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Influence of process parameters on physical dimensions of AA6063 aluminium alloy coating on mild steel in friction surfacing

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Abstract

An attempt is made in the present study to obtain the relationships among process parameters and physical dimensions of AA6063 aluminium alloy coating on IS2062 mild steel obtained through friction surfacing and their impact on strength and ductility of the coating. Factorial experimental design technique was used to investigate and select the parameter combination to achieve a coating with adequate strength and ductility. Spindle speed, axial force and table traverse speed were observed to be the most significant factors on physical dimensions. It was observed that the thickness of the coating decreased as the coating width increased. In addition, the width and thickness of the coatings are higher at low and high torques. At intermediate torque values, when the force is high, the width of the coating is high, and its thickness is thin; and when the force is low, the width and thickness are low. The interaction effect between axial force (F) − table traverse speed (Vx) and spindle speed (N) − table traverse speed (Vx) produced an increasing effect on coating width and thickness, but other interactions exhibited decreasing influence. It has also been observed that sound coatings could be obtained in a narrow set of parameter range as the substrate-coating materials are metallurgically incompatible and have a propensity to form brittle intermetallics.

Keywords: Friction surfacing; Mechtrode; Substrate; Process parameters; Physical dimensions

1. Introduction

Friction surfacing is a solid phase cladding technique that uses a combination of heat and deformation to clean surfaces and metallurgically bonded metals. In its simplest arrangement, a rotating consumable bar is brought into contact, under low load, with stationary substrate in the initial dwell time stage, as shown in Fig. 1, when the rotating bar is preferentially heated by the frictional heat development due to relative motion between the rotating consumable rod and stationary substrate, facilitating to the consumable to plastic state. After the dwell time, the substrate that is mounted on a table is given linear translational motion to facilitate the deposition of the plasticized consumable onto the substrate by shearing, as shown in Fig. 2. Bonding occurs by the combination of self-cleaning between the two materials and the application of heat and pressure to promote diffusion across the interface, thereby forming a solid-phase metallurgical bond. The process relies on producing precisely the right temperature and shear conditions at the interface between the rotating bar and substrate via the plasticized layer. Friction surfacing has gained increasing interest in the area of reclamation of worn components during the recent past as it has been proved to be successful in building-up of worn-out shafts. The process can be performed in open air [1], in inert atmosphere [2] and underwater without sealing [3]. It is suitable for consumables

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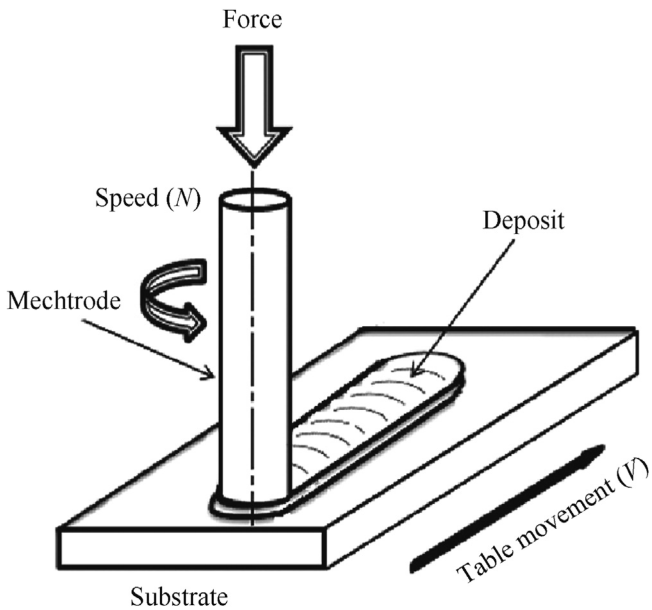

Fig. 1. Schematic of friction surfacing.

