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W-Cu composite materials for electrical contacts used in vacuum contactors

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W-Cu composite materials for electrical contacts to be used in low voltage vacuum contactors were synthesized by means of powder metallurgy (P/M) and infiltration technique. The compacting pressure and sintering temperature were selected in order to achieve the desired skeleton density. Direct infiltration on green compacts of W-Cu-(Ni) was made by using different elements such as Cu and Ag. The influence of chemical composition, nature of infiltrating element and processing parameters on microstructures, and electrical, mechanical and functional properties were emphasized.

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1. Introduction

Over the last two decades, the composite materials have gained great importance and their applications have increasingly become popular due to the specific benefits gained from their different properties given by the existence of the non-identical components [1-3]. Thus, in terms of W-Cu composite materials, there is a huge demand considering the wider possibilities of their practical applications, such as: arc resistance electrodes, electrical contacts, electrodes for electrical discharging machining and heat-sink materials for high density integrated circuits, arcing tips and microwave materials, high temperature erosion resistant materials, CG (centre of gravity) adjusters, ballasts of different shapes and sizes, jet vanes, c-ray shields, deviator plates for fusion reactors etc. [1-7].

This wide range of applications is due to the outstanding properties of W–Cu composites which are a combination of low thermal expansion and high arc erosion resistance of W and high thermal and electrical conductivity of Cu, good machinability and corrosion resistance [4, 5]. There are great differences between Cu and W in melting point and density and the Cu-W system exhibits mutual insolubility or negligible solubility. Therefore, W–Cu composites cannot be produced through traditional metal-casting processes and are currently manufactured through powder metallurgy (P/M). Several manufacturing routes are used for generating the composite structure, including liquid phase sintering (LPS), infiltration technique, as well as combined infiltration and sintering processes [3, 8].

Infiltration technique is an effective method to fabricate pseudo alloys or composites such as Si/Cu, W/Cu, Cr/Cu, SiC/Al-Mg, AlN/Al-Cu, etc. [8]. Usually, the Cu-W composite materials with (10…40) wt. % Cu are fabricated by P/M process *via* infiltration, when a porous tungsten skeleton is commonly infiltrated with liquid copper. At higher copper contents, only a P/M route is used; the two powders are blended, pressed, and subsequently sintered in solid state [5, 6].

For some heavy duty applications, the density of the sintered tungsten skeleton suitable for infiltration is as high as about 80 % of theoretical density.

For its typical production route, *e.g.* a green density of 62 % of the theoretical density is obtained for a compact made from a 6.70 µm powder under 250 MPa compacting pressure [5]. Extra densification takes place during the sintering process.

Due to the large contact angle of liquid copper on tungsten, W skeleton wetting by liquid Cu is not perfect and their interface boundaries cannot achieve metallurgical bond directly [8]. Therefore, alloying process does not occur in the pressures and temperatures usually employed in the infiltration process. However, the wettability may be enhanced by the addition of small amounts of transition metals such as Ni, Co or Fe [9] which have also a positive effect on W-Cu composite densification.

In this work, the fabrication of W-Cu *via* traditional P/M method and infiltration technique was performed. The aim has been to study the effects of chemical composition and infiltrating elements, as well as the influence of processing parameters on the microstructure and, consequently, on the properties of the new W-Cu composites.

2. Experimental procedure

Commercial polygonal W powder (99.9 %, <32 µm, Fig.1), dendritic Cu powder (99.9 %, <32 µm, Fig. 2) and Ni powder (99.9 %, <32 µm) were used to prepare W-Cu-(Ni) skeletons.

