Synthesis of W-Cu composite nanoparticles by the electrical explosion of two wires and their consolidation by spark plasma sintering

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Abstract
This research shows the possibility of obtaining composite W-Cu nanoparticles with the core–shell structure and high content of copper by means of electrical explosion of intertwined W and Cu wires. The use of electric pulse plasma sintering on the obtained W-Cu composite nanoparticles in vacuum in the temperature range 900 °C–1030 °C over 10 min has allowed us to fabricate 3D materials with the relative density of 95.3%–98.9% and a conductivity that is close to the theoretical one (63.5%–64.1%IACS). Also, despite a significant content of copper, the microhardness of the 3D material was (2.68–2.7 GPa). High microhardness of the two-phase composite is attributed to its fine-grain structure. The conductivity and microhardness of the 3D W-Cu composite make it a promising material for different electrical engineering applications.

Introduction
Metal matrix composites comprised of copper and tungsten have gained much attention in terms of their perspective commercial use. The combination of the above metals allows for optimizing such composites properties as plasticity, mechanical strength, corrosion and wear resistance at high temperatures [1]. Composites based on W-Cu combine good electrical and thermal conductivity of the copper skeleton with high strength and electrical erosion resistance of tungsten, and this opens a high avenue of applications for these materials.

W-Cu composites are most widely used in manufacturing electrical contacts for high voltage electrodes of electrical discharge systems [2, 3]. However, manufacturing of these composites is a complex process as tungsten and copper are mutually insoluble in equilibrium conditions. Neither of the three Hume-Rothery rules applies to the above two elements: the structure of the Cu lattice is face-centered cubic, and W has body-centered cubic lattice, the difference between their atomic radii is 20% and the electronegativity of copper is 1.9 while that of tungsten is 2.36. The W-Cu system does not mix even in the liquid state because of a high positive enthalpy of mixing: +35.5 kJ mol⁻¹ [4].

W-Cu is traditionally manufactured by infiltrating porous tungsten matrix with copper melt or by liquid-phase sintering of the mixtures of W and Cu powders [5–8]. Infiltration is a labor-intensive two-stage process that comprises manufacturing of a porous matrix from a hard-melting metal and the subsequent introduction of liquid copper into matrix pores. Infiltration requires high temperatures (from 1200 °C to 1400 °C), and composites with homogeneous structure cannot be obtained by infiltration. Also, we cannot use infiltration to obtain composites with the copper content greater than 30 wt% [9]. Besides that, W-Cu alloys with the content of copper of up to 50 wt% are more promising materials for electrical contacts as compared to alloys with the content of copper below 30 wt% [10]. When W and Cu powders are sintered and the content of copper is high,
continuous matrix with high electrical conductivity is formed. Accordingly, the electrical conductivity and density of the alloy increases as well [11].

W-Cu alloys with high content of copper can be obtained by sintering the mixtures of powders. A drawback of this process is relatively high temperatures at which the mixed powders must be sintered to form dense structures [7]. Also, the mutual insolubility of W and Cu hinders the compaction of the material during the sintering process.

That is why liquid-phase sintering of fine composite particles of tungsten and copper is a more promising process of obtaining high-density material with fine-grain structure [12, 13]. The material obtained by sintering the W-20 wt% Cu composite powder has a higher relative density as compared to the material obtained by sintering the mixtures of tungsten and copper powders [14]. This is due to the high homogeneity of distribution of the components in the composite powder. Therefore, such sintering process results in a more even distribution of W particles in liquid Cu.

In [1, 15] the authors highlight that micron-size W particles with copper coating allow for achieving a homogeneous microstructure with a higher heat conductivity and coefficient of thermal expansion as compared to composites obtained by sintering the mixtures of W and Cu particles. The authors suggest that W-Cu particles with the core–shell structure can be considered as a material with the perfect morphology for achieving a high relative density and a homogeneous microstructure for sintered W-Cu composites. The mechanical properties (such as hardness and compressive strength) of the composites obtained from W particles coated with Cu is higher than those of the composites obtained by mechanical mixing of the components. Homogeneous distribution of Cu is a key factor for the efficient consolidation of powders comprised of tungsten and copper [16].

