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Friction surfaced tool steel (H13) coatings on low carbon steel: A study on the effects of process parameters on coating characteristics and integrity

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Tool steel H13 was friction surfaced on low carbon steel substrates. Mechtrode (consumable rod) rotational speed and substrate traverse speed were varied, keeping the axial force constant. The effects of process parameters on coating characteristics and integrity were evaluated. A process parameter window was developed for satisfactory deposition of tool steel coatings. Coating microstructures were examined using optical microscopy, scanning electron microscopy, and transmission electron microscopy. Microhardness tests, shear tests, and bend tests were conducted on coatings. The results show that coating width is a strong function of mechtrode rotational speed, while coating thickness is mainly dependent on substrate traverse speed. Lower mechtrode rotational speeds results in wider coatings, while higher substrate traverse speeds produce thinner coatings. Thinner coatings exhibit higher bond strength than thicker coatings. Coatings show no carbide particles, yet exhibit excellent hardness (above 600 HV) in as-deposited condition due to their martensitic microstructure.

1. Introduction

Surface engineering techniques are increasingly being used in manufacturing industries to extend the life of components. Fusion welding based techniques such as plasma transferred arc surfacing [1], shielded metal arc welding [2], laser cladding [3], and submerged arc cladding [4] are in wide industrial use for producing overlay coatings. Apart from high levels of dilution (defined as the percentage of base metal in weld metal) and coarse cast microstructures, coatings produced using these processes often suffer from hot cracking and porosity [5]. Further, dissimilar metal combinations are difficult to deal with due to undesirable brittle intermetallic formation.

Friction surfacing, being a solid-state process, overcomes many of these problems and offers great flexibility in terms of materials — a variety of metallic materials can be deposited on a variety of metallic substrates. The process has already been successfully used in industry for edge retention of industrial knifes [6]. Other potential applications of this process include repair of turbine blades, hardfacing of valve seats, agricultural implements, and bucket teeth of earth moving equipment, etc.

In friction surfacing (Fig. 1), a rotating cylindrical consumable rod (mechtrode) is fed against a substrate with certain axial force acting continuously on the rod. Heat is generated due to friction, which softens the rubbing end of the consumable rod. The substrate is traversed horizontally with respect to the vertical consumable rod. As the substrate moves, the plasticized metal at the tip of the mechtrode gets deposited onto the substrate. The axial force consolidates the plasticized metal and results in the formation of a continuous coating. Till date, coatings in materials such as tool steel, stainless steel, inconel, aluminum and aluminum metal matrix composites were attempted on mild steel and aluminum substrates [7–11].

Proper selection of process parameters is vital for obtaining quality coatings using friction surfacing. The three main friction surfacing parameters are: rotational speed of the consumable rod, substrate traverse speed, and axial force acting on the rotating consumable rod. Coating characteristics such as coating width, coating thickness and bond strength strongly depend on these parameters for a given system of consumable rod and substrate materials. Although mathematical models for parameter optimization were developed for friction surfacing of stainless steels over mild steel substrate [6,12,13], information on the effects of these parameters on coating quality characteristics is limited. Moreover, process parameter selection is highly dependent on the properties of the mechtrode material in question. In this work, we aim to develop a process parameter window for producing quality H13 tool steel coatings over mild steel substrates. H13 tool steel was chosen because of its industrial relevance. Coating width, coating thickness, and coating/substrate bond strength were studied as a function of mechtrode rotational speed and substrate traverse speed.

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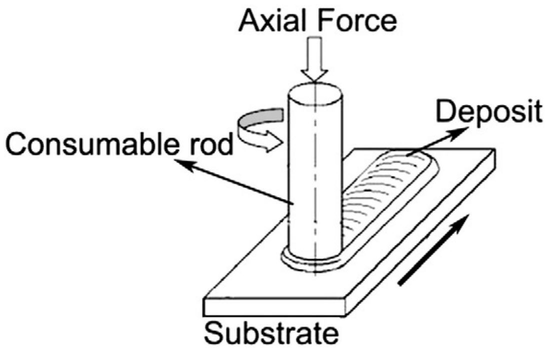

Fig. 1. Schematic of friction surfacing process.

2. Experimental work

Tool steel grade H13 (chemical composition in wt.%: 0.37 C, 0.37 Mn, 5.56 Cr, 0.27 Ni, 1.22 Mo, 1.0 V) consumable rods (18 mm diameter and 150 mm length) were used. A low carbon steel plate (10 mm thick, chemical composition in wt.%: 0.12 C, 0.42 Mn, 0.02 P, 0.01 S) was used as the substrate. The friction surfacing experiments were carried out in a custom designed and developed friction surfacing machine, capable of applying up to 10 kN axial force and of spindle speeds up to 3000 rpm.

In an earlier investigation by the authors [14], it was found that satisfactory tool steel coatings can be obtained using a mechtrode rotational speed of 800 rpm, substrate traverse speed of 4 mm/s and an axial force of 10 kN (corresponding to an axial pressure of 38 MPa). In the current study, with the above settings as the reference, friction surfacing experiments were carried out over a broad range of mechtrode rotational speed and substrate traverse speed. The mechtrode rotational speed was varied from 350 rpm to 2400 rpm while keeping the substrate traverse speed and axial force constant at 4 mm/s and 10 kN, respectively (Table 1). Similarly, the substrate traverse speed was varied from 1.2 mm/s to 4.4 mm/s while keeping the mechtrode rotational speed and axial force constant at 800 rpm and 10 kN, respectively (Table 2). Single-track coatings of 100 mm length were produced for each condition listed in Table 1 and Table 2. Coating width and coating thickness were precisely measured using a digital vernier caliper and a digital micrometer, respectively, which were further verified using an optical microscope.

Transverse sections from friction surfaced deposits were prepared for microstructural examination following standard metallographic procedures. The tool steel coating was etched using 4% Nital and the mild steel substrate was etched using 2% Nital. Optical microscopy and scanning electron microscopy (SEM) were used for examining coating microstructures. Further, transmission electron microscopy (TEM) was used for gaining greater insights into coating microstructures. For TEM examination, 0.3 mm thick slices (in length-width plane) were cut from the coatings using a slow speed saw. These slices were thinned to about 100 μm using emery papers. Further thinning of the samples was carried out in an electrolytic twin jet polisher using a solution consisting of 10% perchloric acid and 90% methanol, maintained at −30 °C. The samples were examined in a Philips CM20 transmission electron microscope operated at 200 kV. Shear tests as per ASTM A264 were conducted on all the coatings to evaluate bond strength. Fig. 2 shows a schematic of the shear test set-up and Fig. 3 shows a typical shear test specimen. These specimens were carefully prepared using

Table 1
Process parameter combinations used in the first set of friction surfacing experiments (for investigating the effects of mechtrode rotational speed).

Mechtrode rotational speed (rpm)	Substrate traverse speed (mm/s)	Axial force (kN)
350	4	10
650	4	10
800	4	10
1200	4	10
1600	4	10
2000	4	10
2400	4	10

Table 2
Process parameter combinations used in the second set of friction surfacing experiments (for investigating the effects of substrate traverse speed).