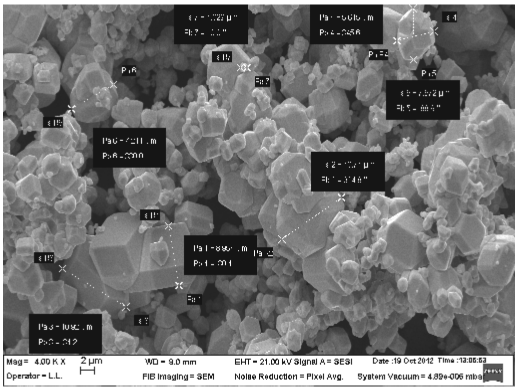

Fig.1. SEM images of initial W powders

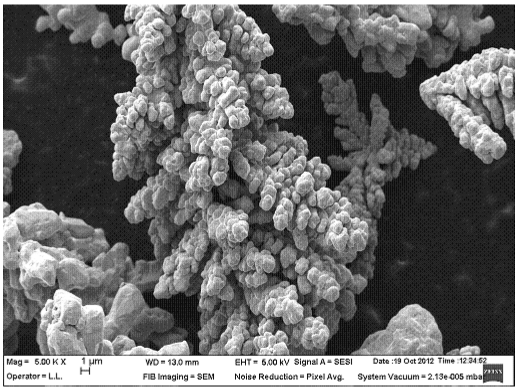

Fig.2. SEM images of initial Cu powders

The W-Cu-Ni powder mixtures containing 97wt % W, 2 wt % Cu and 1 wt % Ni were first mechanical homogenized for 8 h into a Turbula mixer with stainless steel balls (Ø= 5mm, as milling bodies); the rotation speed of the drum of 40 rpm and the ratio of powders to balls weight of 1:1. The homogenized powder mixtures were then, compacted in an automatic Meyer cold press at a pressure of (200-300) MPa to obtain compacts of Ø=17 mm and h = (4…5) mm, with a relative green density of (65…70) %. For comparison, W-Cu composite materials with 10 wt % Cu without addition of Ni were produced in the same conditions as W-Cu-Ni composites (with 1 wt % Ni addition). Pure Cu and Ag (99.90 %) sheets and CuAg50 sheets were used during infiltration. These sheets were first placed on the bottom of each green compact, and then put on graphite plates for sintering and infiltrating in a SAFED furnace, with a band speed of 7 cm/min, in nitrogen and cracked ammonia controlled atmosphere. The infiltrating process of W-Cu-(Ni) skeletons was performed at 1100 ^{o}C for infiltration with Ag and AgCu50, respectively and, at 1150^{o}C for infiltration with Cu, with a 30 dwell time.

The density of contact materials was determined at 24 ^{o}C by the immersion technique with a hydrostatic balance using ethyl alcohol as a displaceable liquid.

The electrical conductivity of the contact materials was measured at room temperature (RT) by using an eddy current conductivity meter.

The Vickers hardness RT values of the obtained electrical contacts were determined by using a micro harness tester with an impression load of 2.942 N and a dwell time of 15 s.

The metallographic analysis was performed with an optical microscope on polished and un-etched samples embedded in epoxy resin.

An important parameter in the case of vacuum contactor is the chopping current value. This value is directly linked to the overvoltage produced in the commutation process. In low voltage contactors, the chopping current value must be up to 5 A (peak value of the current is up to 50 A).

The functional tests for the chopping current measurements of the electrical contact pieces were performed on a specific stand, in an arc quenching chamber at a vacuum degree of $(2…5)\cdot 10^{-5}$ Pa. Each pair of two contact pieces was mechanically fastened on the copper supports.

3. Results and discussions

In Table 1, the physical and pressing parameters of the W-Cu-(Ni) compacted composite materials are presented. In Table 2, the chemical composition and the physical, electrical and mechanical characteristics of the W-Cu-(Ni) sintered and infiltrated composite materials are presented.

The W-Cu-Ni infiltrated green compacts pressed at different compaction pressures (200 MPa, 250 MPa and 300 MPa) had porosities between 32 % and 35 % (Table 1). For the W-Cu infiltrated compacts pressed at a specific pressure of 200 MPa, the porosity degree was around 40 %.

Comparing with the pressed state (Table 1), after sintering treatment and infiltration process of the W-Cu-(Ni) compacts by using sheets of Ag/Cu/AgCu50, the porosity degree decreased from (32...40) % for W-Cu-(Ni) composites to (3.17…4.75) % for W-Cu composites (Table 2). As reported elsewhere [9], Ni is increasing the wettability (adhesion) between W and Cu and consequently, will enhance the densification during sintering process.

The aspect of W-Cu-Ni electrical contacts to be used in vacuum contactors is presented in *Fig. 3*.

Fig.3. The aspect of the W-Cu (Ni) sintered and infiltrated electrical contacts for vacuum contactors.

Table 1. Physical and pressing parameters of the compacted composite materials.

