Article citation info:
KSIAZKIEWICZ A, JANISZEWSKI J. Welding tendency for selected contact materials under different switching conditions. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (2): 237–245, http://dx.doi.org/10.17531/ein.2019.2.7.

Andrzej KSIAZKIEWICZ
Jerzy JANISZEWSKI

WELDING TENDENCY FOR SELECTED CONTACT MATERIALS UNDER DIFFERENT SWITCHING CONDITIONS

TENDENCJA SCZEPIANIA WYBRANYCH MATERIAŁÓW STYKOWYCH W RÓŻNYCH WARUNKACH ŁĄCZENIOWYCH

The flow of significant current through electric contacts may lead to contact welding. In a.c. circuits this phenomena is not only dependent on properties of contact material (i.e. resistance to welding) but on the phase in which current is switched on. Welding tendency for contact materials made from AgNi, AgCdO and $AgSnO_2$ was evaluated based on selected phase at which make operation took place. The test circuit was protected by overcurrent apparatus to simulate real working environment. It is observed that welding tendency for the selected contact materials is contingent to current phase at which make operation is done.

Keywords: *relays, contact materials, contact welding, surface erosion.*

Przepływ znacznego prądu przez styki elektryczne może prowadzić do ich sczepienia. W obwodach prądu przemiennego to zjawisko jest nie tylko zależne od właściwości materiału stykowego (tj. odporności na sczepianie), ale od fazy, w której prąd jest załączany. Zbadana została tendencja do sczepiania się styków, w zależności od fazy załączania prądu, wykonanych z następujących materiałów stykowych: AgNi, AgCdO i $AgSnO_2$. Obwód probierczy zabezpieczony był przez zabezpieczenia nadprądowe, w celu symulacji normalnych warunków pracy. Zauważono, że tendencja do sczepiania styków, dla wybranych materiałów stykowych, jest zależna od fazy, w której wykonuje się załączenie obwodu.

Słowa kluczowe: *przekaźniki, materiały stykowe, sczepianie styków, erozja powierzchni.*

1. Introduction

The relays which are intended for connecting the electrical load are prone to some disadvantageous phenomena. These may include making of overload currents and short-circuit currents, which may lead to shortening the time of maintenance of relays or, in extreme cases, to their complete destruction. Long term exposure to higher temperature may lead to relays degradation, for example change of its contact resistance and opening and closing times [18, 19]. The research already performed by Morin [12], Neuhaus [13] and Doublet [4], who independently undertook work for similar contact materials, concentrate on low-current circuits of direct current and small amperage. There are also articles related to the processes of making circuits of alternating current of average voltage and amperage of several kA [1, 6, 14]. The operation of making significant currents may lead to contact bounces. Altogether with the increase of values for amperage of contacting current, there is the increase of loss of the mass of contact rivet [5, 14, 17]. Apart from that, discharge arc, accompanying commutation of electric circuits, may cause strong, local heating of an arc root, even above the temperature of melting for a certain contact material [7]. If at least on the surface of one contact the material is melted and the contacts close, then welding occurs [7, 9–11]. Primary properties of a contact material may change if the surface of contact or the composition of the material is changed [20]. The composition may change through thermal influence of current. Such conditions are true mostly for making currents of significant amperage, of several kiloamperes. The area of deformation for a contact surface depends on the resistance of a certain material to welding. The lower resistance, the bigger surface of contact is changed [20]. The article describes the influence of the short-circuit current phase on the welding tendency for selected contact materials, which are: AgNi, AgCdO and $AgSnO_2$. Research in this filed is focused mainly on d.c. circuits with low amperages, no exceeding hundreds of amps, or with a.c circuits and amperage level of several kA. Presented results are therefore new in this area as are focused on a.c. circuits and medium amps value with contact materials tested that are widely exploited in industry. Switching a damaged circuit will result in a short-circuit current flow which can be many times higher than the rated current of a relay. This current flow will generate significant heat generation in contacts that may result in contact welding. However the tendency for contact welding in such a.c. circuit is not only related to contact material but also to the phase of current at which the contacts are closed.

2. Contact welding tendency and force of the weld

Contact welding can occur inside the contact areas of the contact surface A_S. When the switching arc is present, it is assumed that the welding takes place inside the area where the A_m surfaces, melted due to the electric arc, meet. Each arc root spot is surrounded by a molten contact material, located completely or partially inside or outside of the contact surface. The pinching force of the contacts depends on the size of area A_0 [13, 16].

The welding force of the contacts also depends on the contact material used. Some contact materials show a higher tendency to welding than others [12]. If the contact material is characterized by a high welding tendency, also the resulting welds will form as strong. Pure silver has the worst properties in this respect, it has a higher tendency for welding [8] and this is one of the reasons why it is not used as a contact material. AgCdO is characterized by slightly better parameters. It has a lower tendency for welding, but they create welds with higher strength.

Contact materials $AgSnO_2$ and AgNi, used in the tested relays, have similar properties in the range of welding tendency and their strength. In this case, the first of these forms stronger joints, but exhibits a lower tendency to form them. The influence on the welding force will also have the type of the load. A resistive-inductive load leads to welds with lower weld force than with a purely resistive load. The greatest welding forces occur with the resistive-capacitive load [13, 16]. In the case under consideration, i.e. the short circuit, the load has a resistive character. The inclusion of a current of higher intensity leads to the welding of the contacts of higher weld strength. The shorter duration of the contact bounce leads to the formation of welds with a greater force than the bounces of a longer duration. According to Rieder and Neuhaus [15] the explanation of this process is related to different contact bounce heights. With a shorter duration of the bounce on the contact surface, a deep arc spot appears with a smaller surface than with a longer bounce. When a bounce occurs for a longer duration, the contact surface is melted, although only on the surface itself, which leads to the formation of a weld of lower strength. Welds with significant force occur with bounces lasting less than 100 µs. The contact bounces of a longer duration lead to splashing the molten contact material away from the contact point [2]. Increasing the content of oxides in the contact material ($AgSnO_2$ In) reduces the strength of welds. Contact welding will be more frequent with time, and they will produce stronger welds [3].

3. Materials and methods

The most difficult working conditions for electromagnetic relays can occur at the moment of closing the damaged circuit in which a short-circuit current occurs. With significant short-circuit currents, processes such as contact heating above the melting point of the material, contact bounces and also welding may occur. Attempts have been made to connect a short circuit with the expected short-circuit current of 320 A. Contact materials that were tested are: AgNi, AgCdO and $AgSnO_2$. Each of them was composed of 90 % silver and a 10 % addition of nickel, cadmium-oxide and tin-oxide respectively. The $AgSnO_2$ was tested in two variations. For the first one contact rivets were made in the process of internal oxidation and refereed in the article simply as $AgSnO_2$. For the second one the rivet was designed to withstand higher inrush currents (up to 80 A for 20 ms) and refereed in the article as $AgSnO_2$ P. The system is designed to test short-circuit currents with prospective values up to $20I_n$ in circuits equipped with typical overcurrent protection apparatus, used in low voltage electrical installations, with rated current 16 A. In addition, the system is equipped with an external device synchronizing the moment of relay activation with the phase of the supply voltage. This system is intended for switching the relay contacts in the selected phase of the mains voltage. Measurements were carried out for two switching on currents:

- switching on the short-circuit current occurs at the moment when the voltage between the contacts reaches zero (case A),
- switching on short-circuit current occurs at the moment when the voltage between the reaches the maximum value (case B).