Mechtrode rotational speed (rpm)	Substrate traverse speed (mm/s)	Axial force (kN)
800	1.2	10
800	1.6	10
800	2.0	10
800	2.4	10
800	2.8	10
800	3.2	10
800	3.6	10
800	4.0	10
800	4.4	10

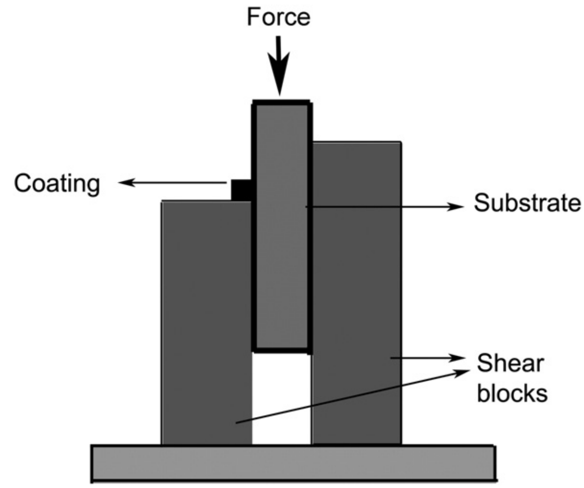

Fig. 2. Schematic of shear test set-up.

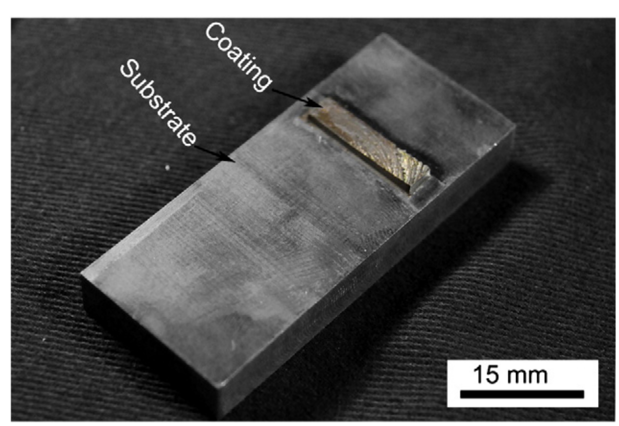

Fig. 3. Typical shear test specimen.

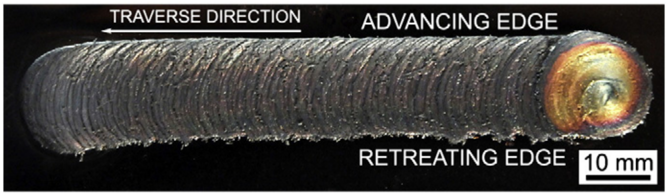

Fig. 4. Typical friction surfaced tool steel coating. Arrow indicates substrate traverse direction.

milling, ensuring that no material removal occurs from the substrate.

Three-point bend tests were performed as per ASTM E290 to assess the coating integrity. On bend test specimens, unbonded coating edges were trimmed off, which would otherwise lead to easy crack initiation (lack of bonding at the deposit edges is an inherent problem in friction surfacing, which will be discussed subsequently). Tests were conducted on a universal testing machine with the coating on the tension side.

3. Results and discussion

3.1. Coating appearance

A typical friction surfaced tool steel coating is shown in Fig. 4. Regularly-spaced ripples can be seen on the coating top surface. Ripple formation is related to the nature of material transfer from the consumable rod to the substrate. The plasticized metal from the tip of the consumable rod is transferred in discrete layers of elliptical shape and each layer gets deposited one after the other with a small offset as the substrate traverses. According to Chandrasekharan et al. [7], there exists a certain time gap between successive material transfer events, while the substrate keeps moving all the time — the layered nature of the coating is a consequence of these two. The frequency of material transfer in layers thus determines the smoothness or roughness of the coating surface.

From Fig. 4, it can be seen that the deposit edge on the advancing side (where mechtrode rotation and substrate movement are in the same direction) is smooth and straight. In contrast, the deposit edge on the retreating side (where mechtrode rotation and substrate movement are in opposite directions) is uneven with serrated appearance (similar designations of advancing and retreating sides are in common use in friction stir welding literature [15]). Further, the serrated edges on the retreating side were observed get more pronounced in coatings produced at higher substrate traverse speeds. These observations suggest that during friction surfacing material flow occurs in a spiral pattern. A closer examination of the end portion of the coating reveals such spiral patterns (Fig. 4). The spiral begins on the advancing side and ends on the retreating side.

Another common feature of friction surfaced coatings is the presence of a small unbonded region at the deposit edges on both advancing and retreating sides, as can be seen in Fig. 5. Generally, the width of this unbonded region on either side is less than 10% of the coating width. Between the advancing and retreating sides, the unbonded region seemed to be slightly wider on latter side. Away from the deposit edges, the coating was found to be well-bonded to the substrate (i.e., without any physical discontinuities), which accounted for more than 80% of the coating width. Similar observations were reported in an earlier study on friction surfacing of stainless steels, in which the width of the well-bonded coating was found to be 0.875 times the diameter of the consumable rod [13]. How to overcome the problem of edge lack of bonding and how to produce a defect-free multi-track coating (for area coverage) are wide open questions at the moment.

3.2. Coating width and thickness

Two sets of friction surfaced coatings were produced using 18 mm diameter H13 grade tool steel rods to study the effects of mechtrode rotational speed and substrate traverse speed on coating characteristics and integrity. Coating thickness, coating width, and coating/substrate interfacial bond strength were considered as the main coating quality attributes [13]. In the first set (Table 1), the substrate traverse speed and axial force were kept constant while varying the mechtrode rotational speed and in the second set (Table 2) the mechtrode rotational speed and axial force were kept constant while varying the substrate traverse speed.

Pictures of friction surfaced coatings produced at different mechtrode rotational speeds are shown in Fig. 6. No coating was obtained at 350 rpm due to insufficient frictional heating; rather a crater was formed along the substrate surface due to the ploughing action of the partially-deformed mechtrode. Discolorations, indicative of significant amount of oxidation, was observed on the coatings produced at rotational speeds greater than 1200 rpm due to higher heat inputs. Coatings produced at higher mechtrode rotational speeds were narrower compared to those produced at lower mechtrode rotational speeds. For example, coatings made using a mechtrode rotational speed of 2400 rpm were only 10.5 mm wide, while those produced using 800 rpm were 18 mm wide. Coatings produced at higher mechtrode rotational speeds were also smoother compared to those produced at lower mechtrode rotational speeds, due to increased frequency of material transfer. However, mechtrode rotational speed did not significantly affect the coating thickness, which was 1.3 mm at 800 rpm and 1 mm at 2400 rpm. Examination of the second set of coatings showed that the substrate traverse speed had no significant effect on the coating width. However, coating thickness decreased from 2.7 mm to 1.35 mm when the traverse speed was increased from 1.2 mm/s to 4.4 mm/s.

A better understanding of the effects of process parameters on coating width can be obtained from Fig. 7. Fig. 7a shows variations in coating width as a function of substrate traverse speed at a constant mechtrode rotational speed of 800 rpm and Fig. 7b shows variations in coating width as a function of mechtrode rotational speed at a constant substrate traverse speed of 4 mm/s. Substrate traverse speed did not significantly affect the coating width. For example, coatings made using a substrate traverse speed of 1.2 mm/s were 23 mm wide, while those produced using 4.4 mm/s were 18 mm wide. For all substrate traverse speeds, the coating width was not less than the diameter of the consumable rod (18 mm). In contrast, a significant

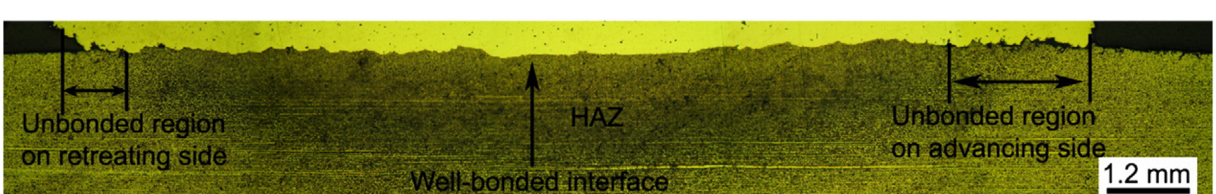

Fig. 5. Transverse section of a friction surfaced tool steel coating.

