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Study of the interfacial phenomena during friction surfacing of mild steel with tool steel and inconel

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Friction surfacing was carried out with tool steel (AISI 01) and inconel 600 consumables on mild steel 1020 substrate in an argon atmosphere. Inconel bonded strongly with the substrate and there was evidence of interfacial compound formation between the substrate and coating. For tool steel coatings, a sharp boundary between the substrate and coating was observed by scanning electron microscopy. X-ray fluoroscopic imaging also revealed this boundary. Mechanical interlocking between the coating and the substrate appears to be insignificant so adhesion between the coatings and the substrate may be caused by solid-phase bonding. For friction surfacing of both tool steel and inconel, a nominal contact pressure as high as 21.8 MPa was required to obtain an adherent coating of uniform quality.

1. Introduction

Surface engineering has gained wide importance owing to the realized advantages in materials technology, and an important form of surface engineering is the friction surfacing technique. Friction surfacing, which is related to friction welding, utilizes the frictional energy dissipated during operation to generate a layer of hot plasticized metal. The layer of plasticized metal is deposited as a coating without the need for an external heat source. In this process the consumable is the rod of coating metal which moves relative to the substrate in a linear direction while rotating relative to the substrate under the action of external load.

Friction surfacing was first patented as a metal-coating process in 1941 by Klopstock and Neelands [1], but only recently has friction surfacing been developed as a practical industrial process [2–7]. This process has been used for obtaining various hard metal coatings, such as tool steel coatings on mild steel or stainless steel on mild steel. The frictional heating of the substrate by the consumable material leads to the formation of a heat-affected zone (HAZ) close to the interface between the substrate and the consumable, but this HAZ is smaller than that caused by welding [7, 8]. Dissimilar metal coatings are made possible by the generation of high contact stress and intimate contact between the coating material and substrate, which initiates solid-state adhesion between coating and substrate [7]. Strong bonding is achieved between the coating and the substrate in the friction surfacing process if a high contact pressure is used, but this requires expensive machinery [2, 8].

Low-pressure friction surfacing at contact pressures less than 10 MPa was studied with a view to developing a friction surfacing technology that requires simple and cheap equipment [2, 8]. Strongly bonded coatings of tool steel [8] and stainless steel [2] were successfully deposited on mild steel substrate. Friction surfacing was found to be improved by the use of an inert gas atmosphere which restricted the formation of an oxide film between the coating and the substrate, thereby enhancing the bonding properties between them [8]. In the present investigation, the coating of inconel and tool steel on mild steel substrate as a function of basic process parameters was studied. The coatings thus obtained were evaluated using various surface characterization tools and mechanical tests for the integrity of the coating.

2. Experimental procedure

A vertical milling machine was adapted for the purpose of friction surfacing of tool steel and inconel consumable on mild steel substrate. The apparatus was described in an earlier report [9]. The consumable was mounted on a holder, which was attached to the arch of the vertical milling machine. The substrate plate was degreased, cleaned and placed in an enclosed perspex box with an opening in the topside for movement of the consumable rod over the substrate as the table is moved. Initially the table was raised to a position to provide a 5 mm clearance between the consumable rod and the starting plate. The perspex box chamber was flushed with argon and the argon pressure was kept just above atmosphere pressure to ensure an inert atmosphere. The pneumatic cylinder was then raised to bring the substrate plate into contact with the consumable rod and the contact pressure was raised to the desired value by increasing the pneumatic pressure. The milling machine spindle was then

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set in motion, and once sliding contact between the consumable and substrate was established, a heated layer formed at the tip of the consumable. When the tip (loaded end) of the consumable rod glowed red, friction surfacing could begin. For most tests, a dwell time of 5 s was allowed and the transverse feed of the milling machine table was switched on to move the consumable rod over the mild steel substrate plate for about 60 mm. The hot consumable material flows plastically over the substrate to form a thick coating [9]. Figs 1 and 2 show a photograph of the apparatus and a line sketch of the friction surfacing process, respectively

The friction surfacing parameters are provided in Table I for a test programme involving five levels of normal contact pressure, five levels of rotational speed, and six levels of feed rate.