For case A short-circuit current increases from zero, and in case B shortcircuit current starts from the maximum value. The effects of such switching on the short-circuit current will have an impact on the electrode processes occurring in the contacts during the short-circuit. Switching on the circuit at the moment when both current and voltage reach zero, puts milder conditions for the operation of the relay. There shouldn't be a preliminary electric discharge between the contacts, thus the contact surface may undergo less erosion. The short-circuit current increase is slower, so that electrodynamic contact bounces may be shorter or won't occur at all. Switching on the circuit at the moment when both voltage and current reach peak value can cause drastically different effects. A sudden increase in the short circuit current value may lead to the appearance of significant electrodynamic forces in the initial phase of the closing process. In consequence, this will lead to the occurrence of contact bounce during the current flow and thus to the ignition of the electric arc. This arc will contribute to further significant erosion of the contact surface.

4. Results

An example oscillogram of short-circuit current and the voltage between the relay contacts when the short-circuit circuit is closed when the voltage reaches zero is shown in Fig. 1. The graph shows that when the supply voltage reaches zero, the short-circuit current begins to flow. It can be noticed that after about a time of 4 ms since the beginning of the current flow, the current decreases slightly, and after the time 5 ms there is a significant reduction in its values. This limitation is related to the effect of overcurrent protection in the circuit. The interruption of the fault circuit occurred after less than 7 ms since the occurrence of a short circuit.

Eight attempts were made for each contact material. The current and voltage between the relay contacts were recorded. After each test, the contacts were checked for welding. On the basis of the oscilloscope recording, it was determined whether in the given test a contact bounce occurred. A summary of the results obtained are presented in table 1. It can be seen that for none of the attempts contact bounce b or welding s was observed. This leads to the conclusion that for switching the circuit at the moment when the current increases from zero value does not cause negative effects related to the relay rivets.

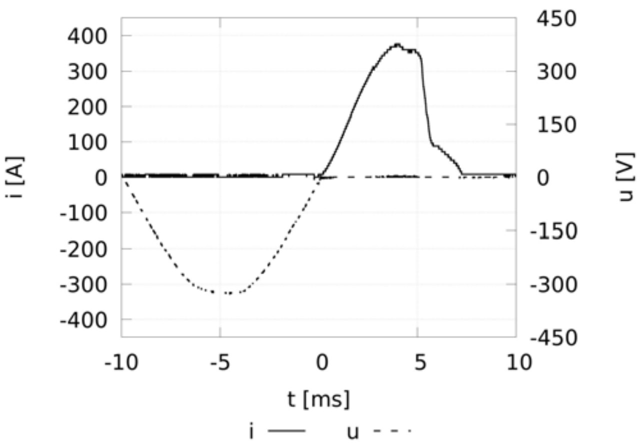

Fig. 1. An exemplary oscillogram of current and voltage waveform between the relay contacts when the circuit is closed when voltage between contacts reaches zero (case A); contact material – AgNi

Table 1. The results of switching the circuit when current reaches zero (case A); n – number of tries, s – number of welds, b – number of contact bounces, s∧b – simultaneous occurrence of contact bounce and contact weld

Lp.	Contact material	n	s	b	s ∧b
1	AgNi	8	0	0	0
2	$AgSnO_2$	8	0	0	0
3	$AgSnO_2$ P	8	0	0	0
4	AgCdO	8	0	0	0

