of silver about 500 micrometers thick. Different numbers of work cycles ranging from 8.5 k to 550 k were applied. AC current in the system was limited to 5 A. The closed/open periods were set at 250/250 ms. The resistance of the contacts was measured every 100 cycles. The microstructure of the working surfaces of the contacts after different numbers of operating cycles was investigated. On the surface of Cu contacts eutectic precipitates are formed and on the complementary bimetal contact tiny Cu-rich precipitates were generated on the silver surface. Crossection observations showed mutual material diffusion between the contacts. The depth of silver diffusion into the copper contact after 550 k operating cycles reaches 30 micrometers. The resistance of the contact system was stabilized after 40 k cycles at a level of 0.25 Ohm.

Key words: bimetal, contact diffusion, contacts wear, electric arc erosion

1. Introduction

Silver and copper are the metals with the best electrical conductivity [1, 2]. In most cases, for electrical applications, pure metals are used. Sometimes, however, it is necessary to use them in a combined form [3–5]. The Ag–Cu system is characterized by a limited and variable solubility of both components [6]. When the copper content is at a level of 28.1 wt% Cu, a low-melting point (779°C) eutectic occurs.

At 20°C, the conductivity of pure silver is 6.3×10^7 S/m, and the conductivity of pure copper is 5.96×10^7 S/m [7–9]. The effect of silver addition on copper conductivity is insignificant [7].

Owing to their high electrical conductivity, materials such as copper and silver are often used for the production of relay-contacts. In addition to high conductivity, contact materials should also provide

- high rate of heat dissipation,
- resistance of contact surfaces to tribological wear,
- high melting point,
- low susceptibility to oxidation,
- high resistance to corrosion, if the contacts are designed to operate in a chemically aggressive environment [7–10].

The low electrical resistance of the contact system and the required condition of heat dissipation can be ensured by the selection of an appropriate material and the use of a sufficiently large contact area. The situation is similar as it regards the problem of heat dissipation during contact operation [11–13].

Tribological wear, melting point and contact surface oxidation are interrelated phenomena. The corrosion mechanism on the relay-contact surfaces includes both mechanical wear caused by friction and pressure as well as burning out of the surface with an electric arc and the accompanying effect of oxidation typical of high-temperature corrosion [14–17].

The atmosphere in which the relay-contacts operate may also result in local corrosion. In this case, typical electromechanical corrosion phenomena will be intensified by temperature generated at the contact boundary during operation. This applies to both Joule-Lenz heat and electric arc degradation. Therefore, the key element here is the proper selection of contact materials [18, 19].

Metals such as Cu and Ag are naturally predisposed to applications involving the conduction of electricity. Both actions are very good electrical parameters, in the normal form the mechanical parameters work, and under specific conditions they can oxidize. For this reason, research covers two ways. One of them focused on Cu-Ag alloys, while the other one focused on composite materials, where both metals are supplied as composite components. The presented work focuses on the second aspect.

Silver-coated copper powder composites have been studied in previous research. Results carried out in the work [13]. The study examined the change in the resistance of copper contact pairs after 6 000 cycles with an AC current of 10 A, which resulted in an increase in the resistance of the system from 0.1 to 0.7 Ω, while at the same time the Cu/Ag contacts tested under the same conditions did not change their resistance, remaining at the level of 0.1 Ω.

Another work [20] focused on the production of Cu-Ag nano composite powders with high oxidation resistance. It is also a potential material for the production of contacts.

In the next work [21], the wear resistance of CuAg alloy contacts working with a second contact in a form of Ni plate was tested in fretting test. The degree of contact wear, changes in the chemical composition of the cooperating surfaces and the depth of microstructure changes, which reached a maximum of 50 microns, were examined.

In the work [14], the authors conducted multi-cycle tests on AgNi10 contacts, the contacts were tested in the range from 125 to 500 thousand work cycles loaded with alternating current. The work investigated the influence of contact wear on the microstructure and electrical properties. Based on the research presented in this article, it was decided to continuation of a research on Cu/Ag bimetallic contacts.

