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Tribological and electrical properties of a dispersion-hardened copper-matrix coating deposited using cold spray

© V.S. Shikalov, T.M. Vidyuk

Khristianovich Institute of Theoretical and Applied Mechanics, Russian Academy of Sciences, Siberian Branch, Novosibirsk, Russia
E-mail: v.shikalov@gmail.com

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A comparative study of tribological and electrical properties of copper and copper-tungsten coatings obtained by cold spraying was conducted. It was shown that embedment of hardening tungsten particles into the copper matrix coating allows significant reduction of the specific wear rate of the obtained composite under dry friction conditions. The presence of hardening particles in the copper matrix does not significantly affect the friction coefficient, wear mechanisms and specific electrical conductivity of the composite coating.

Keywords: cold spray, copper matrix coating, wear rate, friction coefficient.

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Cold spray (CS) is an actively developing method for solid-state application of functional coatings; the basic principle of the method is acceleration of microparticles of the powder material (metal, alloy or metal ceramics) by a supersonic flow of compressed gas (air, nitrogen or helium) to speeds of more than 400 m/s. When impacting the substrate surface, they get plastically deformed and form a continuous coating thus preventing melting [1]. Due to its high plasticity, copper is one of the most popular materials used in CS; the obtained coatings are characterized by high thermal and electrical conductivity and are in demand in various branches of modern production industries [2–4]. To modify the mechanical and tribological properties of copper CS coatings, widely used is the approach of dispersion hardening with the ceramic microparticles by spraying the mixture [5–8]. As a rule, embedment of hardening ceramic particles into the coating promotes an increase in the bonding strength, hardness, and wear resistance; however, high electrical resistance of the ceramics induces a significant decrease in electrical conductivity. As an alternative approach, it is reasonable to consider hardening of the copper matrix coatings with particles of hard refractory metals [9–11]. In this study, we have investigated tribological and electrical characteristics of the copper matrix coating dispersion-hardened with tungsten particles.

In this work, we have studied a composite coating obtained in [12]; its thickness was about 500 μm, tungsten content was 36 wt.% (Cu$-$W36). As the reference material, a pure copper coating obtained at the same spraying parameters was taken. The coating porosity was below 1 %. The coating hardness was measured by the instrumental indentation method on the Nanoscan 4D+ setup (TISNUM, Russia) at the normal force of 0.1 N. The tribological test was performed using setup UMT-2 (Bruker Nano, Germany) in the dry friction mode according to the ball$-$on$-$flat scheme. A counterbody made from hard alloy WC-6Co was moved reciprocally with the frequency of 5 Hz at the normal force of 25 N for 2000 s. The friction coefficient was defined as the ratio of friction force to normal force; the forces were measured by appropriate sensors. The morphology and elemental composition of the wear surface were analyzed by using optical profilometer Contour GT-K1 (Bruker Nano, Germany) and scanning electron microscope EVO MA15 (Zeiss, Germany) equipped with energy dispersive spectrometer X-Max 80 mm^2 (Oxford Instruments, UK). Specific electrical conductivity of the coatings was measured by the eddy current method using device Constant K6 (Russia).

Measurements of the coating properties are presented in the Table. Embedment of hardening tungsten particles into the coating copper matrix increases its hardness by 1.4 times and decreases the wear rate by 4.6 times as compared to those of the pure copper coating. Fig. 1 presents the images of morphology of the coating wear surfaces obtained by optical profilometry and electron microscopy in the secondary electron mode. The average wear track depth and width were 45 and 20 μm and 1.1 and 0.7 mm for the Cu and Cu$-$W36 coatings, respectively. It is evident that the process of wearing for both coatings is accompanied by the material extrusion from the friction zone to the surface, which evidences the presence of plastic deformation (Fig. 1, *a* and *b*). The electron micrographs (Figs. 1, *c* and *d*) exhibit traces of material seizure and tearing-out that are characteristic of adhesive wear. Energy dispersive analysis has revealed a significant oxygen content on the wear surface: 36 at.% for the Cu coating and 41 at.% for the Cu$-$W36 coating. The oxygen content in the initial coatings measured on cross-sections was approximately 2 at%. Friction induced heat generation

