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THE INFLUENCE OF THE MICROSTRUCTURE ON THE SWITCHING PROPERTIES OF Ag-C, Ag-WC-C AND Ag-W-C CONTACT MATERIALS

WPŁYW MIKROSTRUKTURY NA WŁAŚCIWOŚCI ŁĄCZENIOWE KOMPOZYTOWYCH MATERIAŁÓW STYKOWYCH Ag-C, Ag-WC-C I Ag-W-C

The correlation between the microstructure of Ag-C, Ag-WC-C and AgWC composites and their switching properties was investigated. Two methods were used to manufacture the starting powder mixtures, namely classical milling and mechanical alloying . The arc erosion, contact resistance and welding forces of the contact materials obtained by different methods were measured using model devices. This paper presents the results achieved for the tested materials. It was found that weight loss was lower for the contacts produced by high energy milling.

Keywords: electrical contacts, microstructure, switching properties, mechanical alloying

W pracy badano wpływ mikrostruktury kompozytów Ag-C oraz Ag-WC-C i Ag-W-C na ich właściwości łączeniowe. Do wytworzenia kompozytów stosowano dwa sposoby przygotowania mieszanin wyjściowych: klasyczne mieszanie proszków oraz mechaniczną syntezę (MA – mechanical alloying). Porównano odporność kompozytowych materiałów stykowych wykonanych różnymi technologiami na erozję łukową, rezystancje zestykową i odporność na sczepianie. Badania właściwości łączeniowych prowadzono w układach modelowych. Stwierdzono, że zastosowanie procesu MA do przygotowania mieszanin wyjściowych powoduje wzrost odporności na erozję badanych materiałów.

1. Introduction

Powder metallurgy methods are applied to manufacture the majority of contact composite materials. They are used among others to produce Ag-C, Ag-Me (e.g. Ag-Ni, Ag-Fe), Ag-MeO (e.g. Ag-SnO$_2$, Ag-CdO, Ag-ZnO) contacts and Ag-refractory metals (e.g. Ag-W, Ag-WC). Above all, such techniques are selected due to there being no mutual solubility of the composite's components. Powder metallurgy methods include: preparation of the starting powders, pressing, sintering and repressing. The following parameters are selected at each stage of the technological process:
– morphology and the grain size of the starting powders,
– milling conditions for the powders,
– pressing pressure,
– temperature, time and atmosphere of sintering,
– repressing pressure.

The microstructure of a composite and, thus, its physical and electric properties depend on the type of technological operations performed during the process of the composite's manufacture and their parameters [1-4]. So far, the study of the conductive properties of the Ag-C contacts has been focused on the analysis of their dependence on the size and shape of graphite particles [5-8] and on the microstructure, which is inextricably linked with the method of the composite's manu-

facture [9, 10]. Moreover, research on the application of different allotropes of carbon to Ag-C composites has also been conducted [11, 12].

As has been already mentioned, to obtain a good quality microstructure, it is crucial to select and prepare the starting powders in an adequate manner and to mix them properly [13, 14]. Classical milling (CM) performed in ball mills is the method most often used in the process of the manufacture of composites. For some time now, mechanical alloying (MA) in high-energy mills has been more and more often applied. In the available paper databases [15, 16] one can find few works on using the MA technique to manufacture the contact composite materials and little information on the correlation between the parameters of the MA process and the conductive properties of the contacts. In [17], the authors presented the relationship between the manner of mixing and the homogeneity of the microstructure of WC-Ag40 wt% composites and their conclusion was that the most homogeneous microstructure was obtained when powders were mixed in a planetary mill. Peng et al. [11] examined the properties of the Ag-C5 wt% composites with different allotropes of carbon, using the powder mixtures obtained in the MA process. Due to the application of high-energy milling to the manufacture of both Ag-C3.3 and Ag-C4 composites [9], a significant improvement in the resistance of the composites to tack welding was made.