The tests described in this paper were performed on Cu/Ag contacts prepared from solid materials as a bimetal system. The goal was to optimally use the properties of both metals, without creating additional grain boundaries, as was the case in the previously discussed works based on composite powders. The research was carried out in a multi-cycle mode of 0.5 million repetitions, which allowed the analysis of contact wear processes throughout the entire operation cycle. At the same time, the change in the resistance of the contact system was periodically monitored. Previously conducted, by other authors, researches were limited to several thousand cycles [13]. Moreover, operation in a system of two electrical contacts was subject to numerical simulation in terms of the wear of their contact surfaces [22–24]. The analysis performed in this work made it possible to trace the influence of the electric arc and cyclic melting of the contact surfaces on their conductivity and showed the evolution of the contact surfaces during operation. At the same time, the impact moulded method (IMM) used to produce contacts is a cheap and easily available. Does not require advanced powder synthesis. An innovative aspect of the work is the use of bimetal contacts for testing and carrying out a multi-cycle wear analysis combined with continuous monitoring of the electrical properties of the system. A contact wear model was also proposed based on the change in their geometry during operation.

2. Materials and methods

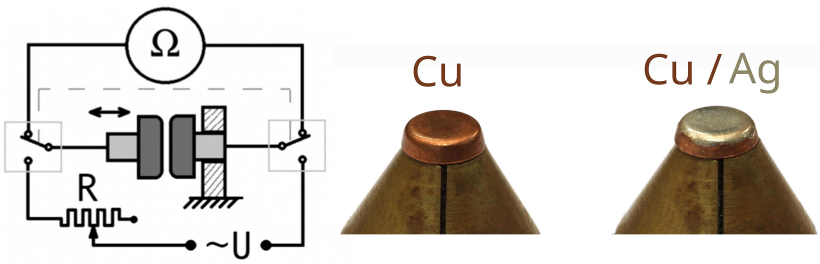
The aim of the experiment was to investigate the effect of two different metals with similar electrochemical potentials (Table 1) on the process of wear during cyclic operation of relay-contacts.

Table 1. Electrochemical potentials of popular (selected) metals with respect to hydrogen [2]

Metal	**Electrochemical potential [V]**
Ag	+0.8
Cu	+0.34
H	0
Sn	–0.14
Ni	–0.22
Cd	–0.4
Fe	–0.43
Zn	–0.76
Al	–1.34

Production of investigated contacts are based on IMM contacts production system of CHUGAI ELECTRIC INDUSTRIAL Co. Ltd. The copper contacts (**A-type**) with the same geometry were selected for testing. In the tested pair of contacts, the active surface of one of the contacts Cu/Ag (**B-type**) was coated with a layer of silver. The use of bimetallic Ag-Cu contacts is economically more viable than the use of pure silver contacts.

The tests were carried out on a specially designed stand schematically shown in Fig. 1(a).



(a) (b)

Fig. 1. (a) Schematic diagram of a device measuring the wear and tear of relay-contacts; (b) tested contacts before operation, left – A-type, right – B-type

Figure 1(b) shows the contacts with holders before the start of operation. Contact A-type was made of pure copper, while contact B-type was made of copper additionally coated on the surface with a layer of silver approximately 500 µm thick. The bimetallic contacts were made of impact-moulded copper and silver wire.

The alternating current (AC) flowing through the contacts was limited to 5 A. The current value was selected in such a way as to prevent the relay-contacts from sticking during operation. This situation may occur as a result of sparking, when the circuit is closed by the contacts.

The contact area in the initial state, was about 5 mm^2, while the lapped-in area was larger and amounted to 8.5 mm^2. The contact closing and opening times were equal and amounted to 250 ms. The measurements were carried out under atmospheric conditions at an ambient temperature of 21–23°C and a relative humidity of 47%. After every 100 close/open cycles, the resistance of the contacts was measured. The Agilent 34401A multimeter (Agilent Technologies, Inc. Headquarters, 5301 Stevens Creek Blvd, Santa Clara, CA 95051 United States) with a measurement accuracy of 0.001 Ω was used for the measurements. Each measurement consisted of a series of 20 readings taken in a time of 5 seconds and then the average value was calculated.

The contact surface was subjected to periodic examinations using a Hitachi S-3400N scanning electron microscope (Hitachi High-Tech Corporation, Address: 882 Ichige, Hitachinaka, Ibaraki 312-8504, Japan) with an attachment for the chemical composition analysis by EDS. The condition of the contacts was examined after the successively performed 8 500, 22 800, 40 800, 100 200, 312 600, 555 900 switching (operating) cycles. Contacts after 100 k and 550 k operating cycles were selected as the most representative ones for further detailed structural analysis.

Additionally, microhardness of the Cu–Cu/Ag active contact surfaces was measured by the Vickers method under a load of 25 G. Microhardness tester Innovatest 240 (INNOVATEST Europe BV MANUFACTURING, Borgharenweg 140,6222 AA Maastricht, The Netherlands) was used.

The aim of the tests was to assess the degree of contact wear after a different number of cycles and the impact of wear on electrical parameters.

