Development and Investigation of Tungsten Copper Sintered Parts for Using in Medium and High Voltage Switching Devices

M V Lungu, M Lucaci, V Tsakiris, A Brătulescu, C D Cîrstea, M Marin, D Pătroi, S Mitrea, V Marinescu, F Grigore, D Tălpeanu, N Stancu, P Godeanu and C Melnic

1 Advanced Materials Department, National Institute for Research and Development in Electrical Engineering ICPE-CA (INCDIE ICPE-CA), 313 Splaiul Unirii Street, 030138 Bucharest, Romania
2 MAIRA MONTAJ SRL, 166 Stirbei Voda Street, 010121 Bucharest, Romania

E-mail: magdalena.lungu@icpe-ca.ro

Abstract. Tungsten-copper (W–Cu) sintered parts with 75 wt.% W, 24 wt.% Cu and 1 wt.% Ni for using as arcing contacts in medium and high voltage switching devices were developed successfully by powder metallurgy (PM) techniques. Sintered parts with diameter of 50±0.5 mm and height of 6±0.5 mm were manufactured by pressing–sintering–infiltration (P–S–I) and spark plasma sintering (SPS) at sintering temperature of 1150°C, and 1050°C, respectively. Physical, chemical, electrical, thermal and mechanical properties of the samples were investigated. Microstructure was analyzed by optical microscopy and scanning electron microscopy. Material properties were influenced by the consolidation processes. The best results were achieved by SPS process. The relative density was more than 95%, Vickers hardness HV1/15 was over 227, elastic modulus was over 143 GPa, and homogeneous microstructure was revealed. These good properties can contribute to higher lifetime of arcing contacts under severe working conditions.

1. Introduction
W–Cu materials are of a major interest for thermal–electrical applications like electrical contacts used in low voltage (LV), medium voltage (MV) and high voltage (HV) switching devices working in vacuum, sulfur hexafluoride (SF6) gas or oil [1-14].

Protecting and controlling the transmission networks and the distribution systems of electric power for industrial and public consumption require technically reliable switching devices such as circuit breakers (CBs) with long service life.

A CB suffers arcing contacts wear during normal operation, as well as when breaking short–circuit currents. During arcing in the switching chamber, arcing contacts are exposed to high mechanical and thermal stresses. Mechanical wear and lubrication of electrical contacts often affect the performance of the CBs. That is why there is a continuous need to be developed high performance electrical contacts.

W–Cu materials are commonly used for arcing contacts in SF6 gas or oil CBs for MV and HV applications [5-14]. Functional properties of W–Cu materials are influenced by their microstructure and physical, electrical, thermal and mechanical properties. These properties are influenced in turn by W and Cu content and their particle size and shape, as well as by obtaining methods for W–Cu
composite powder mixtures and their processing techniques. The final electrical contact pieces are manufactured at the desired compositions, sizes and various simple geometrical shapes or complex non-geometrical shapes depending on their applications. Proprietary methods for manufacture W–Cu materials vary significantly among producers, leading to different properties of the contact materials.

W–Cu materials are heterogeneous compounds made of a refractory component (W) and a soft, malleable and ductile component (Cu). W–Cu composites are considered as pseudo-alloys and advanced engineering materials due to their specific physical, electrical, thermal and mechanical properties. W–Cu powder mixtures are produced by various methods, from which the common methods are mechanical mixing, mechanical alloying and high energy ball milling of elemental powders in dry or wet conditions [2-14].

W–Cu composites with a W content of over 50 wt.%, balance being Cu are manufactured by liquid phase sintering of a pressed W–Cu powder mixture or by pressing–sintering–infiltration (P–S–I) that implies molten Cu infiltration into single pressed and sintered W or W–Cu skeleton with low Cu content [5,8-15]. The porous skeleton is filled up with liquid Cu through capillary force since Cu acts as a filling agent of pores [15]. Amounts of up to 1 wt.% of additives can be used in W–Cu composites to improve the sinterability. Sintering additives are chosen from transition metals (Ni, Fe, Co, Zn, Ag, a.o.) having the role of wetting agents between W and Cu particles [2,8,11-15].