After one pass of the consumable over the substrate, the thus coated substrate was removed from the milling machine for later examination. A 'Fein Focus' X-ray microscope and Cambridge scanning electron microscope (SEM) were used to provide interior and exterior views, respectively, of the coating. The specimens for observation under the X-ray microscope required only limited preparation and, as a result, much of the detail, i.e., structure of the coatings, was preserved which would otherwise be lost due to preparation techniques. Because steel-coated specimens were used, a high target voltage setting in the microscope for obtaining the image on the fluorescent screen was required. Target voltage was varied from 75–85 kV with a filament current of approximately 50–60 μA to obtain the details of the coating. The X-ray images of the coatings were taken on the plane of the coating (i.e., X-rays were passed normal to the plane of the coating).

For SEM observation, the friction-surfaced specimens of tool steel on mild steel (MS) and inconel on MS were plain polished by mounting the specimen in a plastic holder with the transverse side facing upwards. Coating integrity, i.e. the presence of porosity and gaps between the coating and the substrate, were then evaluated by SEM. The evaluation of the bond quality was done by conducting a semi-guided bend test as per ASTM E290-92 (restrained) in which bending of the substrate plate along with the deposit was performed. If the coating detached from the substrate during the test, poor bonding to the substrate is indicated, if the coating failed within itself then good bonding was concluded. The angle at which the coating failed within itself without peeling off during bend test is termed the bend angle, and is used as a measure of bonding between the coating and substrate.

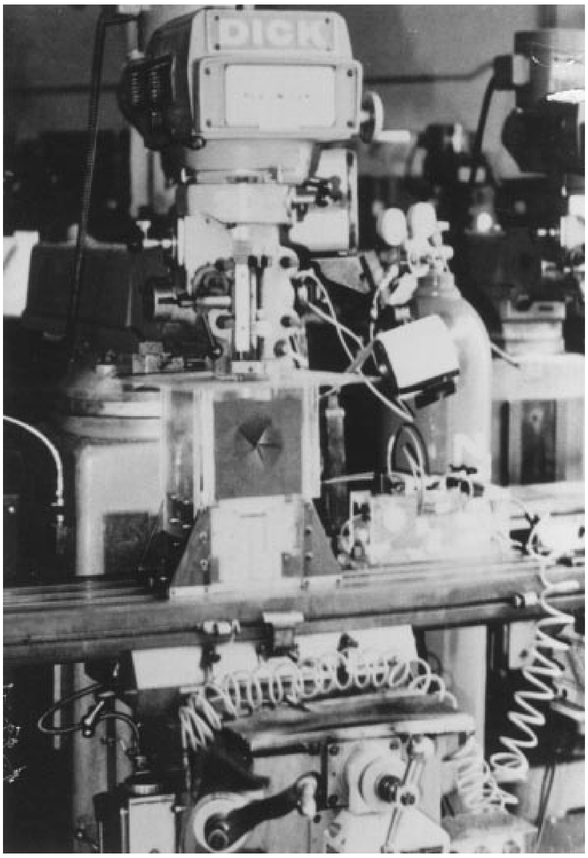

Figure 1 The friction surfacing apparatus.

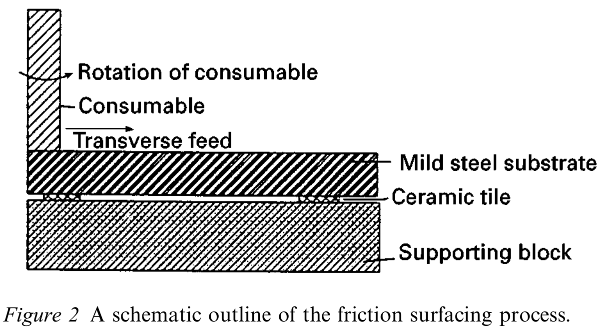

Figure 2 A schematic outline of the friction surfacing process.