3. Results

Figure 2 shows changes in relay-contact resistance as a function of the number of cycles. It was observed that after about 40 k cycles, the contacts were matched. After this stage, the value of resistance remained constant over the entire tested range. Typical value after stabilization did not exceed 0.26 Ohm.

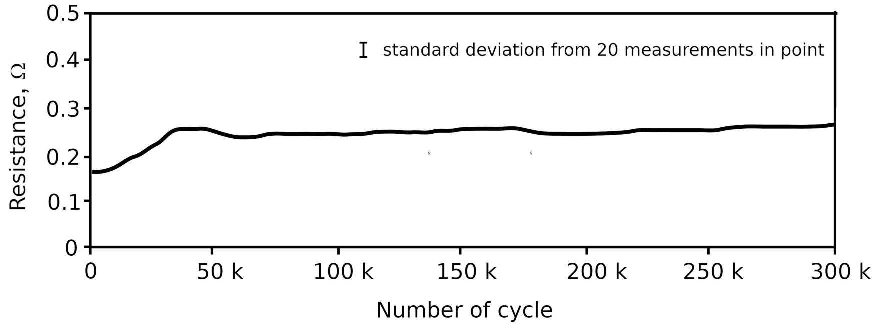


Fig. 2. Changes in relay-contact resistance vs number of operating cycles

Figure 3 shows the tribological wear of contact surfaces after a different number of operating cycles. The left part of the table shows the results obtained for contacts A-type (copper), while the right part shows the results obtained for contacts B-type (silver-plated contact surface). Additionally, for each contact, microscopic examinations were made on longitudinal sections. This enabled determining the depth of degradation of the contact surface and tracing the diffusion-controlled process of silver penetration into the copper structure. Microstructure examinations in frontal projection and on longitudinal sections were carried out for the pair of contacts A-type and B-type before operation and for contacts after 100 k and 550 k switching cycles.

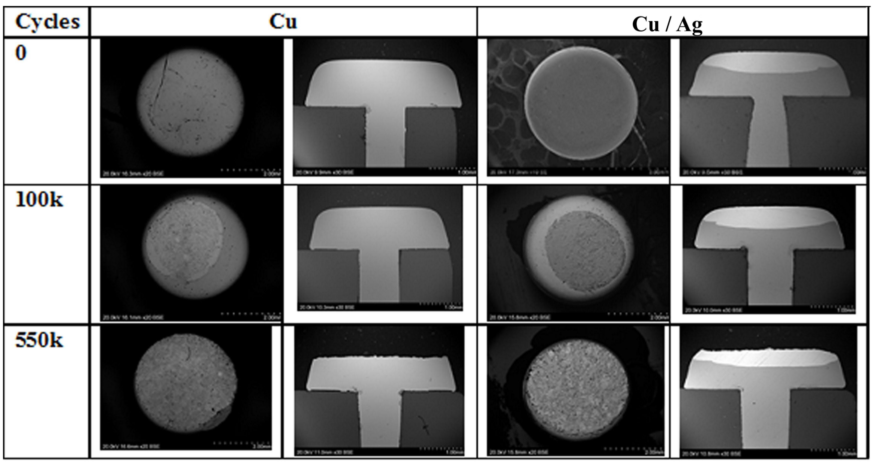


Fig. 3. Tribological wear of contact surfaces after different number of operating cycles

The geometry of the contacts is the reason why changes in the active contact area P_{active}, which occur with the progressing contact wear u, are in the initial period of a non-linear nature, as shown in Fig. 4. Equation 1 and Fig. 5 describe the characteristics of these changes.

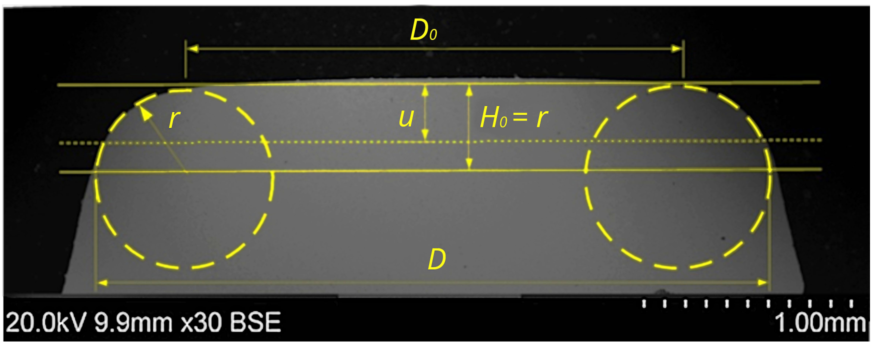


Fig. 4. Schematic representation of the non-linear characteristics of contact wear