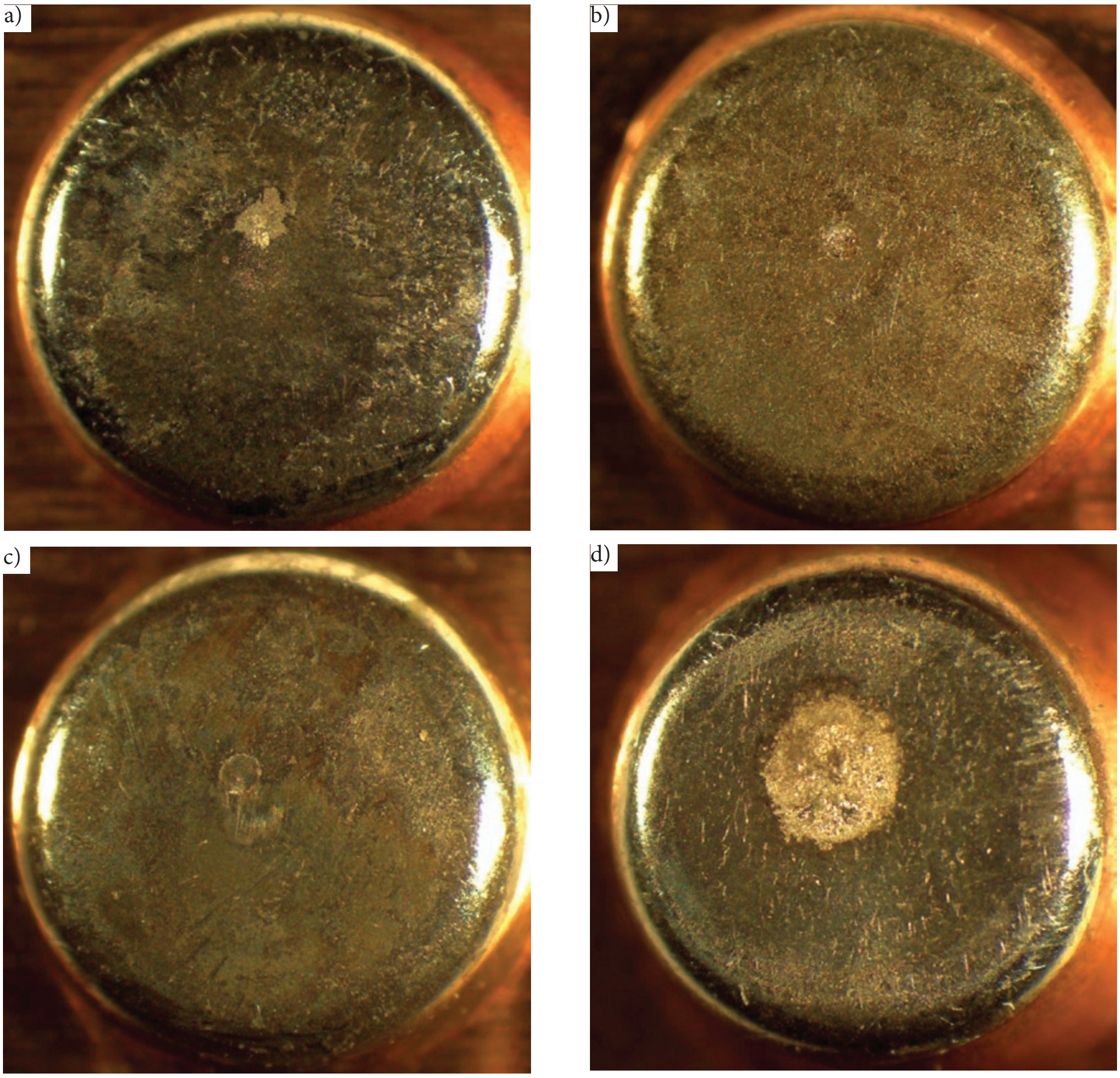

Fig. 2. Contact surface after short-circuit current switched on at zero value (case A), for individual contact materials; a) AgNi, b) $AgSnO_2$, c) $AgSnO_2$ P, d) AgCdO

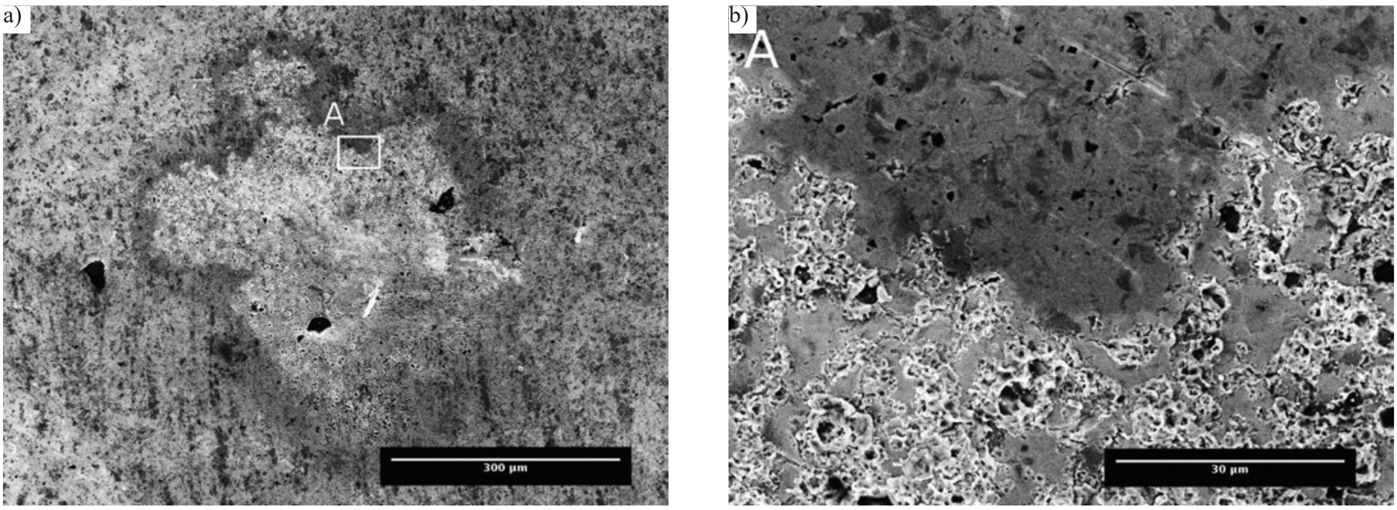

Fig. 3. View of the contact surface under the electron microscope, when the short-circuit current is switched at zero (case A), for contacts made of AgNi

Photographs of the contact surfaces are shown in the Fig. 2. A single erosive contact area is visible on the contact surface. This area has a shape that is clearly similar to circular. Each time it was found that the degraded surface is located almost centrally on the contact, with no visible discolouration. On figures 3, 4, 5 and 6 the view of the eroded areas under the scanning microscope is shown, successively for the contact materials AgNi, $AgSnO_2$, $AgSnO_2$ P and AgCdO. All the eroded surfaces have a distinct round shape, except for the AgNi. Individual contact areas are exposed, where erosive changes in contact surfaces occurred. The sizes of the eroded areas are shown in

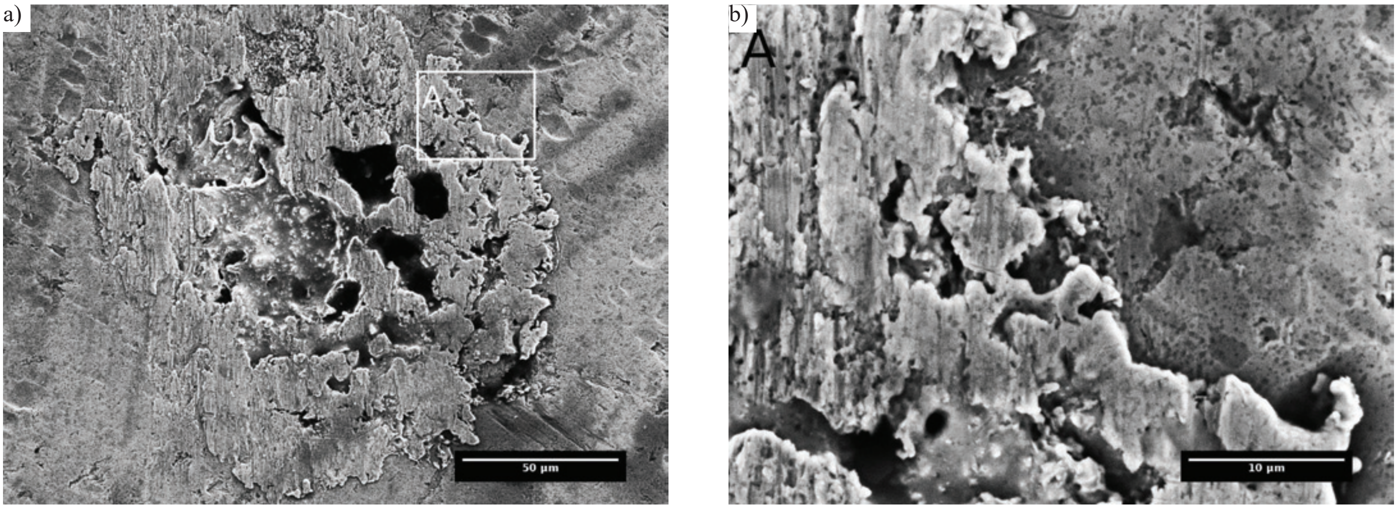

Fig. 4. View of the contact surface under the electron microscope, when the short-circuit current is switched at zero (case A), for contacts made of $AgSnO_2$