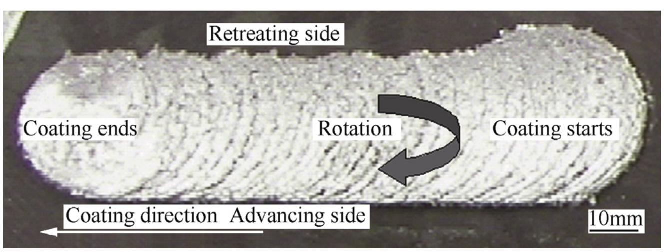

Fig. 2. Typical friction surfaced AA6063 Aluminium alloy.

which exhibit low thermal conductivity as well as high thermal conductivity alloys like aluminium alloys. Minimal dilution, narrow heat-affected zone, ability to deposit metallurgically incompatible materials and freedom from cracking are amongst the most important advantages of friction surfacing in comparison with conventional fusion welding based surfacing methods. Friction surfacing was first patented as a metal-coating process in 1941 by Klopstock et al. [4], but only recently it has been developed as a practical industrial process because of its repair and reclamation capabilities.

Friction surfacing of different substrates with different coating combinations, consisting of hard coatings on soft substrates as well as soft coatings on hard substrates [5,6] and coating of metal matrix composite on aluminium–silicon alloy to improve wear resistance [7], is some of the recent studies. Intelligent support systems have also been reported to have been employed for optimizing friction surfacing parameters [8]. Steels are coated with zinc or aluminium to protect them against atmospheric corrosion [9]. Aluminium is used as anode for the protection of ships by sacrificial anodic protection of steel parts of marine vessels, especially of war ships, exposed to sea water [10]. Aluminium deposition on mild steel by fusion welding is not feasible as it chemically reacts to form iron aluminide, and Fe and Al are immiscible. Hence, a solid state deposition is a possible option. The present study deals with deposition of AA 6063 aluminium alloy on IS2062 mild steel substrate. Detailed characterization of these solid state deposits of aluminium on mild steel has not been well documented, thus, the present study assumes special significance. In the present study, the factorial design of experiments [11] has been selected to investigate the influence of friction surfacing process parameters on the physical dimensions of the coating, namely coating width and thickness with adequate strength and ductility.

Table 2
Mechanical properties of Mechtrode and Substrate.

Material	Tensile strength/MPa	Elongation/%	Hardness/HV
IS2062- MS	410	23	180
AA6063 -Al	241	12	83

2. Experimental procedure

AA 6063 aluminium alloy of 15 mm diameter and 280 mm long rod was taken as mechtrode (consumable rod), and IS2062 mild steel of 250 mm × 300 mm × 10 mm plate was used as substrate. The chemical composition and mechanical properties of mechtrode and substrate are shown in Tables 1 and 2, respectively. Rod end was machined to ensure flatness, and the substrate was milled and its surface was grinded to obtain a flat and even surface free of oxide. Mechtrode and substrate were cleaned with acetone prior to surfacing to minimize the contamination.

Experiments were carried on CNC Friction Surfacing machine with a capacity of 50 kN axial force (F), spindle speed 2400 rpm (N) and table speed of 5000 mm/min(Vx) in the Defence Metallurgical Research Laboratory, Hyderabad, India with the option to conduct experiments either in force controlled or position controlled mode. In the present study, the experiments were conducted in force controlled mode. AA6063 aluminium alloy coatings were deposited on mild steel for 100 mm in length as per the experimental parameter matrix [12] details given in Table 3.

Table 1
Chemical composition of Mechtrode and substrate (wt. %).

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	C	P	S
IS2062 MS	0.17	Bal.	–	1.03	–	–	–	–	–	.0.21	0.02	0.016
AA6063 Al	0.4	0.35	0.10	0.10	0.65	0.10	0.10	0.10	Bal.	–	–	–

Table 3
Design of experimental parametric matrix.

Parameter combinations	Process parameters		
	Axial force (*F*) /kN (X_1)	Spindle speed (*N*) /rpm (X_2)	Table speed (*Vx*) /(mm.min^{-1}) (X_3)
1	4 (−)	800 (−)	600 (−)
2	6 (+)	800 (−)	600 (−)
3	4 (−)	1000 (+)	600 (−)
4	6 (+)	1000 (+)	600 (−)
5	4 (−)	800 (−)	800 (+)
6	6 (+)	800 (−)	800 (+)
7	4 (−)	1000 (+)	800 (+)
8	6 (+)	1000 (+)	800 (+)

3. Characterization of coatings

AA6063 aluminium alloy coatings on mild steel obtained with eight different parameter combinations are shown in Fig. 3(a). The coatings exhibited ripple formation with spacing between the ripples. Coating width and thickness were observed to depend on the surfacing parameters, coating widths of advanced side and retreating side were machined to observe effective contact area and sectioned for measuring the effective coating width and thickness in contact with substrate [13]. Physical dimensions of the coating, namely coating width and thickness, were measured from their stereo micrographs obtained after conventional metallographic sample preparation of transverse sections of the samples, as shown in Fig. 3(b) and (c).

