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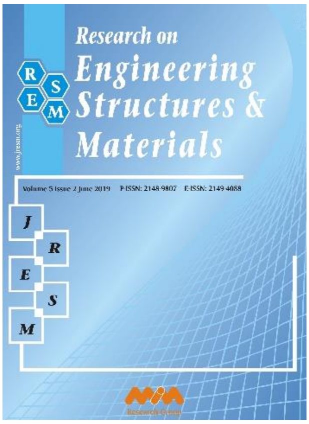

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Research Article

Electrical conductivity, microstructure and wear properties of Cu-Mo coatings

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Abstract

In this study, Cu–Mo composite coatings were produced on copper substrate by plasma spray technique. Electrical conductivity, microstructure and wear properties of the composite coatings were investigated. Microstructure and phase composition of the coatings were examined by using optical microscopy (OM), scanning electron microscope (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDS). The microhardness experiments were also performed by using a microhardness machine. The electrical conductivity properties of the coatings were evaluated with eddy current instruments. Wear tests were performed by pin-on-disc method. Although the electrical conductivities of the coatings are very small compared to the substrate, it has been determined that the coatings exhibit very good tribological property and high hardness in comparison to the substrate.

1. Introduction

During the reason for the copper to remain as the most important engineering materials every day is; high corrosion resistance, excellent electrical and thermal conductivity, attractive appearance, high ductility and ease of forming. Pure copper is widely used in the transmission of electric current in places related to cables, wires, electrical contacts and other electrical works. Copper and some alloys are used in automotive radiators, heat exchangers, home heating systems, panels for solar energy absorption, and applications where heat is required to quickly transfer from one point of metal to another [1]. Despite the high electrical, thermal conductivity and good corrosion resistance of copper, properties such as low hardness, yield strength, creep resistance and low wear resistance limit the use of copper. Because pure copper recrystallizes at temperatures close to 500 °C, even if hardened by cold forming, and therefore quickly loses its strength. A lot of work has been done in the literature to come from above. Most of the researchers have focused on the production of ceramic reinforced copper matrix composites. In the literature, Al_2O_3, SiC, TiB_2, TiC, B_4C and WC particles are usually added to the Cu matrix [2-6]. In these previous studies, pore formation reveals the negative side of the studies. As is known, pore formation adversely affects the mechanical properties as well as the electrical conductivity

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properties. Junjie et al. [7] studied the hardness and electrical conductivity of Cu-matrix nanocomposites reinforced with in-situ TiC fabricated using long-term ball milling and hot pressing. It has been detected that as the ball milling time increased, the hardness and electrical conductivity increased. Chenchen et al. [8] reported that microstructures, mechanical and electrical properties of ZrB_2 microparticles reinforced Cu composites prepared by hot-pressed sintering. The results indicated that the relative density and electrical conductivity of the composites decrease with increasing ZrB_2 content. Huanchao et al. [9] added a new generation of graphite into the copper. The Gr/Cu composites were produced by using ball milling and cold compacting sintering process. The mechanical and physicochemical properties including hardness, relative density, conductivity and oxidation resistance were tested. The relative density, hardness, oxidation weight gain and IACS of the materials obtained by the optimum process parameters were 90.0%, 53.4HB, 1.6 mg cm^{-2} and 76.2%, respectively. While the mechanical properties of the Cu matrix composites are improved, the deterioration of the electrical conductivity properties is normal. The important thing is that the electrical conductivity does not fall too much. Zhan and Zhang report that in the study on graphite and SiC hybrid particles reinforced copper composite and its tribological characteristic, for Cu-23vol.% reinforcements (Gr+SiC) composite, while the electrical conductivity of the composite decreased by 14%, the wear rate decreased by 48% [10].