Significant progress in the fabrication of W-Cu composites with homogeneous copper and tungsten distribution has been achieved when using nanosize powders [17]. The size of particles in the composition is a major factor as well. The smaller the particles size, the more even the distribution of the components in the composite and the higher the composite’s thermal and mechanical characteristics are [17]. According to [18, 19], the reduction of the size of the initial composite particles to nanometer scale may lead to the formation of nanocrystalline composites. In turn, this causes further improvement of mechanical and functional properties of parts made of alloys of immiscible metals. When nanosize initial particles are used to obtain the composite it should be expected that high density of the compacted W-Cu material will be achieved at lower temperatures as compared to the process of sintering submicron-size particles.

However, the formation of composite nanoparticles based on hard-melting metals is a complex problem that has not been fully solved yet. Therefore, such synthesis methods as mechanical and mechanical–chemical alloying [20, 21], and chemical sol-gel methods [22, 23] are currently being developed.

The alloying process is based on continuous grinding of the initial materials, and various organic materials are used in the chemical synthesis processes. As a result, in the process of both alloying and chemical synthesis, the synthesized powders are contaminated, which reduces the conductivity of the sintered 3D materials [24, 25]. The sol–gel process ensures a relatively high purity and homogeneity of the obtained materials [26]. However, it includes multiple stages and consumes quite a lot of resources.

There is constant demand for new electrical engineering materials for high-voltage applications. Therefore, the creation and research of new composites based on W–Cu with high strength and electrical conductivity is a pressing problem.

In the present research, a new single-stage process of obtaining composite W-Cu nanoparticles with the core–shell structure and a high content of copper is considered. The particles are obtained by the electrical explosion of two wires of W and Cu by a pulse of electric current (i.e. the electrical explosion of conductors). The paper contains the results of the investigation of microhardness and electrical conductivity of composites obtained from the W-Cu powder by spark plasma sintering (SPS).

**Materials and methods**

The particles of the W-Cu powder have been obtained by the electrical explosion of two intertwined wires (EEIW) made of tungsten and copper. The technical details of the EEW process and a schematic of the experimental facility are provided in [27].

The energy input into the wires over the pulse of current travel time $(E(t))$ was calculated using the temporal dependencies of currents $(I(t))$ and voltages $(U(t))$ recorded using a TDS2022B oscillograph. The schematics of the current and voltage dependencies recording process are provided in [28].

The relation between the masses of metals in the powder was determined from wire dimensions. The length of both wires was 0.65 mm, the diameter of the copper wire was 0.2 mm, and the diameter of the tungsten wire was 0.14 mm. The wire sublimation energy $(E_s)$ for the said dimensions was $E_{s(Cu)} \approx 94 \ J$ and $E_{s(W)} \approx 90 \ J$. The specific
sublimation energies have been calculated in accordance with the data in [29]. The capacitive storage charge voltage \((U_s)\) was 26 kV, and the electrical capacity \((C)\) of the capacitive storage was 1.2 \(\mu\)F. The wires have been exploded in argon atmosphere at \(3 \times 10^5\) Pa.

The relation between the masses of the intertwined wires can be determined using expression (1)

\[
m_{W} \frac{m_{W}}{m_{Cu}} = \rho_{W} \frac{V_{W}}{\rho_{Cu} V_{Cu}}
\]

where \(m\) — wire mass, \(\rho\) — metal density, \(V\) — wire volume. Since we use wires of identical length in the experiments, expression (1) can be refined as follows (2)

\[
m_{W} = \frac{\rho_{W} (r_{W})^2}{\rho_{Cu} (r_{Cu})^2}
\]

where \(r\) — wire radius. Using the reference data on the density of copper and tungsten and the radii of the wires, we found that the relation between wire masses that defines the content of metals in the final powders was 51.5 wt% for W and 48.5 wt% for Cu.

Nanoparticle size distributions were obtained by the sedimentation method using a CPS DS24000 disc centrifuge (CPS Instruments, Prairieville, LA, USA). The specific surface of the powders was determined using the SORBY-M BET analyzer (by META, Russia). The average particle size \((a_s)\) was determined from the specific surface data using expression (3).

\[
a_s = \frac{6}{\rho S},
\]

where \(\rho\) — the material density (kg m\(^{-3}\)), \(S\) — specific surface (m\(^2\) g\(^{-1}\)).

The TEM data were obtained on a JEOL JEM-2100 microscope (Tokyo Boeki Ltd, Japan).

The x-ray diffraction analysis of the powder and consolidated materials was performed on a Shimadzu XRD 6000 diffractometer with CuK\(_\alpha\) radiation. The size of the areas of coherent scattering (i.e. crystallites) \((D_{co})\) was determined using the Williamson–Hall method.