It is known that it is very difficult to achieve full densification through the above mentioned techniques due to the absence or negligible solubility between W and Cu under the equilibrium condition. High sintering temperatures or long holding times help to improve the densification but Cu may leach out from the skeleton which leads to Cu segregation and results in non-homogeneous microstructure and poor product performance [7,8]. Therefore it is necessary the achievement of new W–Cu composites by alternative techniques than conventional ones like spark plasma sintering (SPS) to minimize microstructure coarsening and to improve homogeneity of contact materials [2,3,16-19]. By SPS process, consolidation of powders is performed rapidly with uniaxial force, high heating/cooling rates and a pulsed (on-off) direct electrical current [18,19].

In this study we present the research results on the development and investigation of W–Cu contact materials with 75 wt.% W, 24 wt.% Cu and 1 wt.% Ni for using as arcing contacts in MV and HV switching devices. The W–Cu composites were manufactured in form of large size sintered parts with diameter of 50±0.5 mm and height of 6±0.5 mm by P–S–I and SPS techniques. The sintered parts were mechanically processed to achieve final products in form of protection rings with non-geometrical shapes. The obtained results recommend using of the realized sintered parts in practical applications as protection rings in MV and HV circuit breakers.

2. Experimental

2.1. Materials

As elemental powders we used W powder (purity of 99.95%, Fisher diameter of 4.37 µm, Scott density of 4.22 g/cm³, tap density of 7.57 g/cm³, Eurotungstene Metal Powder, France), electrolytic Cu powder (purity of 99.9%, particle size up to 63 µm, apparent density of 1.6 g/cm³, GGP Metalpowder AG, Germany) and Ni powder (purity of 99.9%, average particle size of 5 µm, Merck, Germany).

2.2. Methods for manufacture of W–Cu sintered pieces

W–Cu powder mixtures with 75 wt.% W, 24 wt.% Cu and 1 wt.% Ni were prepared by mechanical homogenization for 8 h of the starting powders weighted in the desired amounts using a Turbula mixer and 5 mm stainless steel balls to powder ratio of 1:1.

The W–Cu sintered parts were manufactured in cylindrical shape and large size with diameter of 50±0.5 mm and height of 6±0.5 mm by PM techniques like P–S–I and SPS.

The sintered parts obtained by P–S–I technique were manufactured in a protective hydrogen and nitrogen atmosphere in two sintering steps. W skeletons containing Ni additive were compacted with a hydraulic press (Meyer, Switzerland) and sintered at 950°C for 30 min in a conveyor belt furnace.
(Safed, Switzerland) to form a porous network. After that the skeletons were densified by infiltration with molten Cu for 30 min at a temperature of 1150°C that is above the melting point of Cu (1083°C).

The SPS–ed parts were manufactured in vacuum by processing of W–Cu powder mixtures in graphite molds using a SPS installation of HP D25 type (FCT Systeme GmbH, Germany) equipped with a power source supplying DC pulses. The pressing pressure of the W–Cu powder mixtures increased linearly from 2.5 MPa to 50 MPa being maintained at 50 MPa for 30 min at sintering temperature of 1050°C with heating/cooling rate of 100°C/min.

2.3. Characterization of W–Cu sintered parts

The investigation of physical, electrical and mechanical properties of the samples was carried out at room temperature (RT) on as obtained parts with diameter of 50±0.5 mm and height of 6±0.5 mm. For microstructure analysis and measurements of thermal properties, small size samples with diameter of 12.65±0.5 mm and height of 3±0.1 mm were cut from the core of the initial large parts.

The microstructure was analyzed by optical microscopy (OM) and scanning electron microscopy (SEM) using Carl Zeiss (Germany) optical microscope and an Auriga CrossBeam workstation equipped with backscattered electron (BSE) detector and energy dispersive X-ray spectroscopy (EDS) detector used for compositional (elemental) analysis. Previously the samples were put in resin, polished with fine alumina slurry and etched with Murakami’s solution for 15 s.