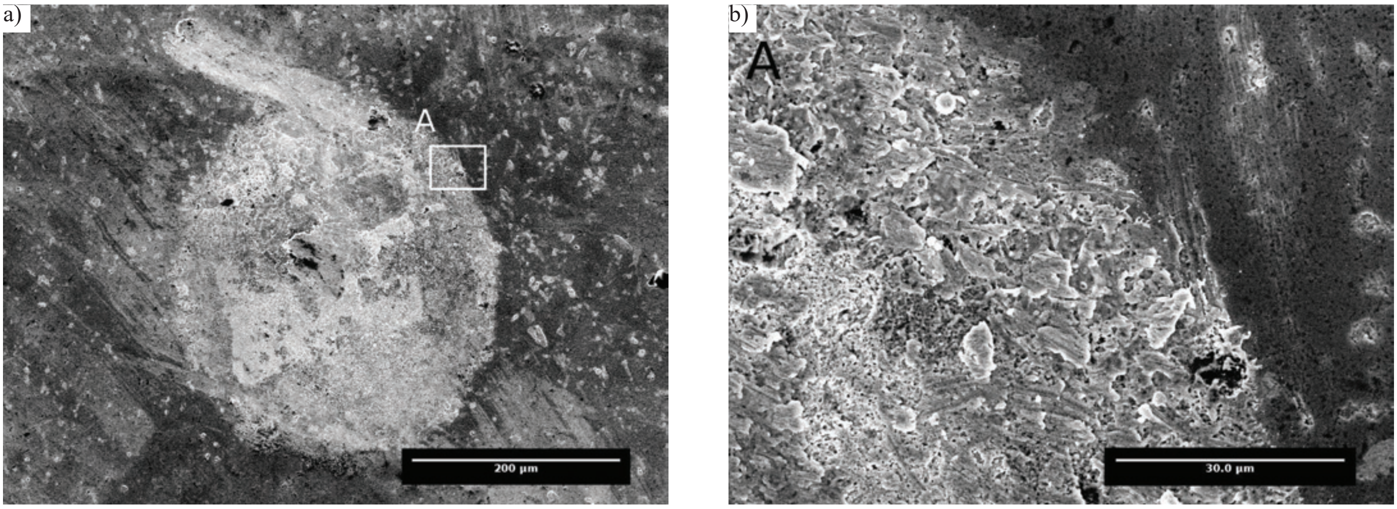

Fig. 5. View of the contact surface under the electron microscope, when the short-circuit current is switched at zero (case A), for contacts made of $AgSnO_2$ P

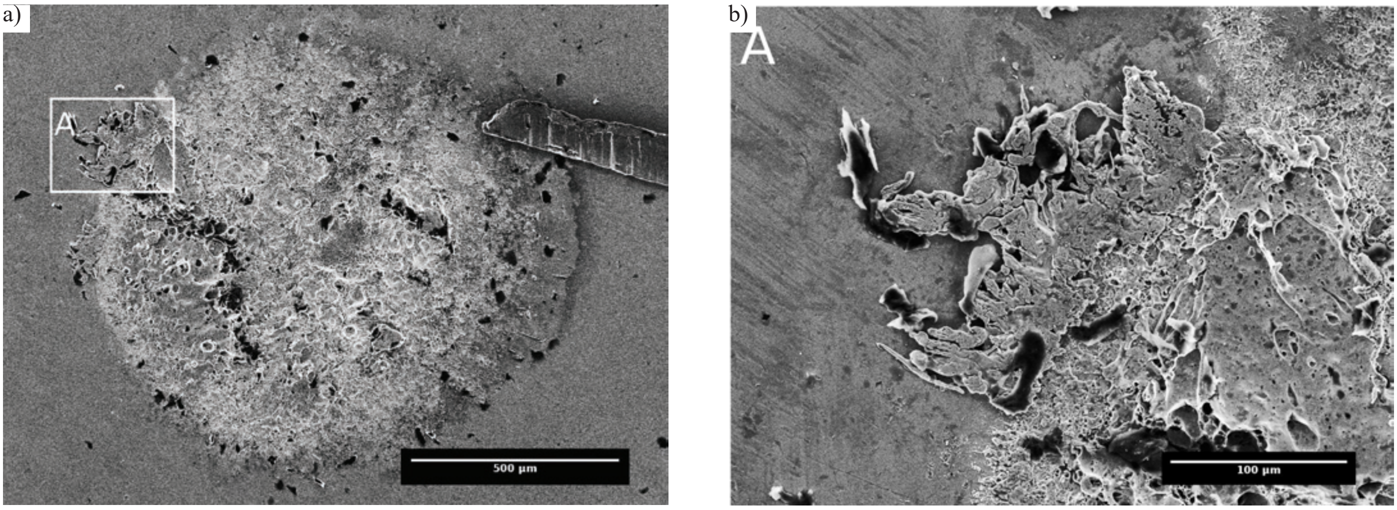

Fig. 6. iew of the contact surface under the electron microscope, when the short-circuit current is switched at zero (case A), for contacts made of AgCdO

table 2. Clearly visible is the boundary between the eroded and unchanged contact surface. For AgNi, the visible change is characterized by a greater graininess of the eroded contact material. For other materials, these changes are characterized by the occurrence of larger flat surfaces. In each case, there are no noticeable splashes of the contact material. This means that there was no melt discharge when closing the contacts. It was eroded only after they were closed under the influence of high temperature generated by the current flow. An exemplary oscillogram of short-circuit current and voltage between the relay contacts at the moment when the voltage reaches the maximal value is shown in Fig. 7. After closing the contacts of the relay, the current starts flowing and reaches a peak value of 432 A after 1 ms.

Table 2. The size of eroded contact surface when switching on the short-circuit current at zero value (case A)

Size of the eroded contact surface $[mm^2]$			
AgNi	$AgSnO_2$	$AgSnO_2$ P	AgCdO
0,13	0,017	0,093	0,864

The significant steepness of the current rise in the circuit results from the negligible value of the inductive reactance of the circuit. At the same time, the process of switching off the current by short-circuit protection apparatus begins. When the current passes through zero, the current flow is interrupted.