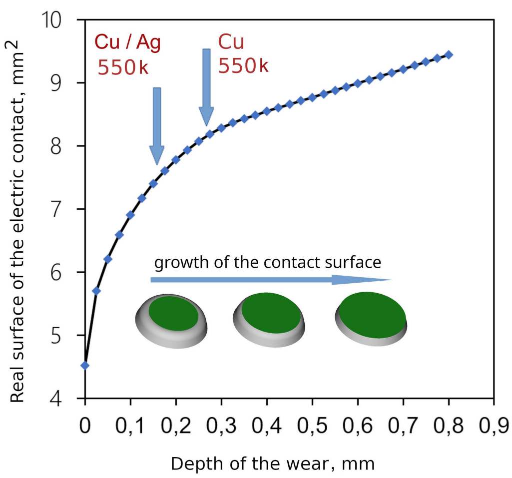


Fig. 5. Changes in active contact area P_{active} vs progress in wear u calculated from Eq. 1

$$P_{\text{active}} = \frac{\pi\left(D_0 + 2\sqrt{r^2 - (r-u)^2}\right)^2}{4}, \tag{1}$$

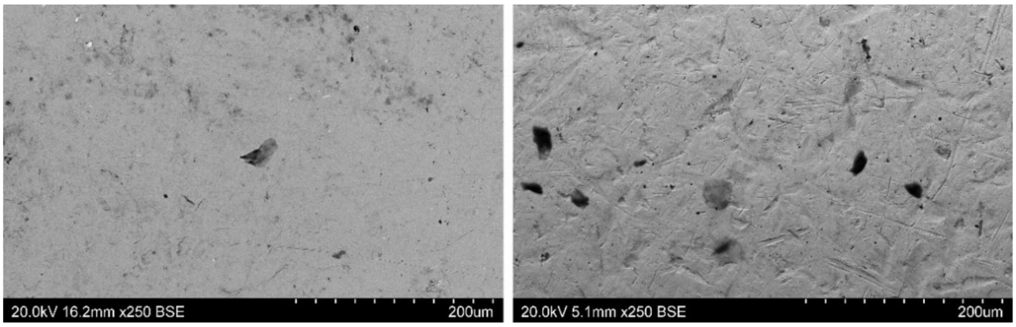
where: $D_0 = 2.4$ mm is initial contact operating diameter, $r = 0.45$ mm is contact curvature radius, $u = 0, \ldots, 0.4$ mm is progress in wear, where changes in the active contact area occur in a non-linear manner following the curvature of a circle with radius r.

With progressing wear, when the value depth of the wear u exceed H_0 value, denoted in Fig. 4 and in Eq. 1, the increase in the active contact area becomes proportional to the change in the square of the diameter D.

With further operation (wear) of the Cu/Ag contacts, after 550 k switching cycles, the thickness of the contact decreased to about 0.85 mm, while the thickness of the Cu contact decreased to 0.75 mm, thus increasing the contact area in the pair of contacts A-type and B-type and improving their fit.

3.1. Microstructural examinations

Figure 6 presents a surface microstructure of the contacts before wear tests.



(a) (b)

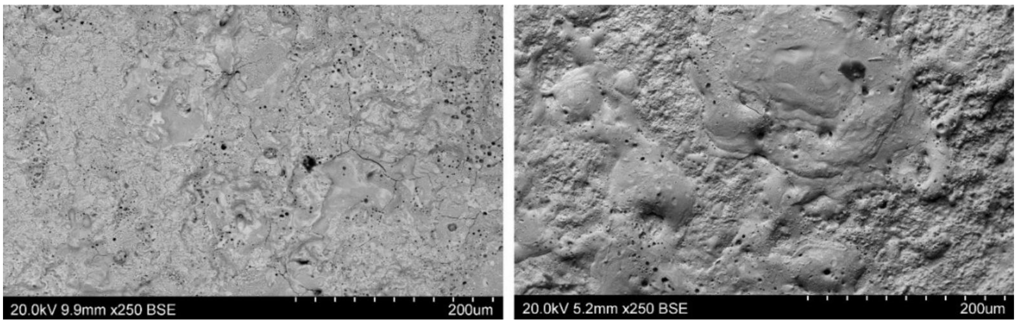
Fig. 6. Microstructure of the Cu–Cu/Ag contact surface in the initial state: (a) Cu; (b) Cu/Ag

The surface of the contacts contains irregularities as a result of the manufacturing process. The observed defects are significant only in the initial phase of the lapping of the cooperating elements. Figure 7 shows the wear process in a pair of Cu–Cu/Ag contacts after 100 k operating cycles. There are clear differences in the mechanism of surface wear. The degree of degradation of the Cu contact microstructure is only insignificant. A much more serious damage to the active surface is observed in the contact coated with a layer of silver. There are numerous traces of surface melting and pore-shaped material losses of the size of 2–0.5 μm surrounded by an Ag-based eutectic, formed as a result of temperature increase and electric arc discharges during contact operation.