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Mechanical alloying is a relatively new method of obtaining composite powders. In the case of this process, the mixture of powders is poured into a high-energy ball mill, inside of which the process of powder particle crushing caused by the moving balls takes place. The kinetic energy in rotary motion is transmitted to the powder through the milling balls. A few characteristic stages, like powder grinding, flaking, cold welding, plastic distortion of the particles etc, can be observed in the MA process [18-20]. As a result of mechanical interactions, namely friction force and high pressure between the powder particles and the balls, mechanical alloying appears, which is schematically presented in Fig. 1. In Fig. 2 an image of a realistic Ag-C composite grain is shown. MA process is conducted in solid-phase material systems, which provides an unusual opportunity for obtaining composite powders, changing the phase composition and achieving high dispersion of components. This is attainable due to a wide range of possibilities related to changing the parameters of the high-energy milling process, among which the most crucial ones include:

- high rotational milling speed, which depending on a device reaches approximately 800 revolutions per minute,
- ball to powder ratio (bpr) reaching 220:1 in some cases,
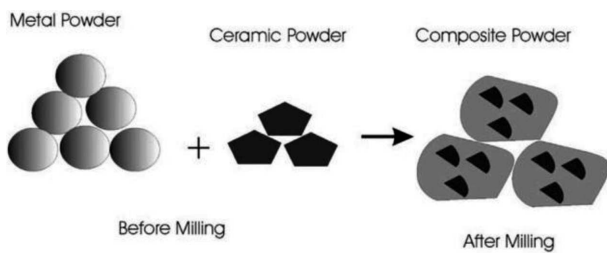- milling time (t).

Fig. 1. Diagram illustrating the formation of a composite grain in the process of mechanical alloying [20]

Silver-carbon composite contacts, usually containing 2-5 wt% of carbon (9-20 vol.%), are frequently used in low-voltage connectors. Ag-C composites are characterized by high welding proof and stable, relatively low contact resistance. Their disadvantages include low arc erosion resistance and low arc mobility. Due to the fact that silver and carbon do not dissolve each other, powder metallurgy methods are used to manufacture composites. Moreover, both silver and tungsten as well as silver and tungsten carbide do not show mutual solubility and, therefore, powder metallurgy methods are also applied in the case of Ag-WC and Ag-W composites (sometimes using the saturation method [1, 2] – the choice of the method depends on the material's chemical composition). In these composites, either tungsten or tungsten carbide forms a low-melting phase, whereas silver ensures good electrical and thermal conductivity. Ag-WC and Ag-W contacts (also with the addition of carbon) are characterized by high arc erosion resistance and relatively low and stable contact resistance. Low welding proof belongs to their drawbacks [2, 22]. Owing to their properties, these contacts are used in high-current air connectors at low and medium voltages.
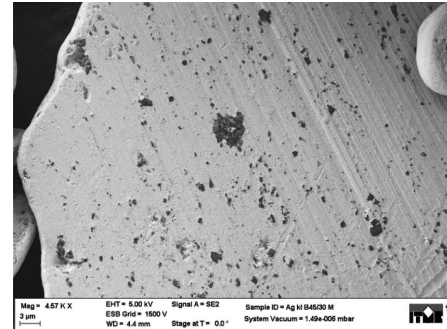

Fig. 2. Ag-C composite powder obtained by high-energy milling (the light phase – Ag, the dark phase – C) [21]

The erosion resistance, contact resistance and welding proof results for Ag-C, Ag-WC-C and Ag-W-C composites have been presented in this paper. The contacts were prepared by powder metallurgy methods, using mixtures obtained in the CM and MA processes.

2. Experimental procedure

Two types of composites were analysed, namely: Ag-C composites (Ag-C3 wt%) and Ag – refractory metals (Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5). The composites were produced applying powder metallurgy methods in a sequence of the following steps: pressing-sintering-repressing. The starting powders were mixed in a ball mill (classical milling) and in a Pulverisette 6 planetary ball mill (high-energy milling). Chemical composition of the composites and their physical properties are presented in Table 1. Powders no. 1-4 were mixed in a steel container using steel milling balls which were 5 mm in diameter; rpm=200, bpr=2:1, t=4 h.