The consolidation of powders obtained by the electrical explosion of two wires of tungsten and copper (hereinafter, W-48.5 wt% Cu) was performed by spark plasma sintering. The SPS 151 S facility (by Syntex, Japan) was used. The pressing pressure was 40 MPa and the temperatures ranged from 900 °C to 1020 °C; the material was exposed to sintering over 10 min and the heating rate was about 60 degrees per minute.

The density of the consolidated materials \((\rho_{c})\) was determined Archimedean method using expression (4).

\[
\frac{1}{\rho_{c}} = \frac{w_{W}}{\rho_{W}} + \frac{w_{Cu}}{\rho_{Cu}},
\]

where \(w_{W}\) and \(w_{Cu}\) is the weight content of W and Cu in the sample and \(\rho_{W}\) and \(\rho_{Cu}\) is the density of W and Cu according to the reference data.

The microstructure of consolidated samples were investigated using scanning electron microscopy (LEO EVO 50, Zeiss, Germany, Quanta 200 3D, FEI Company, USA) and energy-dispersive x-ray spectroscopy (EDS). The content of oxygen in the consolidated sample was determined with a LECO ONH836 analyzer.

The measurements of electrical conductivity were performed on cylindrical samples (diameter—14 mm, thickness—1.7–2.1 mm) using the VE-17NTs/5 instrument. The values are given in percent IACS.

**Result and discussion**

**Synthesis of the W-Cu composite nanoparticles**

Figure 1 shows temporal dependences of currents and voltages peculiar of the EETW of Cu and W. From the data analysis it is evident that the wires explode non-synchronously.

First, the copper wire explodes \((t_{exp} \sim 1.5 \mu s)\), and then, the tungsten wire \((t_{exp} \sim 1.7 \mu s)\). Wire explosions are not synchronous due to the differences in the electrical conductivity, heat capacity and metal melting/boiling temperatures. According to \(E(t)\), 173 J are input into the copper wire by the moment of explosion, and 72 J are input into the tungsten wire. These values translate into the following energy inputs: the copper wire—\(1.85 \times E_{W}\), the tungsten wire—\(0.8 \times E_{W}\). These values result in different phase states of the products of copper and tungsten wire explosions. According to \([30, 31]\), at \(E > 1.5E\), the most part of the wire explosion products expands as a mixture of clusters and gas/plasma. At \(E < E\), the most part of wire explosion products expands as droplets of liquid metal with sizes ranging from tens of nanometers to several micrometers \([30]\).
Figure 2 shows the results of the analysis of the elementary composition of powder obtained by the electrical explosion of intertwined Cu and W wires. According to the data obtained, the powder has the following elementary composition: W - 51.92 wt%, Cu - 45.38 wt%, O - 1.59 wt%, C - 1.11 wt%.

Figure 3 shows the TEM and SEM data of the particles obtained. According to the TEM data (figure 3(a)), the size of most particles is less than 100 nm. The particles have spherical shape. According to the SEM data (figures 3(b), (d)), there are minute quantities of micron-size particles in the sample. Those are tungsten particles (figure 3(d)), and their presence in the sample is due to the small amount of energy input into the tungsten wire ($E < E_s$).

Figure 3(c) shows the distribution of particles by size calculated from the dynamic light scattering data (obtained on the CPS DS24000 disc centrifuge). According to the data analysis, about 80% of particles are less than 100 nm in size.

The specific surface of the sample was 5.8 m$^2$ g$^{-1}$. We have demonstrated by the example of bimetallic Cu-Al nanoparticles that the content of metals in bimetallic nanoparticles obtained by EETW is determined by the relation between wire masses [32]. If we assume 1.062 as the relation between the mass of tungsten and the mass of copper in a single particle, we get the density equal to 12.52 g cm$^{-3}$. When we substituted this value in expression (3) we determined $a_c$ - 83 nm. This value is in a satisfactory agreement with the data provided in figure 3(c).

The analysis of W-Cu composite nanoparticles shows that they mainly have the core–shell structure where the core consists of tungsten on whose surface a shell of copper is located (figure 4).

Nanoparticles have spherical shape, which may allow for increased packing density in the case of consolidation. Also, in the powder, there are single Cu particles less than 100 nm in size (marked with an arrow in figure 4). Since copper precipitates on tungsten nanoparticles as a rather thin layer, copper nanoparticles are probably formed from the vapor created by the electrical explosion of the copper wire. Thus, two fractions are found in the W-Cu powder: a nanosize one represented by nanoparticles with the core–shell structure and
copper nanoparticles, and the micron-size one represented by tungsten particles with the size of up to 10 μm. Here, from the agreement of \(a\), with the data in figure 3(c) we can assume that the number of copper and tungsten nanoparticles in the sample is significantly lower than the number of particles with the core–shell structure.