Composite materials/ Infiltrating element	Sample code	Compaction pressure [MPa]	Green compacts parameters					
			Diameter [mm]	Height [mm]	Mass [g]	Theoretical density [g/cm^3]	Green density [g/cm^3]	Porosity [%]
W-Cu-Ni/Ag	1*, 2*, 3	250	17.04	4.91	13.86	18.60	12.38	33.44
W-Cu-Ni/Ag	4*, 5*, 6	300	17.05	4.82	13.91	18.60	12.65	32.03
W-Cu-Ni/Ag	7*, 8*, 9	200	17.05	5.03	13.91	18.60	12.12	34.87
W-Cu-Ni/Cu	1, 2*, 3*	200	17.05	4.28	11.94	18.60	12.22	34.30
W-Cu-Ni/Cu-Ag	4, 5*, 6*	200	17.05	4.27	11.95	18.60	12.26	34.09
W-Cu/Cu	7*, 8, 9*	200	17.05	4.62	11.98	17.26	11.36	39.93
W-Cu/Ag	16*,17*,18	200	17.06	4.73	11.99	17.26	11.10	40.37

*Functionally tested to determine the chopped current values

Table 2. Chemical composition and properties of the sintered and infiltrated composite materials.

Composite materials/ Infiltrating element	Sample code	Compaction pressure [MPa]	Chemical composition after sintering and infiltration process				Physical, electrical and mechanical properties				
			W [wt.%]	Cu [wt.%]	Ag [wt.%]	Ni [wt.%]	Theoretical density [g/cm^3]	Realized density [g/cm^3]	Relative density [%]	Electrical resisitivity [μΩ x cm]	Vickers hardness $HV_{0,3/15}$
W-Cu-Ni/ Ag	1*, 2*, 3	250	79.7	1.60	17.9	0.8	16.36	15.75	96.29	3.92	232.02
W-Cu-Ni/ Ag	4*, 5*, 6	300	81.0	1.60	16.6	0.8	16.51	15.73	95.28	4.18	212.78
W-Cu-Ni/ Ag	7*, 8*, 9	200	77.9	1.60	19.7	0.8	16.15	15.64	96.83	3.77	239.32
W-Cu-Ni/ Cu	1, 2*, 3*	200	81.0	18.0	-	1.0	15.80	15.05	95.25	6.15	260.90
W-Cu-Ni/ Cu-Ag	4, 5*, 6*	200	80.0	10.0	9.0	1.0	16.02	15.32	95.62	5.78	293.30
W-Cu/Cu	7*, 8, 9*	200	74.0	26.0	-	-	14.82	14.35	96.80	3.12	206.70
W-Cu/Ag	16*, 17*,18	200	73.0	8.00	19.0	-	15.40	14.85	96.44	4.34	185.96

*Functionally tested to determine the chopped current values

In Table 3, the functional properties of the sintered and infiltrated composite materials of W-Cu-(Ni) electrical contacts are presented.

In *Fig. 4…Fig. 8*, the optical microscopy (OM) images of the W-Cu-(Ni) composite materials in sintered and Ag/Cu/AgCu50 infiltrated states are presented.

Table 3. Functional properties of the sintered and infiltrated composite materials.

Composite materials/ Infiltrating element	Sampl e code	Compa ction pressur e[MPa]	Chopped current [A]
W-Cu-Ni/ Ag	1*,2*	250	3.40 ±0.26
W-Cu-Ni/ Ag	4*,5*	300	3.35±0.37
W-Cu-Ni/ Ag	7*,8*	200	3.66±0.41
W-Cu-Ni/ Cu	2*,3*	200	2.84±0.21
W-Cu-Ni/ Cu-Ag	5*,6*	200	3.48±0.19
W-Cu/Cu	7*, 9*	200	3.15±0.2
W-Cu/Ag	16*,17*	200	3.33±0.34