The density was determined at 16°C by Archimedes’ principle, in ethyl alcohol with density of 0.7928 g/cm³, using an analytical balance (Kern AEJ, Switzerland) equipped with a set for density determination of liquids and solids. The measurements were carried out in triplicate, and their mean values are presented. Relative density was determined as percentage of the theoretical density (TD) of the W–Cu–Ni 75–24–1 composite (14,977 g/cm³).

The electrical conductivity, \( \sigma \) (mΩ·mm⁻¹) was determined at 22°C with the phase-sensitive eddy current method using a conductivimeter of EX8 type (Sigmascope, Germany). Three readings were performed on both flat circular surfaces of the samples and their mean values are presented. The electrical resistivity, \( \rho \) (μΩ·cm) was computed as the inverse of the electrical conductivity. The resulted resistivity values were converted to electrical conductivity (σ) in percentages of International Annealing Copper Standard (% IACS) with the equation (1) [10]:

\[
\sigma = 172.41/\rho 
\]

The thermal diffusivity and specific heat of the W–Cu small size samples were measured at 25°C by “flash” method using a LFA 447 NanoFlash apparatus (Netzsch, Germany) and a reference of Inconel 600 having specific heat at 25°C of 0.444 J/(g·K). Previously the samples were coated by spraying on all the surfaces with a thin film of graphite. A xenon lamp was used as radiation energy, and the irradiation time on the front surface of each sample was 0.18 ms. Temperature increase on the back surface of the sample was measured with an infrared (IR) detector of InSb type cooled with liquid nitrogen. The samples were measured three times and their mean values are presented.

The thermal diffusivity, \( \alpha \) (mm²/s) was calculated with the equation (2) [20], where \( l \) (mm) is sample thickness and \( t_{1/2} \) (s) is the half-rise time:

\[
\alpha = 0.1388 \cdot l^2/t_{1/2} 
\]

The specific heat of the W–Cu samples, \( C_p \) (J/(g·K)) was determined from the equation (3) [20], where \( Q \) (J) is absorbed energy, \( m \) (g) is mass and \( \Delta T \) (K) is change in temperature, \( G \) is detector amplifier gain that is a constant equal to 50020, \( AV \) (V) is output voltage of the IR detector:

\[
C_{p\text{sample}} = \frac{Q_{\text{sample}}}{(m \cdot \Delta T)_{\text{sample}}} = \frac{(m \cdot C_p \cdot \Delta T)_{\text{reference}}}{(m \cdot \Delta T)_{\text{sample}}} = \frac{(m \cdot C_p \cdot \Delta V)_{\text{reference}} \cdot G_{\text{sample}}}{(m \cdot \Delta V)_{\text{sample}} \cdot G_{\text{reference}}} 
\]
The thermal conductivity, $\lambda$ (W/(m·K)) of the W–Cu samples was computed with the equation (4) [20], where $\alpha$ (m$^2$/s) is thermal diffusivity, $C_p$ (J/(kg·K)) is specific heat and $d$ (kg/m$^3$) is density:

$$\lambda = \alpha \cdot C_p \cdot d$$

(4)

The mechanical properties were determined at RT by instrumented indentation technique using an Open Compact Platform (CSM Instruments, Switzerland) equipped with Micro Hardness Tester (MHT) and Vickers diamond indenter. The measurements were performed by microindentation with linear loading from 0.01 N to 10 N, holding time of 15 s at $F_{max}$, where approach speed of the indenter was 4 µm/min, loading/unloading rate was 20 N/min and duration of loading from contact to $F_{max}$ and unloading from holding time end to last contact point was 30 s. Ten measurements were performed on both flat circular surfaces of the samples and their mean values are presented. The indentation imprints were visualized by optical microscopy using 50X objective attached to the Open Compact Platform.