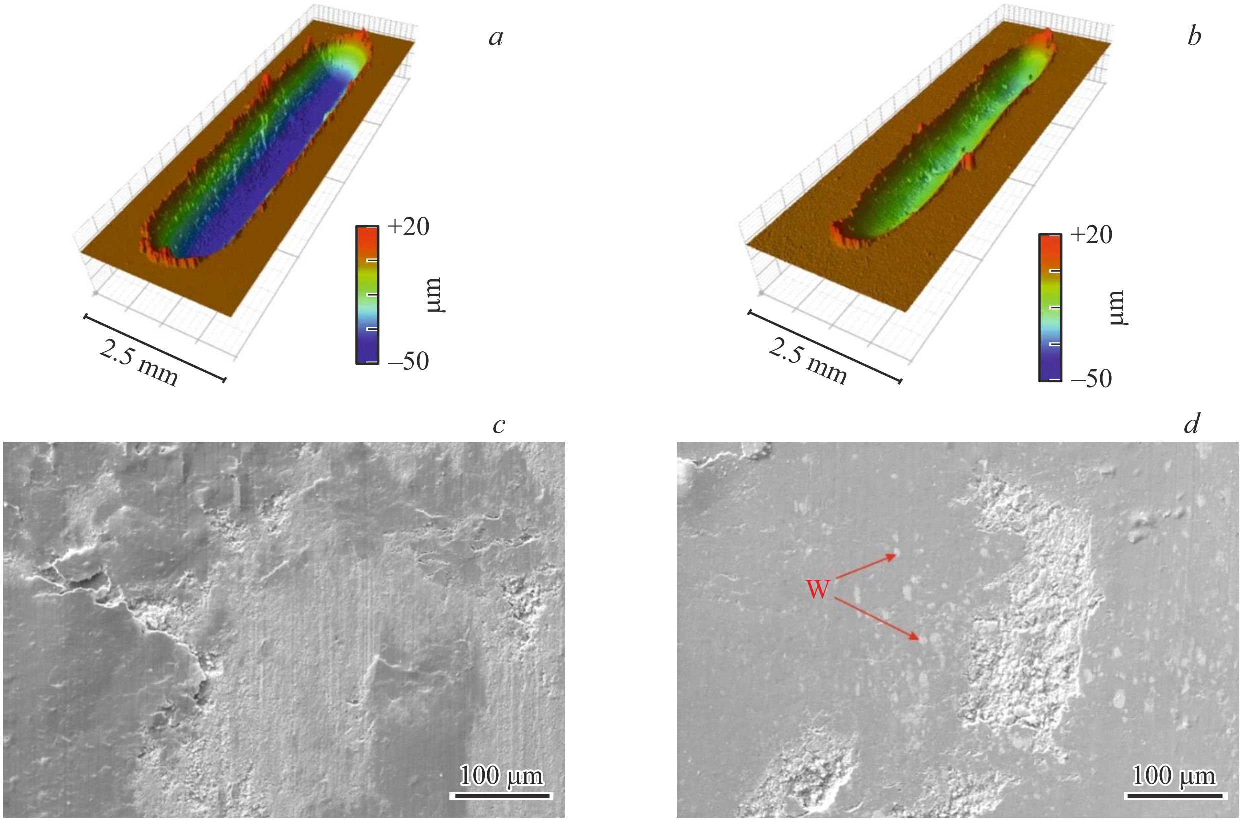

Figure 1. Images of the wear surface morphology of Cu (a, c) and CuW36 (b, d coatings).

Coating properties

Coating	Microhardness, GPa	Wear rate $\cdot 10^{-4}$, $mm^3/N \cdot m$	Friction coefficient	Specific electrical conductivity, % IACS
Cu	1.7 ± 0.3	0.79 ± 0.07	0.44 ± 0.01	43.2 ± 0.3
Cu–W36	2.5 ± 0.7	0.17 ± 0.01	0.49 ± 0.01	43.6 ± 0.2

promotes oxygen diffusion from the environment, which leads to formation of an oxide tribolayer. Thus, the main wear mechanisms for both coatings are the oxidative and adhesive wear.

Fig. 2 shows that the friction process may be conditionally divided into two stages. After ~ 500 s of running-in, the process gets stabilized for both coatings, and the friction coefficient remains, on the average, almost unchanged. The average friction coefficient of the Cu–W36 coating appeared to be slightly higher than that of the Cu coating. Apparently, due to their high cohesive strength, tungsten particles do not crumble during testing and form on the friction surface microprotrusions (Fig. 1, d) prohibiting sliding [6].

The eddy current tests showed that the presence of hardening tungsten particles has virtually no effect on the coatingś specific electrical conductivity. On the one hand, embedding tungsten particles into the coating having a higher electrical resistance ($\sim 5.6 \cdot 10^{-8}\,\Omega \cdot m$) than copper ($\sim 1.7 \cdot 10^{-8}\,\Omega \cdot m$) is expected to decrease the composite electrical conductivity. On the other hand, in the process of spraying the composite mixture, the coating being formed is apparently subjected to intense work hardening by tungsten particles, which promotes compaction of the inter-particle boundaries, decrease in the overall electrical resistance and, hence, increase in electrical conductivity. Both of these effects presumably result in that the composite coatingś specific electrical conductivity remains, on the average, unchanged with respect to that of the copper coating.

Thus, the study has shown that embedment of hardening tungsten particles into the copper matrix coating in the process of cold spraying results in a significant reduction of the specific wear rate of the obtained composite under dry friction conditions. The presence of the hardening

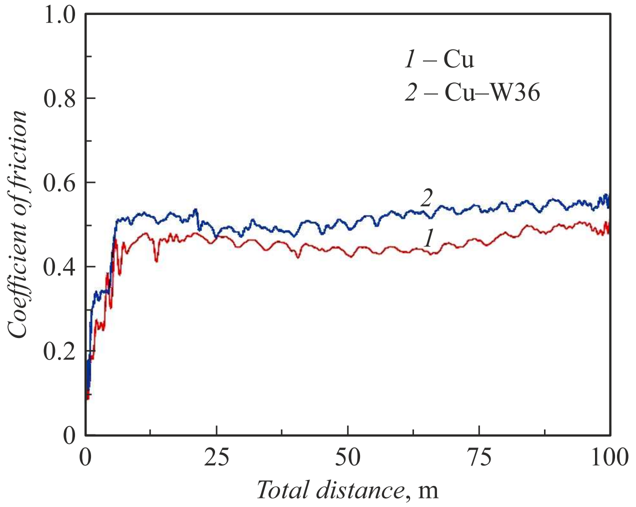

Figure 2. Evolution of the coatingsŕfriction coefficient.

phase has virtually no effect on the friction coefficient, wear mechanisms, and specific electrical conductivity of the coating.

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Conflict of interests

The authors declare that they have no conflict of interests.

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