TABLE 1

The properties of tested Ag-C contact materials

No.	Material	Allotrope of carbon	Milling	[%] theoretical density	Hardness HV10
1.	Ag-C3	graphite	Classical (CM)	98	63.6
2.	Ag-C3	graphite	high energy (MA)	98	64.4
3.	Ag-C3	vitreous carbon	Classical (CM)	97	69.9
4.	Ag-C3	vitreous carbon	high energy (MA)	98	70.8
5.	Ag70-WC29.5-C0.5	graphite	Classical (CM)	95	87.6
6.	Ag70-WC29.5-C0.5	graphite	high energy (MA)	96	91.6
7.	Ag70-W29.5-C0.5	graphite	Classical (CM)	99.8	95.8
8.	Ag70-W29.5-C0.5	graphite	high energy (MA)	99.7	95.8

*the content of elements in wt%

Powders no. 5-8 were mixed in a container made of tungsten carbide using tungsten milling balls which were 10 mm in diameter; rpm=200, bpr=1:1, t=4 h. SEM images of the microstructure of the obtained composites are shown in Fig. 3.
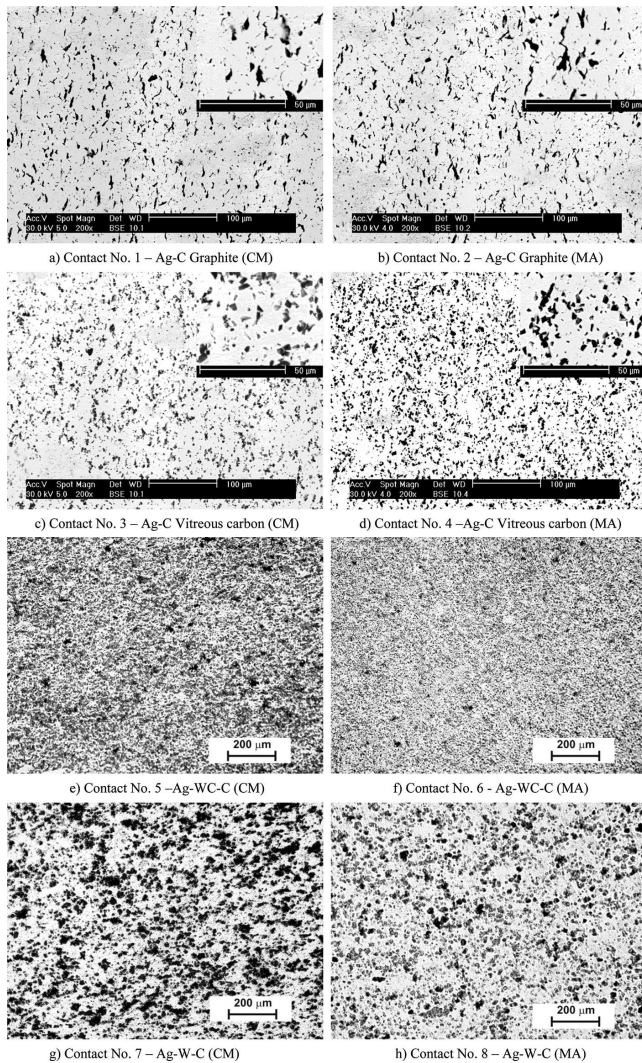

a) Contact No. 1 – Ag-C Graphite (CM)

b) Contact No. 2 – Ag-C Graphite (MA)

c) Contact No. 3 – Ag-C Vitreous carbon (CM)

d) Contact No. 4 – Ag-C Vitreous carbon (MA)

e) Contact No. 5 – Ag-WC-C (CM)

f) Contact No. 6 - Ag-WC-C (MA)

g) Contact No. 7 – Ag-W-C (CM)

h) Contact No. 8 – Ag-W-C (MA)

Fig. 3. Microstructures of the tested contact tips

2.1. Arc erosion tests

Arc erosion tests were conducted using a computer-controlled testing system under model conditions. The testing device is a model single-pole circuit breaker in which the contacts to be tested are mounted symmetrically in a vertical configuration. The lower contact is movable and the mechanical parameters of the contact system are adjustable. A simplified block diagram of the testing system is shown in Fig. 4.

