Effect of deposition parameters on the tribological properties of Aluminum-Bronze coatings by Value Arc Technique on AISI 304 stainless steel

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Abstract— Herein, the tribological properties of aluminum-bronze coatings, deposited by wire-arc spray technique on AISI 304 stainless steel were investigated. All the coatingswere deposited by wire-arc spray technique under various deposition voltages, ranging from 26 to 34 V. Scanning electron microscopy revealed that the morphologies of all coatingscomprised ofCu, Al, and Fe phases with a varying number of splats, level of porosity, and un-melted particles.The microstructural analysis of surface and cross section revealed that the high density coating with minimum defects was resulted at 30V. This coating also demonstrated the highest micro Vickers hardness values 129.26 $HV_{0.01}$ and 134.92 $HV_{1.0}$ from both surface and cross-section. Pin-on-disc tribometer test showed that the coating deposited at 30 V demonstrated the highest wear resistance among all coatings.This fact was clarified by the minimum wear rates of 1.07 cm^3/Nmand 1.95 cm^3/Nmand the lowest coefficients of friction 0.093 and 0.125, offered by this coating under 5 and 8 N loads, respectively.The optimum combination of properties was achieved by deposition at 30 V.

Keywords: Aluminum-bronze; Wear and friction; Electric wire arc; Voltage variation; 304 stainless steel

1. INTRODUCTION:

Aluminum-bronze alloys are known as tribo-materials due to their high wear resistance and low coefficient of friction as compared to ferrous materials[1]. Aluminum-bronze coatings are also widely used as an ideal material in applications where significant mechanical properties, and superior corrosion and wear resistance are required[2,3].Various deposition techniques, including flame-spraying, high-velocity oxy-fuel (HVOF), low-velocity oxy-fuel (LVOF), detonation gun spraying, plasma spraying, electric wire arc, and plasma transferred arc (PTA) techniques, have been employed to deposit aluminum-bronze coatings[4,5]. Among all, the electric wire arc spray technique is one of the widely used techniques for the deposition of a variety of materials[6]. This technique produces significantly clean and machinable coatings[7]. This technique is more economical and very simple to operate with a very low number of operating parameters [8,9].

In addition to the other characteristics, the aluminum-bronze is recognized for its high strength, wear properties, and tarnish-resistant, compared to other bronze alloys [5,10,11]. At high temperatures, aluminum-bronze coating also does not oxidize or react with sulfurous compounds [9]. Over sometime, many researchers studied the tribological, electrochemical, and mechanical properties of aluminum-bronze coatings with different spraying techniques for different industrial applications. Alam et al. [12]studied the tribological properties of aluminum-bronze coatings, deposited by low-pressure plasma spraying techniqueunder various operating parameters. They achieved high wear resistance, low coefficient of friction, and high hardness. Dallaire [13]found that coatings deposited by the wire-arc processexhibited superior wear and erosion resistance compared to coatings deposited by other thermal spraying processes. Attaiwi et al. [14]deposited 13%Cr steel coatings on nodular cast iron by wire-arc process under various processing parameters, including voltage, spraying distance, feed rate, and coating thickness. The authors concluded that the coating deposited between 28 to 30 V, exhibited an optimum combination of properties. Ibrahim et al. [15]studied the tribological properties of various copper and its alloys based coatings deposited by the twin wire-arc technique on the steel substrate. They found that Cu-17%Al-1%Fe coatings demonstrated the highest hardness, lowest wear, and coefficient properties, compared to other compositions. Limited studies have been carried out on the effect of operating parameters of the electric wire-arc spray technique on tribological properties of aluminum-bronze coatings.

Therefore, in the present work, the tribological properties of aluminum-bronze coatings, deposited by wire-arc spraytechnique on AISI 304 stainless steel,under various deposition voltages were investigated. Optical microscopy, X-ray diffraction analysis, image J software were used to evaluate the morphologies, phases, and mean porosity of all coatings from both surface and crosssections. Micro Vickers hardness testing was also carried out under loads of 1 kg and 0.01 kg. Tribological properties of all coating were also evaluated using pin-on-disc tribometer, and scanning electron microscope (SEM).