In this study, we tried to improve the wear and hardness properties without compromising the electrical conductivity of the copper material too much. For this purpose, a Cu + Mo coating layer with different ratios was produced on copper substrate using plasma spraying method. Molybdenum is a typical refractory metal with body-centered cubic (BCC) lattice structure. The high melting point (2610 °C) is characterized by low thermal expansion coefficient and high thermal/electrical conductivity [11]. In the literature, the use of Mo in copper alloys is very limited, and coating production is not available. Plasma spraying is effectively and economically applied to various machine parts to reduce surface defects [12]. In this method, the complete or partial melting of the powders varies depending on their thermal properties. The controllability of the system at extremely high heating and cooling rates makes it possible to produce coatings made of metallic, non-metallic and ceramics and combinations with this method [13]. In this study, Cu-Mo coatings produced on copper substrate with plasma spray method have both ideal wear resistance and relatively suitable electrical conductivity. In addition, these substrates are repeatedly coated with the plasma spray method and the worn parts become resistant to wear again. These two cases clearly reveal the contribution of the study to science.

2. Materials and Methods

Pure copper plates at 20 mm x 60 mm x 5 mm and 99.9% purity were selected as the substrate. Cu and Mo powders with -90+45 μm (Metco 55) and -75+45 μm (Metco 63NS) grain sizes respectively were coated on the substrate using plasma spray method. Mo was added to Cu in proportions of 10, 25 and 50% by weight. In the production of the coating layers, a Sulzer Metco F4-MB model plasma spray coating system with a power of 55 kW was used. The principle scheme of the plasma spray coating process is shown in Fig. 1. The production parameters of the coatings are summarized in Table 1. The flow rate of the argon gas used to produce the plasma beam was set at 35 l / min in all coatings. Spraying was made at a distance of 80 mm. The coating powders are injected externally into the gun. The injected powders are oriented parallel to the plasma flow. The coating powder feed rate was set to 50 g/min, the H_2 gas flow rate to 10 l/min and the carrier gas rate to 3 l/min.

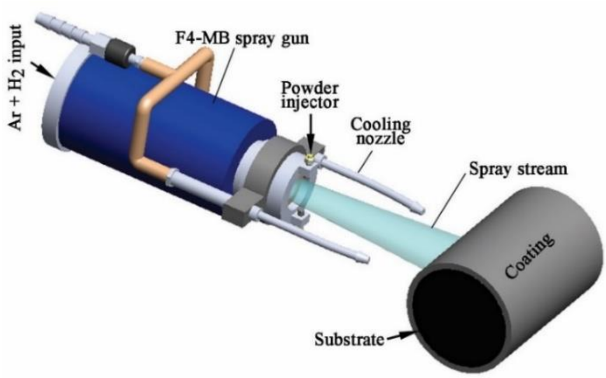


Fig. 1 Sulzer Metco F4-MB model plasma spray coating system

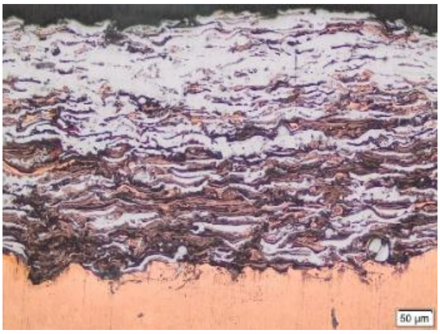
Table 1 Production parameters

Parameters	
Gun type	Sulzer-Metco F4
Current (A)	580
Volt (V)	60-65
Ar gas flow (l/min)	35
H_2 gas flow (l/min)	10
Spray distance (mm)	80
The amount of powder feed (g/min)	50
Carrier gas (Ar) flow (l/min)	3.0

The microstructure and phase formation properties of the coatings were determined by SEM-EDS and XRD analyses. The hardness was measured under a load of 300 grams with a microhardness device and at a waiting time of 15 seconds by using SHIMADZU HMV-G21 model microhardness machine. The electrical conductivities of coatings (Cu-Mo) and substrate (Cu) were measured according to ASTM E1004-02 standard with eddy current principle. Wear tests were performed by pin-on-disc method and ASTM G133 standard with 10 N loads, wear rate of 5 cm/s, 300 m slip distance and balls Ø6 mm 100Cr6 steel. Profiles of wear surfaces are determined by surface profilometer device. The wear volumes were determined using the wear profiles. After calculating volumes, wear rates were calculated according to Archard's law [14].

