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TRIBOLOGICAL BEHAVIOR OF ARCING CONTACT MATERIALS BASED ON COPPER INFILTRATED TUNGSTEN COMPOSITES

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Abstract: Tungsten copper composites with 70±3 wt.% W, maximum 1.5 wt.% Ni, and balance Cu were achieved as disks (diameter × height of 50×6 mm) by copper infiltration process of tungsten skeletons. Elemental analysis was assessed by WDXRF spectroscopy. Hydrostatic density was evaluated in ethanol. Vickers hardness and Young's modulus were determined in ambient air by instrumented indentation technique and Oliver&Pharr computation method. Tribological behavior was investigated under 30 N up to 400 m sliding distance and naphthenic mineral oil lubricant with a standard tribometer of ball-on-disk type. The results yielded highly dense materials with relative density over 96%, Vickers hardness (HV_{IT}) of 244…323, Young's modulus (E_{IT}) of 156…185 GPa, mean coefficient of friction of 0.11…0.22 and specific wear rate up to 8×10^{-6} $mm^3/(Nm)$. The developed composites with low coefficient of friction and high wear resistance for use as arcing contacts in oil circuit breakers will endow high performance in service.

Keywords: tungsten copper composites, coefficient of friction, wear rate, naphthenic mineral oil lubricant.

1. INTRODUCTION

Tungsten copper (W–Cu) materials are perceived as multifunctional materials because of the synergy between properties of their constitutive elements. W is a refractory metal with high density, high melting temperature, high hardness and resistance to mechanical stress, as well as very good resistance to wear, sticking or welding, and excellent resistance to metal transfer and arc erosion [1]. Cu yields outstanding thermal and electrical conductivities, high arc erosion resistance and good arcing endurance under mineral oil [2]. Properties of these composites are influenced by the content of their constitutive elements, too. When W content increase, the resistance to wear and arc erosion will increase but the thermal and electrical conductivity will reduce due to Cu content decrease. W–Cu composites have good mechanical properties and high resistance to contact wear, welding, and melting at high currents and voltages [1, 3–14]. These superior properties recommend W–Cu composites as arcing contacts in medium and high voltage circuit breakers operating at high contact pressures in SF_6 gas or mineral oil. Usually, W–Cu arcing contacts of various shapes and sizes contain 55…90 wt. % ultrafine or fine particles of W, and balance is composed of Cu and up to 1…3 wt. % sintering activator (Ni, Fe, Co, or other transition element) [3–8, 14]. Pressing, sintering, and infiltration (PSI) technique is one of the common techniques used for manufacturing W–Cu composites containing over 50 wt. % W for power switching applications. PSI technique consists in infiltration at 1100…1400 °C with molten Cu into W based skeleton that was previously pressed to certain porosity and sintered at 800…1000 °C [3–8]. Consequently, highly dense copper infiltrated tungsten composites are obtained. Even in literature many studies report on manufacture and characterization of W–Cu composites by various methods there are few information about their tribological behavior. Available studies were focused mainly on pin-on-disk testing of Cu–W composites with 5…15 wt. % W or W–Cu composites with 75…85 wt. % W in dry sliding conditions [9–12].

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Our study was focused on the tribological behavior in lubricating conditions (naphthenic mineral oil) of some copper infiltrated tungsten composites having 70±3 wt. % W, maximum 1.5 wt. % Ni, and balance Cu. Experimental data on chemical composition, hardness, friction and wear of the developed W–Cu composites revealed their suitability to be used as arcing contacts in power switching apparatuses operating in oil.

2. EXPERIMENTAL

W–Cu composites were manufactured from high purity W, Ni and Cu microcrystalline powders (average particle size of 4.4 μm for W, and 5 μm for Ni, and maximum particle size of 63 μm for Cu) acquired from Eurotungstene Metal Powder (France), Merck (Germany) and GGP Metalpowder AG (Germany). The nominal composition (in wt. %) of the samples was designed as follows: (i) 75% W, 1% Ni, and balance Cu for the first composition (C1), (ii) 75% W, 0.5% Ni, and balance Cu for the second composition (C2), (iii) and 75% W, and balance Cu for the third composition (C3). All compositions have theoretical density (TD) of 14.98 g/cm^3.