A ram tensile test similar to Mil-J-24445A was designed in order to determine the interfacial strengths of the coating and the substrate, as shown in Fig. 4. For this, the coating material was machined from the substrate as a circular area forming an inner circle without the coating while retaining the outer circular area to form an annular space consisting of intact coating and substrate. The outer circle coating was machined to facilitate to support the substrate on a fixture such that part of the inner circular area in the annular space is only subjected to loading under loading on the area. The test was conducted on a 100 kN INSTRON universal testing machine. Ram tensile test samples are shown in Fig. 5.

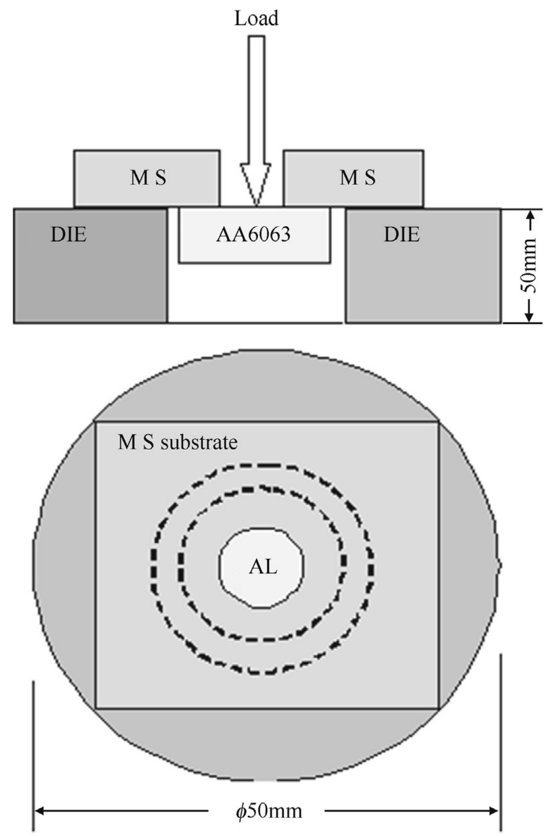

Fig. 4. Schematic of ram tensile test method.

The coatings were subjected to face bend test by three point bend test as per ASTM-E190, AWSB4.0 guided bend test. Samples after testing are shown in Fig. 6. Bending was discontinued at the instant of pealing or cracking of the coating. From the bend sample the radius of bend was obtained to estimate bend ductility. Bend ductility was calculated by measuring the bend angle and bend radius using the following relation:

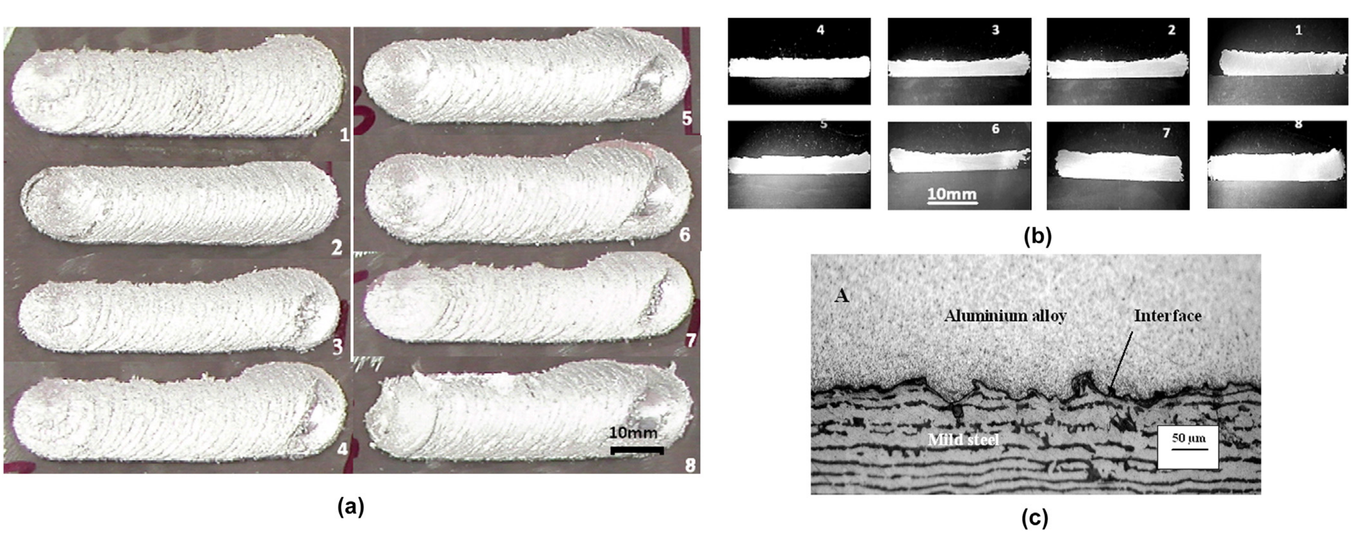

Fig. 3. (a) Deposit of aluminium alloy on mild steel by eight parameter combinations. (b) Transverse section of coatings. (c) Interfacial microstructure.

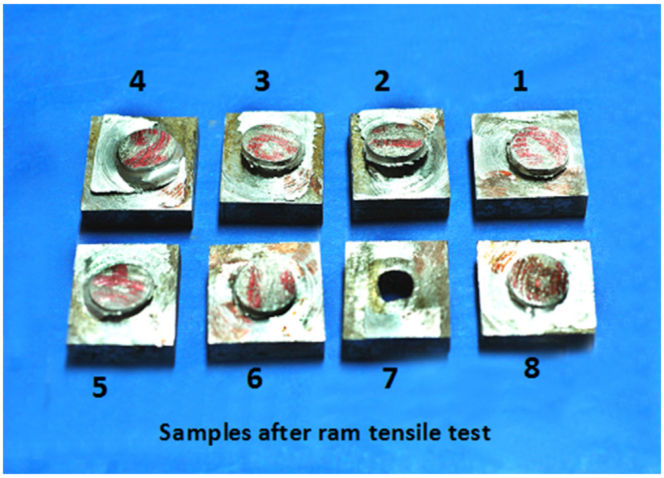

Fig. 5. View of ram tensile samples after testing.

Fig. 6. Samples after face bend test.

$$\varepsilon = [1/(2R/t + 1)] \times 100$$

where ε is percentage (%) of elongation; R is radius of curvature of the bend; and t is thickness of the specimen (substrate + coating), in mm.

4. Results and discussion

4.1. Physical dimensions of the coatings

The physical dimensions and the corresponding mechanical properties of the coatings for selected parameter combinations based on factorial design of experiments are presented in Table 4.The influences of axial force, spindle speed and table travel speed on coating thickness and width are presented in Figs. 7–9, respectively. It has been observed that, as the axial force (F) increases the coating width increases, however, the coating width at higher levels of constant rotational speed and table travel speed the is less than that at lower levels of constant spindle speed (N) and table traverse speed (V_x). The thickness varied from 1.5 mm at lower axial force to 1 mm at higher axial force in respect of lower levels of spindle speed and table speed while at higher level of these combinations the thickness is around 2 mm under higher axial force.

At both levels of constant axial force and table traverse speeds the width of the coating decreases while its thickness remains nearly constant with the increase in spindle speed. It is also noted that the width of the coating is narrow at lower levels. At higher levels of constant axial force and spindle speed, the width of the coating decreases while its thickness remains nearly constant with the increase in table speed. However, at lower levels of constant axial force and spindle speed, the coating width and thickness remain nearly constant with the increase in table speed.