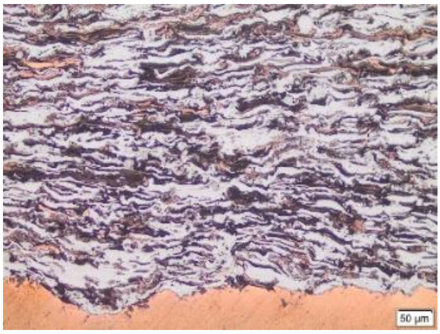
3. Results and Discussion

Fig. 2 illustrates optical images of coatings. The thickness of the interlayer coating is 300 µm. It is seen that the coating layers are homogeneous. As the Mo content increased, the porosity increased. The bond between the coating and the substrate is compatible. There is a covering layer in the appearance of a laminated structure. In all coatings, a lamellar microstructure is observed, which is well known in thermal spray coatings and is formed by molten metal droplets impacting the substrate and continuously wetting it [15, 16]. The lamellar structure occurs in the form of impingement of molten particles on the substrate, deformation, and solidification. [17]. According to Kuroda and Kobayashi [18] the lamella is formed parallel to the substrate and the middle part of the lamella is thick and the thickness is decreased towards the end parts.



(a)

(b)



(c)

Fig. 2 (a) Cu-10 Mo coating (b) Cu-25 Mo coating, (c) Cu-50 Mo coating.

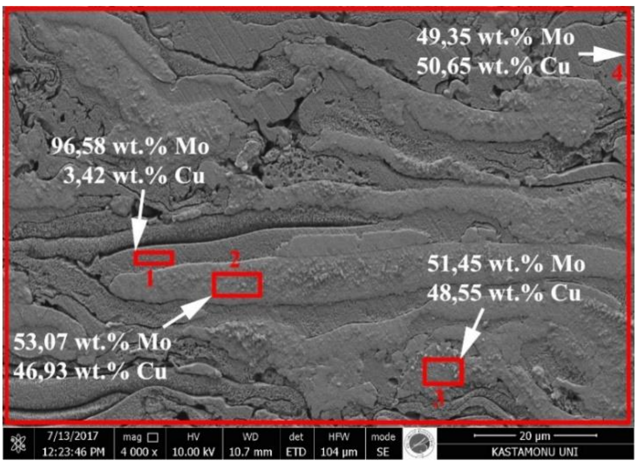


Fig. 3 EDS analysis of Cu-50 wt.% Mo coating

The EDS analysis of the Cu-50 wt.% Mo coating produced by the plasma spray method on the Cu substrate is given in Fig. 3. The chemical compositions of different lamellae are formed in the coating. When the area from the coating layer EDS is examined, it is seen that the coating represents the Cu-50 wt.% Mo content. The MAP analysis of Fig. 4 shows that all three coatings with relatively homogeneous distribution of the elements present in the coating layer. The distribution of the elements in the coating affects the electrical conductivity and mechanical properties.