Ni doped and undoped W porous skeletons were manufactured in form of disks (diameter × height of 50×6 mm). In this aim, uniaxial pressing of elemental powder mixtures, sintering and Cu infiltration of W based skeletons under protective hydrogen and nitrogen atmosphere were performed in modified conditions described by us elsewhere [8]. After Cu excess removing by mechanical polishing, the both circular surfaces of the disk samples were finished to obtain a surface roughness with Ra of 0.10…0.16 μm and Rz of 0.7…1.4 μm.

Elemental analysis was assessed on both circular surfaces of three samples from each composition using a Bruker S8 Tiger 1 K Wavelength Dispersive X-ray Fluorescence (WDXRF) spectrometer.

Hydrostatic density was evaluated in triplicate at 23 °C in ethanol, using a Kern AEJ analytical balance, and their mean values are reported.

Electrical conductivity was measured in triplicate at 24 °C using a Sigmascope EX8 eddy current conductivity meter. Their mean values are tabulated along with calculated electrical resistivity values.

Mechanical properties of W–Cu composites with Poisson's ratio of 0.29 were measured by instrumented indentation technique (IIT) using Oliver&Pharr computation method [15]. Equipment and testing conditions are detailed in other paper published by us [8]. Mean values of ten measurements performed in ambient air at 30±2 °C and humidity of 32±3% are presented further for hardness (H_{IT}, HV_{IT}), Young's modulus (E_{IT}), contact stiffness (S), elastic and plastic behavior of indentation work and creep indentation (C_{IT}). The top surface with higher hardness that will be the contact surface of arcing contacts into operation was noted TS, and the bottom surface was noted BS.

Tribological behavior was investigated in ambient air at 30±2 °C and humidity of 32±3% with a tribometer of ball-on-disk type made by CSM Instruments (Switzerland). The tests were performed in Prista Trafo A naphthenic mineral oil lubricant, under 30 N normal load exerted constantly to the disk sample, linear speed (V_l) of 5 cm/s or 8 cm/s, track radius (R) ranging 9…18 mm, and sliding distance of 200 m or 400 m. As static partner, a 6 mm in diameter 100Cr6 steel ball (Vickers hardness HV10 of 838±21, Young's modulus of 210 GPa, Poisson's ratio of 0.3) was used in each test. Coefficient of friction (CoF) was determined during the ball-on-disk test by measuring the deflection of the tribometer elastic arm. Track profiles and worn track section were measured with a S25 contact stylus profilometer (Taylor & Hobson, UK) using a Gaussian filter, a cut-off of 0.8 and an evaluation length of 4 mm. The specific wear rate of the disk sample (W_{s-disk}) was calculated as the volume loss (V_{disk}) normalized by the applied load (P) and sliding distance (L), by using the equation (1):

$$W_{s\text{-}disk} = V_{disk}/(P \cdot L) \quad (1)$$

The specific wear rate of the 100Cr6 steel ball was calculated as the volume of the removed cap (V_{ball}), normalized by the applied load (P) and distance (L), by using the equation (2):

$$W_{s-ball} = V_{ball}/(P \cdot L) \quad (2)$$

V_{ball} was calculated with the equations (3) and (4), where R_{ball} is the ball radius, h_{cap} and d_{cap} is the height and respectively the diameter of the removed cap from the ball:

$$V_{ball} = \pi \cdot h_{cap}^2 \cdot (3R_{ball} - h_{cap})/3 \quad (3)$$

$$h_{cap} = R_{ball} - \sqrt{R_{ball}^2 - d_{cap}^2/4} \quad (4)$$

3. RESULTS AND DISCUSSIONS

Table 1 presents chemical and physical properties obtained for W–Cu composites.

Table 1. Chemical and physical properties obtained for W–Cu composites.