2. Experimental work:

2.1 Materials:

AISI 304 stainless steel was selected as a substrate. The chemical composition of selected steel was determined by optical emission spectrometer (OES) (*MetaLab, Germany*) is given in Table 1. Five coupons of samples, having dimensions 76 × 38 × 5 mm were selected and grit blasted with alumina grits of size 0.005 mm. After grit blasting, the surface roughness of all steel samples was measured, using a surface profilometer(*Surfcorder SE1700α, USA*), having a diamond tip of radius 2 μm, moved at a rate of 1 mm/sec for a distance of 4 mm.An average surface roughness, ranging from 0.005 to 0.006 mm, was achieved after grit blasting. The aluminum-bronze wires of diameter 1.62 mm*(SPRA BRONZ-AA, Sulzer Metco, USA),* having 9–10% Al,1% Fe, and 90% Cu in chemical composition (wt.%), was selected as a coating material.

Table 1. Chemical composition (wt%) of AISI 304 stainless steel

C	Mn	Si	Ni	Cr	S	P	Fe
0.019	0.998	0.154	8.779	17.900	0.001	0.010	Balance

2.2 Wire-arc spray deposition process:

The wire-arc spray technique was utilized to deposit aluminum-bronze material as a coating on AISI 304 stainless steel substrate. For this purpose, aluminum-bronze wire of diameter 1.62 mm was fed into the wire-arc spray system (*Sulzer Metco, USA*). All the five steel samples were coated at a spraying distance of 100 mm, air pressure of 40 psi, and current feed rate of 6.5 kW, under five different voltages; 26 V, 28 V, 30 V, 32 V, and 34 V. The deposited coatings were then cleaned for subsequent characterization.

2.3 Morphological analysis:

The surface morphology of all coated samples was analyzed using light optical microscope (*Leica Model DM 4000M, Germany*). The Image J software was used to measure the porosity percentage of all deposited coatings. To analyze the coating from cross-section and measure the coating thickness, all the samples were manually ground on grinding papers of grades; P200, P400, P600, P800, and P1000 and polished on an automatic polisher (*StruersTegrapol–15 Grinder/Polisher, USA*) using diamond pastes (6, 3, 1 and 0.25 μm) and nylon and velvet cloths. Finally, samples were etched in 50% NH_4OH + 30% H_2O_2 + 20% H_2O solution for 5 sec to reveal the morphology.The average coatings thickness was measured by the light optical microscope (*Nikon, UFX-DX, Japan*), which was observed to be in the range of 200–250 mm. The deposition of aluminum-bronze coatings was validated,usingan X-ray diffractometer (*XRD, model FEI 800 Powder, USA*) and CuK_α radiations of wavelength 1.5418Å. The diffraction patterns were obtained in the 2θ range of 20º–140º.

2.4 Micro Vickers hardness testing:

The micro Vickers hardness testing of all coated samples wascarried out on a micro Vickers hardness tester (Shimadzu Model HMV, Kyoto, Japan) under loads of 1 kg and 0.01 kg using diamond indenter. Five readings were taken and averaged to get the final hardness value for each sample.

2.5 Tribological analysis:

Before testing, all the coated samples were ground, and polished by the aforementioned procedure, and washed with isopropyl alcohol. The tribological properties, including wear rate and coefficient of friction of aluminum-bronze coatings, were determined throughthe pin-on-disc tribometer (*CSM-Instruments, Switzerland)*in dry condition. All coated samples were treated with fresh alumina ball of diameter 6 mm. The normal loads of 5N and 8 N were applied and a wear track of radius 3 mm was observed aftertraveling a distance of 180 m. The morphology of coatings after wear test in the form of the wear tracks were also analyzed using SEM*(S-3700 N Hitachi, Japan)*.