The surface of contacts after 550 k operating cycles (Fig. 8) bears visible signs of an aggravation of these phenomena. The presence of a liquid phase formed by the complementary, silver-plated contact is an additional factor increasing the degradation of the Cu contact surface.

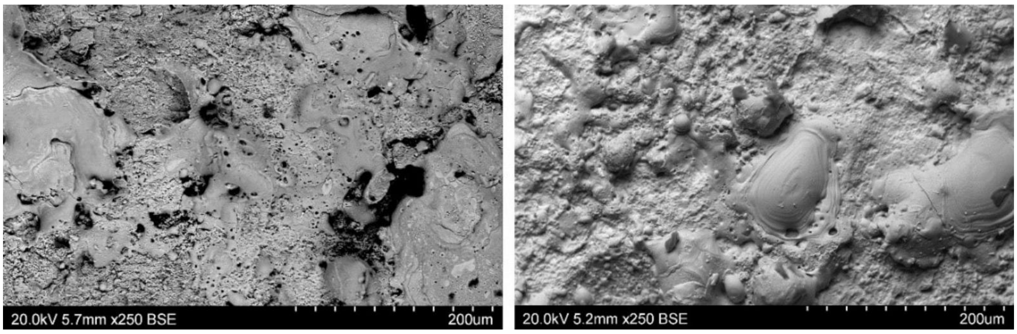
The next drawing (Fig. 9) shows in high magnification the surface of copper contacts after 100 k and 550 k operating cycles. Examinations revealed numerous traces of the surface melting of contact material and the presence of craters. Additionally, cracks were also found in the microstructure of the Cu contact surface (Fig. 9(a)). The formation of micro-cracks on the contact surface was due to oxidation of the contact metal surface layer. Oxides have the coefficient of thermal expansion different from the coefficient of the metallic matrix and are also characterized by high brittleness.

Figure 10 shows the surface of silver-plated contacts after 100 k and 550 k operating cycles, both in high magnification. Like copper contacts, also silver-plated contacts have cracks on their surface. There are also precipitates (phases) formed as a result of the silver enrichment with copper during contact operation in the presence of a liquid phase.



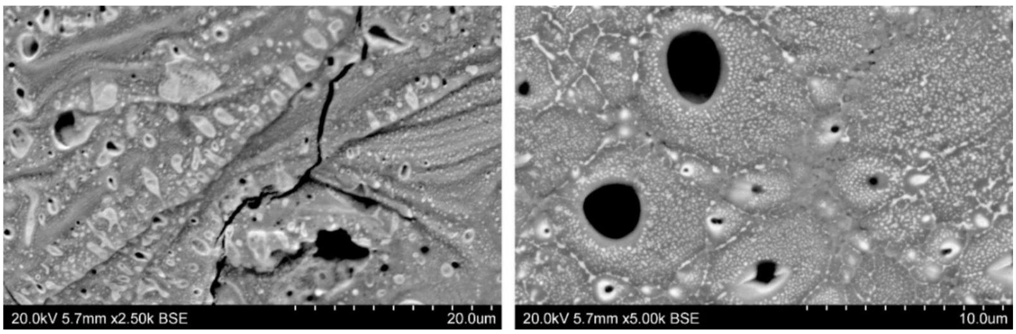
(a) (b)

Fig. 7. Microstructure of the Cu–Cu/Ag contact surface after 100 k operating cycles: (a) Cu; (b) Cu/Ag