The system high-current circuit is supplied from a 6 kV/250 V, 500 kVA transformer. The high-current circuit consists of a contactor C, a load resistor R, a thyristor switch TS, a measurement shunt S and the contacts to be tested. The testing device TD comprises a pneumatic drive closing the tested contacts, a ball-type lock and a quick-action tripping device ETCBD supplied from a capacitor bank. The thyristor switch limits the flow of current through the tested contacts to one half-cycle of 50 Hz current. The contacts are opened at a phase angle preset with the use of a control device TSC. After the separation of the contacts, their movement is accelerated. At the moment of arc extinguishing, the contact gap is equal to approximately 4 mm. No transverse magnetic blow-out switch is used.

The measurement system consists of an input measurment device ID, a controlling device CD, a digital voltmeter V, a digital balance B and a personal computer PC with a measurement card MC. Contact resistance is measured using the technical method (measurement of voltage across the contacts) at a 5 A current supplied by a direct current source DC.
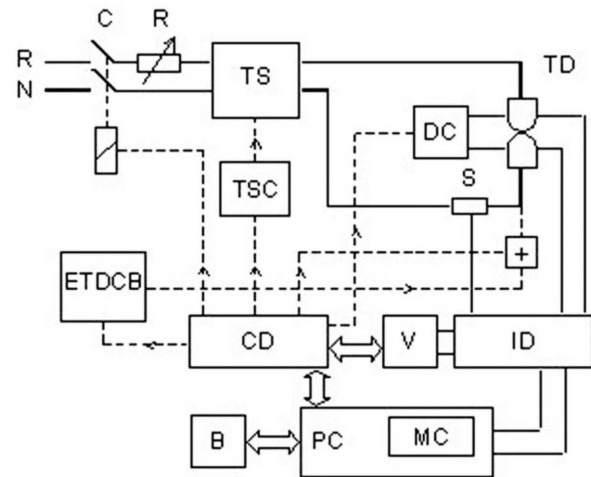

Fig. 4. A block diagram of the computer-controlled testing system

The electronic devices of the system are only an interface between the testing device and the computer. All controlled objects are accessible to the software, which allows automatic testing conducted according to a preset measurement sequence [23]. The system records arc current and voltage across the tested contacts. These records provide a basis for the determination of time-related curves, the value of integral $\int idt$, arc energy, etc. Contact resistance is measured after each switching operation.

The Ag-C contacts (diameter-7.5 mm, high-2 mm) and Ag-WC-C, Ag-W-C contacts (diameter-11 mm, high-2 mm) were investigated. The test parameters are given in Table 2.

TABLE 2

Contact test conditions

Test parameter	Unit	Value	
		Ag-C	Ag-WC-C Ag-W-C
MECHANICAL PARAMETERS			
Contact diameter	mm	7.5	11
Contact gap	mm	8	8
Contact tilt	mm	2	2
Contact force	N	50	50
Opening spring force	N	50	50
ELECTRICAL PARAMETERS			
Current (peak value)	kA	4	6
Integral $\int idt$	As	23	34
Contact opening phase angle	deg	30	30
Polarity of contacts :			
– upper contact		anode (+)	anode (+)
– lower contact		cathode (−)	cathode (−)
Number of switching operations		8 – 40	13 – 200

2.1.1. Results

Arc erosion

Total anode and cathode mass loss is a parameter crucial to the evaluation of arc erosion resistance of the contacts in alternating current connectors. Diagrams presenting results of anode and cathode mass loss measurements and total mass loss for both electrodes appear in Fig. 5 and 6. The data were obtained for an equivalent number of switching operations.

Arc erosion studies showed that regardless of the composite's type, the erosion characteristics $\Delta m = f(N)$ appear similar and weight loss is directly proportional to the number of switching operations. The cathode and anode consumption is practically identical, with the exception of the Ag-C composite containing graphite.