3. Results

The quality of the friction-surfaced coating was evaluated using the bend test and visual inspection. The results are given in Table I.

From Table I it is evident that both tool steel and inconel failed to coat at lower speeds (r.p.m.) and lower loads. At lower feed rates, a deposit was formed but the bonding was poor. For both the inconel and tool steel coatings, the maximum bend angle was obtained at 3000 r.p.m. and a nominal contact pressure of 21.8 MPa. However, the optimum feed rates for strong adhesion were different for inconel and tool steel coatings, which is presumably due to the difference in material properties. For tool steel, the bend angle did not exceed 10 °, whereas for inconel the bend angle reached a maximum of 85°. This indicates that the inconel/MS bond strengths were higher than the tool steel/MS bond strengths and that the plasticity of inconel was better than that of the tool steel (85° is close to the limiting angle of bending in the adhesion test).

3.1. Observations by scanning electron microscopy

Fig. 3 shows the interface between the mild steel and the tool steel (specimen T2) interface at a magnification of × 600. It can be clearly seen that the coating side of the interface was smoother in comparison to

TABLE I Friction surfacing parameters of tool steel/inconel coating on mild steel

Test deposit	Coating material	(r.p.m.)	Consumable diameter (mm)	Nominal contact pressure (MPa)	Transverse feed rate (mm s^{-1})	Deposit	Bend angle (deg)
T1	Tool steel (T1)	2500	12	21.8	0.96	Good	Poor bond
T2	Tool steel (T2)	2500	12	21.8	2.93	Good	8
T3	Tool steel (T3)	1000	12	21.8	1.38	Good	Poor bond
T4	Tool steel (T4)	2000	12	21.8	1.38	Good	Fair bond
T5	Tool steel (T5)	3000	12	21.8	1.38	Good	8
T6	Tool steel (T6)	3250	12	21.8	1.38	Good	10
T7	Tool steel (T7)	2500	12	2.72	1.38	–	Observation not possible
T8	Tool steel (T8)	2500	12	10.9	1.38	Poor	Observation not possible
T9	Tool steel (T9)	2500	12	16.7	1.38	Good	8
T10	Tool steel (T10)	2500	12	33.4	1.38	Poor	Observation not possible
I1	Inconel (I1)	2500	12	21.8	1.03	Good	Poor bond
I2	Inconel (I2)	2500	12	21.8	3.04	Good	85
I3	Inconel (I3)	1000	12	21.8	1.60	Good	Poor bond
I4	Inconel (I4)	3000	12	21.8	1.60	Good	85
I5	Inconel (I5)	2500	12	2.72	1.60	–	Observation not possible
I6	Inconel (I6)	2500	12	10.9	1.60	Poor	Observation not possible
I7	Inconel (I7)	2500	12	16.7	1.60	Good	8
I8	Inconel (I8)	2500	12	33.4	1.60	Poor	Observation not possible

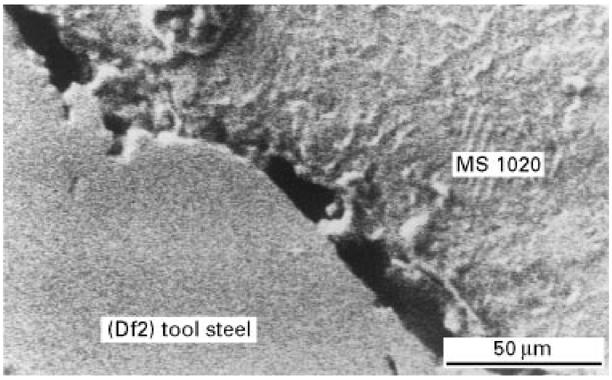

Figure 3 Scanning electron micrograph of tool steel/mild steel interface.

