MODERN COMPOSITE MATERIALS FOR SWITCHING AND WELDING EQUIPMENT. Information 1. POWDERED COMPOSITE MATERIALS

E.V. KHOMENKO, N.I. GRECHANYUK and **V.Z. ZATOVSKY**
I.M. Frantsevich Institute of Problems of Materials Science, NASU
3 Krzhizhanovsky Str., 03142, Kiev, Ukraine. E-mail: homhelen@mail.ru

The paper presents modern developments in the field of powdered composite materials of pseudoalloy type based on Cu (Ag) and refractory metals W (Mo, Cr), used as electric contact materials and welding electrodes. Main requirements made of materials of arcing contacts and resistance welding electrodes are briefly described. Main data from world manufacturers on compositions and regulated characteristics of this material type are given, and main process schematics of their manufacturing are listed. Certain technological difficulties of producing nanodispersed composites are pointed out that slow down their production on an industrial scale. It is noted that application of mechanical alloying method during high-energy milling of powders allows producing copper, dispersion-strengthened by refractory oxides and carbides (Al_2O_3, TiO_2, Cr_2O_3, SiO_2, etc.) with recrystallization temperature close to that of copper melting and higher level of electric conductivity, strength and oxidation resistance, compared to chromium and chromium-zirconium bronzes. 41 Ref., 5 Tables, 4 Figures.

Keywords: *copper-based powdered composite materials, switching and welding equipment*

At present it is difficult to imagine an engineering field, not using composite materials. Their wide application area is due to high performance level, being greatly superior to that of metals and alloys, as well as a combination of high strength and stiffness, fatigue fracture resistance with high-temperature strength and wear resistance [1–3].

Powdered composite materials (PCM) of metal matrix type based on copper and silver, strengthened by particles of refractory metals and chemical compounds, have been the most widely accepted in switching and welding equipment. Owing to a unique combination of properties, metal-matrix CM are used as contacts and electrodes operating under the conditions of simultaneous impact of high temperatures, mechanical stresses, and impact loads in different gas media. Matrix provides a high level of heat- and electric conductivity, and refractory phase — high hardness, erosion, mechanical and thermal resistance. These systems belong to pseudoalloys, produced mostly by powder metallurgy methods. Pseudoalloy term is commonly understood as a heterogeneous system, represented by components, which do not interact or weakly interact with each other in a broad temperature range, thus preserving their individual properties in the mixture [4].

CM based on copper or silver and refractory metals of VIa group (Cr, Mo, W) have found application as arcing contacts for switching high (25 kA and higher) currents in high voltage networks (up to 570 kV) [5–8]. Arcing contacts are the most critical parts of switching devices, taking up the main impact of closing and opening electric arc [9–11]. For effective operation these contacts should have good heat- and electric conductivity, high melting and boiling temperatures, high values of electron work function and ionization potential, considerable fatigue strength and high-temperature oxidation resistance, low values of contact resistance, low solubility of gases and other properties [4, 10].

Metals with good conducting properties (Ag, Cu, Au, Pt, etc.) are characterized by low melting and recrystallization temperatures, high susceptibility to welding, low strength and low thermal stability, resulting in their quite limited application. Such refractory metals, as W, Mo, Re, Ta, Cr, etc., featuring high mechanical characteristics, have insufficient heat and electric conductivity. Fusion of low-melting and refractory metals, usually, involves technological difficulties, associated with significant differences in their physico-chemical characteristics [12, 13]. Moreover, partial dissolution of elements in liquid and solid phases occurs at fusion that may lead to loss of their individual properties [14].