In the same way as in the previous case, each time the contact was checked and whether or not a bounce occurred during the time of the given test. The results are presented in the table 3. Almost for every registered sample there was a contact bounce. This bounce, as already discussed earlier, can be a dominant contributor to the welding process. In the scope of the short-circuit current switching experiments with the expected value of 320 A, when closing the relay contacts in the maximum supply voltage, the tested contact materials showed their different susceptibility to welding. They were noted for two contact materials: AgNi and AgCdO. The other two materials showed higher resistance to welding despite contact bounces. Therefore, one should also pay attention to the convergence of these two processes (s ∧ b) as shown in Tab. 3. The appearance of the bounce almost or each trial ended with contact weld. Although the contacts made with AgNi should show a higher resistance [12], according to the presented results it did not. It has been shown that in the unfavourable switching

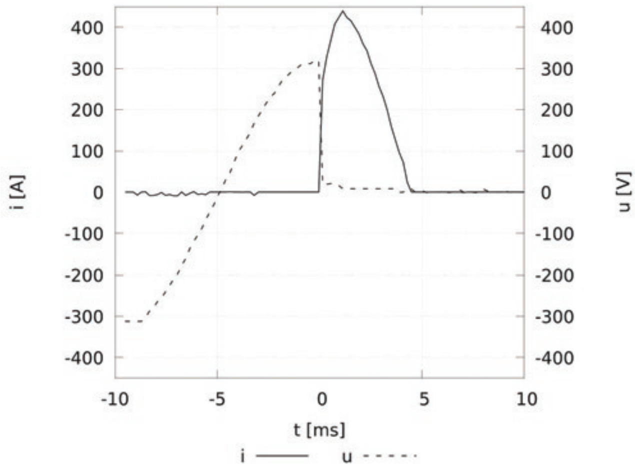

Fig. 7. Exemplary current and voltage waveform between the relay contacts when the short circuit circuit is switched on at peak voltage (case B), contact material – $AgSnO_2$ P

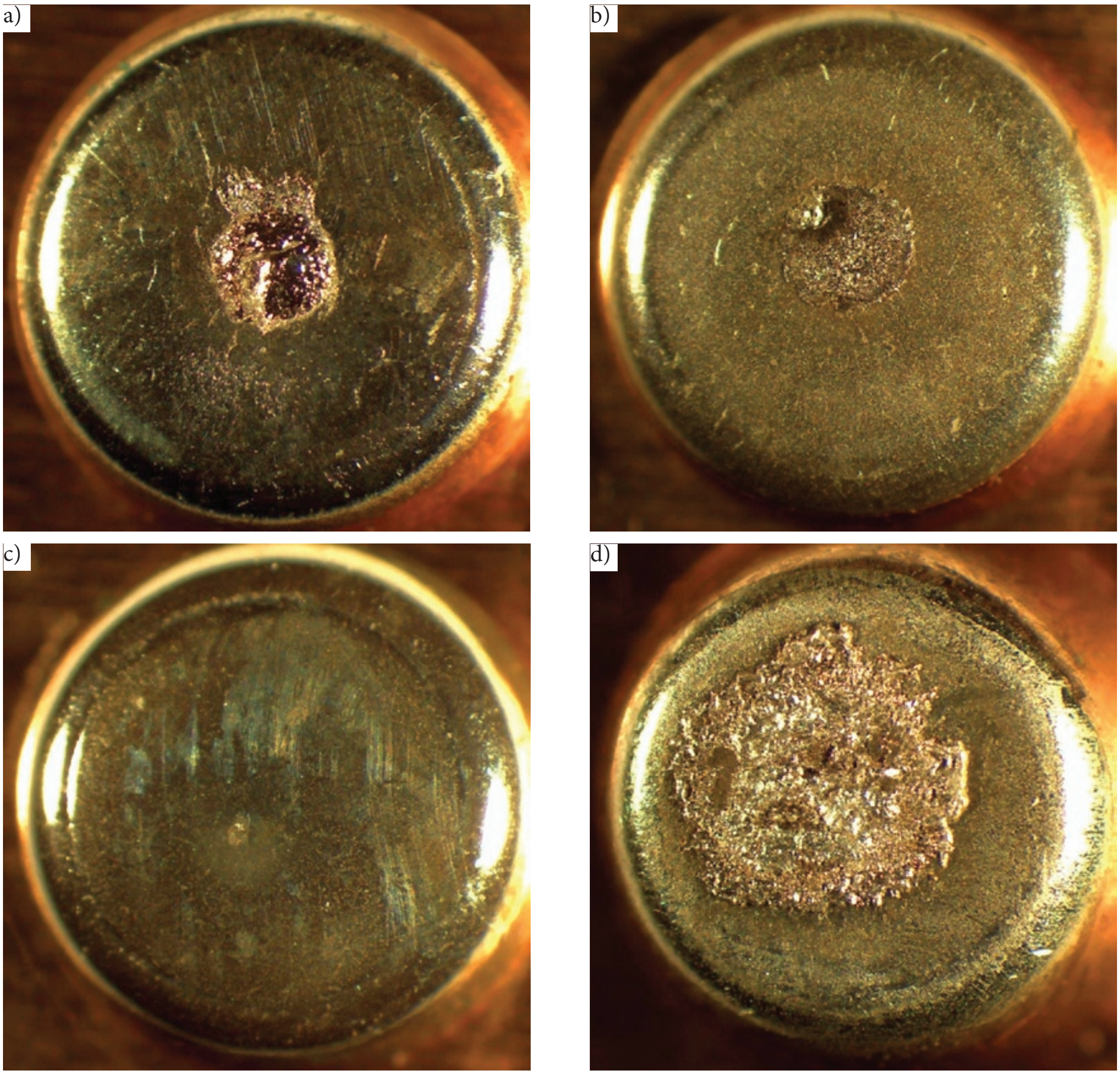

Fig. 8. Contact surface after short-circuit current switched on at peak value (case B), for individual contact materials: a) AgNi, b) $AgSnO_2$, c) $AgSnO_2$ P, d) AgCdO

Table 3. The results of switching the circuit when current reaches peak value (case B); n – number of tries, s – number of welds, b – number of contact bounces, s ∧ b – simultaneous occurrence of contact bounce and contact weld

Lp.	Contact material	n	s	b	s ∧b
1	AgNi	8	7	7	7
2	$AgSnO_2$	8	0	5	0
3	$AgSnO_2$ P	8	0	6	0
4	AgCdO	8	8	4	4

conditions that occur in operation - switching on damaged circuits, the contacts made of AgNi and AgCdO are characterized by low resistance to the welding process. Photographs of the contact surfaces are shown in Fig. 8. Clearly very different erosion of the contact surfaces can be observed (Tab. 4). In particular, this applies to the contact materials for which the welding process has been observed. For them, erosive changes relate to a significant part of the surface. The smallest surface changes occurred for $AgSnO_2$ P. For this material (and $AgSnO_2$), no welds were observed, despite the occurrence of bounces.

In the figures 9, 10, 11 and 12, photographs of eroded areas made with scanning microscope are presented, successively for contact materials AgNi, $AgSnO_2$, $AgSnO_2$ P and AgCdO. Due to thermal processes occurring during the switch-on time (mainly due to the electric arc) part of the contact material has been melted. When closing the contacts, this material is thrown out of the contact area. It can be seen that the direction of ejection of this material is centrifugal from the point of contact. The ejection range of the molten material reaches, in the extreme case, for AgNi even 300 μm counting from the border of the periphery of the region in the shape of a circle. For $AgSnO_2$ P, changes of a similar nature are virtually imperceptible.