The conducted studies for composites prepared by MA show a reduction of mass loss of the contacts (Δm_{A+K}): by about 13% for Ag-C composites (Fig. 5) and above 30% in the case of the Ag-refractory contacts (Fig. 6).
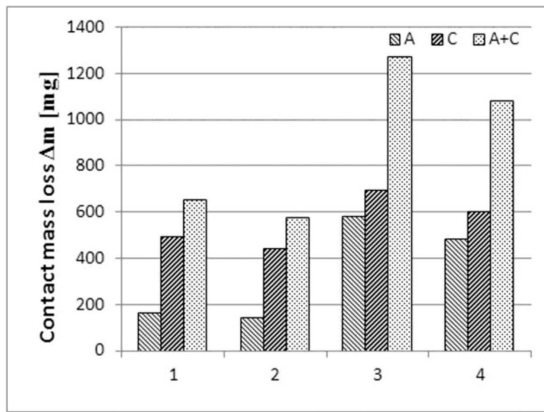

Fig. 5. Results of arc erosion tests at 4 kA current ($\int idt = 3$ As), N=6: 1 – Ag-C3 graphite (CM), 2 – Ag-C3 graphite (MA), 3 – Ag-C3 vitreous carbon (CM), 4 – Ag-C3 vitreous carbon (MA)
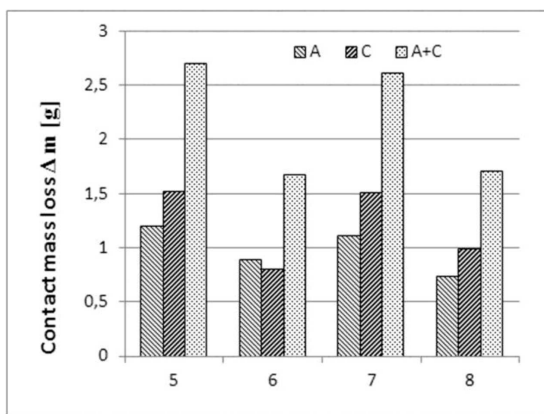

Fig. 6. Results of arc erosion tests at 6 kA current ($\int idt = 34$ As), N=10: 5 – Ag70-WC29.5-C0.5 (CM), 6 – Ag70-WC29.5-C0.5 (MA), 7 – Ag70-W29.5-C0.5 (CM), 8 – Ag70-W29.5-C0.5 (MA)

Contact resistance

It is desirable that the contact material should have low contact resistance which remains stable during its operation. The research of contact resistance have been made at the Department of Electric Apparatus of Lodz University of Technology on automated meter circuit for 4 kA or 6 kA electrical current. These measurements made for various composite materials evidence that the first or one of the first values of measured resistance is usually the lowest. This stems from the fact, that there are no oxides on the starting surface of the contacts. The value of contact resistance is raised with the increase in the number of switch offs and the results of the measurements are inconsistent. The value of current intensity exerts a profound influence on both medium and maximal values of contact resistance. Usually, at a lower current even a tenfold increase in resistance as compared with the starting value is observed. Such results of measurements were recorded for Ag-C3, Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5 composites, irrespective of the nature of the starting powder mixture.

The contact resistance measurements carried out at a switching duty cycle proved that using mechanical alloying reduced the average value of R_C contact resistance in the case of AgC3 (Fig. 7), Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5 (Fig.8) composites. For Ag-refractory metal contacts, the maximal value of contact resistance was also lower.
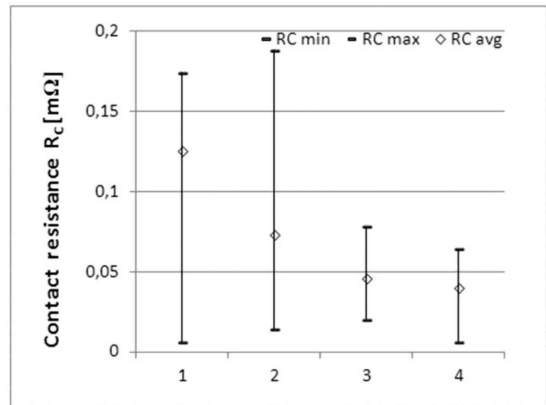