Production of powdered pseudoalloys is an example of effective application of powder metallurgy method, allowing regulation of material

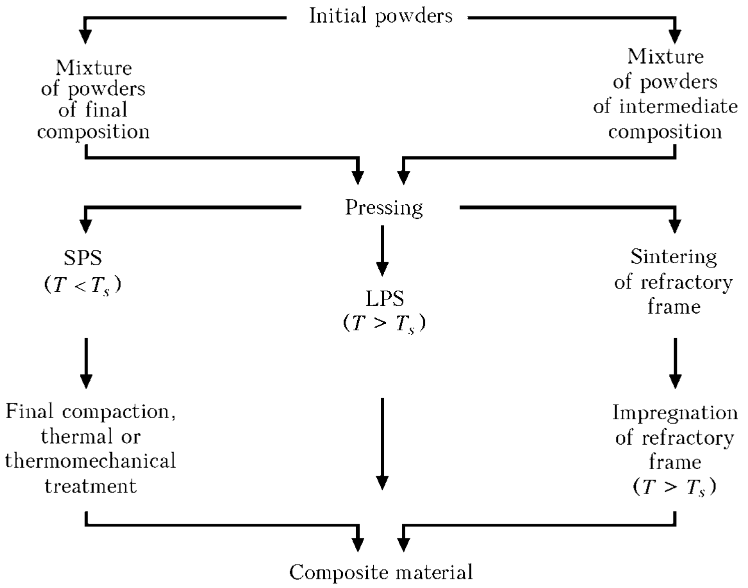

Figure 1. Technological schematic of producing Ag (Cu)–W (Mo, Cr) CM (T_s – low-melting phase melting temperature)

properties by quite cost-effective and relatively simple means, due to selection of initial raw material and technological manufacturing schematic.

Technology of producing these materials includes [1–17] the stages of powder mixing and pressing, subsequent heat treatment (sintering) and final compaction to achieve maximum density close to theoretical one (Figure 1).

Pre-compacted mechanical mixture of powders can be sintered in the solid state (SPS) or in the presence of the liquid phase (LPS).

SPS advantages consist in that composite composition is not limited by low-melting phase content. As a rule, however, maximum density cannot be achieved in one cycle, and deformational or thermodeformational treatment is required. LPS technology allows acceleration of the processes of component diffusion in the material and provides the possibility of its maximum compaction during sintering. Sintering atmosphere depends on item purpose, and, as a rule, is a reducing or degassing medium (hydrogen, vacuum). Such alloying additives as Fe, Co, Ni, Ti, Zr, etc. (up to 1–3 wt.%) are used to improve wetting of refractory phase surface by the liquid phase during LPS [4, 18, 19]. This technology limits liquid phase content (not more than 50 vol.%) to prevent item shape loss. An optimum technological measure is impregnation by melts of Al (Cu) or their alloys of refractory frame, formed with addition of low-melting component or without it (see Figure 1, on the right). This process does not require limitation of liquid phase volume, and provides the density, close to the theoretical one. Moreover, liquid phase excess at impregnation can be used as a transition conducting layer on the contact reverse surface for welding to the unit current-conducting components.

As regards CM, correlations are often found between contact performance and refinement of refractory phase particle size to micron and submicron dimensions [20–22]. In this connection, hot dynamic pressing is a promising technology of producing Ag (Cu)–W (Mo, Cr) CM, at which mechanical mixture of powders of final composition is subjected to high-speed pressing and heat treatment in vacuum in one operation. Such combined treatment provides degassing of powders, preservation of their high dispersity, formation of highly-dense material of higher strength and hardness and satisfactory level of electric conductivity [23].

In production, CM technical characteristics are usually regulated as to their composition, density, specific electric resistance and hardness (Tables 1–3). Selection of material and technological production sequence is determined by contact service conditions. All the materials are characterized by a general tendency of increase of the characteristics of hardness and erosion resistance and lowering of heat- and electric conductivity with increase of refractory phase content. Nature of refractory filler and schematic of CM manufacturing also influence the nature of its property change.

Ag–WC CM are characterized by higher hardness and lower specific electric resistance, compared to Ag–W CM in a similar concentration range of matrix content. Here, the impregnation schematic provides high-density material with high values of hardness, heat- and electric conductivity, compared to materials produced by SPS schematic with final compaction (see Ta-

Table 1. Main properties of Ag–W, Ag–WC and Ag–Mo composite materials (DODUCO materials [24])