To explain the trends observed from the influence of surfacing parameters on the physical dimensions, corresponding strength and bend ductility of coating, an attempt has been made to explore the role of frictional energy which produces heat between mechtrode and substrate. For each parameter combination from the data generated by friction surfacing machine the interfacial coefficient of kinetic friction, power and heat input were calculated using the formulae $\mu_k = F_k/N_k$, where F_k is friction force offered by substrate along the table traverse speed, and N_k is normal force offered by substrate along the mechtrode feed, $P = 2\pi NT/60$ and $Q = P/V_x$, where P is input power, and V_x is table traverse speed. From the results data it is observed that the strength and ductility are maximum for parameter combinations 3 and 6 for which the heat input is 67.1 and 40.82 J/mm, respectively. These heat inputs are intermediate to the highest and lowest heat inputs. The coefficient of friction for these parameter combinations is maximum (0.3744). Higher heat input could result in the formation of brittle intermetallics while low heat input can be inadequate to develop metallurgical bonding between the coating and the substrate [14]. Incidentally these are the parameter combinations for which coating thickness is

Table 4
Mechanical properties of the coatings at different parameter combinations.

Parameter combinations (PC)	Inter- facial friction coefficient $\mu_k = F_k/N_k$	Input power/W $P = 2\pi NT/60$	Heat input/(J·mm^{-1}) $Q = P/V_x$	Coating width/mm	Coating thickness/mm	Torque(T) /Nm	Tensile strength /MPa	Bend ductility (ε)/%
1	0.2838	722.98	72.29	13.38	1.5768	8.63	55	4.46
2	0.2923	716.28	71.62	15.42	1.1950	8.55	64	4.88
3	0.3744	671.25	67.1	12.44	1.2511	6.41	147	11.40
4	0.3657	452.16	45.21	13.17	1.2582	4.32	61	1.45
5	0.1834	547.61	41.07	15.95	1.2054	6.54	78	1.68
6	0.3676	544.26	40.82	16.09	1.2996	6.50	159	10.63
7	0.2761	470.79	35.26	13.11	1.7248	4.49	66	1.55
8	0.2710	459.71	34.47	14.16	1.8820	4.39	98	7.04

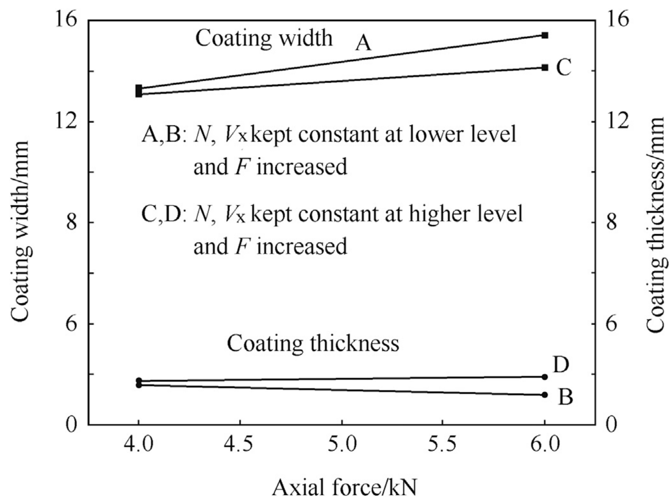

Fig. 7. Influence of axial force on coating width and thickness.

around 1.25 mm and the coating width is at the extreme ends of 12 and 16 mm. It may be noted that the torque for these combinations is nearly same (around 6.5 N-m). This implies that axial force has a dominating influence on all the physical and mechanical properties of the coating.

4.2. Mechanical properties

The dependence of mechanical properties of the coating, namely strength and bend ductility, on the coating width and thickness is observed from the output responses. The output responses are shown in conjunction with the plots in Fig. 10. The maximum strength and bend ductility are observed at the lowest and highest values of coating width and lower thickness (parameter combinations 3 and 6), as shown in Fig. 11.