*Functionally tested for the chopped current values

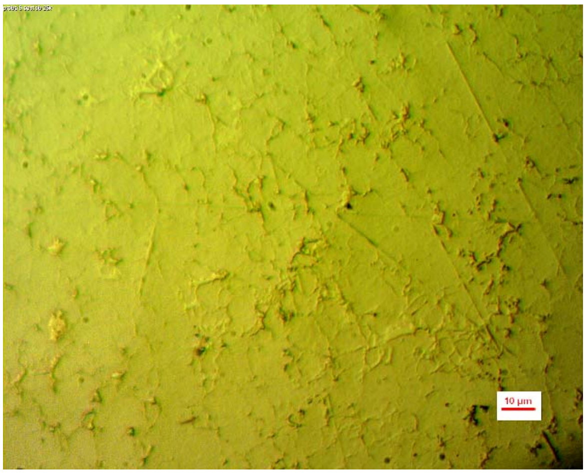

Fig.4. OM image of the W-Cu-Ni sintered and Ag infiltrated electrical contacts (cross section, un-etched state, 300 MPa).

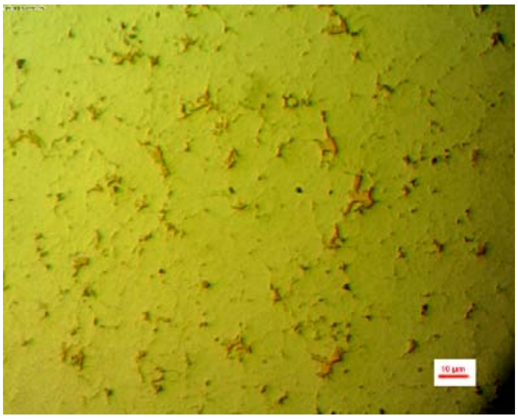

Fig.5. OM image of the W-Cu-Ni sintered and Cu infiltrated electrical contacts (cross section, un-etched state, 200 MPa).

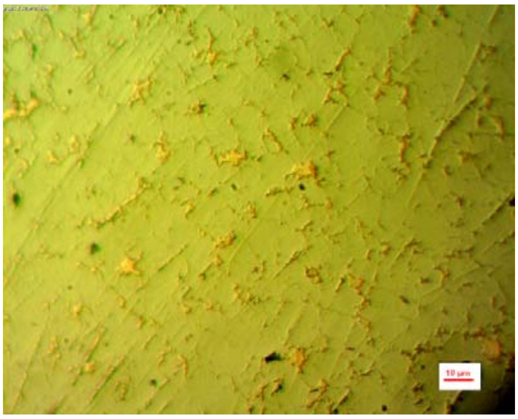

Fig.6. OM image of the W-Cu-Ni sintered and AgCu50 infiltrated electrical contacts (cross section, un-etched state, 200 MPa).

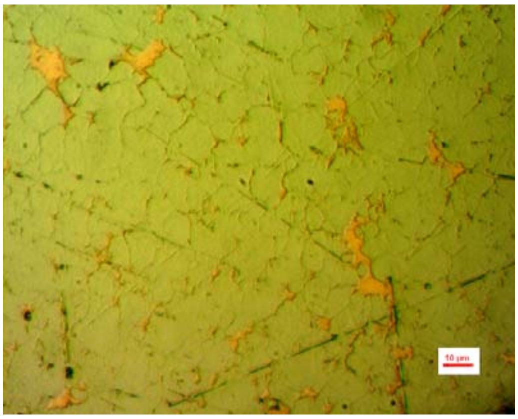

Fig.7. OM image of the W-Cu sintered and Cu infiltrated electrical contacts (cross section, un-etched state, 200 MPa).

Typically, the W-Cu/Ag composites have a microstructure which consists of a Cu/Ag network and distributed W particles. It is known that fine powders have a greater tendency to form locally agglomerates and even lumps during processing due to their small grain size. By the use of standard mixing operation of the W, Cu and Ni powders, the energy is too low to destroy these agglomerates.

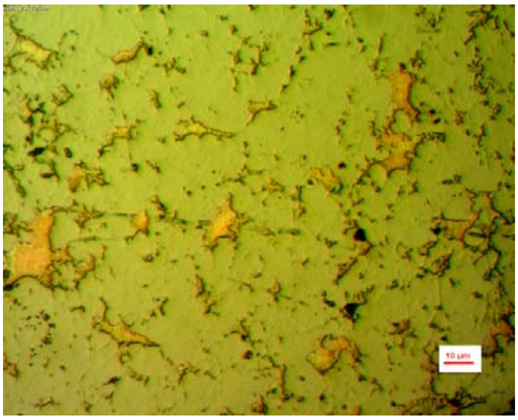

Fig.8. OM image of the W-Cu sintered and Ag infiltrated electrical contacts (cross section, un-etched state, 200 MPa).