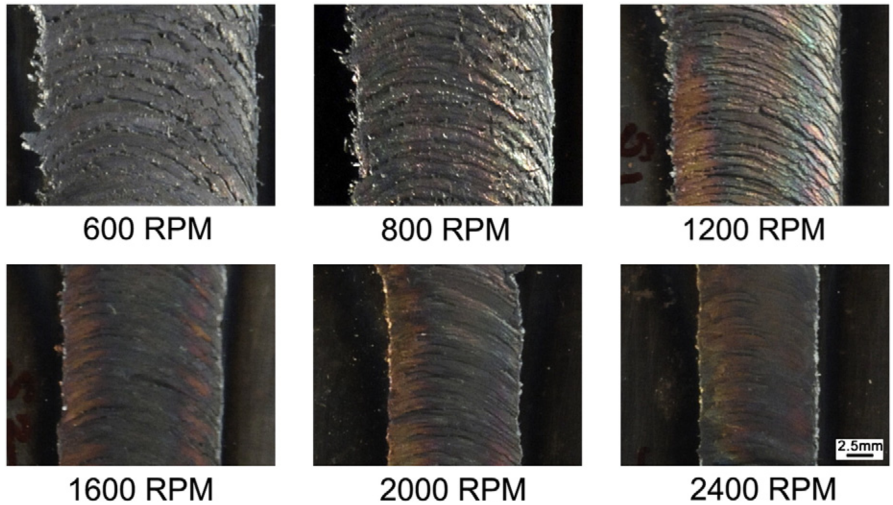

Fig. 6. Plan view of coatings produced at different mechtrode rotational speeds.

reduction in coating width was observed at higher mechtrode rotational speeds. When the mechtrode rotational speed was increased from 800 rpm to 2400 rpm (at a constant traverse speed of 4 mm/s), the coating width decreased from 18 mm to 10.5 mm. The results thus show that coating width is more sensitive to mechtrode rotational speed. This can be explained based on the concept of “real

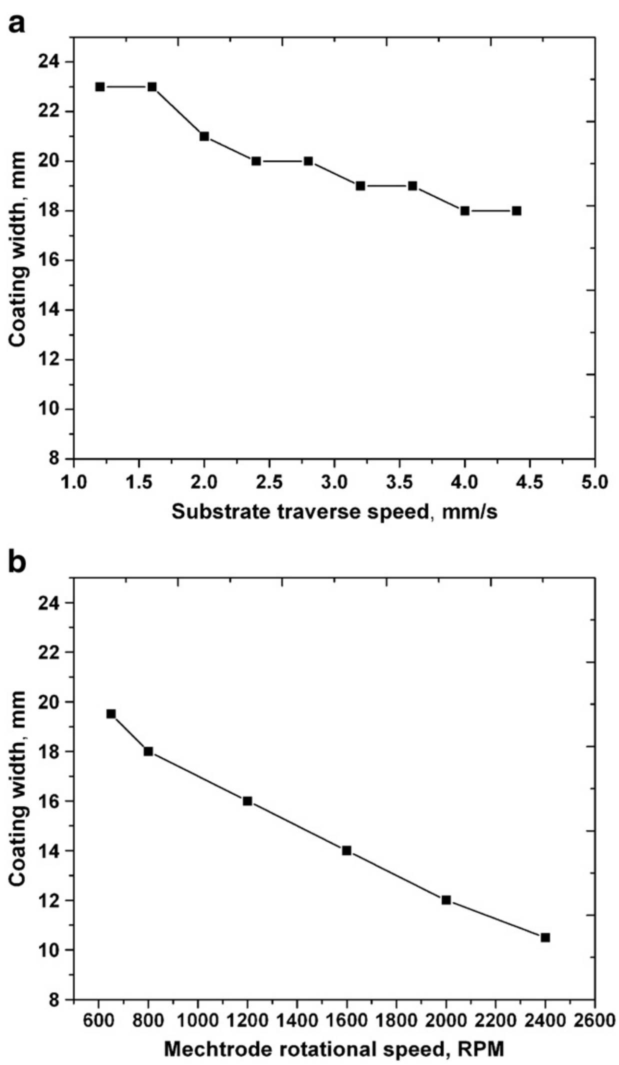

Fig. 7. Coating width as a function of substrate traverse speed (a) and mechtrode rotational speed (b).

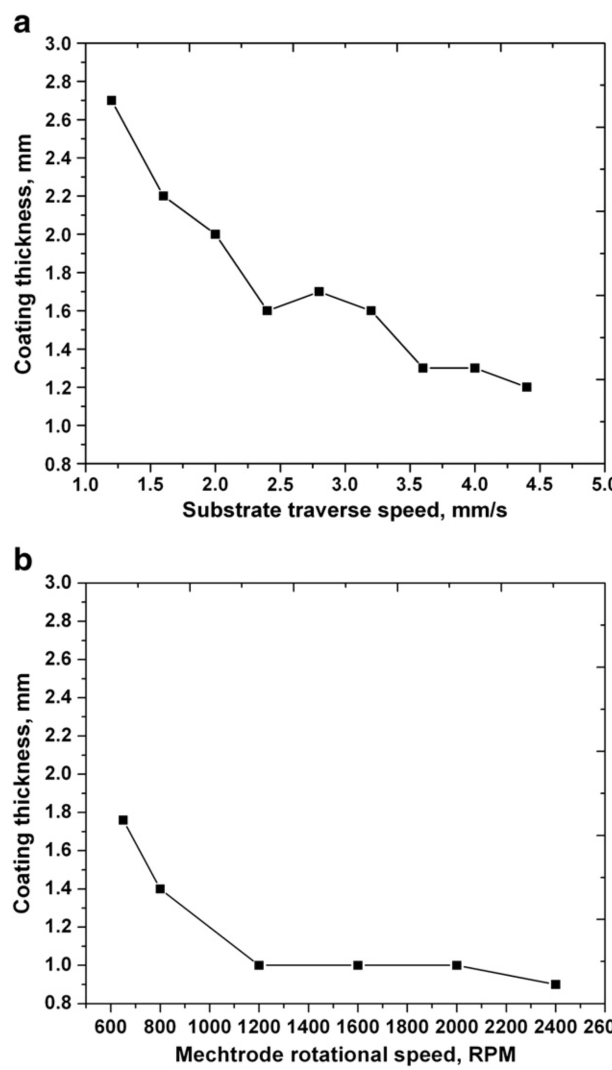

Fig. 8. Coating thickness as a function of substrate traverse speed (a) and mechtrode rotational speed (b).

rotational contact plane" [19]. Real rotational contact plane refers to the actual/instantaneous contact plane between the rotating consumable rod and the substrate during friction surfacing. It is through this plane that metal transfer occurs from the mechtrode to the substrate. The area of the real rotational contact plane has been shown to decrease with increase in mechtrode rotational speed [19]. Hence, at higher rotational speeds metal transfer is restricted to a smaller contact plane, leading to narrower coatings.

Fig. 8 shows variations in coating thickness as a function of substrate traverse speed and mechtrode rotational speed. The retreating edge of the deposit became more and more irregular (serrated) with increasing substrate traverse speed. Considerable reduction in coating thickness was observed with increase in substrate traverse speed. While there was some reduction in coating thickness with increase in mechtrode rotational speed, the effect was not as strong as that of substrate traverse speed. The results thus show that coating thickness is more sensitive to substrate traverse speed than mechtrode rotational speed.

3.3. Bond strength

Coating/substrate bond strength is a more critical requirement when compared to coating width and thickness. Fig. 9 shows the interface microstructures (at the center of the coating width) of the coatings produced at different mechtrode rotational speeds. In all the cases, the coating/substrate interface was free from physical discontinuities. It is thus possible to achieve well-bonded coatings over a wide range of mechtrode rotational speed. Variations in mechtrode rotational speed did not seem to affect the character of the interface. However, some differences were noticed in the substrate microstructure near to the coating/substate interface due to heat input variations.