Material	Ag content, wt.%	Density, g/cm^3	Specific electric conductivity		Hardness *HV*10
			% IACS	MSm^{-1}	
AgW 50/50 SIWODUR 50-1	48–52	13.0–13.4	45	26	120–140
AgW 40/60 SIWODUR 60-1	38–42	14.0–14.4	41	24	140–160
AgW 30/70 SIWODUR 70-1	28–32	15.0–15.4	34	20	160–190
AgW 20/80 SIWODUR 80-1	18–22	15.8–16.3	31	18	180–230
AgWC 60/40 SIWODUR C 40-1	58–62	11.6–11.9	41	24	130–160
AgWC 50/50 SIWODUR C 50-1	48–52	12.0–12.4	38	22	140–170
AgWC 40/60 SIWODUR C 60-1	38–42	12.4–12.8	36	21	150–180
AgWC 84/16C2 SIWODUR C16/C2-2	80–84	9.8	60	35	55
AgWC 73/27C3 SIWODUR C16/C3-2	68–72	9.6	36	21	50
AgMo 50/50 SILMODUR 50-1	48–52	9.9–10.2	34	20	120–140
AgMo 40/60 SILMODUR 60-1	38–42	9.9–10.2	31	18	130–170
AgMo 30/70 SILMODUR 70-1	28–32	10.0–10.4	29	17	140–180

Note. Manufacturing method is marked at the end of CM grade designation as follows: 1 — impregnation; 2 — SPS with final compaction.

ble 1). W–Cu CM are characterized by an essential improvement of strength properties at reduction of tungsten grain dimensions (see Table 2). Structure of Ag (Cu)–W (Mo,Cr) PCM is characterized by presence of two or more phases based on refractory and low-meting components with particles from submicron size up to 300–500 μm (Figure 2). Depending on requirements to the level of heat- and electric conductivity, as well as erosion resistance and mechanical wear, CM can consist of conducting phase frame with refractory particles dispersed in it, or of refractory frame, the capillaries of which are filled with low-melting phase. Simultaneous existence of two interpenetrating frames of low-melting and refractory components is also possible.

Producing CM with ultradispersed particles of refractory phase involves technological difficulties, associated with the need for powder protection from oxidation, producing a uniform distribution of components in the mixture, preservation of specified dispersity of the structure and achievement of maximum possible density [27–29]. This requires performance of preparatory

Table 2. Main properties of W–Cu composite materials (Plansee Group materials [25])

Material	Composition, wt.%		Density, g/cm^3	Electric conductivity, MSm^{-1}	Hardness *HV*30	Compression strength, MPa	Melting resistance	Grain size, μm
	W	Cu						
A15Ni	85	15	15.7	17	205	250	Excellent	Up to 50
A20Ni	80	20	15.2	18	200	200	Very good	Up to 50
A20NiF	80	20	15.2	18.5	190	240	Same	20 25
FG20	80	20	15.2	18.5	220	350	Excellent	4 8
A25NiF	75	25	14.5	21	190	160	Good	20 25
A30Ni	70	30	14.0	23	135	60	Same	Up to 50

*All CM compositions are additionally alloyed with nickel (not less than 1 wt.%).

Table 3. Main properties of Cr–Cu composite materials and qualitative evaluation of performance of arcing contacts from them (Plansee Group materials [26])

Characteristic	Material			
	CC-98	CC-75	CC-70	CC-57
Cr, wt.%	2	25	30	43
Cu, wt.%	98	75	70	57
O, wt.%	0.15	0.65	0.675	0.7
H, wt.%	0.005	0.005	0.005	0.01
N, wt.%	0.015	0.1	0.105	0.11
Density, g/cm^3	8.70	8.05	7.90	7.60
Hardness *HV*30	110 (*HB* 2.5)	70	75	85
Electric conductivity	Excellent	Excellent	Very good	Good
Melting resistance	o	Very good	Excellent	Excellent
Current interruption ability	o	Excellent	Same	Same
Interrupt current	o	Good	Very good	»
Wear resistance	o	Same	Same	»
Welding resistance	o	Very good	»	»

Note. o — CC-98 is applied as substrate for contact with vacuum chamber current-conducting parts.

technological operations, such as, for instance, refractory component cladding by interphase active elements to improve adhesion characteristics on matrix–refractory phase interphase [30], long-time high-energy milling with the purpose of mechanical alloying and producing composite pow-