Fig. 7. Results of contact resistance measurements at 4 kA: 1 – Ag-C3 graphite (CM), 2 – Ag-C3 graphite (CM), 3 – Ag-C3 graphite (MA), 4 – Ag-C3 vitreous carbon (CM)
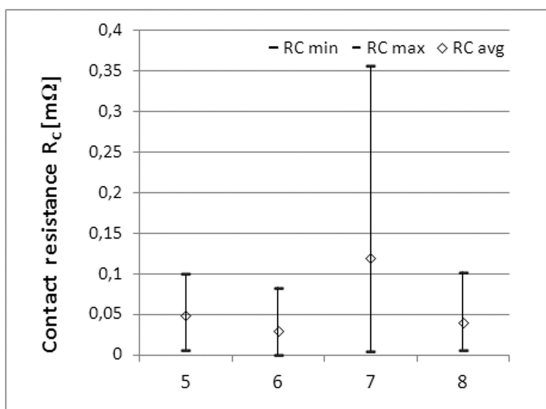

Fig. 8. Results of contact resistance measurements at 6 kA: 5 – Ag70-WC29.5-C0.5 (MA), 6 – Ag70-WC29.5-C0.5 (CM), 7 – Ag70W29.5C0.5 (MA), 8 – Ag70-W29.5-C0.5 (CM)

3. Contact welding tests

Tests of static contact welding were conducted with the use of a computerized testing stand (Fig. 9). The stand consists

of a testing device (TC – tested contacts, AP – a contact opening mechanism), a heavy-current circuit (PS – a heavy-current disconnecting switch, TS – a thyristor switch, R – a resistor) with a heavy-current transformer (T – 80 kVA, 230 V), a control system (CD) and measuring circuits (S – a measuring shunt). The computer measuring and controlling system comprises a personal computer with a universal measuring card of PCL-818 type, a controlling device, an electronic input module (ID) and an amplifier (A) connected to a piezoelectric force sensor.
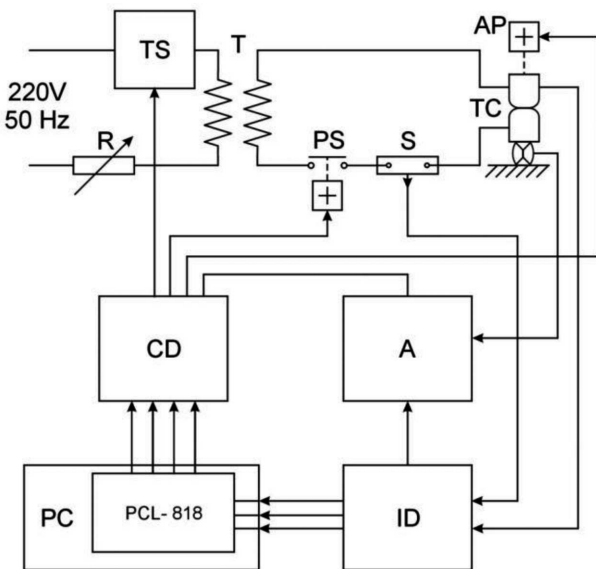

Fig. 9. The block scheme of the stand for testing static contact welding

The system operates in a programmed, automatic measuring cycle that consists of test current flow repeated in cycles and welding force measurement. During the measurement, the course of current and contact voltage, as well as contact separation force are measured. Simultaneously, characteristic quantities are determined: current amplitude, maximum contact voltage, contact force and welding force. The courses and values are recorded on the computer screen (PC) and then in computer memory [24].

The following testing procedure was accepted: for each contact material 10 measuring series were conducted, each consisting of 20 automatically performed tests. In total, 200 measurements were performed. Before each series of measurements, the tested contacts were cleaned and polished with abrasive paper, first 250 grain and then 600 grain. The welding test parameters are given in Table 3.