Fig. 10 shows the interface microstructures of the coatings produced at different substrate traverse speeds (at the center of the coating width). Coatings produced at lower substrate traverse speeds showed some undonded regions along the coating/substrate interface. These coatings were found to be thicker as well (due to increased residence time). At higher substrate traverse speeds, above 3.2 mm/s, the coatings were well-bonded and were also thinner. The coating/substrate interface is shown at a higher magnification in Fig. 11. At higher traverse speeds, the coating/substrate interface tended to be more irregular, resulting in a mechanical anchoring effect in addition to metallurgical bonding between the coating and the substrate [7].

The coatings, in all cases, showed no carbide particles (Fig. 12a), while the consumable rods used for friction surfacing consisted of a large number of carbide particles (Fig. 12b). A lath martensitic microstructure was observed in the coatings, as can be seen in Fig. 12a. The individual martensitic laths can be clearly seen in the TEM bright field image shown in Fig. 13. Selected area diffraction (SAD) was used to further confim the presence of martensite in the coatings. During friction surfacing, temperatures attained in the contact region are in the range of 1100 °C to 1300 °C. Thus, during heating, the tool steel rod gets effectively austenitized with the carbide particles more or less completely dissolved. During cooling,

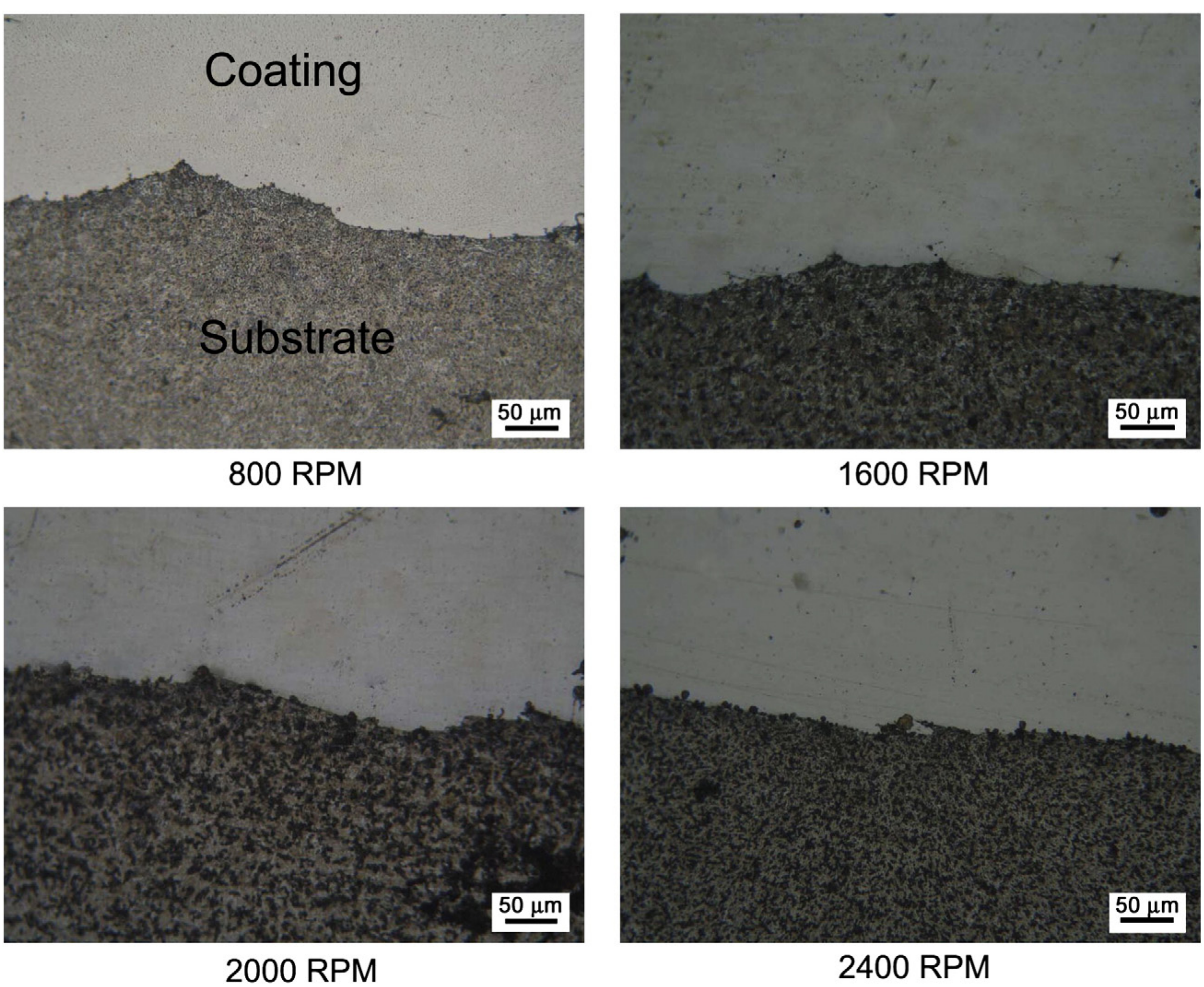

Fig. 9. Interface microstructures of coatings produced at different mechtrode rotational speeds.