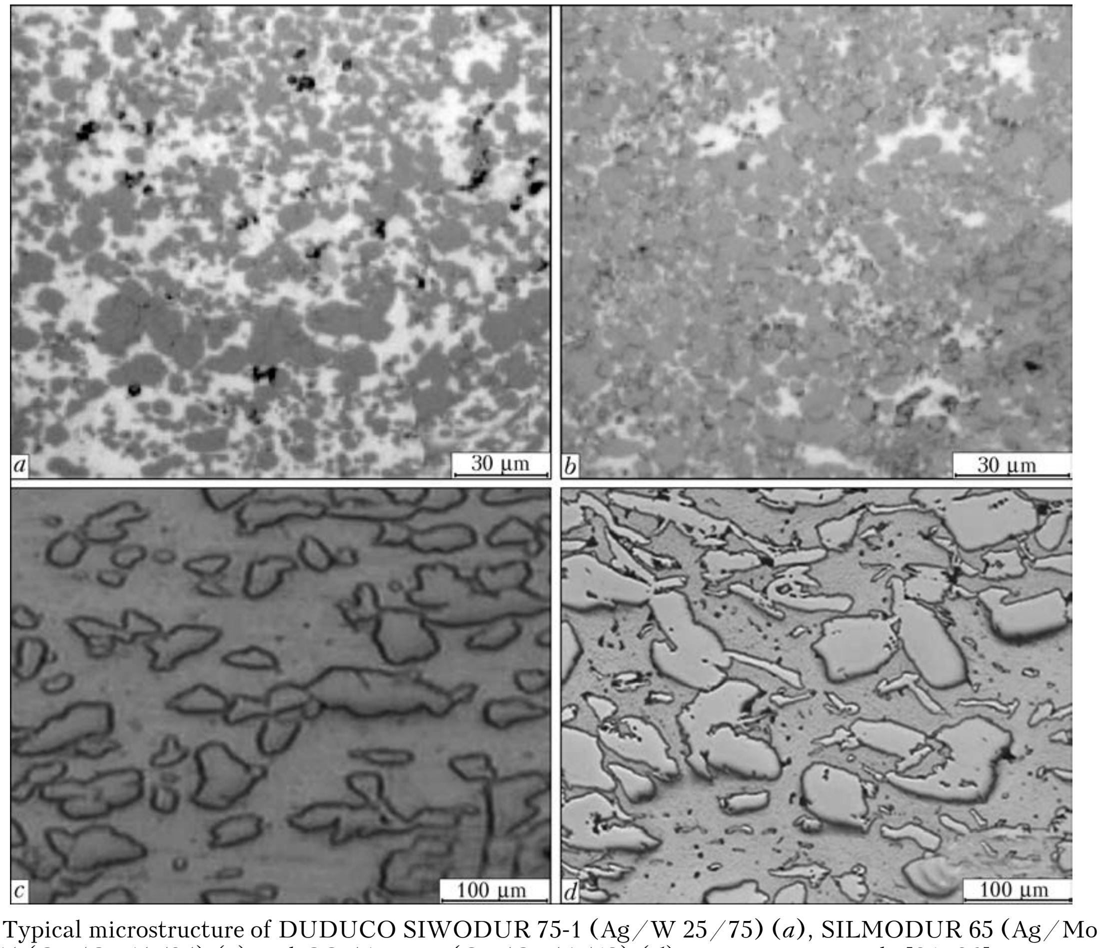

Figure 2. Typical microstructure of DUDUCO SIWODUR 75-1 (Ag/W 25/75) (*a*), SILMODUR 65 (Ag/Mo 35/65) (*b*), CC-75 (Cu/Cr 75/25) (*c*) and CC-57 HMA (Cu/Cr 57/43) (*d*) composite materials [24, 26]