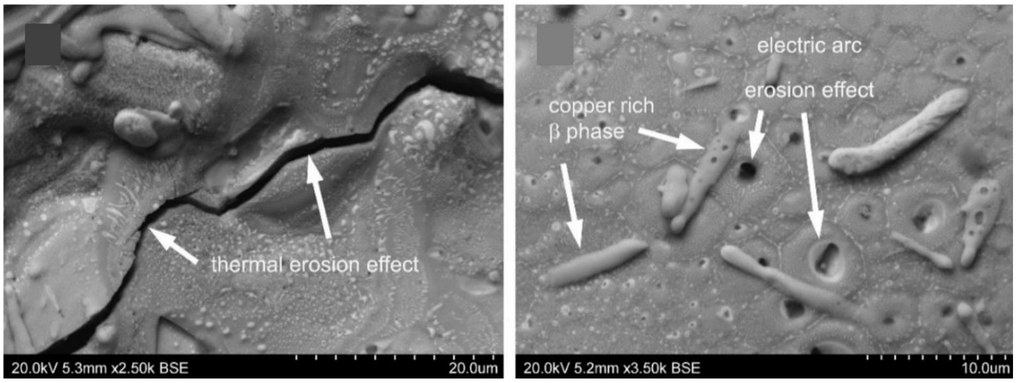
(a) (b)

Fig. 8. Microstructure of the Cu–Cu/Ag contact surface after 550 k operating cycles: (a) Cu; (b) Cu/Ag



(a) (b)

Fig. 9. Microdefects on the surface of Cu contacts after: (a) 100 k and (b) 550 k operating cycles. Visible are eutectic precipitates formed as a consequence of contact diffusion of silver from the complementary contact



(a) (b)

Fig. 10. Microdefects on the surface of Cu/Ag contacts after (a) 100 k and (b) 550 k operating cycles. Visible are tiny precipitates generated on the silver surface enriched with a small amount of copper

3.2. Analysis of the chemical composition of contacts after operating cycles

During operation, the relay-contacts are exposed to constant heating and surface melting, especially when sparking occurs, which favour the diffusion process and transfer of material between contact surfaces. The analysis of the chemical composition (Fig. 11) carried out by EDS on the longitudinal sections of contacts has confirmed the high rate of contact material migration between contact pairs A-type and B-type after 100 k operating cycles. The effect of eutectic reactions taking place between copper and silver is also visible on the contact surfaces.

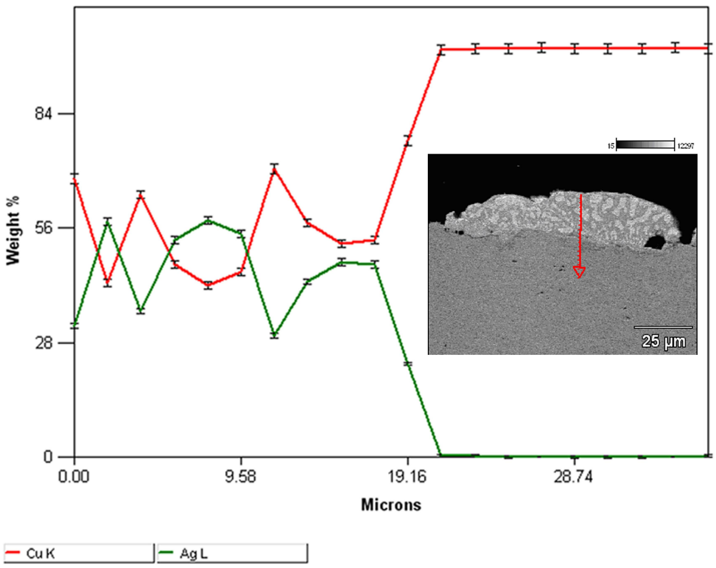
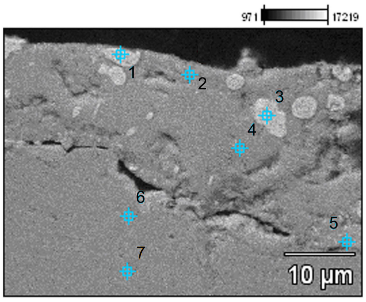


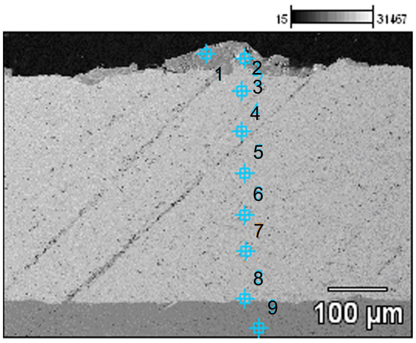
Fig. 11. Linear chemical analysis between substrate and surface phase

Subsequent research focused on the analysis of the chemical composition of the microstructural constituents present in the relay-contacts. In contact A-type (copper, Fig. 12), numerous point-like areas rich in Ag were found on the cross-section, while contact B-type (silver-plated, Fig. 13) showed a uniform enrichment of the entire contact surface with copper which, together with silver, formed numerous fine precipitates. On the cross-section of copper contact, silver-containing zones of material are visible which, combined with an uneven contact surface, have a significant impact on the current parameters during contact operation.