The values of the mechanical properties were calculated by the power law method (Oliver & Pharr) [21] shown in the equation (5) to describe the upper part of the unloading data, where $F_{max}$ (N) is the maximum force, $h$ (µm) is the indentation depth under applied test force, $h_p$ (µm) is the remnant depth, $h_{max}$ (µm) is the maximum depth at $F_{max}$ and $m$ is a constant ranging 1.15…1.3 that depends of indenter shape. The values of $m$ and $h_p$ were determined by a least squares fitting procedure.

$$F = F_{max} \cdot [(h-h_p)/(h_{max}-h_p)]^m$$

(5)

The contact stiffness, $S$ (N/µm) at $F_{max}$ was calculated from the equation (6) [21]:

$$S = (\frac{dF}{dh})_{h=h_{max}} = m \cdot F_{max} \cdot (h_{max}-h_p)^{-1}$$

(6)

The contact depth of the indenter, $h_c$ (µm) with the sample at $F_{max}$ was determined from the equation (7), where $\varepsilon$ is the geometric constant ranging 0.77…0.81 that depends on indenter shape:

$$h_c = h_{max} - \varepsilon \cdot F_{max}/S$$

(7)

The projected contact area, $A_p$ (µm$^2$) was determined from a fit method based on the equation (8), where $C_0$ and $C_1$ are constants determined on fused silica reference:

$$A_p = C_0 \cdot h_c^2 + C_1 \cdot h_c$$

(8)

The indentation hardness, $H_{IT}$ (N/mm$^2$) was determined from the equation (9) [21]:

$$H_{IT} = \frac{F_{max}}{A_p}$$

(9)

The Vickers hardness $HV_{IT}$ was determined from the equation (10) [21], where $F_{max}$ (N) is the maximum force, and $A_c$ (µm$^2$) is the developed contact area:

$$HV_{IT} = \frac{F_{max}/(9.81 \cdot A_c)}{10.58}$$

(10)

The reduced modulus, $E_r$ (GPa) of the indentation contact was calculated from the equation (11) [21], where $\beta$ is the geometric factor ($\beta = 1.012$ for Vickers indenter):

$$E_r = (\pi/A_p)^{1/2} \cdot S/(2 \cdot \beta)$$

(11)
The plane strain modulus, \( E^* \) (GPa) was calculated from the equation (12) [21], where \( E_r \) is the reduced modulus, \( E_i \) is the elastic modulus of the indenter (\( E_i = 1141 \) GPa for diamond) and \( \nu_i \) is the Poisson’s ratio of the indenter (\( \nu_i = 0.07 \) for diamond):

\[
E^* = \frac{1}{E_r - (1 - \nu_i^2)/E_i}^{-1}
\] (12)

The indentation modulus, \( E_{IT} \) (GPa) that represents the elastic modulus of the sample was calculated from the equation (13) [21] using an estimated Poisson’s ratio of W–Cu samples (\( \nu_s \)) of 0.29:

\[
E_{IT} = E^* \cdot (1 - \nu_s^2)
\] (13)

The elastic part of the indentation work, \( \eta_{IT} \) (%) was calculated from the equation (14) [21], where \( W_{\text{total}} \) (N m) is the total mechanical work of indentation, \( W_{\text{elastic}} \) (N m) is the elastic reverse deformation work of indentation and \( W_{\text{plastic}} \) (N m) is the plastic deformation work of indentation:

\[
\eta_{IT} = \frac{W_{\text{elastic}}}{W_{\text{total}}} \cdot 100 = \frac{[W_{\text{elastic}}/(W_{\text{elastic}}+W_{\text{plastic}})] \cdot 100}{(W_{\text{elastic}}+W_{\text{plastic}})}
\] (14)

The difference between 100 % and \( \eta_{IT} \) [%] represents the plastic part of the indentation work.