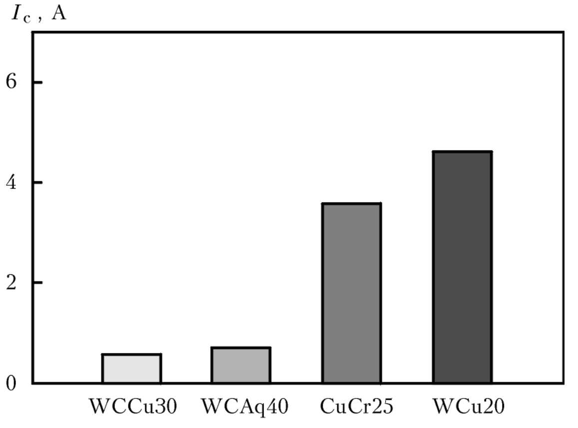

Figure 3. Cut-off current for different contact materials at testing 24 kA/24 kV vacuum contactor at maximum current of 30 A [26]

ders of intermediate composition [31], simultaneous reduction of oxygen-containing compounds of refractory and low-melting components [32].

Selection of composition for contacts also allowed for specific requirements, arising from service conditions of contact-parts. In particular, to switch-off high currents in vacuum, the material of arcing contacts should have minimum content of gas-forming impurities, in particular, oxygen, nitrogen and hydrogen (see Table 3). By changing CM composition, emission properties of the contacts can be controlled, in order to ensure current cutting-off near zero value (Figure 3).

The disadvantages of this CM class consist in that their machinability deteriorates with increase of refractory component content, and with increase of low-melting component content, the tendency to welding at short-circuiting currents becomes stronger. Moreover, the environments, in which arc extinguishing takes place, should be taken into account. So, at operation of Ag–W contact in oxygen-containing environments silver tungstates (Ag_2WO_2) form on their surface that increases the contact resistance [33]. In [34] it is shown that in the presence of weak electro-

Table 4. Technical characteristics of Elkonite composite materials of CMW Inc. (USA) [38]

Elkonite materials	Composition, wt.%	Density, g/cm^3	Specific electric conductivity		Ultimate bending strength, MPa	Hardness *HRB*
			% IACS	at 20 °C, W/(m·K)		
1W3	55W/45Cu	12.50	53	310	758	77
3W3	68W/32Cu	13.93	50	280	896	90
5W3	70W/30Cu	14.18	48	280	965	95
10W3	75W/25Cu	14.84	43	260	1030	98
10W53	75W/25Cu	14.79	28	150	1380	109
30W3	80W/20Cu	15.56	41	250	1170	103
TCS	50WC/50Cu	11.26	45	290	1100	94
TC10	56WC/44Cu	11.64	42	280	1240	100
TC20	70WC/30Cu	12.65	30	240	1380	*HRC* 37

Table 5. Technical properties of Cu-based dispersion-strengthened composite materials of Discom-Welding (Russia) [40]

Material characteristics	Material type						
	Cu–Al–C–O		Cu–Ti–C–O				Cu–Al–Ti–C–O
	C16.101	C16.106	C16.201	C16.202	C16.204	C16.205	C16.404
Density, g/cm^3	8.70	8.57	8.69	8.55	8.67	8.55	8.65
Hardness *HB* 5/750/30	185	140	159	147	218	228	193
Electric conductivity, % IACS	50	85	73	79	56	55	65
Heat conductivity, W/(m·K)	185	–	302	305	265	230	271
Ultimate compressive strength, MPa	1010	1410	1170	1040	1060	1070	955
Relative shrinkage to fracture, %	36	59	45	42	27.5	26.5	30
Ultimate tensile strength: at 20 °C	717	492	490	510	740	785	700
at 500 °C	154	–	118	128	199	233	220
Relative elongation, %: at 20 °C	8.7	15.0	17.0	10.2	8.7	6.5	10.9
at 500 °C	5.2	–	3.2	6.5	5.1	4.0	7.3
Recrystallization temperature, °C	930	870	930	880	960	970	940

magnetic fields, arising, for instance, at opening of Ag–W arcing contacts, formation of the so-called Taylor cones is observed on the tungsten surface, which increases the breakdown probability after arc re-striking. It is supposed that surface tension of liquid tungsten in an oxygen-containing environment can have a value lower by several orders of magnitude than that of tungsten in vacuum, as such experiments with other metals (Ta, Mo, Nb, Cu) in air and with tungsten in vacuum did not reveal the presence of Taylor cones. Ag–Mo CM are characterized by a more stable contact resistance in air, compared to Ag–W CM, owing to the fact that molybdenum oxides are less stable, and the effect of working layer surface self-cleaning occurs during current switching.