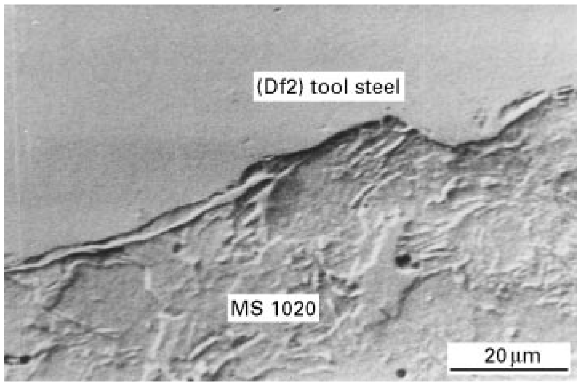

Figure 4 Scanning electron micrograph of the tool steel/mild steel interface.

the substrate side of the interface and it also shows the formation of some smeared particles dispersed along the interface on the substrate side of the coating. This could be due to the lower frictional heat generated, which was just sufficient to initiate plastic flow by softening the tool steel. The mild steel substrate had a deformed structure resembling bonded filaments on the surface near the interface, which is probably due to the frictional heat [10]. This frictional heat could have transformed the mild steel into a semi-solid state where the pressure and sliding speed was sufficient to deform plastically the steel and roll the deformed mild steel, as the coating of the tool steel is continued over the mild steel substrate.

Fig. 4 shows a scanning electron micrograph of the interface between the tool steel and the mild steel (specimen T6) at a magnification of × 1200. It can be observed there is a clear demarcation line between the two surfaces and, similar to Fig. 3, the coating surface was found to be flat and smooth in comparison to the substrate surface which appeared to be wavy [11]. The bonding between the coating and the substrate appears to involve mechanical locking of asperities.

Figs 5 and 6 show the tool steel and the mild steel interface (specimen T6) at a magnification of ×299 and the corresponding X-ray mapped image. It is evident that the coating had a smoother surface compared to the substrate; this is similar to specimen T2. It can also be seen from the X-ray mapped image in Fig. 6, that there is no clear demarcation (plane) line between the tool steel and the mild steel substrate. Instead, mixing between the coating and the substrate is observed, indicated by small light-coloured regions along the interface. This indicates that the generated frictional heat facilitated mixing across the interface. There is no evidence of the formation of a reaction

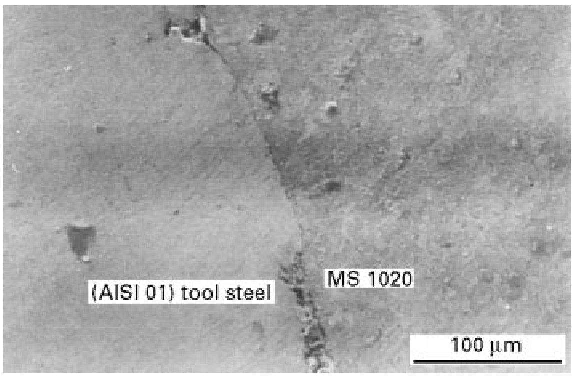

Figure 5 Scanning electron micrograph of the tool steel/mild steel interface.

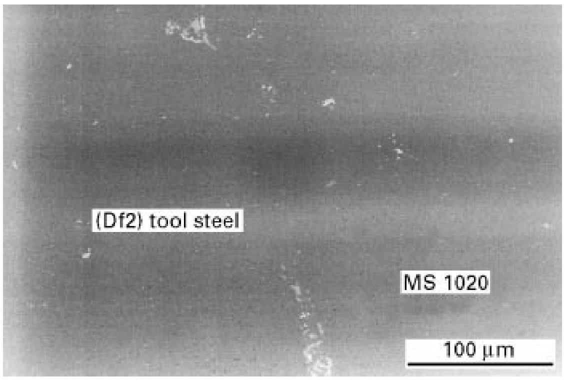

Figure 6 Corresponding X-ray mapped image of the tool steel/mild steel interface.

compound on the coating side of the interface and this is presumably due to such reactions requiring higher frictional heat and longer time to react. The mixing across the interface could be the reason for stronger coating adhesion to the substrate [12, 13].