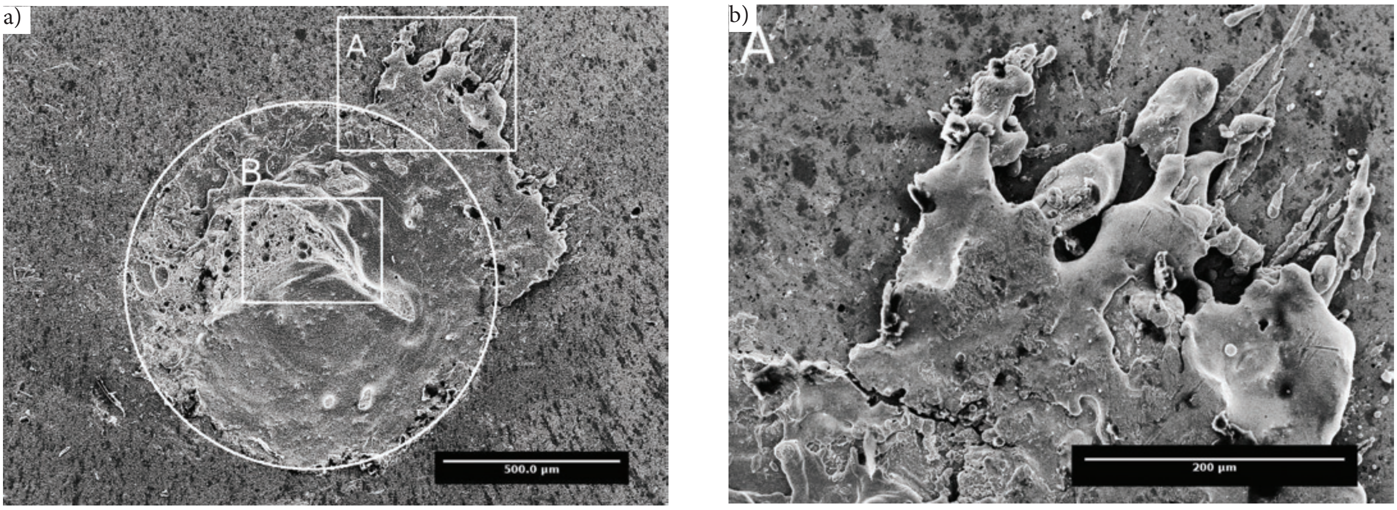

Fig. 9. View of the contact surface under the electron microscope, when the short-circuit current is switched at peak value (case B); contact material AgNi

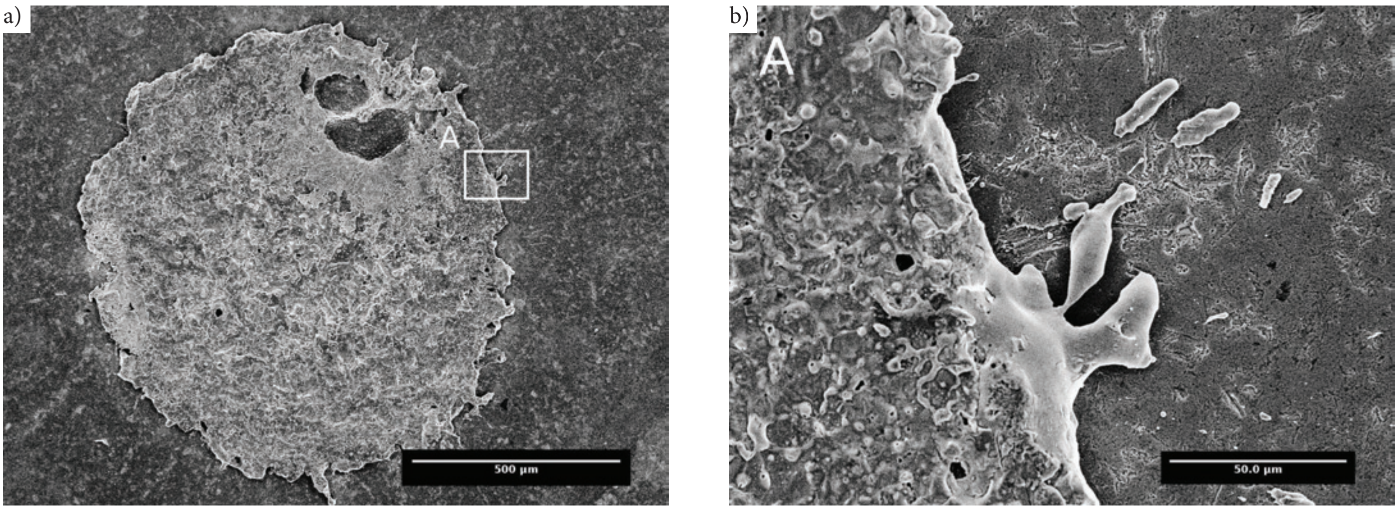

Fig. 10. View of the contact surface under the electron microscope, when the short-circuit current is switched at peak value (case B); contact material $AgSnO_2$

Table 4. The size of eroded contact surface when switching on the short-circuit current at peak value (case B)

Size of the eroded contact surface [mm^2]			
AgNi	$AgSnO_2$	$AgSnO_2$ P	AgCdO
1,029	0,838	0,022	3,525

In figure 13 the state of the contact surface is presented, for a selected case in which the contacts have been welded. Two areas clearly stand out. In the middle of the figures, porous changes are visible on the contact surfaces. These are the places where the contacts have interfered and then mechanically broken. These surfaces are characterized by an elevation (convexity) in relation to the base of contact surface. Both for AgNi and AgCdO the areas of torn bonding joints