TABLE 3

Welding test parameters

Test parameter	Unit	Value	
		Ag-C	Ag-WC-C Ag-W-C
Contact tip pressure	N	50	50
Test current (amplitude)	kA	4 and 6	6 and 8
Test voltage	V	48	48
Current impulse duration (50Hz)	ms	10	10
Contact diameter	mm	7.5	11
Surface curvature radius	mm	$\geqslant 50$ mm	$\geqslant 50$ mm
Contact force	N	30	50

3.1. Results

Apart from having high arc erosion resistance as well as low and stable contact resistance related to it, the contact material ought to show high welding resistance. The contact tips tend to weld during the switching operations, which represents a serious threat to electric elements working in the same circuits. The welding is particularly dangerous in the event of short-circuits in electrical circuits.

The results of the average and maximal welding force measurements, obtained under test conditions given in TABLE 3 and presented in Fig. 10 and 11 indicate, that all analyzed contacts have high welding resistance.

Electrical measurements suggest that the application of the MA technology to the manufacture of contact tips decreased the average value of the tack welding force as well as both average and maximal contact voltage for the composite containing glassy carbon. In the case of the composite containing graphite, the maximal welding force (F_{Wmax}) was higher than for the contacts obtained by the classical method. The maximal welding force values did not exceed 50 N (Fig. 10).

A similar effect was observed for Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5 contacts: the maximal welding forces were slightly higher for the contacts obtained using the MA method; however, the values did not exceed 80 N, which equals 1.6 of the value of the contact's clamping force used in the drives of compact switches. In such cases the propulsion mechanism of low-voltage switches makes it possible to separate the welded contact easily. Moreover, in the case of the Ag70-WC29.5-C0.5 composite, the mechanical alloying process decreased the maximal voltage value on the contact (Fig. 11).
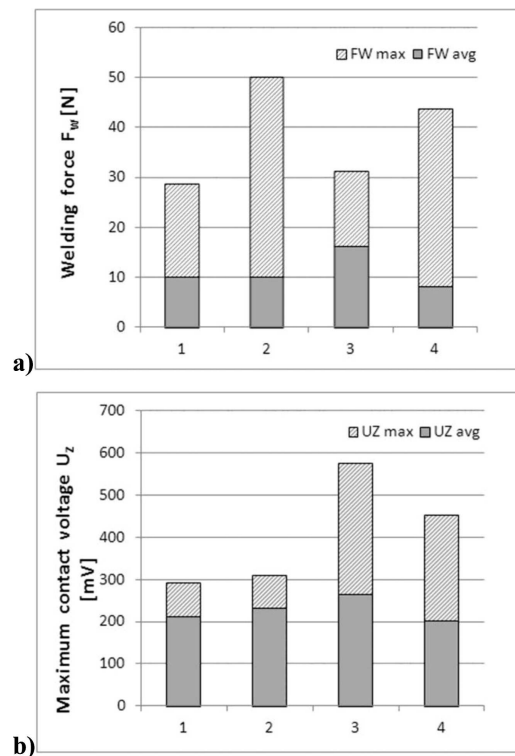

Fig. 10. The results of welding force (a) and contact voltage (b) measurements at 4 kA current: 1 – Ag-C3 graphite (CM), 2 – Ag-C3 graphite (MA), 3 – Ag-C3 vitreous carbon (CM), 4 – Ag-C3 vitreous carbon (MA)
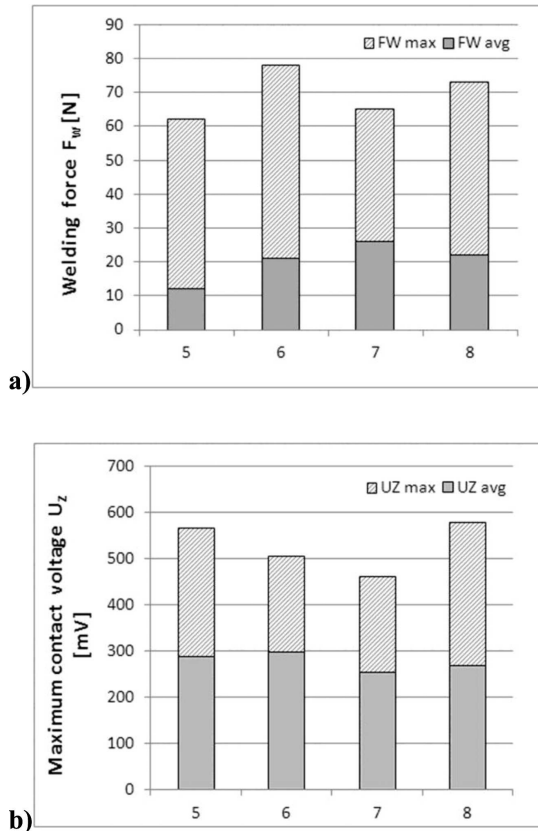
a)