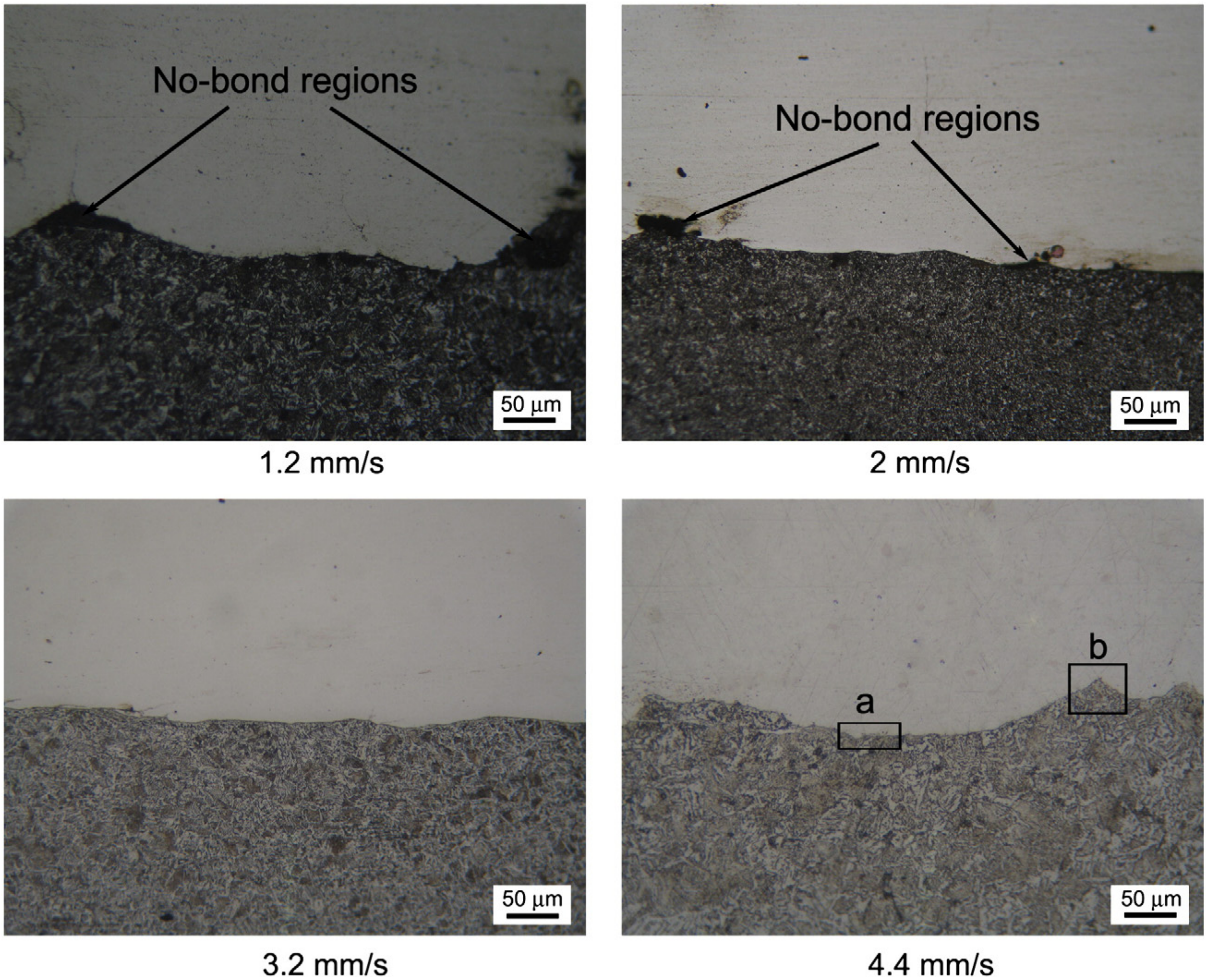

Fig. 10. Interface microstructures of coatings produced at different substrate traverse speeds.

since H13 tool steel is air-hardenable, cooling rates in friction surfacing are high enough to prevent carbide re-precipitation and to cause transformation of austenite to martensite.

Shear tests and bend tests were conducted to evaluate the coatings. In an earlier work, "push-off testing" was employed to estimate the bond strength of friction surfaced stainless steel coatings [6]. This method involved drilling a hole from the back of the substrate and pushing a pin through the hole. Shear testing can facilitate a better assessment of the coating/substrate bond strength. The results of shear testing, carried out according to ASTM 264, are shown in Fig. 14. The shear strength was calculated by dividing the applied load by the coating cross-sectional area. It should be noted that while this may not actually represent the shear stress acting on the coating, the procedure adopted can facilitate a relative assessment of coatings produced under different process conditions.

Three possible failure locations can be expected in shear tests: (1) failure at the interface, (2) failure in the coating, (3) failure in the substrate. All the coatings produced in the current work failed either at the coating/substrate interface or in the coating. Thicker coatings (produced at substrate traverse speeds less than 2 mm/s) were observed to fail at the coating/substrate interface at relatively lower shear loads, which corroborates well with the observation that bonding was not satisfactory in these coatings. At lower substrate traverse speeds, material gets transferred to the substrate in thicker layers. Under these conditions, effective consolidation may not occur for want for sufficient axial thrust. At substrate traverse speeds above 2 mm/s, failures were found to occur in the coating at higher shear loads. This is possibly due to: (1) at higher substrate traverse speeds material transfer occurs in thinner layers, facilitating better consolidation of the plasticized metal, (2) the hard martensitic microstructure of the coating is inherently brittle, making crack initiation and propagation easier.

As can be seen in Fig. 14b, an increase in interfacial bond strength was observed with increase in mechtrode rotational speed. Coatings produced at 2400 rpm showed the highest interfacial bond strength (295 MPa). At higher mechtrode rotational speeds, more heat is generated, facilitating sound bonding. In an earlier study on friction surfacing of tool steel over mild steel, improper bonding was reported at mechtrode rotational speeds close to 3000 rpm, which is probably a consequence of using too low a substrate traverse speed (1.38 mm/s) [9]. In the current study, no such degradation in bonding at higher mechtrode rotational speeds was observed. Based on the findings of this investigation, it appears that higher mechtrode rotational speeds and higher substrate traverse speeds benefit coating/substrate bond strength.

Three-point bend tests were carried out to assess the coating integrity. All the coatings began to crack at a bend angle of about 10°, which is not surprising given the inherent brittleness of tool steel coatings. Similar observations were reported in a previous work [9]. Continued bending of the specimens to higher bend angles (more than 90°), which was deliberate, resulted in development of multiple cracks in the coating, but, interestingly, there was no coating peel-off or delamination. Fig. 15 shows some of the bent specimens of coatings produced at various substrate traverse speeds. Although the cracked

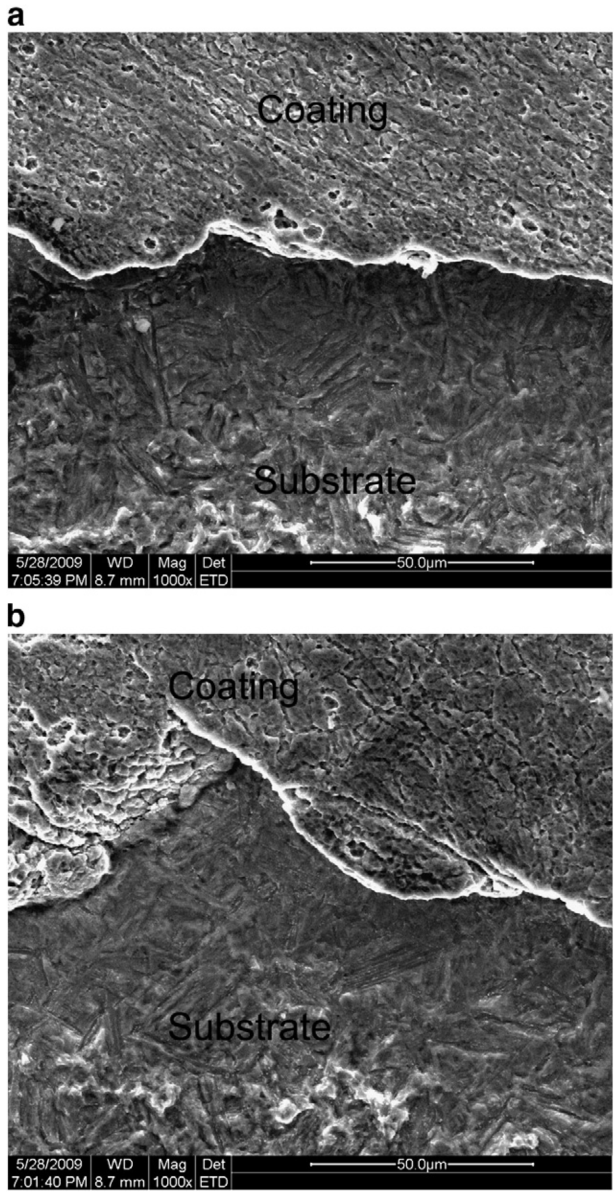

Fig. 11. SEM microstructures of a coating produced using a substrate traverse speed of 4.4 mm/s (corresponding to regions a and b in Fig. 10).