3. Results and discussion:

3.1 Morphological properties:

The nature of morphology plays an important role in the tribological properties of aluminum-bronze coatings. The change in voltages affects the melting conditions in the arc zone. Due to thisinstability of arc, the velocity of particles causes thechange in structural morphologies, splats formation, and gathering of splats on the surface [12]. The optical micrographs, captured from the surface and cross-section of all aluminum-bronze coatings,deposited under various voltages,ranging from 26–34 V, are illustrated in Figs. 1and 2. The morphologies of all coatings exhibited the Cu, Al, and Fe phases with variations in the number of splats, level of porosity, and un-melted particles with varying voltages. Coating deposited at 26 V demonstrated more porosity (dark spots)and un-melted particles and less number of splats (Fig. 1(a)). With the increase in voltages to 28 V and 30 V, the level of porosity was observed to decrease (Fig. 1(b)and (c)) and againincreasedwith the further increase in voltage to 32 V and 34 V (Fig. 1(d)and (e)). Varying values of voltage also caused variations in the number of splats in all coatings. In coatings deposited at 26 V and 28 V, the formation of splats was less and broken in length, whereas in coating deposited at 30 V, the splats were quite better and wavy in length. A similar trend of defects and splats formation was observed in coatings deposited at 32 V and 34 V.

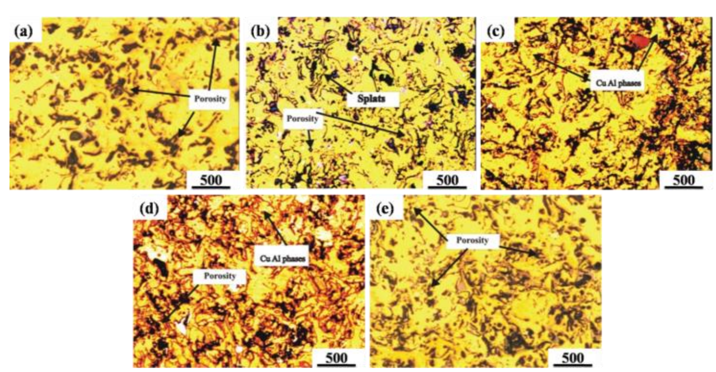


Fig. 1. Morphologies of all aluminum-bronze coatings, deposited on 304

stainless steel samples at various voltages; (a)26 V, (b) 28 V, (c) 30 V, (d) 32 V, and (e) 34 V, captured from the surface.

Cross-sectional micrographs of all aluminum-bronze coatings demonstrated the formation of splats and fusion of coating boundaries with the substrate material (Fig. 2). As the voltage increased from 26 to 30 V, a low level of defects and better splats in the form of wavy and lengthy splatswere observed. The proper fusion with a minimum level of defects was exhibited by coating deposited at 30 V similar to the literature [14,16]. Further increase in voltage to 34 V disturbed the stability of the arc,over melted the deposited particles, and thus resulted in an increased level of defects particularly the porosity [14].

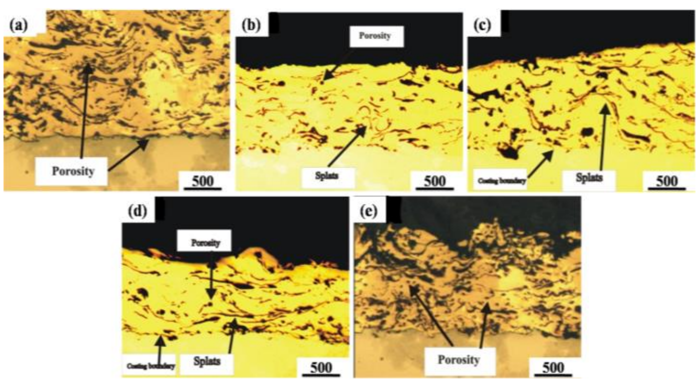


Fig. 2. Morphologies of all aluminum-bronze coatings, deposited on 304 stainless steel samples at various voltages; (a)26 V, (b) 28 V, (c) 30 V, (d) 32 V, and (e) 34 V, captured from the cross-section.