Fig. 7 shows the interface between the inconel and mild steel (specimen I2) at a magnification of $\times 400$. The formation of a reaction product can be clearly seen across the interface. The white areas along the interfaces were confirmed to be an alloy of nickel and trace niobium in inconel. This could be due to the frictional heat inducing the formation of intermetallic compounds. The exterior coating side of the interface was smoother than that of mild steel substrate, which can be attributed to excessive frictional heat, affecting the substrate in a similar manner to that of the tool steel–mild steel interface.

Figs 8 and 9 show the interface of inconel and mild steel (I4) at a magnification of $\times$ 134 and its corresponding X-ray mapped image. It can be clearly seen that the substrate had a deformed structure similar to that observed for tool steel coating. This could be attributed to the frictional heat affecting the substrate rather than the coating, due to the lower plasticizing temperature of mild steel in comparison to both tool steel and inconel. However, effective coatings at lower speeds and loads than for tool steel were possible for inconel. The lower speed and the load requirement for friction surfacing of inconel when compared to the tool steel is due possibly to the rapid reduction in

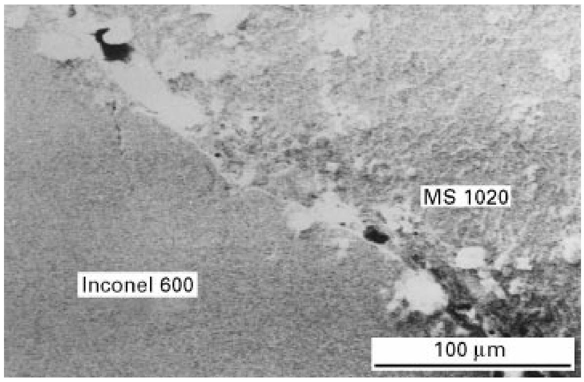

Figure 7 Scanning electron micrograph of the inconel/mild steel interface.

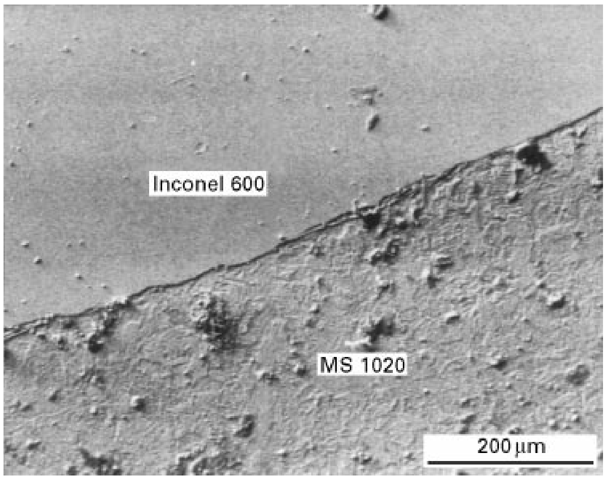

Figure 8 Scanning electron micrograph of the inconel/mild steel interface.

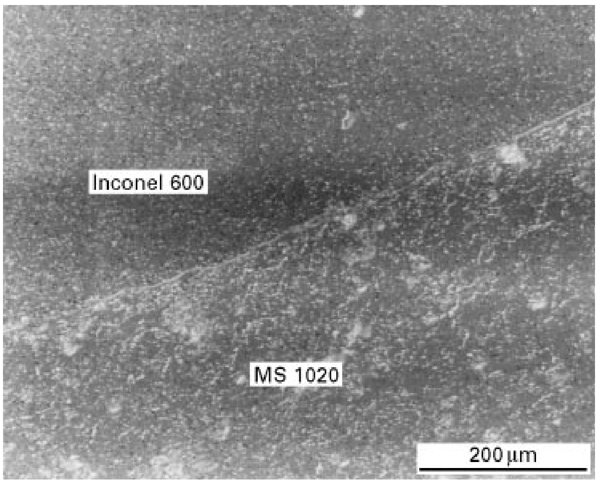

Figure 9 Corresponding X-ray mapped image of the inconel/mild steel interface.

shear strength of inconel above 1000 °C [14], lower than the imposed shear stress of the friction surfacing process. This leads to bonding of the tip of the inconel consumable to the substrate and thus allowing friction surfacing to begin.