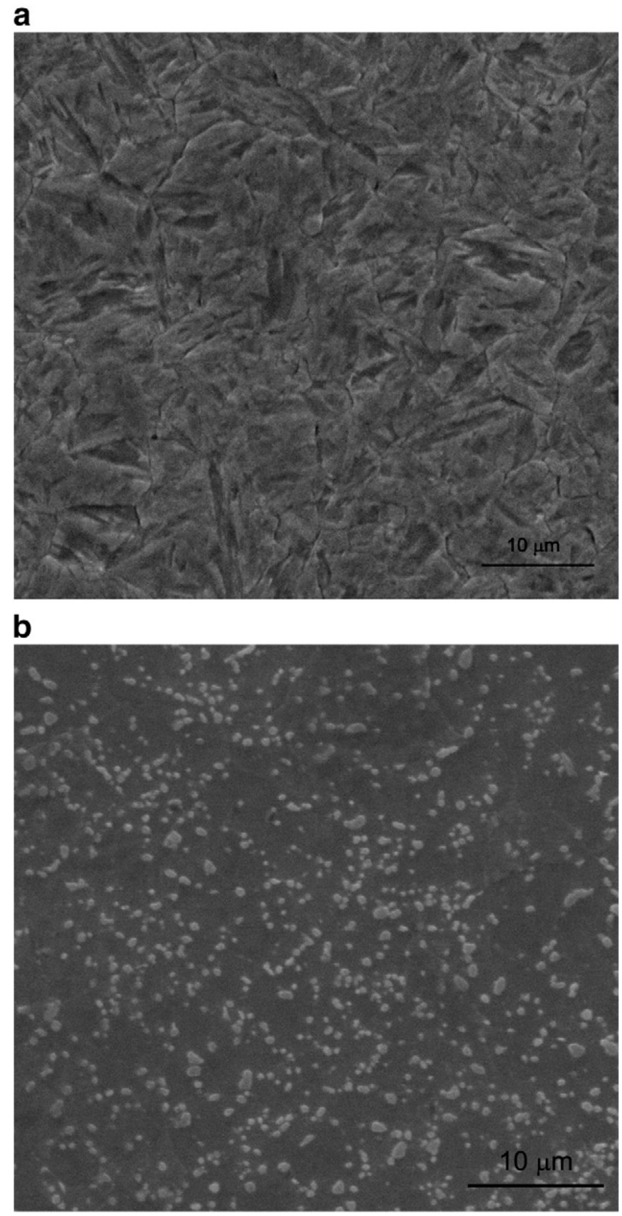

Fig. 12. SEM microstructures: (a) friction surfaced tool steel coating, (b) tool steel consumable rod.

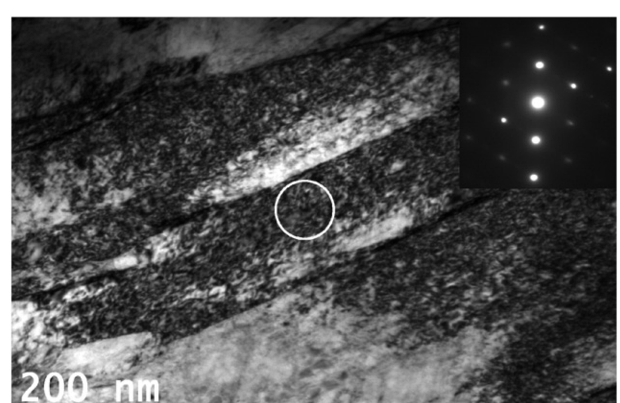

Fig. 13. Bright field TEM image of a tool steel coating showing lath martensite. The SAD pattern shown in the inset was obtained from the encircled region.

portions of the coatings showed a tendency to lift up, there was no coating delamination, which can be seen in Fig. 16. Further, cracks initiated in the coating were observed to propagate into the substrate upon continued bending. This can be clearly seen in Fig. 16 (indicated by arrow). Bend test results were still better for coatings produced at higher mechtrode rotational speeds. As can be seen in Fig. 17, coatings showed multiple parallel cracks, but without any delamination and lift-up. The cracked portions remained in good contact with the substrate (Fig. 18). Overall, the results of bend testing suggest good coating integrity and strong bonding between the coating and the substrate.

3.4. Heat-affected zone

In friction surfacing, heat is primarily generated by friction between rotating mechtrode and substrate. The process begins with rotating the mechtrode against the substrate. The substrate is not immediately moved. With time, the mechtrode gets sufficiently heated up and the material at the rubbing end of the mechtrode

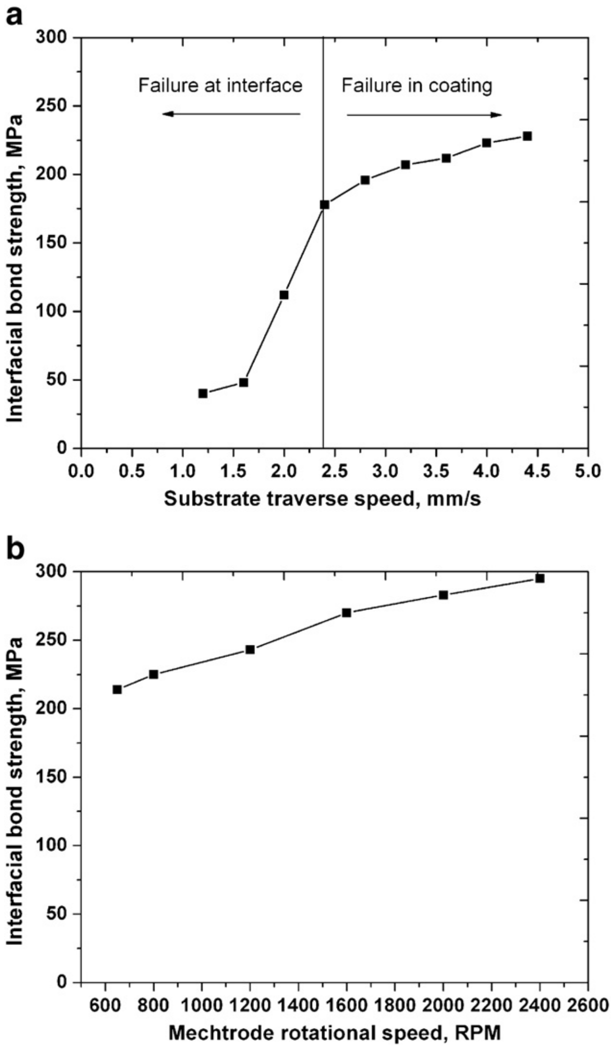

Fig. 14. Interfacial bond strength as a function of substrate traverse speed (a) and mechtrode rotational speed (b).

Fig. 16. Close-up picture of a bent coating, produced using a substrate traverse speed of 3.2 mm/s.

becomes sufficiently plastic. It is after this little wait time (referred as touch-down period or the dwell time) that the substrate is made to move. For stainless steels, the dwell time required for satisfactory coating falls in the range of 30 s to 37 s for different mechtrode rotational speeds [16]. In the current study, a dwell time of 30 s was found to be adequate. Heat generated at the rubbing interface flows into the mechtrode as well as into the substrate. At the rubbing end of the mechtrode, temperatures high enough to cause significant localized softening of the material are quickly attained. Plastic flow occurs under the influence of axial force. On the substrate side, however, temperatures attained are much lower as heat dissipates faster away from the rubbing interface through the substrate owing to its larger size. Nevertheless, frictional heating results in a thin heat-affected zone (HAZ) in the substrate directly underneath the coating. The dark-etched region underneath the coating in Fig. 5 is the HAZ. As can be seen, it was about 1.5 mm deep (at the center of the coating) and spans practically over the entire coating width. The depth of HAZ is the maximum at the center of the coating, which gradually reduces towards the deposit edges on either side.

Heat-affected zone size is basically a function of the amount of heat generated at the coating/substrate interface, which is dependent on friction surfacing process parameters [17]. Fig. 19 shows how substrate traverse and mechtrode rotational speeds influence the depth of HAZ. The HAZ depth was found to increase considerably with decrease in substrate traverse speed (Fig. 19a), which implies more heat input into the substrate. In contrast, mechtrode rotational speed only marginally affected the HAZ depth, as can be seen in Fig. 19b. Thus, HAZ depth appears to be more sensitive to substrate traverse speed than mechtrode rotational speed. Higher substrate traverse speeds help minimize the size of HAZ.