The creep indentation, \( C_{IT} \) (%) was determined from the equation (15) [21], where \( h_1 \) is the indentation depth at time \( t_1 \) of reaching the test force that is kept constant and \( h_2 \) is the indentation depth at time \( t_2 \) of holding the constant test force:

\[
C_{IT} = \frac{(h_2 - h_1)}{h_1} \cdot 100
\] (15)

3. Results and discussions
OM and SEM micrographs along with EDAX results of the W–Cu–Ni 75–24–1 composites manufactured by P–S–I and SPS techniques are depicted in figure 1 to figure 6.

![Figure 1. OM image of the infiltrated composite (500X).](image1)

![Figure 2. OM image of the SPS-ed composite (500X).](image2)

Microstructure investigation revealed the finer structure in the SPS-ed composite compared to the sintered part obtained by P–S–I technique.

The microstructure appears to be dense for both W–Cu–Ni 75–24–1 composites with lower porosity in case of the SPS-ed composite. It confirms the existence of three phases corresponding to W, Cu and Ni elements.
Since these three metals can be differentiated based on contrast and their atomic number (Z) in backscattered electron (BSE) images, the heaviest element, W (Z of 74) can be identified by the bright gray colour, and the transition elements Cu (Z of 29) and Ni (Z of 28) can be noticed by the dark gray
and black colour, respectively (figure 3 and figure 4). These observations are in agreement with other reports from the literature [10], [13].

EDAX spectra (figure 5 and figure 6) confirmed also the presence of W, Cu and Ni elements although compositions of both samples differ from nominal one probably due to the lack of mutual solubility and sufficient bonding between W–Cu and W–W particles that contributed to the removal of some particles from the surface of the composites during polishing with alumina particles [17].

Physical, electrical and thermal properties (mean values) of the developed W–Cu–Ni 75–24–1 sintered parts are summarized in table 1.

| Table 1. Physical, electrical and thermal properties (mean values) of the W–Cu–Ni 75–24–1 sintered parts manufactured by P–S–I and SPS techniques. |
|---------------------------------------------------------------|
| **Composites and fabrication method** | **Density** (g/cm³) | **Relative density** (% of TD) | **Electrical conductivity** (m/Ω·mm²) | **Electrical resistivity** (µΩ·cm) | **Electrical conductivity** (% IACS) | **Thermal diffusivity** (mm²/s) | **Specific heat** (J/(g·K)) | **Thermal conductivity** (W/(m·K)) |
|-------------------------------------|---------------------|-----------------------------|---------------------------------|-------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|
| W–Cu–Ni 75–24–1 P–S–I              | 14.26               | 95.21                       | 12–14.5                         | 6.90–8.33                     | 21–25                           | 35±0.5                        | 0.197±0.002                   | 98±2                          |
| W–Cu–Ni 75–24–1 SPS                | 14.45               | 96.48                       | 14–14.5                         | 6.90–7.14                     | 24–25                           | 46±0.4                        | 0.188±0.005                   | 124±2                         |

The measurements of the densities in ethyl alcohol show that the P–S–I composite achieved a density of 14.26 g/cm³ (95.21% of TD) after infiltration of the skeleton with melted Cu. A better result (14.45 g/cm³ meaning 96.48% of TD) was obtained in case of the SPS-ed composite, indicating a higher densification of the composite. Accordingly, the SPS-ed composite showed lower porosity (3.52%) than the infiltrated composite (4.79%) and better electrical and thermal properties.

Better consolidation of the W–Cu–Ni 75–24–1 powder mixture and lower porosity of the SPS-ed composite can be explained by the mechanism of SPS. It relays on rapid consolidation of powders without significant grain grow due to very rapid heating rates under pulsed (on-off) direct electrical current that generates spark plasma, spark impact pressure, Joule heating and an electrical field diffusion effect through powder particles [18]. The granular boundaries of the initial powder particles start to partially heat up because the pulse current passes through the graphite die, leading to the occurrence of an electrical field having a plasma effect [19]. Thus a short process cycle of about an hour was achieved in our study in comparison with P–S–I process that lasts over ten times longer with supplementary costs for protective gases and energy consumption at higher sintering temperature and duration.