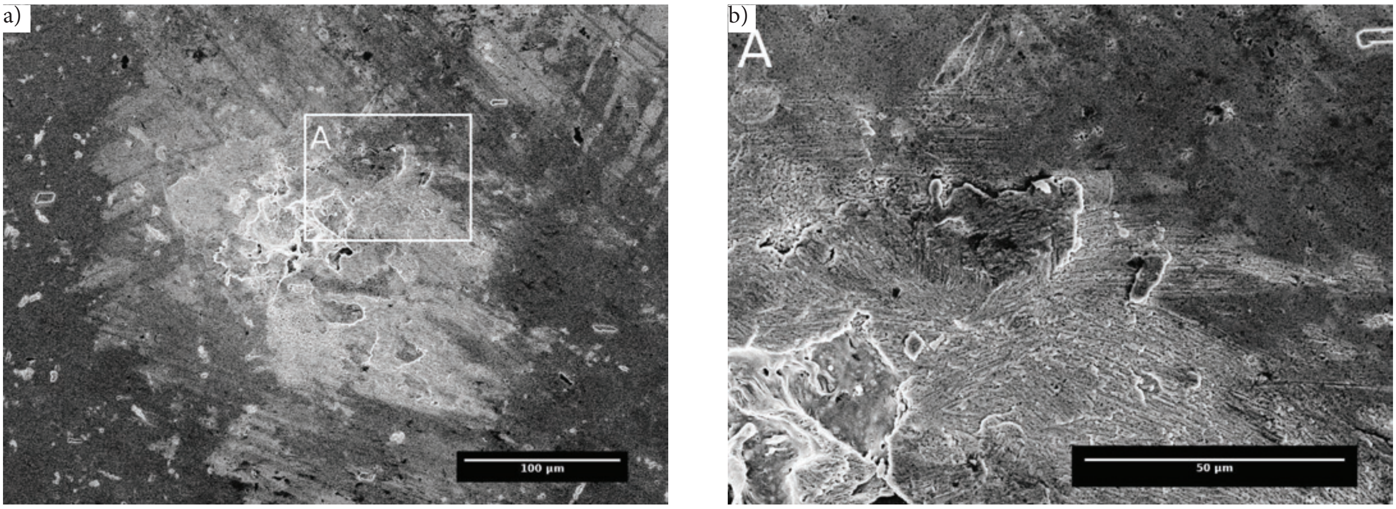

Fig. 11. View of the contact surface under the electron microscope, when the short-circuit current is switched at peak value (case B); contact material $AgSnO_2$ P

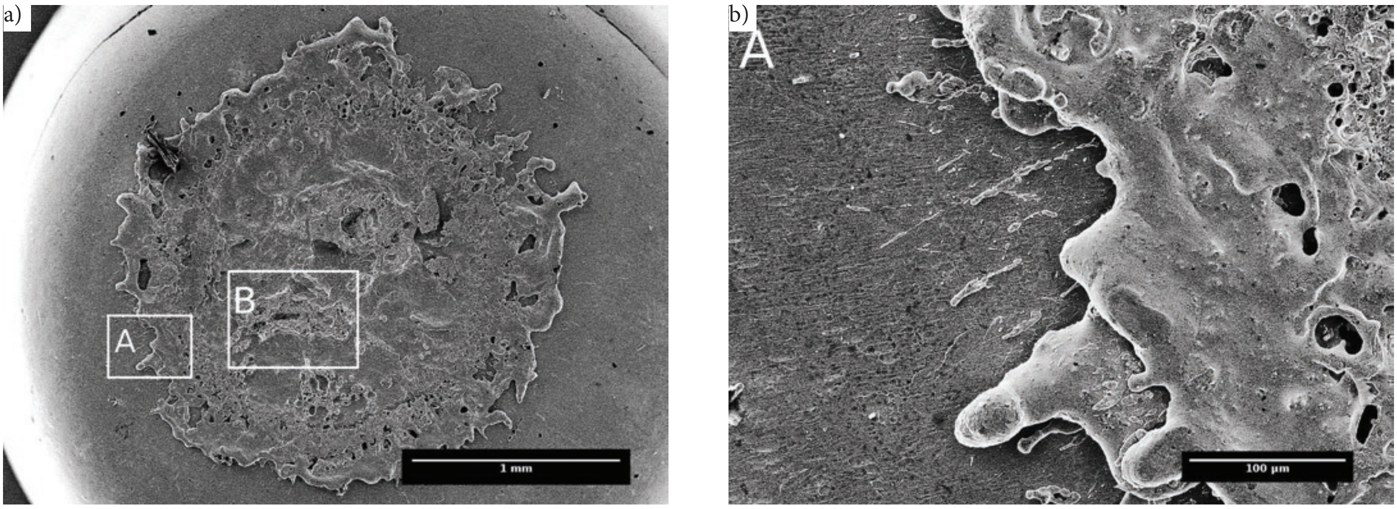

Fig. 12. View of the contact surface under the electron microscope, when the short-circuit current is switched at peak value (case B); contact material AgCdO

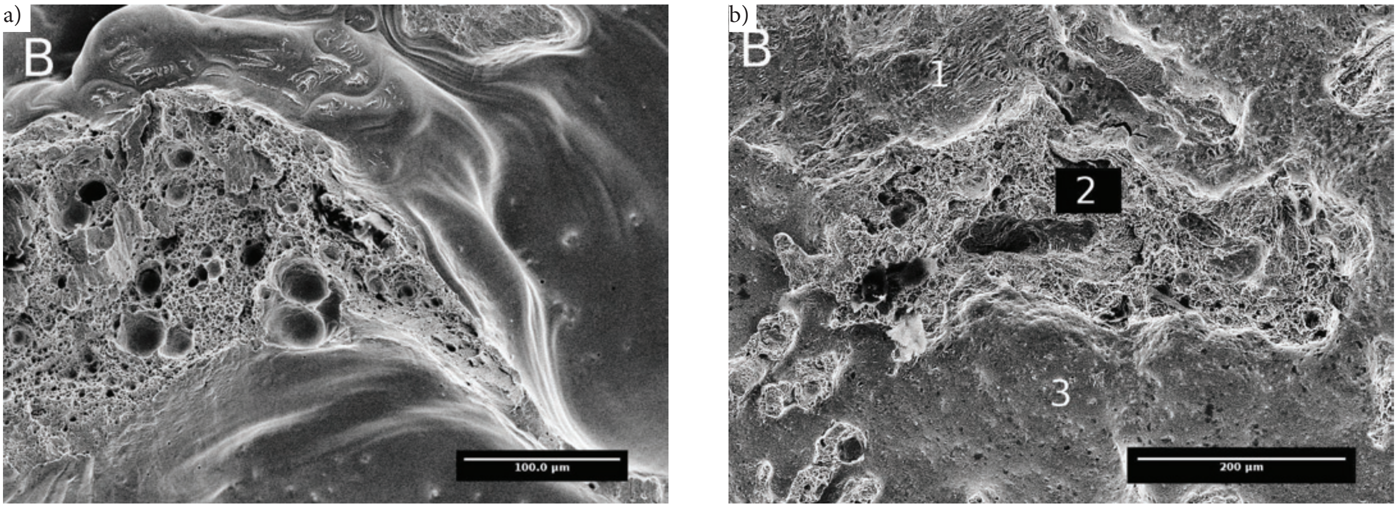

Fig. 13. Photo of the contact surface at the point where the contacts are welded: a) AgNi, b) AgCdO, test current I =320 A

have length from 500 µm and width 200 µm, and their area is approximately 0.107 mm^2 and 0.09 mm^2. For the AgNi material it is seen that the melted material flows from the area where the weld has occurred. For AgCdO, there are three levels of the contact area, where the 1 area is higher and 3 lower than the area 2. The boundary of material disruption and their breakthrough is plastic-brittle.

5. Conclusions

Based on these results, it can be concluded that the most resistant to welding ($AgSnO_2$) [12] was characterized by the smallest deformation of the contact surface. In the next order is AgNi, and the biggest changes are observed for AgCdO. The melting point of these materials, according to the manufacturer's data, is identical (961 °C). The differences occur in the case of thermal conductivity. For $AgSnO_2$ the coefficient of thermal conductivity is not described by the manufacturer, but for AgCdO it is by 12 % smaller than for AgNi, hence the susceptibility of this material to the effects of thermal interactions can be greater. This may justify the observed increase in surface degradation at the AgCdO contacts.