b)

Fig. 11. The results of welding force (a) and contact voltage (b) measurements for the contact specimens at 6 kA current: 5 – Ag70-WC29.5-C0.5 (CM), 6 – Ag70-WC29.5-C0.5 (MA), 7 – Ag70-W29.5-C0.5 (CM), 8 – Ag70-W29.5-C0.5 (MA)

4. Discussion

The switching properties of electrical contacts are inextricably linked with the microstructure of a composite. In the majority of cases, it is desirable that the microstructure should be fine-grained and homogeneous, with a uniform dispersion of components. High density, near to the theoretical density, no closed pores and internal discontinuities are required. Obtaining a homogeneous fine-grained microstructure depends on as early stages as the selection of powders and their mixing.

The fine-grained structure of the contact material is fundamental to their conductive properties. While the current passes through the contacts, they heat up. When the heat wave transfers through any interface of the composite phases, a partial reflection appears and the heat wave dissipates in the contact tip. This effect necessitates a change in the direction of heat transfer into the material, as a result of which an increase in temperature is observed only in the case of the subsurface layer of the contacts. In consequence, weight loss due to the electric arc's switch off (related, among others, to the material's evaporation from the surface) is much lower than if the total volume of the contact was heated up. That is why, the lower the weight loss of the contact, the smaller its erosion.

Ag-C composites are characterized by high erosion, which is related, inter alia, to non-wettability on the Ag/C interface and the presence of micro-pores on the interface. Finer graphite particles with a large specific surface hinder

sintering of the Ag matrix. The application of the MA process changes conditions for the manufacture of the contact material – powder mixtures are replaced by a composite powders.

The study of Ag-C3, Ag70-WC29.5-C0.5 and Ag70-W29.5C-0.5 contacts demonstrated that the manufacturing method does not influence their physical properties. Only a slight increase in hardness is observed in the majority of cases (see Table 1). On the other hand, the analysis of the microstructure of the composites shows higher homogeneity of the components and their better dispersion. It is particularly evident for Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5 composites (Fig. 3.e-h).

Using different methods of starting mixtures preparation had a strong influence on the conductive properties of the examined contacts. It is clearly observable that the arc erosion resistance of the contacts was raised. In the case of the Ag-C3 contacts weight loss was decreased by a dozen percent and in the case of Ag70-WC29.5-C0.5 and Ag70-W29.5-C0.5 contacts by more than 30%. It is worth noting that increasing the arc erosion resistance of the Ag-C contacts is a fundamentally important issue, which has been investigated for years by the producers of contacts.

Mechanical alloying as a method for producing a mixture of the starting powders brings positive effects since one obtains a composite with higher and more homogenous dispersion of components and increased particle fragmentation. It should be stressed that for the purpose of this paper only one set of parameters was applied to the high-energy milling process in order to obtain the mixtures.

5. Conclusions

The manner in which the starting powder mixtures are prepared has a significant impact on the final microstructure of a composite. The application of high-energy milling to the production of the starting powder mixtures enables obtaining composites characterized by raised particle fragmentation and higher dispersion. This structural effect is reflected in the increased arc erosion resistance, decreased contact resistance and increased welding resistance, which was also observed in [9]. The advantages of applying the MA process in the case of the examined contacts included higher resistance of the composites to arc erosion and decreased weight loss in the case of Ag − refractory metal composites (even by 30%). Moreover, by using MA in some instances it is attainable to lower contact resistance, resistance to tack welding and contact voltage.

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