The variation of electrical conductivity and resistivity on both surfaces of the SPS-ed part is in a narrow range (~3.4%) indicating a good material homogeneity. On contrary, the infiltrated composite showed five time higher variation (~17.2%) in electrical properties on both surfaces. The bottom surface that contained an excess of Cu resulted after infiltration exhibited similar values for electrical properties as SPS-ed part whereas on the opposite surface electrical conductivity has smaller values due to lower Cu content. This happened since during Cu infiltration the capillary force acts on the W and Ni particles from the skeleton to pull the melted Cu between W and Ni hard particles and to fill in the pores but Cu viscosity decreases with temperature [10]. Besides capillary force there are some other forces like gravity, drag and buoyancy forces that influence sintering and infiltration process [10]. Our results are in agreement with other studies in which it was revealed that Ni addition lowers significantly electrical conductivity of W–Cu composites but contributes to the improvement of hardness [8].

The measured thermal diffusivity of the SPS-ed part (46±0.4 mm²/s) was 1.3 times greater than in case of the sample manufactured by P–S–I technique (35±0.5 mm²/s). Both values are lower than the values obtained in other reports (73.2…77.6 mm²/s) where Ni free W–Cu composite contained 22.33…26 wt.% Cu and balance W [13]. However, specific heat values obtained by “flash” method for both composites ranging 0.183…0.199 J/(g·K) conform with other reported data [13]. A possible explanation arises from the fact that specific heat of W–Cu–Ni composites can be estimated using the
mixture rule [13], [22]. Thus, the computed specific heat of W–Cu–Ni composites was defined from the equation (16) adapted from [13], [22], where w means weight fraction of each component:

\[ C_p = w_W \cdot C_p^W + w_{Cu} \cdot C_p^{Cu} + w_{Ni} \cdot C_p^{Ni} \] (16)

The computed specific heat of the W–Cu–Ni 75–24–1 composite is 0.196 J/(gK) since the specific heat at 25°C of W (\( C_p^W \)) is 0.132 J/(g·K), Cu (\( C_p^{Cu} \)) is 0.385 J/(gK) and Ni (\( C_p^{Ni} \)) is 0.444 J/(gK) [23].

Thermal conductivity of the SPS-ed composite was with 26% higher than in case of the infiltrated composite. However, the values of thermal conductivity of both developed W–Cu–Ni composites are lower than other reported values for Ni free W–Cu composites. Also, the existence of 3.52...4.79% porosity in the sintered parts may contribute to hinder the heat transfer to some extent [24].

The mean force-displacement curves for all the sintered parts on each flat circular surface, together with optical images of some residual imprints are shown in figure 7 to figure 10.

**Figure 7.** Mean force-displacement curve for W–Cu–Ni 75–24–1 SPS part (top surface). The inset represents an optical micrograph (50X) of a Vickers indentation into the sample (imprint diagonal, \( d = 87.12 \) µm, HV = 249).

**Figure 8.** Mean force-displacement curve for W–Cu–Ni 75-24-1 P-S-I part (bottom surface). The inset represents an optical micrograph (50X) of a Vickers indentation into the sample (imprint diagonal, \( d = 89.76 \) µm, HV = 235).

**Figure 9.** Mean force-displacement curve for W–Cu–Ni 75–24–1 SPS part (top surface). The inset represents an optical micrograph (50X) of a Vickers indentation into the sample (imprint diagonal, \( d = 81.53 \) µm, HV = 285).

**Figure 10.** Mean force-displacement curve for W–Cu–Ni 75-24-1 SPS part (bottom surface). The inset represents an optical micrograph (50X) of a Vickers indentation into the sample (imprint diagonal, \( d = 81.65 \) µm, HV = 284).
The samples obtained by P–S–I and SPS processes show no significant difference in imprint shape. Only the diagonal sizes of the imprints are various indicating different values for Vickers hardness. All the imprints exhibit convex edges, which suggest a rigid plastic response to indentation.