An x-ray diffraction image of W-Cu composite nanoparticles is provided in figure 5. According to XRD, the initial composite nanoparticles only contains copper and \(\alpha\) and metastable \(\beta\) phases of tungsten in the proportion of approximately 50 wt% W and 50 wt% Cu. The average \(D_{csr}\) size for the \(\alpha\) phase of tungsten is
49 ± 5 nm; for the β phase of tungsten it is 40 ± 3 nm, and for copper it is 56 ± 6 nm. No solid solutions have been found. The formation of the β phase of tungsten is characteristic of intense cooling conditions of liquid phase particles [33]. The presence of the tungsten β phase in the sample provides an additional proof of the fact that the most part of the tungsten wire breaks up into liquid metal droplets during the electrical explosion.

Fabrication of W-Cu composites by SPS

Figure 6 shows the results of the analysis of the elementary composition of the sample obtained by the sintering of the W-Cu powder at 950 °C. According to the data obtained, this sample has the following elementary composition: W = 52.64 wt%, Cu = 44.74 wt%, O = 1.73 wt%, C = 0.89 wt%.

According to XRD (figure 7) the sintered samples in the temperature range of 900 °C - 1030 °C contain α and β phases of tungsten, copper and tungsten oxide.

According to the existing literature data, the β(W) → α(W) phase transition takes place at 520 °C [34]. Such gases as O2 and N2 have a stabilizing effect on the tungsten β phase [35]. According to these data, the presence of the β phase in our samples is most probably the result of the stabilization of the β phase by oxygen atoms, as this stabilization prevents the β(W) → α(W) transition at temperatures exceeding 520 °C.

The β phase of tungsten influences the electrical and mechanical properties of 3D materials. According to [36], two-phase tungsten samples (α + β) have higher specific electrical impedance as compared to the single-phase one (α). This is due to the higher electrical impedance of the β phase (150–300 μΩ-cm) as compared to the α-phase (5.3 μΩ-cm) [35].

The presence of the β phase in the samples influences the mechanical properties of the materials. According to [37] tungsten films with the structure based on the β phase with the thickness of up to 100 nm are harder as compared to films based on the α phase. For films with thickness over 100 nm, the hardness has close values for both phases. The compression strength of two-phase samples (α + β) is significantly lower (780 MPa) than that of samples based on the α phase (1480 MPa) [38].
The theoretical value of conductivity of W-48.5 wt%Cu calculated from the rule of mixtures is 37.5 MS m$^{-1}$ (64.68% IACS). The samples consolidated at 970, 990, 1010 and 1030 °C have the following respective conductivities: 63.5 ± 1.2, 62.0 ± 1.2, 63.5 ± 1.2 and 64.1 ± 1.2% IACS. The proximity of the values of calculated and measured conductivity demonstrates that the impact of the $\beta$ phase on the conductivity of the consolidated samples is insignificant.

Figure 8 shows the dependencies of D$_{csr}$ for Cu and $\alpha$-W, the Vickers hardness of sintered composites (Hv), and the dependence of the sample’s density after sintering ($\rho$) on the sintering temperature. It ensues from the provided data that an increase in the samples sintering temperature leads to an insignificant increase in the D$_{csr}$ of copper and it has virtually no effect on the D$_{csr}$ of tungsten. These data suggest that the samples have the thermal stability necessary for electrical engineering applications. Increasing samples sintering temperature from 900 °C to 1030 °C leads to an increase in the density from 11.27 ± 0.11 to 11.94 ± 0.12 g cm$^{-3}$ and an increase in the hardness from 2.68 ± 0.06 to 2.70 ± 0.17 GPa.

When investigating samples sintered in the temperature range of 900…1030 °C, we have not discovered any significant differences in their structures (figure 9).

The characteristic images of the samples of sintered W-Cu composite nanoparticles are provided in figure 9. The possibility of low-temperature sintering of copper nanoparticles obtained by the electrical explosion of wires is demonstrated in [39, 40]. It ensues from [41] that the sintering of copper and in bimetallic Fe-28 wt% Cu nanoparticles takes place in the temperature range from 400 to 600 °C. Based on these data we can assume that in the case of the W-Cu composite nanoparticles, the sintering process consists in the sintering of the copper component of core–shell nanoparticles with copper nanoparticles.