3.2 *Phase analysis:*

XRD spectra of all aluminum-bronze coatings deposited on 304 stainless steel at various voltages, ranging from 26–34 V, are plotted in Fig.3.XRD spectra validated the deposition of aluminum-bronze coatings on all steel samples by exhibiting different stable intermetallic Cu and Al phases. These phases included Cu_9Al_4, Cu_3Al_2, Cu_4Al_3, CuAl, and $CuAl_2$, with two terminal solid solutions of Cu(Al). The αCu, β(Cu_3Al_2), ϒ2(Cu_9Al_4), and $AlFe_3$ phases were found in all coatings. It was observed that the αCu was the major matrix in all five spectra. Υ_2 phase was a solid solution, based on an intermetallic compound of Cu_9Al_4 (D 83) cubic type. It affected the microstructure and resulted in higher micro-hardness and better wear-resistant [17,18].

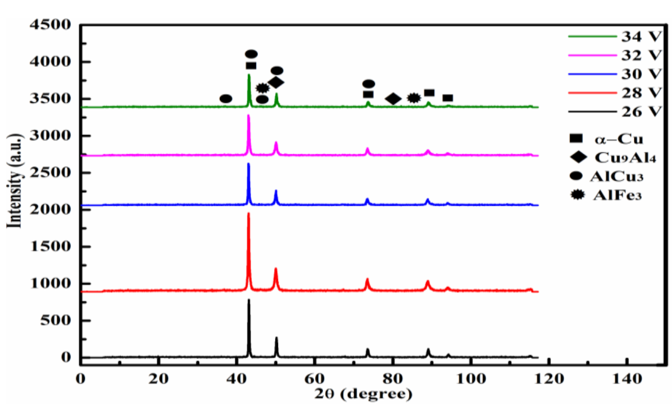


Fig. 3. XRD spectra of all aluminum-bronze coatings, deposited on 304 stainless steel at various voltages.

3.3 *Average porosity:*

Optical micrographsand Image J softwarethresholds used to calculate the percentages of porosity in all aluminum-bronze coatings are illustrated in Fig. 4, whereas the obtained porosity percentages are plotted in Fig. 5. Optical micrographs revealed the relationshipbetween the deposition voltage and the percentage of porosity in all coatings. With the increase in deposition voltage from 26–34 V, the porosity level first decreased and then increased. At a voltage of 26 V, the porosity percentage was high. As the voltage increased to 28 V and 30 V, the porosity levelgradually decreased. The minimum porosity level was observed in coating deposited at 30 V, compared to other coatings. This behavior can be attributed to the effect of applied voltage on the melting condition in the arc zone. The voltage, ranging from 30 to 32 V had maximum arc stability compared to other voltages. This arc stability provided the uniform and consistent coating, with minimum defects (porosity, voids). Porosity resulted in poor coating adhesion, higher wear rate, and lower hardness.