The mean results obtained by instrumented indentation with Vickers indenter and Oliver & Pharr method for the W–Cu sintered parts are presented in Table 2 and Table 3.

**Table 2.** Main mean results obtained by instrumented indentation with Vickers indenter and Oliver & Pharr method for the W–Cu sintered parts investigated on both flat circular surfaces.

| Composites and fabrication method (flat circular surface) | $H_{IT}$ (MPa) | $HV_{IT}$ (GPa) | $E'_{IT}$ (GPa) | $E_s$ (GPa) | $E_{IT}$ (GPa) | $C_{IT}$ (%) |
|----------------------------------------------------------|----------------|----------------|----------------|-----------|--------------|------------|
| W–Cu–Ni 75–24–1 (top surface)                            | 2690±109       | 254±10         | 162±5          | 142±4     | 148±5        | 2.51±0.16  |
| P–S–I                                                    | 2535±125       | 239±12         | 167±7          | 146±5     | 153±6        | 2.47±0.17  |
| W–Cu–Ni 75–24–1 (bottom surface)                         | 3255±105       | 307±10         | 193±4          | 165±2     | 176±3        | 2.58±0.15  |
| SPS (top surface)                                         | 3211±233       | 303±12         | 190±7          | 163±5     | 174±6        | 2.46±0.10  |

**Table 3.** Additional mean results obtained by instrumented indentation with Vickers indenter and Oliver & Pharr method for the W–Cu sintered parts investigated on both flat circular surfaces.

| Composites and fabrication method (flat circular surface) | $F_{max}$ (N) | $b_{max}$ (µm) | $S$ (N/µm) | $h_c$ (µm) | $h_t$ (µm) | $h_p$ (µm) | $A_p$ (µm²) | $W_{elast}$ (µJ) | $W_{plast}$ (µJ) | $\eta_{IT}$ (%) |
|----------------------------------------------------------|---------------|----------------|-----------|-----------|-----------|-----------|-----------|----------------|------------------|----------------|
| W–Cu–Ni 75–24–1 (top surface)                            | 10.04±         | 13.10±         | 9.88±     | 12.29±    | 12.08±    | 11.93±    | 3734±    | 5.32±         | 44.20±          | 10.75±         |
| W–Cu–Ni 75–24–1 (bottom surface)                         | 11.93±         | 13.42±         | 13.42±    | 10.47±    | 12.66±    | 12.47±    | 3964±    | 5.18±         | 45.94±          | 10.15±         |
| SPS (top surface)                                         | 10.07±         | 11.93±         | 11.18±    | 10.97±    | 10.78±    | 10.97±    | 3094±    | 5.97±         | 40.20±          | 12.93±         |
| SPS (bottom surface)                                      | 10.02±         | 12.00±         | 11.25±    | 10.40±    | 11.04±    | 10.85±    | 3133±    | 5.96±         | 40.36±          | 12.87±         |

Table 2 clearly shows that the indentation hardness ($H_{IT}$), Vickers hardness (HV) and elastic modulus ($E'$, $E_s$ and $E_{IT}$) depend on the consolidation process. The SPS-ed composite with a finer and more homogeneous microstructure yielded increased values compared to the composite manufactured by P–S–I technique for maximum penetration depths in the order of about 12 µm. Thus, $H_{IT}$ that is a measure of the resistance to permanent deformation or damage showed an increase of 6%...43% for the SPS-ed composite along with an increase of 10%...40% for $HV_{IT}$ hardness and an increase of 6%...26% for $E_{IT}$. The homogeneity of the SPS-ed composite was proved by the small variation between results concerning mechanical properties determined by microindentation on both surfaces of the sample.

The contact stiffness ($S$) at $F_{max}$ that corresponds graphically on the load-displacement curve to the slope of the tangent to the unloading curve yielded close values for all the samples, ranging 10.11…10.83 N/µm for the SPS-ed composite and 9.80…10.69 N/µm for the infiltrated composite.