It ensues from figure 10 that tungsten particles are evenly distributed in the copper matrix. Meanwhile, the materials are strongly bound at the interfaces, and there are no ruptures at the boundary between tungsten and
copper. Dark and light-colored round-shaped areas in figure 10(a) correspond to copper (figure 10(b)) and tungsten (figure 10(c)).

When W-Cu composite nanoparticles are heated, the copper component is sintered, filling the interstices between tungsten particles. The pressure applied during SPS in the powder sintering process leads to the formation of a virtually non-porous structure of the composite. Due to the higher sintering temperature and greater size, tungsten particles in the composite retain their initial size (i.e. their size is the same as in the powder). The structure formed when the composite nanoparticles are sintered provides for high hardness of the samples obtained.

According to [42] and in accordance with the rule of mixtures, the upper boundary of the microhardness of the W-Cu composite can be determined by the rule of mixtures (5):

$$H_{W-Cu} = H_W F_W + H_{Cu} F_{Cu}$$  \hspace{1cm} (5)

where $F_W$ and $F_{Cu}$ are the volume ratios of iron and copper in the composite, respectively.

For the W-Cu composite, the value of hardness estimated from expression (5) is 1.95 GPa. The values of Hv obtained experimentally (figure 6(b)) are significantly higher (2.68 GPa—2.87 GPa). Relatively high hardness values of the W-Cu composite obtained in the experiment can be attributed to the fine-grain structure of the two-phase composite. According to the XRD data (figure 7(a)), $D_{cyst}$ values vary in the range of 50 ÷ 90 nm in the sintered composite. These values are close to the size of tungsten and copper crystallites in the initial powder.

Figure 11 shows the structure of the W-Cu composite obtained by the sintering of composite particles at 950 °C. The image was obtained using TEM.

Figure 12 shows the maps of the elemental distribution in the W-Cu composite. According to the research results, spherical W particles larger than 50 nm are evenly distributed throughout the copper matrix. The sample also contains closed pores. The spherical shape of W particles suggests that in the experimental conditions W particles are not sintered. The relatively low porosity of the sample results in a higher relative density and electrical conductivity of the composite. Homogeneous distribution of tungsten particles in the copper matrix makes it possible to prevent the growth of grains at high temperatures while also improving the mechanical characteristics of the composite [17].

Figure 9. The SEM image of the sintered W-Cu composite: a—heating rate—52 °C min⁻¹, temperature—990 °C, pressure—40 MPa, time of exposure at 990 °C—10 min; b—heating rate—52 °C min⁻¹, temperature—1030 °C, pressure—40 MPa, time of exposure at 1030 °C—10 min.

Figure 10. The SEM image of the sintered W-Cu composite at 950 °C (a), copper (b) and tungsten (c).
Figure 13 shows EBSD data for the sample obtained at 950 °C. In figure 13(a) the analyzed area is highlighted, and figures 13(b)–(d) show phase maps. The scanning pitch was 100 nm. Figure 14 shows the distribution of grains by size obtained from the EBSD analysis data. According to the analysis of these data, the structure of the consolidated sample includes micron-size and submicron-size grains. Such bimodal distribution of grains by size results in better mechanical properties of both copper and tungsten [43, 44].
Figure 13. EBSD data of W–Cu composite analysis ($T = 950 ^\circ C$).

Figure 14. The grain size distribution in a sample of W–Cu ($T = 950 ^\circ C$).
It is known from the data of a series of publications (see [45], for example) that the microhardness of W–Cu composites increases as the content of tungsten is increased. Thus, for a W–30wt%Cu composite pressed at 1200 MPa and sintered at 1400 °C over 2 h, the microhardness is 2.3 GPa (and the electrical conductivity is 58.62% IACS).

For a W–20 wt%Cu composite sintered by hot pressing at 950 °C and 100 MPa over 2 hours and comprised of W particles coated in Cu (the particle size of about 10 μm), the microhardness was 2.25 GPa and the electrical conductivity was 50.6% IACS [46].

The resulting microhardness exceeds the microhardness of a composite with the tungsten content of about 80 wt%. In our opinion, high microhardness of the W–Cu composite is attributed to its fine-grain structure, which is achieved by the presence of tungsten nanoparticles in the core–shell particles. A high electrical conductivity of the composite is due to presence of 46.38 wt% of copper.