During sintering and infiltration, the shape of the W agglomerates is unaffected. This aspect leads to local areas with higher concentration of W. In the process of sintering the agglomerates melt and the formed cavities are infiltrated by Cu/Ag. Consequently, these liquid matrix pools or W aggregates formed during sintering increase the W-W grain contact areas or contiguity, as reported in [10]. After consolidation, Cu/Ag clusters are formed, as it may be observed in all analyzed samples.

All the contact materials prepared had a good infiltration behavior. Although there are not any significant differences between the samples with and without Ni addition (between 0.8 % and 1 wt % Ni) due to the selected sintering parameters, Ni improved the infiltration process. The sintering temperature of (1100…1150) °C was lower than the melting temperature of Ni (1443°C) and as a result the wettability (adhesion) was assured by Cu/Ag alloying elements.

The contact materials without Ni in the consolidated state show an inhomogeneous microstructure with relatively large W agglomerates and Cu/Ag clusters (Fig. 7 and Fig. 8). These inhomogeneities are non-uniformly distributed over the cross section of the samples.

For all investigated samples comparable values for density and electrical resistivity were found. As it is well known, in W-Cu composite materials, the electrical conduction preferentially occurs through the Cu or Ag phase which has a higher conductivity than the W phase. A lot of factors like composition, porosity, impurity levels, W-W contiguity and microstructural parameters such as W grain size, affect the electrical and thermal conductivity [11].

In the experimented compacting pressure interval (200…300 MPa), the relative density obtained was in the range of (95.25 … 96.83) %. Therefore, the microstructural characterization showed near fully dense materials with very few closed pores (round black spots). The decrease of porosity degree and the improving on the bonding strength of the phase interface enhance the electrical performance of W-Cu materials.

The assessed values of mechanical properties in the W-Cu-(Ni) composites have been compared. As expected, the highest values for hardness (260-290 HV) were obtained for Cu and Cu-Ag infiltrated samples (Table 2) especially the ones containing Ni which has an additional effect of improving the mechanical strength.

Another important parameter in service is the arc chopping current of the W-Cu contacts. During the commutation process the quenching arc in vacuum has a peculiar behaviour. Due to the severe radial expansion of the plasma arc in vacuum, the arc column has the tendency to extinct before the natural current zero moment, producing a chopping current.

The arc chopping current will develop an overvoltage by the inductance in a circuit. The overvoltage is very disadvantageous to the electric system. Generally, the higher the vapour tensions of contact materials are, the lower the arc chopping current is [10].

The values of the chopped currents for the tested samples were included in the interval (2.84 – 3.66) A, the lowest values being obtained for the samples after Cu infiltration.

4. Conclusions

The W-Cu-(Ni) composites were successfully obtained at low compacting pressures (200-300 MPa), sintered and infiltrated at 1100-1150°C by using pure Ag, Cu and AgCu50 sheets.

The relatively low compaction pressures which do not change the initial state of the powder particles (*e.g.* morphology), lead to the obtaining of a relative green density of (65…70) % for all samples. This provides significant open channels for Cu or Ag to move into capillary opening during liquid phase sintering.

For the W-Cu-Ni composites, a homogeneous distribution of Cu or Ag throughout the matrix prevents the formation of large Cu, Ag or CuAg pool during liquid phase sintering, in which the dominant sintering mechanism is the particle rearrangement. Consequently, a uniform distribution of the alloying elements in the matrix determines the improvement of contact material homogeneity.

The lowest values for the chopped currents and, consequently, low amplitude overvoltage, were obtained for the electrical contact samples made of W-Cu-Ni and Cu infiltrated (2.84 … 0.21 A). Besides the mechanical and physical properties of the contact materials, the microstructures and homogeneity are essential for the arcing behaviour of the contacts in commutation process.

The fabricated composites with a relative density of (95…96) % showed good properties in terms of electrical, mechanical and functional properties.

High density as well as, fine and homogeneous microstructures, are the key factors to decide the properties of W-Cu composites.

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