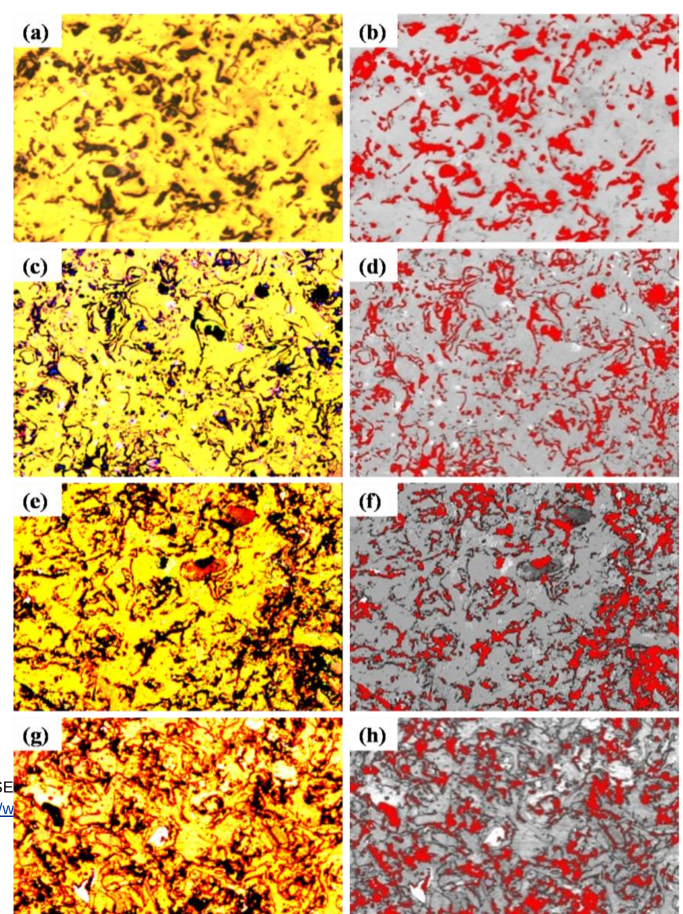


Fig. 4. Optical micrographsand Image J softwarethresholds of all aluminum-bronze coatings, deposited on 304 stainless steel samples at various voltages (a & b)26 V, (c & d) 28 V, (e & f) 30 V, (g & h) 32 V, and (i& j) 34 V, demonstrating the porosity in all the coatings

The porosity commonly associates with a high number of unmelted or re-solidified particles, entrapped in the coating. Poor particle or splat adhesion leads to untimely cracking, delamination, or spalling of the coatings. Due to open porosity, the corroding or oxidizing elements interconnect to the coating interface and attack the base metal [19].

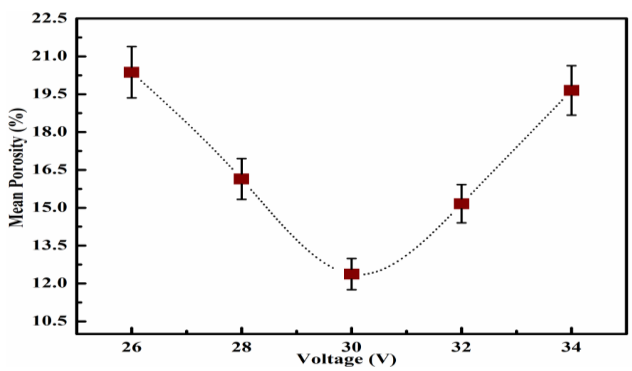


Fig. 5. Variations in mean porositypercentagesin the aluminum-bronze coatings, deposited on 304 stainless steel at various voltages

3.4 *Micro Vickers hardness:*

The values ofmicro Vickers hardness of all aluminum-bronze coatings,deposited on 304 stainless steel at various voltages, are plotted in Fig. 6. With the increase in deposition voltage, micro Vickers hardness of aluminum-bronze coatings first increased and then decreased under both the loads of 1 kg and 0.01 kg. Aluminum-bronze coatings deposited at 26 V and 28 V exhibited the lowest micro Vickers hardness valuesunder both loads. This might be attributed to improper and incomplete melting, fusion, and deposition of aluminum-bronze particles on the substrate material at low voltages. This may also be associated with the non-uniform distribution of micro-porosity in the coatings.The aluminum-bronze coating deposited at 30 V demonstrated the highest micro Vickers hardness under both loads.