According to the research results, the electrical explosion of copper and tungsten wires produces composite nanoparticles with the core–shell structure. The input of energy that is not sufficient for the sublimation of the tungsten wire results in the presence of tungsten particles that are several micrometers in size in the powder. Sintering of the powders based on nanoparticles and microparticles makes it possible to obtain composites with high hardness and electrical conductivity. According to [47], one of the promising methods of improving the mechanical properties of 3D nanostructure materials lies in the adjustment of the volume ratio of micron-size and submicron-size grains. The volume ratio of microparticles and nanoparticles in the powder can be changed using different approaches. By decreasing the energy introduced into the wires we increase the content of micron-size particles in the wire explosion products [30, 33].

The energy input into the wires can be reduced by increasing the length of the exploded wires or by decreasing the charging voltage ($U_0$). We can also achieve higher content of micro-size particles in the powder by using thicker wires or increasing the buffer gas pressure [48–50].

The particle size distribution of the particles obtained by the electrical explosion of intertwined W and Cu wires may largely vary, from tens of nanometers to tens of micrometers. We can change the ratio between the content of microparticles and nanoparticles not only to achieve homogeneous elemental distribution throughout the volume of the composite material. By doing so we also obtain materials with high strength, plasticity and also high electrical conductivity and erosion resistance when exposed to arc discharge.

It must be noted that we can theoretically use the electrical explosion of three wires to obtain three-component W–Cu–Me particles (Me = Zn, Ti). By alloying the W–Cu binary system with Zn and Ti atoms we can increase the wettability of tungsten by copper, and this eventually increases the density and mechanical characteristics of the fabricated 3D materials [17]. This effect suggests that we can improve the physicomechanical characteristics of the samples obtained in the research work. This adjustment makes it possible to produce powders with different distribution of nanoparticles and microparticles, thus providing ample opportunity for obtaining 3D nanostructure materials with multi-function properties.

**Conclusion**

It has been shown in the present research that the explosion of intertwined tungsten and copper wires may lead to the formation of nanoparticles with the core–shell structure where the tungsten makes the core and copper makes the shell.

Spark plasma sintering of the consolidated W–Cu powder samples in vacuum takes place in the temperature range of 900 °C–1030 °C, and the time of exposure is 10 min. Here, a relatively high density of the composite is achieved (90–98.9%).

The homogeneity of the structure of the sintered W–Cu composite and high content of the copper component allow for achieving the electrical conductivity of the material close to the theoretical one while maintaining a high microhardness.

The experimentally measured microhardness of the W–Cu composite exceeds its estimated microhardness, and this phenomenon is attributed to the fine-grain structure of the two-phase composite.

The properties of the W–Cu composite (high hardness and electrical conductivity) make it a promising material for different electrical engineering applications.

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III.23. Spark plasma sintering of the W–Cu powders was conducted in the Nano-Center of the National Research Tomsk Polytechnic University.