Point number	Weight %		Atomic %	
	Cu	Ag	Cu	Ag
1	29.84	70.16	41.93	58.07
2	74.96	25.04	83.56	16.44
3	28.98	71.02	40.92	59.08
4	71.88	28.12	81.27	18.73
5	64.37	35.63	75.41	24.59
6	99.65	0.35	99.79	0.21
7	100.00	0.00	100.00	0.00

Fig. 12. Chemical identification of phases on the contact surface Cu 550 k cycles



Point number	Weight %		Atomic %	
	Cu	Ag	Cu	Ag
1	68.26	31.74	78.49	21.51
2	33.88	66.12	46.52	53.48
3	0.92	99.08	1.55	98.45
4	0.56	99.44	0.94	99.06
5	0.00	100.00	0.00	100.00
6	1.69	98.31	2.84	97.16
7	2.35	97.65	3.92	96.08
8	1.58	98.42	2.65	97.35
9	99.5	0.50	99.71	0.29

Fig. 13. Chemical identification of phases on the contact surface Cu/Ag 550 k cycles

3.3. Microhardness tests

Vickers microhardness tests were also carried out on the contact cross-sections, including contact surface layer and core material. The results are shown in Fig. 14.

The obtained results show that the microhardness of individual material layers remains at a similar level as the contact wears out. The greatest differences were observed in the Cu/Ag contacts. The reason was lower hardness of the silver layer and of the intermediate phases formed at the copper substrate boundary.

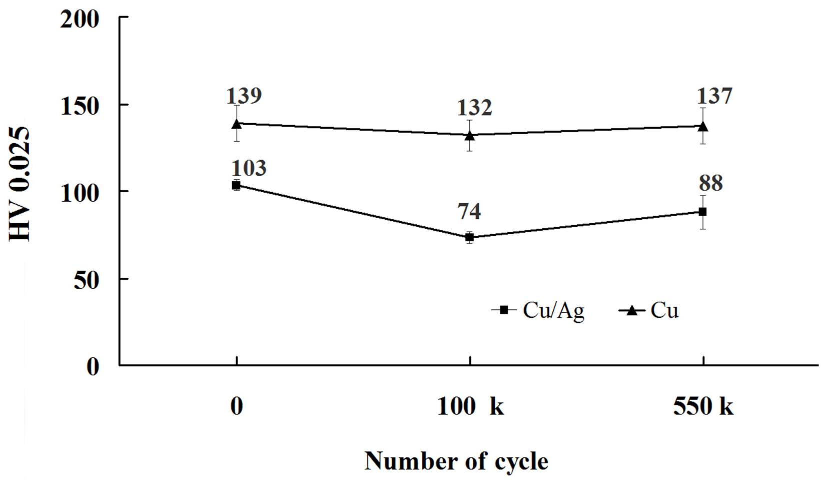


Fig. 14. Microhardness on the cross-sections of Cu and Cu/Ag contacts

4. Discussion

Metal contacts through which the electric current flows result in strong local heating of the contact surfaces. This is caused by the interaction of two factors, namely:

– heat released by the resistance at the contact boundary,

– ignition of an electric arc.

The effect of resistance heating favours diffusion phenomena. In the case of materials coated with metals different from the core material, this means restructuring of the intermediate layers, in this case of the Ag/Cu connection (Figs. 12 and 13).

At room temperature, the diffusion coefficients D for Cu and Ag are 147 and 241 cm^2/s, respectively [4]. A much higher diffusion coefficient D of silver should translate into faster diffusion of silver into copper. However, the analyzed situation is slightly different, because contacts heat up and undergo surface melting during operation. The result is faster diffusion taking place in metal with a lower melting point – silver in this case. As a result of diffusion exchange, the Ag/Cu intermediate layer is becoming thicker. Bilateral diffusion makes silver penetrate into the copper layer (A-type) and copper into the silver layer (B-type). After a sufficiently long time of exposure, this results in the formation of a eutectic structure on the contact surface. The second factor, i.e. the electric arc, makes the contact surface heat up to a temperature exceeding the melting point of both components. This causes degradation of the surface. At the same time, the existence of the liquid phase favours silver migration from the contact surface type B to the contact surface A (which has not been coated with silver). As a result, a Cu layer rich in silver is formed on the contact surface type A. Observed at 3500x magnification, on the Figs. 10(b) and 12, the surface of the copper contact shows the existence of porosity. This effect was not observed to occur in the silver coating on the second contact in the pair. The surfaces of both contacts are rough, which is the result of the technological process.