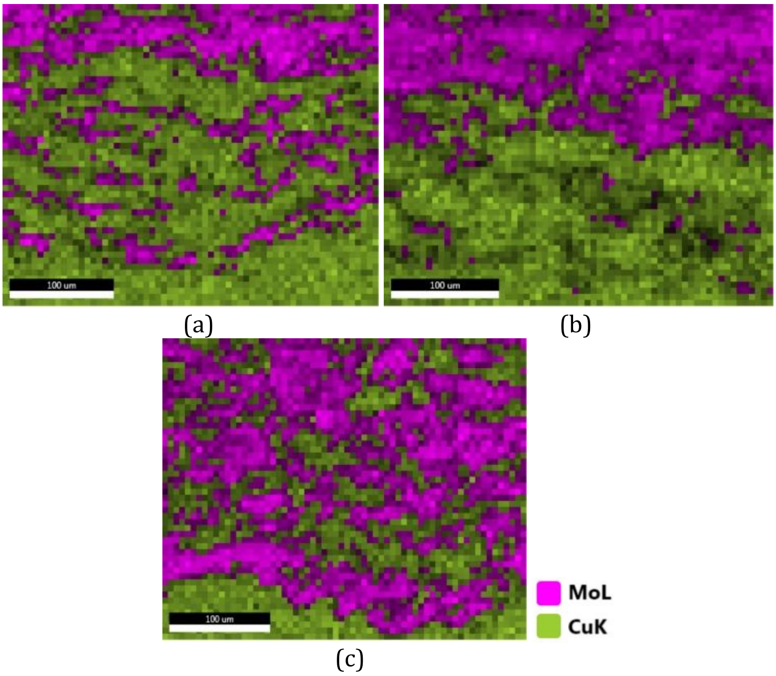


Fig. 4 SEM-MAP analyses of coatings; (a) Cu-10 wt.% Mo coating (b) Cu-25 wt.% Mo coating, (c) Cu-50 wt.% Mo coating

Fig. 5 illustrates the XRD graphic of Cu-Mo composite coatings which are produced with plasma spray. Cu and Mo phases are present in the coating layers. No oxide formation has occurred in the coatings and substrate. No phase formation occurred between Cu and Mo. According to the Cu-Mo phase diagram, this is normal. Because the Cu-Mo phase diagram is a monotectic diagram [19]. The result is that Cu-Mo coatings are mechanical mixtures of the refractory metal Mo and Cu with a face-centered cubic structure. Fathy et al [20] investigated effect of ZrO_2 content on properties of Cu-ZrO_2 nanocomposites synthesized by optimized high energy ball milling. They reported that no chemical reaction occurred between Cu and the reinforcing element and no new phase was formed.

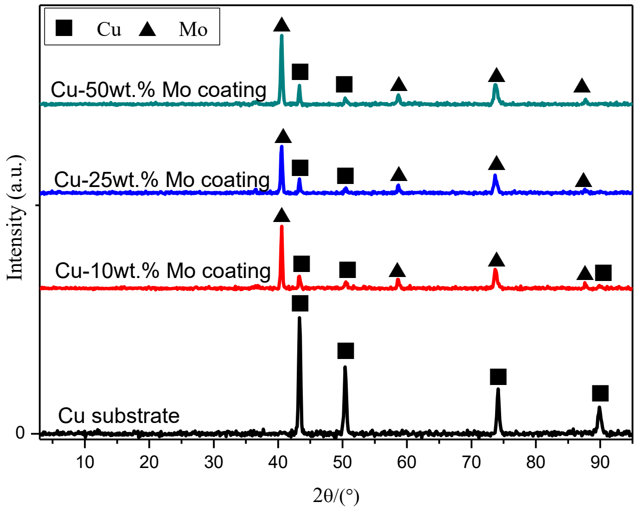
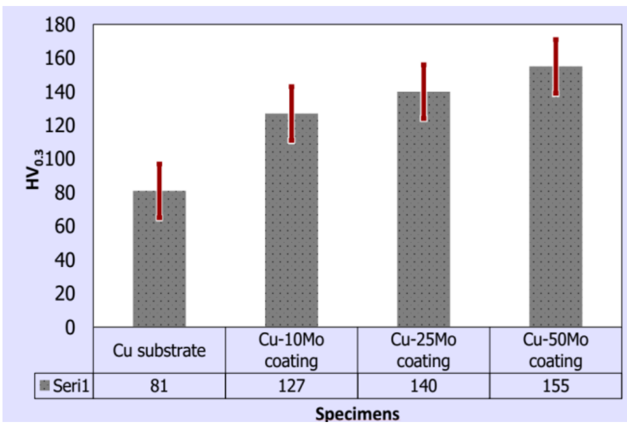
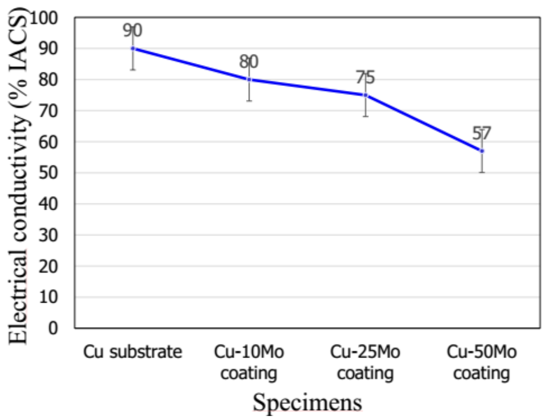