Sample	Chemical composition [wt. %]			Density [g/cm^3]	Relative density [% of TD]	Electrical conductivity [m/Ω·mm^2]	Electrical resistivity [μΩ·cm]
	W	Cu	Ni				
C1	66.5–72.8	26.7–32.0	0.5–1.5	14.40–14.54	96.01–97.02	14.2–16.3	6.12–7.04
C2	66.5–73.0	26.7–32.7	0.3–0.8	14.39–14.52	96.08–96.94	16.2–20.0	5.00–6.17
C3	66.5–72.5	27.5–33.5	–	14.38–14.50	96.27–97.07	24.8–28.5	3.51–4.03

The chemical composition assessed by WDXRF analysis on the surface layers with thickness between 6.4 μm and 9.1 μm confirmed the existence of W, Cu and Ni elements (Table 1). All the found compositions are different from the designed nominal compositions possibly because of lack or insignificant solubility among W and Cu constitutive elements [8]. Another reason can be related to a deficient coupling between component particles, leading to the loss of unbounded particles from the both circular surfaces of the disk samples within polishing step for eliminating Cu excess. These observations conform to other literature reports for mechanical processing of W–Cu composites developed by various techniques [8, 14]. All the composites developed in this study yielded high density ranging 14.38…14.54 g/cm^3 and low porosity of 3…4%. Electrical conductivity decreased with Ni content increase. The lowest electrical resistivity was found for Ni free composite (C3).

The mean results of the mechanical properties obtained by IIT using Oliver & Pharr computation method [15] for W–Cu composites are summarized in Table 2.

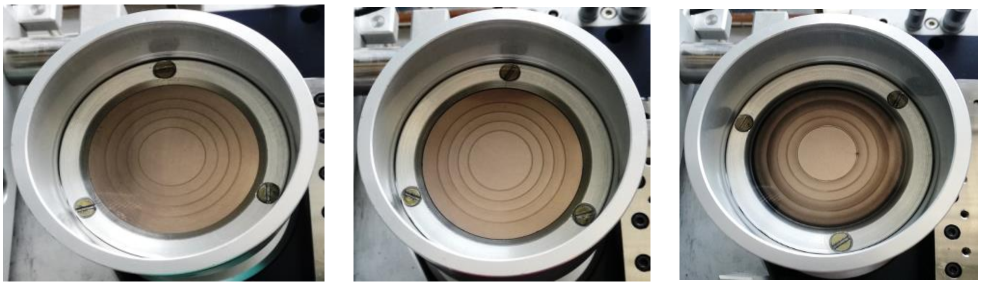
Table 2. Mechanical properties of W–Cu composites obtained by IIT using Oliver & Pharr computation method.

Sample	H_{IT} [MPa]	HV_{IT}	E_r [GPa]	E^* [GPa]	E_{IT} [GPa]	F_{max} [N]	h_{max} [μm]	S [N/μm]	W_{elast} [μJ]	W_{plast} [μJ]	η_{IT} [%]	C_{IT} [%]
C1–TS	3352± 73	316±7	171±1	201±1	184±1	10.04± 0.01	11.72± 0.11	10.71± 0.17	6.82± 0.29	37.32± 0.18	15.45± 0.63	2.25± 0.08
C1–BS	3005± 110	284±10	158±5	184±7	168±7	10.02± 0.01	12.35± 0.23	10.43± 0.16	6.40± 0.06	43.11± 1.12	12.92± 0.20	2.83± 0.07
C2–TS	3210± 81	303±8	160±4	186±5	170±4	10.05± 0.02	12.01± 0.15	10.21± 0.15	6.71± 0.20	39.14± 0.94	14.64± 0.50	2.45± 0.08
C2–BS	2930± 140	277±13	162±3	188±4	172±4	10.02± 0.01	12.48± 0.27	10.81± 0.18	6.13± 0.15	41.79± 1.14	12.80± 0.53	2.58± 0.17
C3–TS	2946± 40	278±4	170±3	148±2	156±3	10.03± 0.01	12.52± 0.05	9.85± 0.23	6.50± 0.13	41.57± 1.88	13.52± 0.30	2.83± 0.16
C3–BS	2802± 62	264±6	153 ± 2	176±3	161±3	10.02± 0.01	12.77± 0.14	10.43± 0.10	6.18± 0.13	42.88± 0.70	12.60± 0.32	3.31± 0.18