In welding engineering Cu-based PCM are a special material group, often used in flash-butt and resistance butt welding of mould inserts, in spot welding of ferrous metals and stainless steel, projection welding of casting moulds, etc. In the general case, welding electrodes should have high heat- and electric conductivity, good high-temperature strength, hardness and recrystallization temperature, as well as low susceptibility to mass transfer through electrode–part contact. Cold-worked copper or its alloys with additives of Cr, Cd, Ni, Be, Si, etc. (bronzes) often meet these requirements [35, 36].

However, in welding of low-deformable metals with low conductivity, different thickness, dissimilar or thick-walled materials, etc., there is a need for electrodes of higher hardness, strength and oxidation resistance in combination with relatively low electric conductivity (~75 % of copper).

Combined electrodes are often used under such conditions, consisting of electrode-insert from refractory metal (W, Mo) or CM on its base, placed into a copper base with cooling system. Such a design provides an essentially longer service life, compared to solid copper electrodes. W (WC)–Cu CM with 55 wt.% and greater content of refractory component are often used for welding electrodes. This type of CM are applied also as electrodes for electroerosive machining, and they are sometimes called by a general term of Elkonite [37, 38]. By varying the composition, it is possible to essentially increase CM strength, while preserving a high level of electric conductivity (Table 4).

A relatively new class for resistance welding electrodes are dispersion-strengthened materials based on powdered copper with dispersed in it refractory phase particles: oxides and carbides

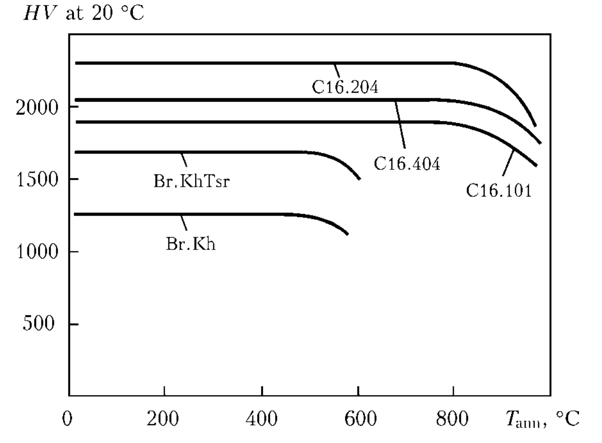

Figure 4. Change of hardness of various Cu-based materials depending on annealing temperature [40]

(Al_2O_3, TiO_2, Cr_2O_3, SiO_2, SiC, etc.) [39–41]. Application of the method of high-energy powder milling with mechanical alloying of copper by oxides enabled producing CM with a high level of strength characteristics and recrystallization temperature, close to copper melting temperature (Table 5). Thermal stability and dispersity of oxides provides higher oxidation resistance of dispersion-strengthened CM, compared to Cr- and Cr–Zr bronzes (Figure 4).

Conclusions

Powdered composite materials of metal-matrix type, based on copper with refractory filler, belong to the class of pseudoalloys and efficiently operate under the conditions of high temperatures, mechanical and electroerosive wear and impact of various media. Owing to uniqueness of their properties, these materials are used for production of arcing contacts of high-voltage switches and for manufacturing welding electrodes for resistance welding.

The main technological production schemes applying powder metallurgy methods include preliminary mixing of powders of initial components of intermediate or final composition with their subsequent sintering at temperatures below or above the melting temperature of low-meting component. Manufacture of nanodispersed CM of this class involves certain difficulties, arising from the need for protecting powders from oxidation, achieving a uniform distribution of components in the mixture, preserving the dispersed structure, and achieving maximum possible density.

A relatively new class for resistance welding electrodes are dispersion-strengthened materials based on powdered copper, containing dispersed oxides and carbides (Al_2O_3, TiO_2, Cr_2O_3, SiO_2, SiC, etc.), with increased level of strength and oxidation resistance.

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