Fig. 5 XRD graphic of Cu-Mo composite coatings

The hardness graph of the coatings is given in Fig. 6a. Six hardness measurements were taken from each sample. Averages of hardness were taken and evaluated. The hardness of the Cu substrate was 81 $HV_{0.3}$, while the hardness of the 10, 25, and 50% Mo coating was measured as 127 $HV_{0.3}$, 140 $HV_{0.3}$ and 155 $HV_{0.3}$, respectively. The hardness was increased by coating with Cu substrate (56-91%). As the addition of Mo increases, the hardness of the coatings increases. This is due to the natural hardness of Mo (2 GPa) [21]. The electrical conductivity graph of the coatings is given in Fig. 6b. With the increase of molybdenum, the electrical conductivities of the coatings decreased. This is due to the fact that the electrical conductivity of Mo is lower than that of Cu and the porosity is increased by the addition of Mo.



(a)



(b)

Fig. 6 (a) Hardness graph (b) Electrical conductivity graph

Coating of Cu substrate with Cu-Mo powder mixture resulted in a significant increase in the hardness. The electrical conductivity of the Cu substrate is measured as 90% IACS, while the electrical conductivities of the coatings are in the range of 57-80% IACS. These coatings can be used in areas where the electrical conductivity value is not too high than 57-80% IACS and the hardness is high.

The friction coefficient and wear rates of all samples are given in Figure 7. The friction coefficient for the copper base is 0.596. It varies in the range of 0,515-0,554 depending on the Mo additive in the Mo doped samples. As it is understood from these values, Mo particles showed solid lubricant and lowered the friction coefficient according to the substrate material. The wear rate for the copper substrate is ~ 0.112x10^{-3} mm^3/Nm, while the wear rates for 10%, 25 and 50% of Mo are changed as ~0.097x10^{-3} mm^3/Nm, ~ 0.095x10^{-3} mm^3/Nm and ~ 0.075x10^{-3} mm^3/Nm, respectively.