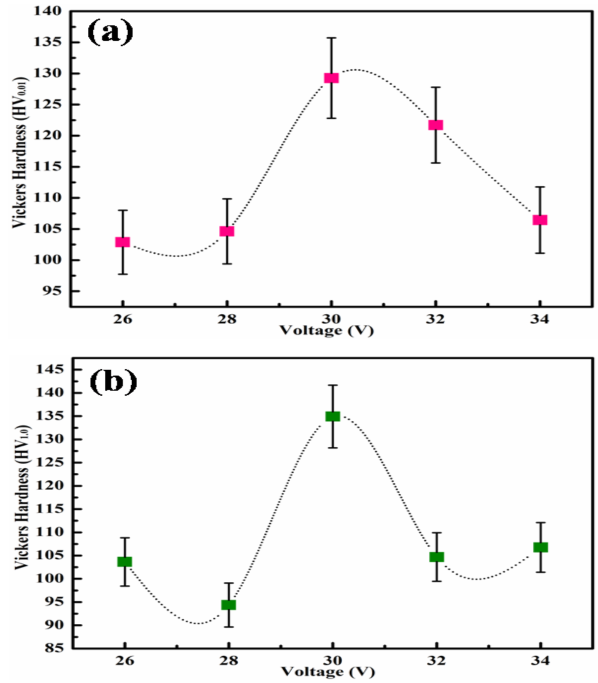


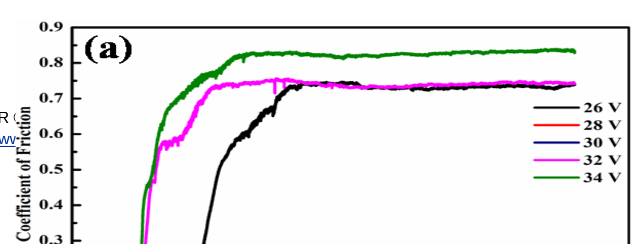
Fig. 6. Variations in micro Vickers hardness of aluminum-bronze coating, deposited on 304 stainless steel at various voltages, measured under the loads of (a)0.01 kg and (b) 1 kg.

The coatings, deposited at 32 V and 34 V, demonstrated the moderate hardness values, greater than coatings deposited at 26 V and 28 V, and lower than coating deposited at 30 V. The optimum micro Vickers hardness value was offered by coating deposited at 30 V, attributed to the maximum arc stability, uniform and consistent deposition, minimum structural defects, and good compact between deposited particles.

3.5 *Tribological properties:*

3.5.1 *Friction property*

Values of coefficient of friction of all aluminum-bronze coatings, deposited on 304 stainless steel at various voltages, ranging from 26–34 V measured under the loads of 5 N and 8 N,as a function of distance travelled are plotted in Fig. 7, whereas the corresponding values of mean coefficient of friction as a function of deposition voltage are plotted in Fig. 8. With the increase in deposition voltage, the values of coefficient of friction of all coatings were first decreased and then increased. Sudden variations in coefficient of friction of aluminum-bronze coating, deposited at 26 V,was observed under a load of 5 N (Fig. 7(a)), which might be attributed to the presence of un-melted particles and porosity in this coating. The un-melted particles were dragged over the surface of the coating during the sliding of the ball.Both the coatings, deposited at 26 V and 28 V exhibited moderate values of coefficient of friction (0.613, 0.505) under both 5 N and 8 N loads. The coating deposited at 30 V demonstrated the lowest values of coefficient of friction (0.125, 0.093) under both loads. This might be associated with theminimum level of defects and breaking of particles [23].



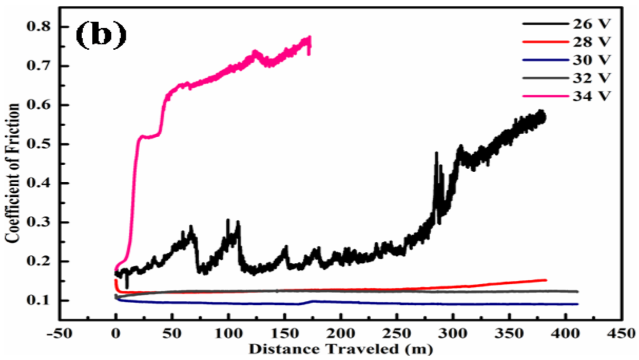


Fig. 7. Coefficient of friction curves of all aluminum-bronze coatings, deposited on 304 stainless steel at various voltages measured under the loads of (a) 5 N and (b) 8 N.

With the further increase in deposition voltage, an increase in the values of coefficient of friction was observed under both loads. The coating deposited at 34 V, demonstrated the highest values of coefficient of friction (0.783, 0.622) under both 5 N and 8 N loads. This increase in coefficient of friction might be attributed to the expulsion of un-melted particles [20].