All C1 and C2 samples containing Ni have greater Vickers hardness (HV_{IT}) and higher resistance to permanent deformation or damage (H_{IT}) compared with C3 sample. These values ranging from 258 to 323 for HV_{IT} and from 2740 MPa to 3425 MPa for H_{IT} increased with Ni content increase in the series C3–BS, C3–TS, C2–BS, C2–TS, C1–BS and C1–TS. As a result, h_{max} at F_{max} decreased with hardness increase. E_r, E^* and E_{IT} values were improved with Ni addition, having the highest values for C1–TS. Higher elastic modulus for C1 and C2 samples suggests more elastic behavior than C3 sample. It was confirmed mainly on harder surfaces by both higher values of elastic energy ($W_{elastic}$) and ratio of elastic energy to total energy (η_{IT}). S values of 10…11 N/μm are usual found by IIT and Oliver &

Pharr method for bulk metallic materials. On all harder TS surfaces C_{IT} values decreased with Ni content increase. The best creep resistance yielded C1–TS. All BS surfaces exhibited more plastic behavior with lower η_{IT} values, respectively higher $W_{plastic}$ and C_{IT} values than TS surfaces since infiltration of porous skeletons with molten Cu occurred through capillary force from BS to TS surface and molten Cu acted as a filling agent of pores [7, 8]. The beneficial effect of Ni in improving infiltration efficiency and hardness of W–Cu based composites but in detriment of electrical and thermal properties can be noticed regardless of their manufacturing methods [6, 8, 13, 14].

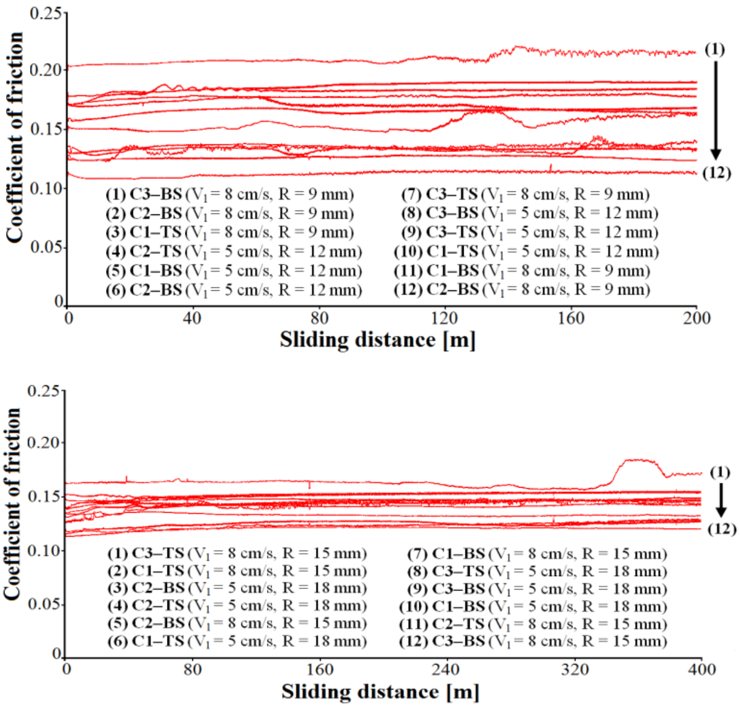
Figure 1 shows the aspect of the TS surfaces after ball-on-disk tests in naphthenic mineral oil lubricant of Prista Trafo A type with kinematic viscosity at 40°C of 9.6 mm^2/s. This kind of oil is used in circuit breakers due to very good heat transfer characteristics that reduce frictional heat generated between materials in contact, convect away heat between contact materials, and decrease thermal stresses.



a) b) c)

Figure 1. Aspect of TS surfaces of W–Cu composites: (a) C1, (b) C2, and (c) C3, after ball-on-disk tests in oil.

Figure 2 plots the variation of CoF with sliding distance for W–Cu composites, which revealed that the steady state regime in which friction is relatively constant, was reached after 40…80 m for C1 and C2 composites due to their hard nature and possibly a better cohesive strength between W, Cu and Ni particles. C3 showed a different tribological behavior with variation in CoF due to the accumulation of wear debris that cleared out after few meters but afterwards the accumulations was continued.