The analysis of the contact surfaces after 100 k operating cycles shows the existence of numerous spots with surface melting and micro-cracks. These defects are the result of a cyclic temperature increase and, consequently, oxidation process, which leads to the formation of a brittle oxide layer. Moreover, Ag/Cu diffusion exchange also takes place. The analysis of the chemical composition of the samples showed that the diffusion was bilateral. As a consequence, the Ag/Cu eutectic appeared in both samples with differences in the size of the precipitates of phases rich in silver. The copper sample contained large precipitates of the primary phase, formed as a result of spot deposition of silver on the copper surface. Rapid heat transfer in the contact material did not allow for chemical homogenization of the structure and large silver-rich particles remained on the surface.

The B-type contact surface was enriched by copper diffusion from the second contact (A-type). Due to the higher melting point of copper, this exchange was less intense than in the previous case. The observed eutectic precipitates were of a secondary nature and were formed as a result of precipitation from the solid phase, mainly due to the artificial aging caused by high operating temperature of the contact.

The next variant was tested after 550 k cycles, which was adopted as the limit value of the experiment. The structure of the A-type contact surface shows a large number of the remelted spots; the amount of silver transferred to the surface has also increased. At the same time, the surface roughness remained at a level similar to that after 100 k cycles. The situation is different in the case of B-type contact. The lower temperature of silver, and thus the increased content of the liquid phase during contact operation, resulted in the formation of a smooth surface on which recrystallized grains, decorated on boundaries with the precipitates of $\alpha + \beta$ phases.

The 3500× magnification of Figs. 10(a) and 10(b) shows numerous fine precipitates inside the grains formed as a result of the secondary precipitation in the solid state. The surfaces of both samples also show the effect of oxidation but with no adverse impact on the electrical conductivity of the system.

The examination of longitudinal sections showed that the Cu contact surface contained oval areas rich in silver, inside which a eutectic structure prevailed. The distribution of these areas was non-uniform and their content in the contact surface coating was low. In the case of the silver-plated surface, the content of the eutectic phase was much higher and its distribution was more uniform. Chemical analysis showed that the depth of copper penetration into silver after 550 k cycles was about 30 μm. This layer was stable, and possible losses were compensated by copper diffusion from the contact area.

The bimetallic Cu/Ag contacts after 550 k and 100 k operating cycles showed lower microhardness values than the bimetallic contact before the start of operation; the decrease in microhardness was dictated by high temperature and constant changes in the chemical composition of the contact area during operation. However, it was observed that as the number of the switching cycles increased to 550 k, the microhardness values of the Cu/Ag contacts were by 19% higher than the microhardness of the Cu/Ag contact running 100 k switching cycles. Copper contacts were characterized by higher microhardness values than the bimetallic Cu/Ag contacts, and similarly to bimetallic contacts, their microhardness showed a downward trend during operation, but after 550 k switching cycles, the microhardness values were comparable to the microhardness of the copper contact in the initial state.

5. Conclusions

After approximately 40 k cycles, stabilization of the contact pair resistance occurred. This was due to better matching of the contact surfaces and stabilization of the chemical composition in both contact areas. Despite progressive mechanical wear of the contact surfaces, higher number of cycles did not deteriorate the electrical parameters of the contact system. The higher resistance resulting from the degradation of the contact surface was compensated by the increasing size of the contact area.

The flow of current through the contact pair ignited the electric arc, which caused local melting of the contact surfaces. Because of high temperature in the contact area, the silver coating on one of the contacts was transferred to the contact made of pure copper, and copper diffused into silver, which led to the formation of Ag-Cu eutectic on both surfaces.

After about 100 k cycles, cracks appeared on the surface of the copper contact as a result of multiple thermal shocks and surface oxidation. Similar defects were not observed on the silver-plated contact surface.

After 550 k cycles, the surface of the silver-plated contact underwent a significant modification, which consisted in its strengthening with dispersion particles of $\alpha + \beta$ phases. The result was inhibition of the tribological wear process in the silver-plated contact. The thickness of the copper contact decreased by 25%, while the thickness of the silver-plated contact decreased by 15% relative to the initial thickness of the contact.

Taking into account the increase in the wear resistance of Cu/Ag contacts and the well-preserved high electrical conductivity, the impact moulded method (IMM) can be used as a means to improve the surface of bimetallic contacts with silver-plated active surfaces.

Acknowledgments

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