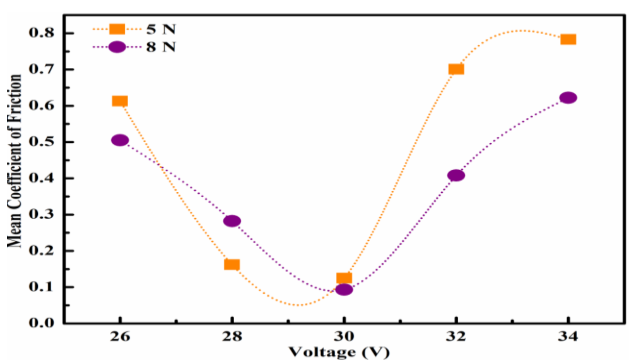


Fig. 8. Mean values of the coefficient of friction of the aluminum-bronze coatings, deposited on 304 stainless steelat various voltages, measured under the loads of 5 N and 8 N.

3.5.2 Wear property

Thewear rates (*Kv*) of all aluminum-bronze coatings, deposited on 304 stainless steel at various voltages ranging from 26–34 V, were determined by pin-on-disc tribometer. The volumetric wear loss (*Vwear*) wasfirst calculated by equation (2);

$$Vwear = \frac{Mass\ loss\ (g)}{Density\ (gm/cm3)} \quad (2)$$

On the other hand, the *Kv*was calculated by equation (3);

$$Kv = \frac{Vwear}{FNxS} > cm^3.\mathrm{N}^{-1}.\mathrm{m}^{-1} \quad (3)$$

The porosity, oxide content, flattening ratio, and bonding strength of splats significantly affect the wear properties of aluminum-bronze coatings[12].It has been reported that the onset of wear always accompanies by friction. Therefore, the results of coefficient of friction provide the initial information about the wear behavior of the coatings [22]. Variations in wear rates of all aluminum-bronze coatings, deposited on 304 stainless steel at various voltages ranging from 26–34 V, are plotted in Fig. 9.

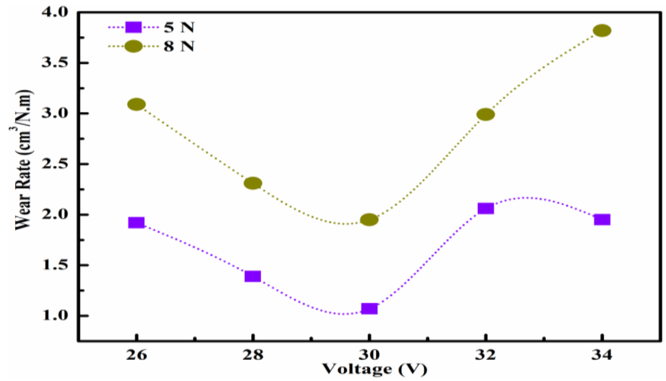


Fig. 9. Mean wear rates of aluminum-bronze coatings, deposited on 304 stainless steelat various voltages, measured under the loads of 5 N and 8 N.

As the deposition voltage increased form 26–34 V, wear rate of aluminum-bronze coatings was first decreased and then increased. At low voltages, the wear rate was high, as the voltage increased, the wear rate was decreased up to 30 V and then again increased in voltage resulted in an increase in the wear rate. Thus the minimum wear rates of 1.07 $cm^3.N^{-1}m^{-1}$and 1.95 $cm^3.N^{-1}m^{-1}$were obtained at 30 V under both loads of 5 N and 8 N respectively. On the other hand, the aluminum-bronze coating deposited at 32 V exhibited the highest wear rate (2.06 $cm^3.N^{-1}m^{-1}$) under 5 N load and coating deposited at 34 V demonstrated the highest wear rate (3.82 $cm^3.N^{-1}m^{-1}$ under 8 N load.

3.5.3 Wear tracks morphologies

SEM micrographs of wear tracks developed on all aluminum-bronze coatings after wear testing under loads of 5 N and 8 Nare illustrated in Figs. 10 and 11.The coating, deposited at 26 V exhibited minor wear under 5 N load, but considerable wear under8 N load (Fig. 10(a and b)).The wear track developed on coating deposited at 28 V was visible but this coating exhibited better wear resistance compared to a coating deposited at 26 V because as the voltage increased, the coating resistance to wear also increased (Fig. 10(c and d)). The wear track of coating deposited at 30 V presented the maximum wear resistance under the load of 5N and 8 N compared to other coatings (Fig. 10(e and f)).