In conventional frictional welding, where two rods are rotated against each other, heat generation has been shown to be maximum in the peripheral regions (where linear velocity is maximum) and minimum at the center (where linear velocity is zero) [18]. Consequently, friction welds show a relatively wider HAZ at the periphery. In friction surfacing, however, this does not seem to hold, despite very close similarities between the two processes. As can be

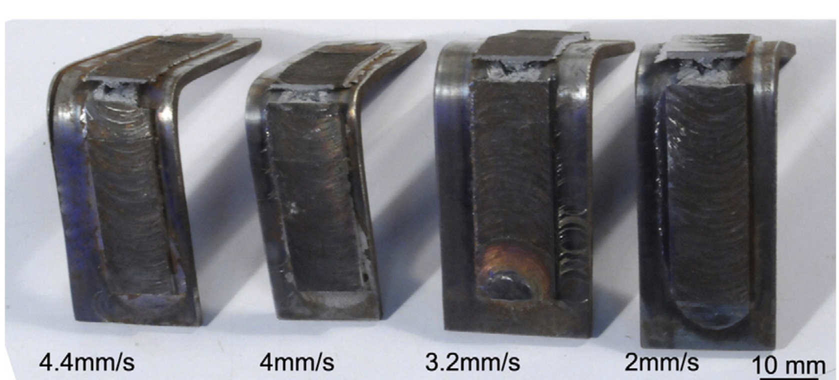

Fig. 15. Bent specimens of coatings produced at different substrate traverse speeds.

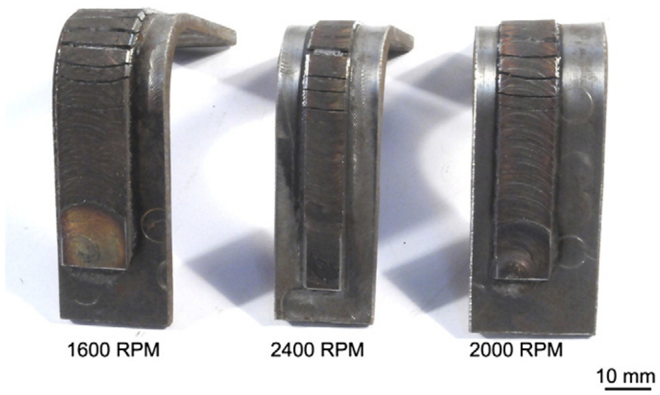

Fig. 17. Bent specimens of coatings produced at different mechtrode rotational speeds.

seen in Fig. 5, the depth of HAZ is the maximum at the center of the coating, which gradually reduces towards the deposit edges on either size. This suggests that higher heat concentration occurs at the center of the rubbing interface than in the peripheral regions, which is counter-intuitive. In standard friction welding, two rods of equal dimensions are rotated against each other. Both sides experience plastic deformation and the interface can be expected to remain flat throughout the process. In contrast, in friction surfacing, a smaller consumable rod is rotated against a larger plate substrate. The consumable experiences large amounts of deformation, while on the substrate side plastic deformation is minimal. Under these conditions, a situation arises, when the process assumes steady-state, in which the mechtrode core maintains good frictional contact with the substrate, while the mechtrode peripheral regions curl-up with no frictional contact. This can possibly explain why the depth of HAZ is more at the center of the coating.

Examination of the consumable rod after friction surfacing revealed some interesting features. As can be seen in Fig. 20a, the center of the consumable rod was slightly concave. This, again, suggests that greater energy concentration occurs at the center of rod. Liu et al. [19] attempted to explain this based on “close-contact melting” phenomenon with an assumption that partial melting occurs during friction surfacing. Close-contact melting can be described as a basic phase change phenomenon occurring at the interface of two solids in contact, one of which was heated above the melting temperature of the other [20]. While partial melting can occur in friction surfacing, in this work, detailed

Fig. 18. Close-up picture of a bent coating, produced using a mechtrode rotational speed of 1600 rpm.

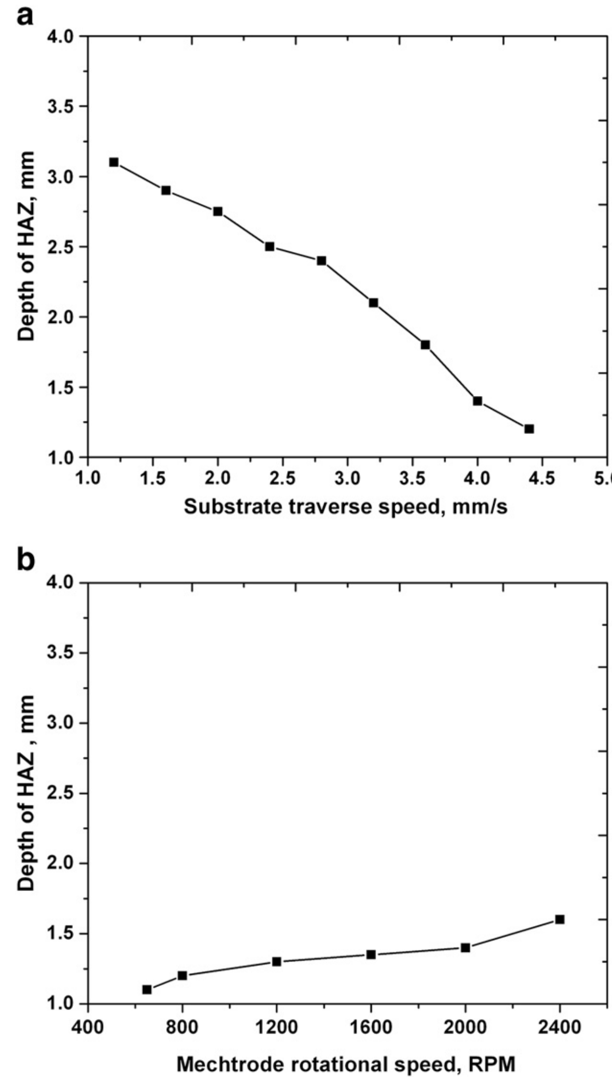

Fig. 19. Depth of HAZ as a function of substrate traverse speed (a) and mechtrode rotational speed (b).

microstructural examination revealed no signs of incipient melting. Therefore, we offer an alternative explanation to mechtrode concavity based on vortex formation, a well-known phenomenon in fluid mechanics. This was based on our observation that all friction surfaced coatings show a discernible spiral pattern at the end portion (Fig. 20b). It is known that the motion of fluid swirling rapidly around a center with an angular velocity is called vortex. Any spiral motion with closed stream line is vortex flow. Forced vertex flow is a situation in which the liquid makes a rotary movement along the flow line, and, at the same time, the liquid element itself rotates [21]. Although it is not appropriate to draw one-to-one correlations between metal flow in friction surfacing and classical fluid flow as the velocities involved are widely different, there are striking fundamental similarities between the two. In friction surfacing a layer of plasticized metal, which is in a visco-plastic state, undergoes swirling action when the consumable rotates at higher speeds resulting in a typical forced vortex flow. The circulating visco-plastic metal tends to get sucked towards the core of the vortex, that is, the center of the consumable rod. At the center, there will be an updraft towards the core of the vortex, causing the hot plasticized metal to move towards the center of the consumable rod, from where the metals gets transferred to the substrate. This possibly