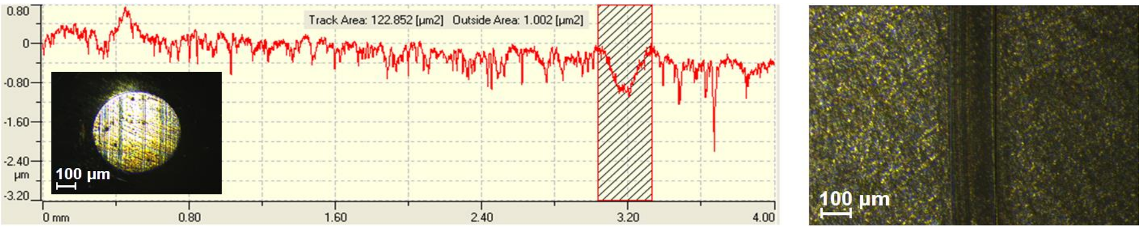


a)

b)

Figure 2. Variation of CoF with sliding distance: (a) L = 200 m, (b) L = 400 m, for W–Cu composites.

Table 3 shows tribological results for W–Cu composites and 100Cr6 steel balls, and Figure 3 depicts an example of wear track profile in Hertzian contact recorded for C1–TS surface, along with optical images of worn track width and diameter of the removed cap from the steel ball.



a) b)

Figure 3. Wear track profile recorded for C1–TS surface (P = 30 N, V_l = 5 cm/s, R = 12 mm, L = 200 m) (a), along with optical images of worn track width (b) and diameter of the removed cap from the ball (inset of (a)).

Table 3. Tribological results for W–Cu composites and 100Cr6 steel balls.

Sample	Testing conditions			Coefficient of friction (CoF)			Wear of disk sample		Wear of steel ball	
	V_l [cm/s]	R [mm]	L [m]	Minim CoF	Maxim CoF	Mean CoF	Worn track section [µm²]	$W_{s\text{–}disk}$ [mm³/(Nm)]	d_{cap} [µm]	$W_{s\text{–}ball}$ [mm³/(Nm)]
C1–TS	8	9	200	0.020	0.189	0.183±0.003	108.16	1.02×10^{-6}	442.58	10.8×10^{-8}
	5	12	200	0.128	0.179	0.134±0.002	122.85	1.54×10^{-6}	505.33	17.8×10^{-8}
	8	15	400	0.131	0.156	0.153±0.001	131.31	1.03×10^{-6}	510.30	9.27×10^{-8}
	5	18	400	0.003	0.147	0.144±0.003	133.66	1.26×10^{-6}	537.29	11.4×10^{-8}
C1–BS	8	9	200	0.020	0.129	0.127±0.001	747.68	7.05×10^{-6}	320.92	2.89×10^{-8}
	5	12	200	0.161	0.226	0.170±0.004	589.89	7.41×10^{-6}	317.00	2.76×10^{-8}
	8	15	400	0.135	0.150	0.143±0.002	701.05	5.51×10^{-6}	333.06	1.68×10^{-8}
	5	18	400	0.001	0.128	0.125±0.002	611.20	5.76×10^{-6}	375.00	2.73×10^{-8}
C2–TS	8	9	200	0.015	0.117	0.113±0.002	114.83	1.08×10^{-6}	413.46	7.98×10^{-8}
	5	12	200	0.171	0.226	0.178±0.002	132.81	1.67×10^{-6}	420.03	8.50×10^{-8}
	8	15	400	0.113	0.129	0.123±0.003	205.70	1.94×10^{-6}	457.04	5.96×10^{-8}
	5	18	400	0.001	0.150	0.147±0.002	188.89	1.78×10^{-6}	507.08	9.04×10^{-8}
C2–BS	8	9	200	0.015	0.191	0.187 ±0.004	235.57	2.22×10^{-6}	368.56	4.50×10^{-8}
	5	12	200	0.066	0.265	0.166±0.006	173.64	2.18×10^{-6}	355.64	4.37×10^{-8}
	8	15	400	0.131	0.148	0.145±0.003	203.25	1.60×10^{-6}	423.44	4.39×10^{-8}
	5	18	400	0.002	0.155	0.152 ±0.003	269.41	2.54×10^{-6}	481.01	7.32×10^{-8}
C3–TS	8	9	200	0.014	0.166	0.155±0.005	618.30	5.83×10^{-6}	368.96	5.06×10^{-8}
	5	12	200	0.123	0.167	0.134± 0.003	687.30	6.45×10^{-6}	422.12	8.67×10^{-8}
	8	15	400	0.088	0.185	0.164±0.006	386.66	3.04×10^{-6}	336.66	1.75×10^{-8}
	5	18	400	0.001	0.149	0.143±0.004	263.14	2.49×10^{-6}	422.36	4.35×10^{-8}
C3–BS	8	9	200	0.060	0.221	0.211±0.004	662.57	6.24×10^{-6}	343.18	3.79×10^{-8}
	5	12	200	0.129	0.192	0.135±0.003	693.62	7.00×10^{-6}	339.68	3.63×10^{-8}
	8	15	400	0.094	0.122	0.120±0.002	721.52	5.67×10^{-6}	283.96	0.89×10^{-8}
	5	18	400	0.001	0.136	0.133±0.002	368.11	3.47×10^{-6}	353.29	2.13×10^{-8}