4.3. The effects of parameters

In order to find out the direct effect of individual parameters on the physical characteristics of the coatings and their

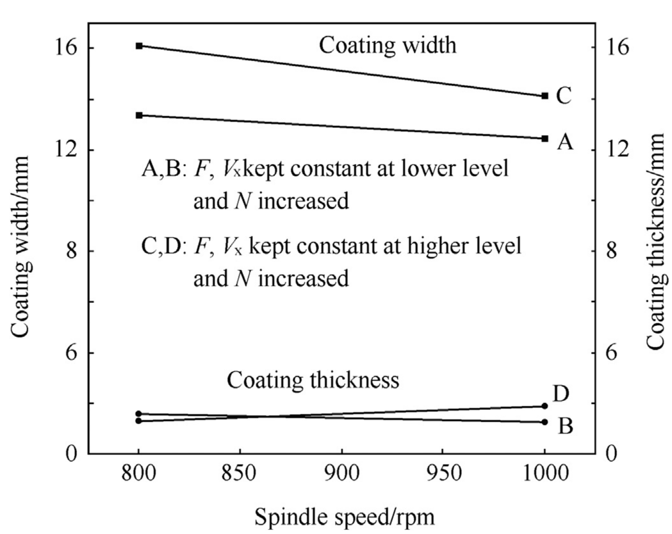

Fig. 8. Influence of spindle speed on coating width and thickness.

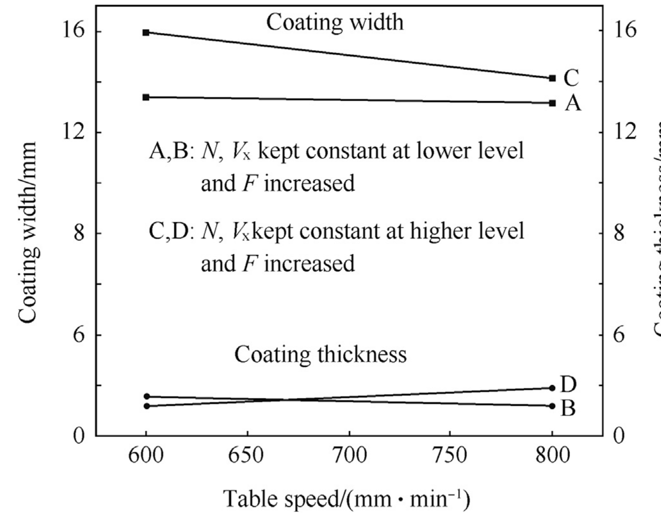

Fig. 9. Influence of table speed on coating width and thickness.

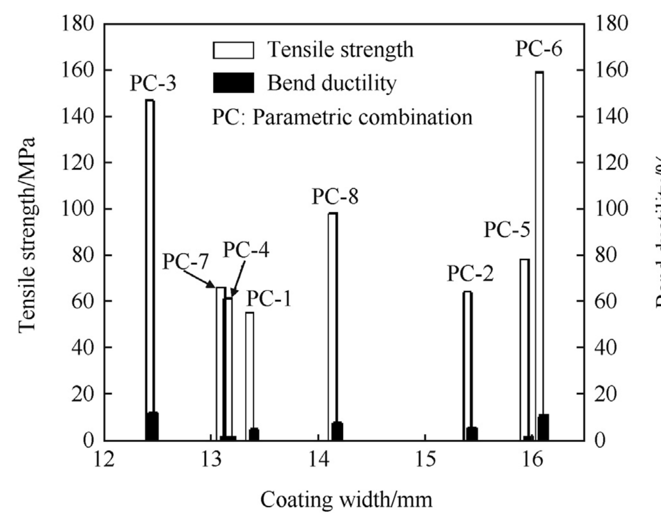

Fig. 10. Mechanical properties of coating width.

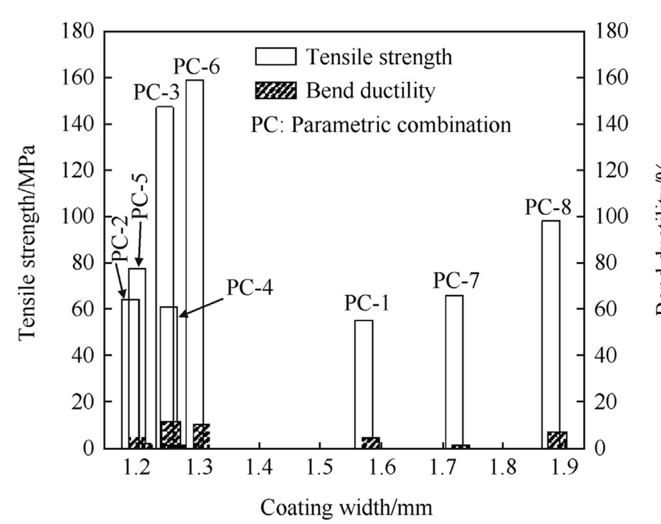

Fig. 11. Mechanical properties of coating thickness.