Figs 10 and 11 show the dot mapping of the interface with the characteristic radiations of NiK_{α}, FeK_{α}, respectively. It can be clearly seen that there is mixing

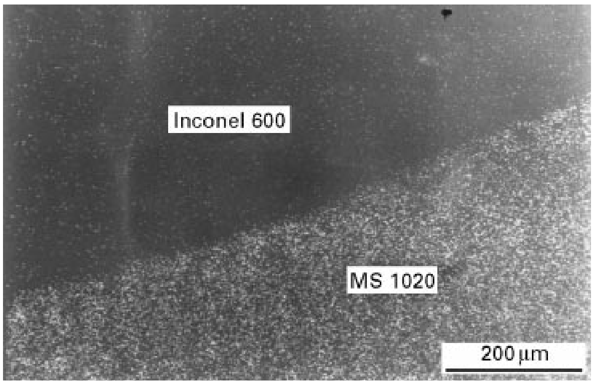

Figure 10 X-ray dot mapped image of the inconel/mild steel interface using FeK_{α}.

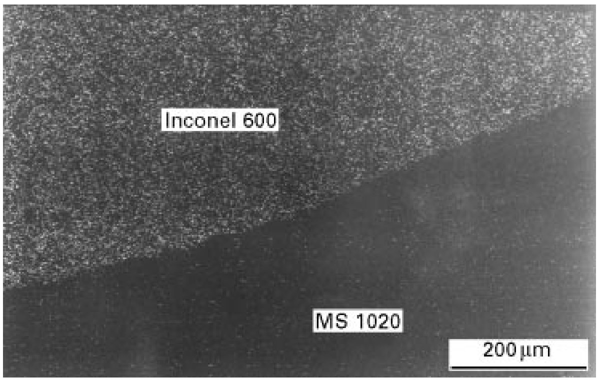

Figure 11 X-ray dot mapped image of the inconel/mild steel interface using NiK_{α}.

across the interface and some phase formation is observed.

3.2. X-ray fluoroscopic images

Fig. 12 shows the mask-processed X-ray fluoroscopic image of a representative friction surfaced specimen of tool steel on to mild steel substrate. It can be observed from Fig. 12 (viewed along the normal plane, specimen T6) that the coating is of almost uniform width throughout the length of the coating. A layered structure of the coating is also evident from the X-ray images processed using digital image processing. Fig. 12 (specimen T6) shows the pseudocolour function applied to the coating. The coating seems to have cavities along the edge, as is evident from black spots. The black region near the coating indicates that the subsurface of the substrate may have sustained plastic deformation and the material has flowed laterally to accommodate the frictional load during the coating process. This image also confirms the observations from SEM (Figs 3 and 4) that the roughness of the coating at the interface with the substrate is less than the exterior substrate roughness. A possible cause for this roughness difference may have been that the substrate attained a semisolid state while the frictional heat was generated, and plastic tearing of the substrate occurred.