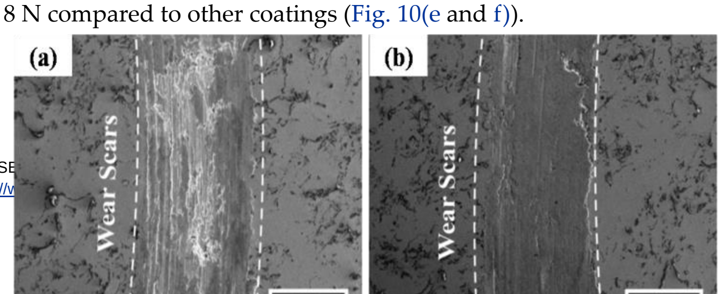


Fig. 10. SEM micrographs of wear tracks, developedon aluminum-bronze coatings after wear testing, deposited on 304 stainless steelat 26 V; (a) 5 N, (b) 8 N, 28 V; (c) 5 N, (d) 8 N, and 30 V; (e) 5 N, (f) 8 N.

In sample (d) the wear tracks showed the increase in wear rate at 5 N and 8 N loads. In sample (e) at 5 and 8 N load, the wear tracks showed that the wear of material was more than the previous samples. From this trend of wear, it can be said that at 30 V the minimum wear rate was observed. Below and above this voltage, the wear of the coating material was more.

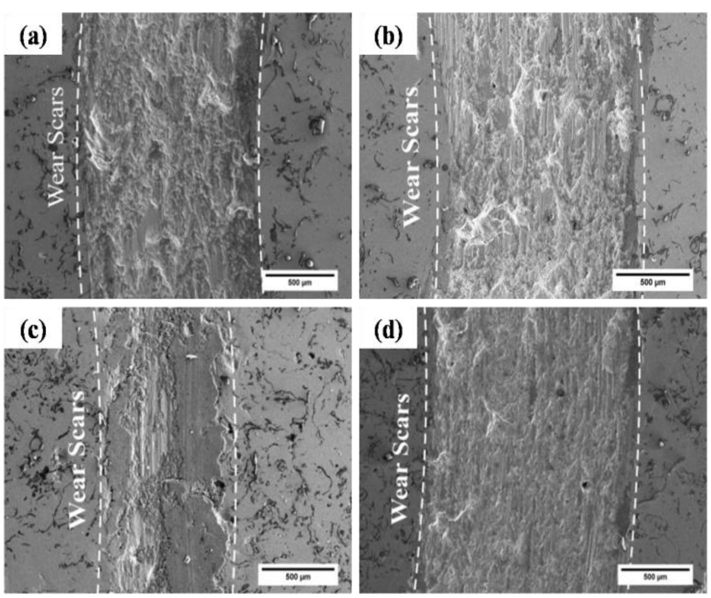


Fig. 11.SEM micrographs of wear tracks, developedon aluminum-bronze coatings after wear testingdeposited on 304 stainless steelat 32 V; (a) 5 N, (b) 8 N, and 34 V; (c) 5 N, (d) 8 N.

4. Conclusions:

Based on above-presented results, following conclusions were extracted;

- The voltage played a significant role in the deposition of aluminum-bronze coatings on the steel substrate. Thecoating deposited at 30 V demonstrated the dense microstructure and high hardness values of 129.26 $HV_{0.01}$ and 134.92 $HV_{1.0}$ at both the surface and cross-sectionof coating, respectively. This coating also exhibited the minimum porosity and un-melted particles.
- The minimum wear rates of 1.07 cm^3/Nmand 1.95 cm^3/Nmwith the lowest coefficient of friction 0.093 and 0.125 were offered by coating deposited at 30 V under 5 and 8 N loads, respectively. This decrease in coefficient of friction and increase in wear rate could be attributed to the low level of porosity and un-melted particles.
- The optimum combination of properties of aluminum-bronze coatings, including the high harness, dense microstructure, high wear resistance, and low coefficient of friction was achieved at 30 V.

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