Generally, CoF showed higher values for lower sliding distance and higher linear speed. On harder surfaces, maxim CoF was 0.189 for C1, 0.226 for C2, and 0.185 for C3, while on softer surfaces maxim CoF was 0.226 for C1, 0.265 for C2, and 0.221 for C3. Mean CoF varied in the range of 0.123…0.186 for C1, 0.111…0.183 for C2, and 0.122….0.215 for C3. The harder C1 and C2 composites exhibited lower weight loss than C3 composite whose worn debris were observed at visual inspection (Figure 1). The removal of material on wear tracks was caused by the hard protruding point of the 100Cr6 steel ball with hardness HV10 of 838±21 that was pressed during testing into the softer disk sample and kept into contact with a constant load of 30 N. Thus the steel ball acted as a Brinell ball indenter, who scratched and mechanically deformed the softer surface of the disk samples in combination with tangential motion, and abrasive wear occurred with visible circular wear tracks. All composites revealed irreversible plastic deformation in the surfaces due to ploughing caused by wear particles, hard particles entrapped from the environment and by hard asperities of the counterface [16]. The maximum Hertzian stress yielded values ranging 1.86…1.96 GPa for C1, 1.89…1.91 GPa for C2, and 1.82…1.87 GPa for C3. Composites with lower elastic modulus and hardness exhibited lower contact pressure, resulting in higher specific wear rate. $W_{s\text{–}disk}$ values increased in the series C1–TS, C2–TS, C2–BS, C3–TS, C3–BS and C1–BS. $W_{s\text{–}ball}$ values were higher for balls tested on TS surfaces.

These observations are in agreement with Archard's law of abrasive wear [16]. Hence, the tribological behavior of all the samples under lubricating conditions was influenced by physical, chemical and mechanical properties of materials, and by normal pressure, track radius, sliding speed and distance.

4. CONCLUSIONS

W–Cu composites having 70±3 wt.% W, maximum 1.5 wt. % Ni, and balance Cu were manufactured by copper infiltration process of tungsten skeletons as disks with diameter x height of 50×6 mm. Experimental results yielded the achievement of over 96% relative density and hardness HV1/15 of 244…323. The influence of Ni sintering activator on the properties of composites was assessed.

The ball-on-disk tests performed in naphthenic mineral oil under normal load of 30 N, linear speed of 5 cm/s or 8 cm/s and up to 400 m sliding distance revealed a mean CoF of 0.111…0.186 for composites with 0.3…1.5 wt. % Ni, and of 0.118….0.215 for Ni free composite. The differences between both circular surfaces of the samples were obvious in wear behavior. W–Cu–Ni composites exhibited lowest specific wear rate of up to 2×10^{-6} $mm^3/(Nm)$ on harder surfaces and higher wear rate of the 100Cr6 steel ball counterbody. All composites revealed irreversible plastic deformation in the surfaces due to abrasive wear and ploughing with visible circular wear tracks. These data recommend using of the developed composites as arcing contacts in power switching apparatuses operating in oil.

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