Table 5
Analysis of direct and interaction effects of parameters on responses.

Parameter combinations (PC)	Tensile strength/MPa	Bend ductility (ε)/%	Coating thickness/mm	Coating width/mm
F	21.5	1.19	−0.03	0.99
N	4	−0.03	0.20	−1.99
Vx	18.5	−0.35	0.20	1.22
F N	−75	−4.32	−0.48	−8.13
F Vx	78	6.72	0.78	6.19
N Vx	−10	−1.11	0.97	6.19
F N Vx	11.5	1.73	−0.08	0.55

Table 6
Regression analysis of coating width and thickness.

S. No	Responses	Average/Y	Standard deviation/S	Coefficient of correlation (r)	Regression equation
1	Coating width/mm	14.25	0.53	0.9895	$Y = 14.25 + 1.18X_1 - 0.29X_2 - 0.07X_3 - .04 X_1X - 0.22X_1X_3 - 0.19X_2X_3 - 0.40X_1X_2X_3$
2	Coating thickness/mm	1.60	0.10	0.9859	$Y = 1.60$ Friction surfacing parameters do not show appreciable influence on coating thickness as evident low standard deviation as well as absence of any coefficients for the parameters in the regression equation

interaction effect, the data have been subjected to Yates 'analysis [15] presented in Table 5. The salient observations from this analysis are that the increase in axial force leads to the wider and thin coatings, and the increase in spindle speed has an opposite effect to that observed in respect of axial force while increasing the table speed leads to the increase in both width and thickness of the coating. Increase in the values of $F V_x$ and $N V_x$ results in an increase in width and thickness while the increase in FN leads to the decrease in width and thickness of the coating. The increase in $F N V_x$ leads to the higher width and lower thickness of coating.

4.4. Regression analysis

To understand the influences of surfacing parameters on the physical dimensions of the coatings, the multiple linear regression analysis was made as per the following regression equation

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3$$

where X_1 is the axial force; X_2 is spindle speed; X_3 is table traverse speed; b_0, b_1, b_2 and b_3 are coefficients of response for the respective parameters and their combination; and Y is the response,namely strength, ductility, hardness, width and thickness. Table 6 shows the regression equations for various responses after identifying the most significant factors and interaction effects. The average error for all the responses has been found to be less than 3. The values of the coefficients of the linear regression equation were calculated by the regression method,. All the coefficients were tested for their significance at 95% confidence level. The validity of the regression equations developed is evident from their extremely high coefficients of correlation (r) value for coating width (0.98) and thickness (0.98). It has however been observed that coating thickness trends indicate that process parameters do not exhibit any influence on the thickness of the coating, and hence the standard deviation for this has also been observed to be low.

5. Conclusions

1) The influences of process parameters on coating width and thickness in friction surfacing of mild steel with aluminium alloy AA6063 were studied. It has been observed that the physical dimensions of coating were influenced by process parameters.
2) Heat input calculations revealed that the parameter combinations with heat input in the range of 67.1 and 40.82 J/mm result in better combination of strength and bend ductility. Either higher heat input or low heat input is not favourable. The coefficient of friction for these parameter combinations is the highest (0.3744)
3) Analysis of the mechanical properties by Yates' Order revealed that the increase in axial force leads to improved strength as higher axial force results in lower coating thickness.
4) Individual parameters and their interactive effects have also been observed in respect of physical characteristics of the coatings.
5) Increase in the values of combination of axial force and table speed leads to higher coating width and thickness.
6) Increase in the values of three parameter combinations results in the increase in width and the decrease in the thickness of the coating

7) Maximum strength and ductility were observed at a coating thickness of 1.25−1.3 mm at extreme ends of coating width.

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