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References

[1] Ibrahim A, Abdallah M, Mostafa S F and Abouroseb Hegazy A 2009 An experimental investigation on the W–Cu composites Mater. Des. 30 1398–403
[2] Szentesi R N, Munzt R J and Drouet M G 1994 Copper–niobium and copper–tungsten composites as plasma torch cathers J. Phys. D: Appl. Phys. 27 1443–7
[3] Tsakiris V, Lungu M V, Elena E, Pavesescu D, Dumitrescu G, Radulian A and Bravic V 2013 W–Cu composite materials for electrical contacts used in vacuum contactsors J. Optoelectron. Adv. Mater. 15 1090–1094
[4] Raghu T, Sundaresan R, Ramakrishnan P and Rama Mohan T R 2001 Synthesis of nanocrystalline copper–tungsten alloys by mechanical alloying Mater. Sci. Eng. A 304 306 438–41
[5] Ho P W, Li Q F and Fuh J Y H 2008 Evaluation of W–Cu metal matrix composites produced by powder injection molding and liquid infiltration Mater. Sci. Eng. A 485 657–63
[6] Duan L, Lin W, Wang J and Yang G 2014 Thermal properties of W–Cu composites manufactured by copper infiltration into tungsten fiber matrix Int. J. Refract. Met. Hard Mater. 46 96–100
[7] Kim J-C, Ryu S-S, Kim Y-D and Moon I H 1998 Densification behavior of mechanically alloyed W–Cu composite powders by the double rearrangement process Scripta Mater. 39 669–76
[8] Kim J-C and Moon I-H 1998 Sintering of nanostructured W–Cu alloys prepared by mechanical alloying Nanostruct. Mater. 10 283–90
[9] Rosinski M, Fortuna E, Michalski A, Pakiela Z and Kurzydlowski K J 2007 W/Cu composites produced by pulse plasma sintering technique (PPS) Fusion Eng. Des. 82 2021–6
[10] Fan J, Liu T, Zhu S and Han Y 2012 Synthesis of ultrafine/nanocrystalline W–(30–50) Cu composite powders and microstructure characteristics of the sintered alloys Int. J. Refract. Met. Hard Mater. 30 53–7
[11] Sahoo P K, Kamal S K, Premkumar M, Sreedhar B, Srivastava S K and Durai L 2011 Synthesis, characterization and densification of W/Cu nanocomposite powders Int. J. Refract. Met. Hard Mater. 29 547–54
[12] Li Y, Qu X, Zheng Z, Lie C, Zou Z and Yu S 2003 Properties of W–Cu composite powder produced by a thermo- mechanical method Int. J. Refract. Met. Hard Mater. 21 259–64
[13] Dorfman I P, Houch D I and Scheithauer M J 2002 Consolidation of tungsten-coated copper composite powder J. Mater. Res. 17 2075–84
[14] Hong S H and Kim B K 2003 Fabrication of W–20 wt% Cu composite nanopowder and sintered alloy with high thermal conductivity Mater. Lett. 57 2761–7
[15] Kim K-H, Choi H and Han C 2017 Tungsten micropowder/copper nanoparticle core/shell-structured composite powder synthesized by inductively coupled thermal plasma process Metallurgical and materials transactions A 48A 439–45
[16] Zhou Q and Chen P 2015 Characterization of fine-grained W–10 wt% Cu composite fabricated by hot-shock consolidation Int. Journal of Refractory Metals and Hard Materials 52 137–42
[17] Hou C, Song X, Tang F, Li Y, Gao L, Wang J and Nie Z 2019 W–Cu composites with submicron- and nanostructures: progress and challenges NPG Asia Materials 11 74
[18] Zhiming Li, Lining Fu, Bin Fu and Aiyang Shan 2012 Effects of annealing on microstructure and mechanical properties of nano- crystalline tungsten produced by combination of asymmetric and symmetric rolling Mater. Sci. Eng. A 558 309–318
[19] Herzer G 2013 Modern soft magnets: amorphous and nanocrystalline materials Acta Mater. 61 718–34
[20] Kim T H, Yu H J and Lee J S 1997 The mechanism of hydrogen reduction synthesis of nanocomposite W–Cu Nanostruct. Mater. 9 213–6
[21] Ardestani M, Arabi H, Razaviadze H, Rezaie H R, Jankovic B and Mentus S 2010 An investigation about the activation energies of the reduction transitions of fine dispersed CuWO4–x/WO3–x oxide powders Int. J. Refract. Met. Hard Mater. 28 383–7
[22] Wan L, Cheng J, Fan Y, Liu Y and Zheng Z 2013 Preparation and properties of superfine W–20Cu powders by a novel chemical method Mater. Des. 51 136–40
[23] Kim J Y, Rodriguez J A, Hanson J C, Fenakel A I and Lee P L 2003 Reduction of CuO and Cu2O with H2: H embedding and kinetic effects in the formation of subs oxides J. Am. Chem. Soc. 125 10684–92
[24] Cheng J, Song P, Gong Y, Cai Y and Xia Y 2008 Fabrication and characterization of W–15Cu composite powders by a novel mechano- chemical process Mater. Sci. Eng. A 488 453–7