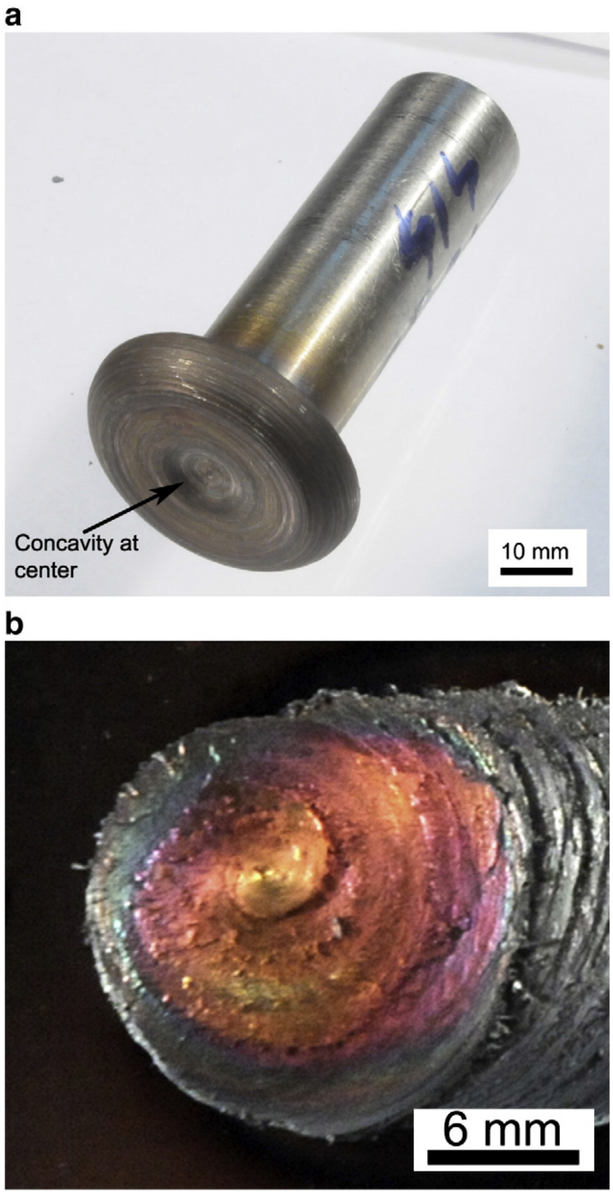

Fig. 20. (a) Condition of the consumable rod after friction surfacing, (b) End portion of a friction surfaced coating.

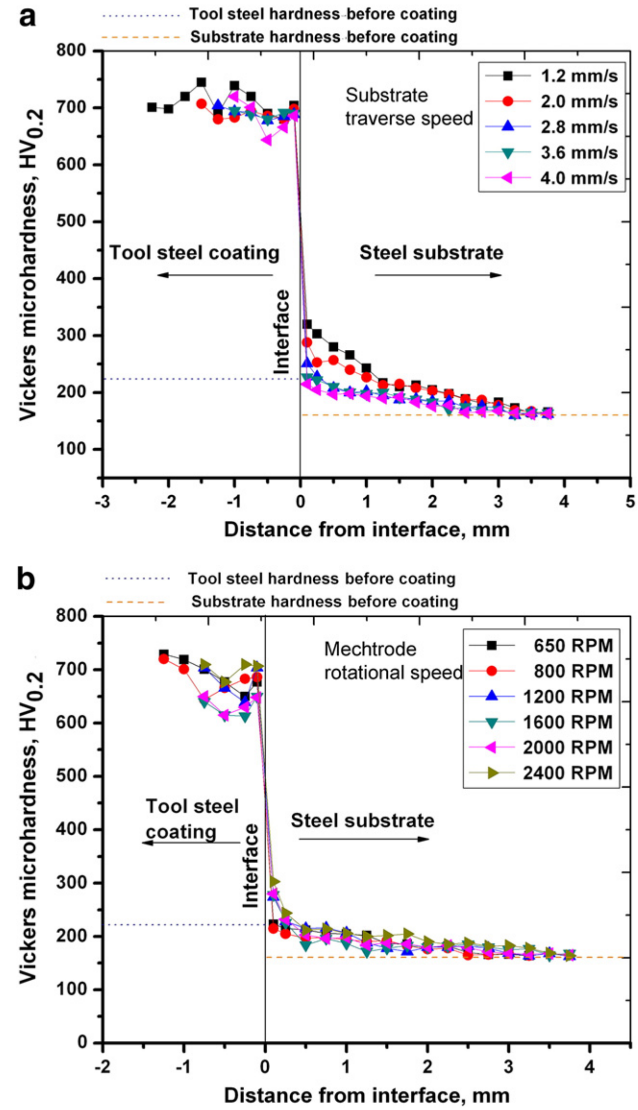

Fig. 21. Microhardness profiles of coatings produced at different substrate traverse speeds (a) and different mechtrode rotational speeds (b).

gives the mechtrode a slight concavity at the center when the process is abruptly ended. Further studies are required to fully understand the flow characteristics in friction surfacing.

3.5. Microhardness

Microhardness profiles of the coatings produced at different substrate traverse speeds and mechtrode rotational speeds are shown in Fig. 21. The tool steel rods used for friction surfacing were in annealed condition with an average hardness of 220 HV. In comparison, all the coatings showed a substantially higher hardness (above 600 HV), although there were no carbide particles. The lath martensitic microstructure observed in the coatings is responsible for this. During surfacing the material attains a temperature in the range of 1100 °C to 1200 °C [16,17], which is well above the austenizing temperature of H13 tool steel. As H13 tool steel is air hardenable, the cooling rates in friction surfacing are high enough to result in martensite formation. Not much difference in coating hardness was observed as a function of process parameters. However, within a given coating, in all cases, there were subtle differences in hardness from the top surface to the interface, probably because of the differences in local cooling rates. On the other hand, process parameters were found to have a significant effect on the hardness of HAZ in the substrate. Coatings produced at lower substrate traverse speeds showed considerably higher hardness, especially in the near-HAZ (immediately adjacent to the interface). In all cases, HAZ hardness was found to decrease as a function of distance away from the interface, eventually attaining the unaffected substrate hardness. Thus, in the case of H13 tool steel, process parameters affect HAZ hardness rather than coating hardness.

Overall, the results suggest that the substrate traverse speed has a greater influence on coating thickness, while the width of the coating is mainly controlled by the mechtrode rotational speed. Lower substrate traverse speed produces thicker coatings, but results in inferior bond strength. Further, it results in a wider HAZ in the substrate, a consequence of higher heat input. Higher substrate traverse and mechtrode rotational speeds result in higher bond strength. However, higher mechtrode rotational speeds lead to substantial reduction in coating width (up to 50%), which is a matter of concern. Therefore, substrate traverse and mechtrode rotational speeds are to be carefully chosen, keeping application requirements in view. All things considered, for tool steels, a mechtrode rotational speed in the range of 800 rpm to 1200 rpm is beneficial in combination with 4 mm/s substrate traverse speed, and 10 kN axial force. It should be noted that these optimum levels of substrate traverse and mechtrode rotational speeds may not result in satisfactory coatings at lower levels of axial force. Our experience shows that use of a sufficiently high axial force is essential for obtaining satisfactory coatings, which is in line with the observations made by Chandrasekaran et al. [9].

4. Conclusions

1) Satisfactory tool steel coatings on mild steel substrate can be obtained by friction surfacing under optimum process parameters (Mechtrode rotation speed: 800 rpm–1200 rpm, Substrate traverse speed: 4 mm/s, and Axial force: 10 kN when using 18 mm diameter consumable rods). Coating width and thickness were found to be strongly influenced by mechtrode rotational speed and substrate traverse speed, respectively. Wider coatings result at lower mechtrode rotational speeds, while higher substrate traverse speeds produce thinner coatings. Coating thickness can thus be controlled by appropriately choosing substrate traverse and mechtrode rotational speeds.
2) For a given mechtrode diameter, process parameter settings that result in thinner coatings favor stronger bonding between the coating and the substrate. For 18 mm diameter H13 tool steel mechtrodes, a coating thickness of 1 mm is recommended.
3) Friction surfaced tool steel coatings show excellent hardness (above 600 HV) in as-deposited condition. There is no need for a post-deposition heat treatment to increase coating hardness.

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