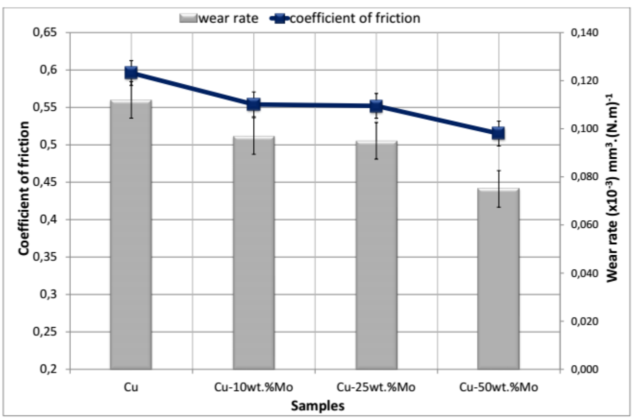


Fig. 7 Wear rate and COF of Cu-Mo composite coatings

Figure 8 shows the morphology of the worn surfaces of the substrate and coating layers under 10 N load. Both the adhesive and abrasive wear types dominate the substrate and coating layers. Material wastage after abrasion of the substrate, dense plastic deformation and micro-wedge gutters, and at least wedge formation and debris appear. On the wear surface of the coating layer, plastic deformation and micro-waviness are not to be investigated. This is due to the fact that the coating layer is hard and friction coefficient are low.

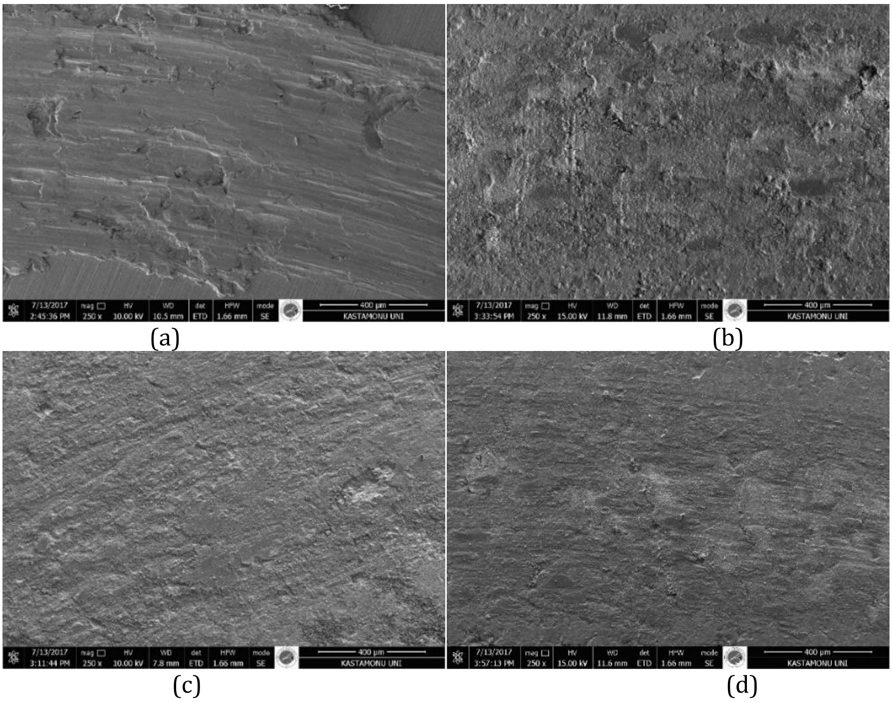


Fig. 8 Morphology of worn surfaces (a) Cu substrate, (b) Cu-10wt.%Mo, (c) Cu-25wt.%Mo and (d) Cu-50wt.%Mo

4. Conclusion

Cu-Mo composite coatings have been successfully produced on copper substrate by using plasma spray technique. Microstructure, wear and electrical properties of coatings were investigated. Coating of Cu substrate with Cu-Mo powder mixture resulted in a significant increase in the hardness. The hardness value for the uncoated Cu was measured as $HV_{0.3}$, while the hardness value for Cu-50wt.% Mo was measured as 155 $HV_{0.3}$. The electrical conductivity of the Cu substrate is measured as 90% IACS, while the electrical conductivities of the coatings are in the range of 57-80% IACS. Although the electrical conductivities of the coatings are very small compared to the substrate, it has been determined that the coatings exhibit a very good hardness values in comparison to the substrate. These coatings can be used in areas where the electrical conductivity value is not too high than 57-80% IACS and the hardness is high. Although the electrical conductivities of the coatings are very small compared to the substrate, it has been determined that the coatings exhibit a very good tribological performance in comparison to the substrate.

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