[25] Ardestani M, Arabi H, Rezaie H R and Razaviadze H 2009 Synthesis and densification of W–30 wt%Cu composite powders using ammonium meta tungstate and copper nitrate as precursors Int. J. Refract. Met. Hard Mater. 27 796–800
[26] Guo Y, Guo H, Gao B, Wang X, Hu Y and Shi Z 2017 Rapid consolidation of ultra fine grained W–30 wt% Cu composites by field assisted sintering from the sol–gel prepared nanoparticles J. Alloys Compd. 724 155–62
[27] Lerner M, Pervikov A, Glazkova E, Svarovskaya N, Lozhkomoev A and Psakhie S 2016 Structures of binary metallic nanoparticles produced by electrical explosion of two wires from immiscible elements Powd. Techn. 288 371–8
[28] Pervikov A, Glazkova E and Lerner M 2018 Energy characteristics of the electrical explosion of two intertwined wires made of dissimilar metals Phys. Plasma 25 070701
[29] Haynes W M 2017 CRC Handbook of Chemistry and Physics 97th ed. (Boca Raton, FL: CRC Press) p 2643
[30] Saksiev G S, Sasorov P V, Strukov K W and McDaniel D H 2004 State of the metal core in nanosecond exploding wires and related phenomena J. Appl. Phys. 96 1674
[31] Romanova V M, Ivanenkov G V, Mingaleev A R, TerOganesyan A E, Shlekovenko T A and Pikuz S A 2015 Electric explosion of fine wires: three groups of materials Plasma Phys. Rep. 41 617
[32] Pervikov A and Lerner M 2017 Mechanism of the formation of the structure and phase state of binary metallic nanoparticles obtained by the electric explosion of two wires made of different metals Curr. Appl. Phys. 17 1494–500
[33] Kotov Y 2009 The electrical explosion of wire: a method for the synthesis of weakly aggregated nanopolymers Nanotechnol. Russ. 4 415–24
[34] Morcom W, Worrell W, Sell H and Kaplan H 1974 The preparation and characterization of beta-tungsten, a metastable tungsten phase Metall. Trans. 5 155–61
[35] Choi D 2017 Phase transformation in thin tungsten films during sputter deposition Microelectron. Eng. 183-184 19–22
[36] Lee J-S, Cho J and You C-Y 2016 Growth and characterization of α and β—phase tungsten films on various substrates J. Vac. Sci. Technol. A 34 021502
[37] Sun H, Song Z, Guo D, Ma F and Xu K W 2010 Microstructure and mechanical properties of nanocrystalline tungsten thin films J. Mater. Sci. Technol. 26 87–92
[38] Yanwei L, Xiaodong Y, Tiefeng S, Kunsong M and Hongnian C 2011 Effect of the β phase on compressive mechanical property of CVD tungsten Rare Met. Mater. Eng. 40 1138–40
[39] Mittal J and Lin K I. 2015 Exothermic low temperature sintering of Cu nanoparticles Mater. Charact. 109 19–24
[40] Kim C, Lee G, Rhee C and Lee M 2015 Expeditious low-temperature sintering of copper nanoparticles with thin deficient carbon shells Nanoscale 7 6627–35
[41] Lozhkomoev A, Lerner M, Pervikov A, Naidenkin E, Mishin I, Vorozhtsov A, Apkarian A and Eskin D 2019 The formation of Fe–Cu composite based on bimetallic nanoparticles Vacuum 159 441–6
[42] Bachmaier A, Kerber M, Setman D and Pippan R 2012 The formation of supersaturated solid solutions in Fe–Cu alloys deformed by high-pressure torsion Acta Mat. 60 860–71
[43] Wang Y, Chen M, Zhou F and Ma E 2002 High tensile ductility in a nanostructured metal Nature 419 912–5
[44] El-Atwani O, Quach D V, Efe M, Cantwell P R, Heim B, Schultz B, Stach E A, Groza J R and Allain J P 2011 Multimodal grain size distribution and high hardness in fine grained tungsten fabricated by spark plasma sintering Mater. Sci. Eng., A 528 S670–7
[45] Abu-Oqail A, Ghanim M, El-Sheikh M and El-Nikhaily A 2012 Effects of processing parameters of tungsten–copper composites Int. Journal of Refractory Metals and Hard Mater. 35 207–12
[46] Chen P, Shw Q and Luo G 2016 Effect of interface modification by Cu-coated W powders on the microstructure evolution and properties improvement for Cu–W composites Surf. Coat. Technol. 288 8–14
[47] Sabirov I, Enikeev N A, Murashkin M Y and Valiev R Z 2015 Bulk nanostructured materials with multifunctional properties Materials (Springer Briefs) p 118
[48] Pervikov A V, Rodkevich N G, Glazkova E A and Lerner M I 2017 Bimodal metal micro-nanopowders for powder injection molding AIP Conf. Proc. 1915040045
[49] Lerner M I, Pervikov A V, Rodkevich N G and Glazkova E A 2019 Sintering of Cr-60Ni-W and Cr-70Ni-Al alloys bimodal powders prepared by electric explosion of wires Mater. Res. Express 6 126524
[50] Sindhu T K, Sarathi R and Chakravarthy S R 2008 Understanding nanoparticle formation by a wire explosion process through experimental and modelling studies Nanotechnology 19 025703 (11pp)