The creep behaviour is similar for both composites that yielded $C_{IT}$ values in a narrow range, namely 2.36…2.73% for the SPS-ed composite and 2.30…2.67% for the infiltrated composite. The report between Vickers hardness ($HV_{IT}$) and elastic modulus ($E_{IT}$) was included in the range of 1.72…1.77 GPa$^{-1}$ for the SPS-ed composite and 1.54…1.73 GPa$^{-1}$ for the infiltrated composite.

The SPS-ed composite revealed better elastic behaviour in contrast to the infiltrated composite, with higher values for the elastic part of the indentation work ($\eta_{IT}$) ranging 12.62…13.15%, whereas
the infiltrated composite showed $\eta_{IT}$ values ranging 9.69–11.39%. As a result, the plastic part of the indentation work was higher for the infiltrated composite.

The enhancement of the mechanical properties of W–Cu–Ni composites due to the addition of Ni transition element and different processing techniques was reported in other studies, too [2], [24]. The very short processing time of about one hour used in SPS process was beneficial in controlling the grain growth and thus obtaining finer microstructure. Moreover, the finer microstructure of the SPS-ed composite has a positive effect in improving its mechanical properties.

The sintered parts produced by both processes had a good behaviour at mechanical processing in form of protection ring. In figure 11 it is exemplified the macrographic image of the W–Cu–Ni 75–24–1 SPS part, whereas in figure 12 it is shown the final aspect of the protection ring.

![Figure 11. Macrographic image of W–Cu–Ni 75–24–1 SPS part.](image1)

![Figure 12. Macrographic images of protection ring (left image – top surface and right image – bottom surface).](image2)

The obtained results recommend the developed W–Cu sintered parts to manufacture protection rings for use in MV and HV switching devices. However, further investigation concerning functional tests of the protection rings as arcing contacts in MV and HV circuit breakers and their certification are needed in order to introduce these products into the market.

4. Conclusions

W–Cu composites with 75 wt.% W, 24 wt.% Cu and 1 wt.% Ni for using as arcing contacts in MV and HV switching devices were developed successfully in form of sintered parts having diameter of 50±0.5 mm and height of 6±0.5 mm by P–S–I and SPS techniques.

The infiltrated composite showed a relative density of about 95%, Vickers hardness HV1/15 of 227–264, elastic modulus of 143–159 GPa, contact stiffness of 9.8–10.69 N/µm, electrical conductivity of 12–14.5 m/(Ω·m²) and thermal conductivity of 96–100 W/(m K).

After SPS processing, the W–Cu composite exhibited a relative density of about 96.5%, Vickers hardness HV1/15 of 291–317, elastic modulus of 168–180 GPa, contact stiffness of 10.11–10.83 N/µm, electrical conductivity of 14–14.5 m/(Ω·m²) and thermal conductivity of 122–126 W/m K.

The investigations showed that material properties were influenced by the consolidation processes. Preliminary results regarding mainly microstructure, density, Vickers hardness and elastic modulus were very encouraging for the sintered part achieved by SPS technique.

The sintered parts were mechanically processed to achieve final products in form of protection rings having non-geometrical shapes. The obtained results recommend using of the realized sintered parts in practical applications as protection rings in MV and HV circuit breakers.

References
[1] Wei X, Yu D, Sun Z, Yang Z, Song X and Ding B 2014 Vacuum 107 83–9
[2] Lungu M, Tsakiris V, Enescu E, Pătroi D, Marinescu V, Tălpeanu D, Pavelescu D, Dumitrescu Gh and Radulian A 2014 Acta Phys. Pol. A 125 327–330
Acknowledgments
This work was supported by a grant of the National Romanian Authority for Scientific Research and Innovation, CNCS/CCCDI – UEFISCDI, project number PN–III–P2–2.1–PED–2016–1987, contract number 118 PED/2017, within PNCDI III.