In the analysed case, the level of local destruction of the contact surface will be significantly affected by the value of thermal conductivity, and not by the hardness or melting temperature (which are almost identical) of the contact material. Higher thermal conductivity means better heat transfer from its source (contact area) deeper into the material. Thus, with better conductivity, the heating in the contact zone, up to the melting point, will take longer or will require more energy (higher current). In the discussed experimental conditions, the worst conditions occur for the material with the least thermal conductivity.

Contacts bounces occurred only when the current was switched on in maximum voltage. Switching on the circuit at the moment when the voltage (and current) reaches the value of zero does not cause unambiguously negative effects on the contact surfaces of the tested relays. In the range of the applied test currents, welding occurred only for contacts made with AgNi and AgCdO and only for switching the circuit when the current reached its peak value (case B). One should also pay attention to the convergence of the occurrence of contact bounce and its welding. The appearance of the bounce almost for each trial ended with contact weld. Thus, contacts made with AgNi and AgCdO are characterized by low resistance to the welding process. On the contact surfaces, a single contact area is visible, with the shape of a circle that has eroded. This area is located almost in the middle of the contact.

There is no visible discolouration of the unevened contact surface. The material most resistant to welding ($AgSnO_2$) was characterized by the smallest erosion of the contact surface, higher erosion is visible for AgNi and AgCdO respectively. When switching on the voltage, splashes of the contact material are not noticeable. This means that the erosion of the contact area occurred under the influence of its heating without the participation of arc. For switching on the maximum voltage, a significant part of the contact material is melted and can be ejected out of the contact area. The direction of ejection of this material is radiant from the point of contact.

Acknowledgement

The research was financed from resources of the Ministry of Science and Higher Education for statutory activities No. 04/41/DSMK/4133, name of the task: Switching and electrode processes in low voltage relays – the effect of switching on nominal and short-circuit currents.

References

1. Borkowski P. Arc erosion of contacts on switching high currents. Archives of Electrical Engineering 2004; 53(209): 259–287.
2. Chen Z, Witter G. Dynamic welding of silver contacts under different mechanical bounce conditions. 45th IEEE HOLM Conference on Electrical Contacts 1999: 1–8, https://doi.org/10.1109/HOLM.1999.795920.
3. Chen Z K, Witter G J. A study of dynamic welding of electrical contacts with emphasis on the effects of oxide content for silver tin indium oxide contacts. 56th IEEE Holm Conference on Electrical Contacts 2010: 121–126, https://doi.org/10.1109/HOLM.2010.5619552.
4. Doublet L, Jemaa N B, Hauner F, Jeannot D. Make arc erosion and welding tendency under 42 VDC in automotive area. 49th IEEE Holm Conference on Electrical Contacts 2003: 158–162.
5. Kharin S, Sarsengeldin M. Influence of contact materials on phenomena in a short electrical arc. Key Engineering Materials 2012; 1: 321–329, https://doi.org/10.4028/www.scientific.net/KEM.510-511.321.
6. Kolimas S. Analysis of the making arcing time during current switching. Przegląd Elektrotechniczny 2004; 84:72–74.
7. Ksiazkiewicz A, Janiszewski J, Batura R. Influence of short-circuit ac currents on electrical contact resistance of low voltage relays. Poznan University of Technology Academic Journals. Electrical Engineering 2012; 70: 99-103.
8. Leung C, Streicher E. Material transfer in dynamic welding of ag and ag/sno2 contact material. 48th IEEE Holm Conference on Electrical Contacts 2002: 21–28.
9. McBride J. An experimental investigation of contact bounce in medium duty contacts. IEEE Transactions on Components, Hybrids, and Manufacturing Technology 1991; 14(2):319–326, https://doi.org/10.1109/33.87312.
10. McBride J W. Electrical contact bounce in medium duty contacts. 34th IEEE Holm Conference on Electrical Contacts 1988: 141–149, https://doi.org/10.1109/HOLM.1988.16110.
11. McBride J, W Sharkh S M. Electrical contact phenomena during impact. IEEE Transactions on Components, Hybrids, and Manufacturing Technology 1992; 15(2):184–192, https://doi.org/10.1109/33.142893.
12. Morin L, Jemaa N B, and Jeannot D. Make arc erosion and welding in the automotive area. IEEE Transactions on Components and Packaging Technologies 2000; 23(2): 240–246, https://doi.org/10.1109/6144.846760.
13. Neuhaus A, Rieder W, Hammerschmidt M. Influence of electrical and mechanical parameters on contact welding in low power switches. IEEE Transactions on Components and Packaging Technologies 2004; 27(1): 4–11, https://doi.org/10.1109/TCAPT.2004.825777.
14. Pons F, Cherkaoui M. An electrical arc erosion model valid for high current: Vaporization and splash erosion. 54th IEEE Holm Conference on Electrical Contacts 2008: 9–14, https://doi.org/10.1109/HOLM.2008.ECP.15.
15. Rieder W, Neuhaus A. Contact welding influenced by anode arc and cathode arc, respectively. Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts 2004: 378–381, https://doi.org/10.1109/HOLM.2004.1353144.
16. Rieder W F, Neuhaus A R. Short arc modes determining both contact welding and material transfer. Short arc modes determining both contact welding and material transfer 2007; 30(1): 9–14.
17. Walczuk W, Borkowski P, Ksiarek S, Missol W, Rdzawski Z, Durst K. Evaluation of basic electrical parameters of silver-based contact materials of different chemical composition and manufacturing technology. 56th IEEE Holm Conference on Electrical Contacts 2010: 134–141, https://doi.org/10.1109/HOLM.2010.5619550.
18. Wang Z, Huang Z, Wang J, Shang S, Zhai G, The failure mechanism of electromagnetic relay in accelerated storage degradation testing.

IEEE Holm Conference on Electrical Contacts 2017: 164–168, https://doi.org/10.1109/HOLM.2017.8088080.
19. Wang Z, Shang S, Wang J, Huang Z, Sai F. Accelerated storage degradation testing and failure mechanisms of aerospace electromagnetic relay. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2017; 19(4): 530–541, https://doi.org/10.17531/ein.2017.4.6.
20. Zhenbiao L, Lichun C, Jiyan Z. The metallurgical research on contact surface deterioration of agni, agw, agfe, agcu contact materials. 41st IEEE Holm Conference on Electrical Contacts 1995: 346– 349, https://doi.org/10.1109/HOLM.1995.482890.

Andrzej KSIAZKIEWICZ
Jerzy JANISZEWSKI
Poznan University of Technology
5 M. Sklodowska-Curie Square
60-965 Poznan, Poland

e-mail: andrzej.ksiazkiewicz@put.poznan.pl,
jerzy.janiszewski@put.poznan.pl