Figs 13–15 show the mask-processed images of the transverse section of the friction surfacing of tool steel

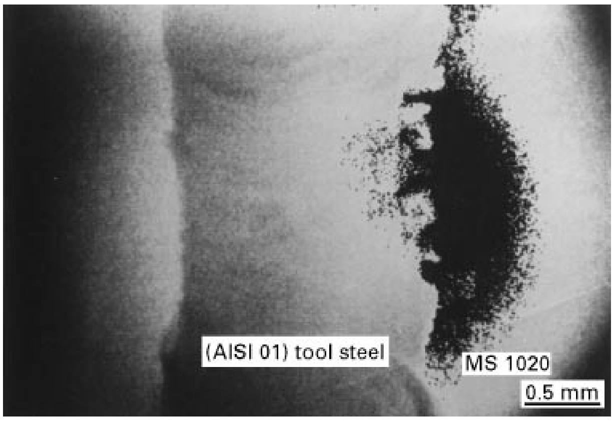

Figure 12 Normal plane X-fluoroscopic image of the tool steel/mild steel interface (specimen T6).

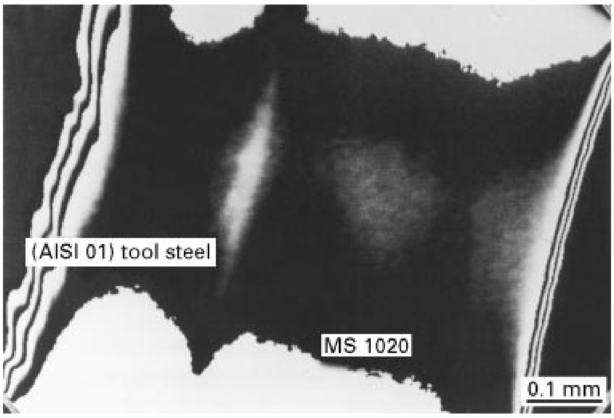

Figure 13 Transverse plane X-fluoroscopic image of the tool steel/mild steel interface (specimen T6).

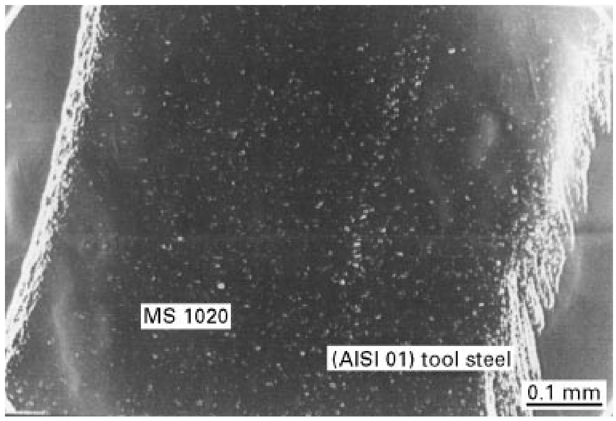

Figure 14 Transverse plane X-fluoroscopic image of the tool steel/mild steel interface (specimen T2).

on the mild steel substrate. Fig. 13 shows the mask-processed image using the pseudocolour function (specimen T2) which defines the defects by enhancing the grey level. It can be clearly seen from the white region that the interface had large defects. It is also evident from the grey level difference near the centre of the load that the substrate had undergone large-scale plastic flow to accommodate the frictional heat and load at the centre of application of the load.

Fig. 14 (specimen T6) shows the mask-processed image using the edge definition function. The image

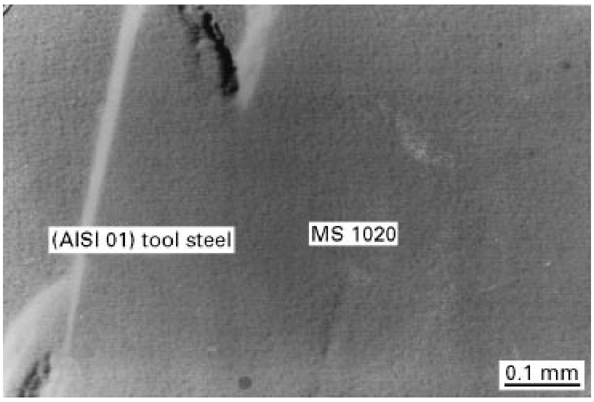

Figure 15 Transverse plane X-fluoroscopic image of the tool steel/mild steel interface (specimen T6).

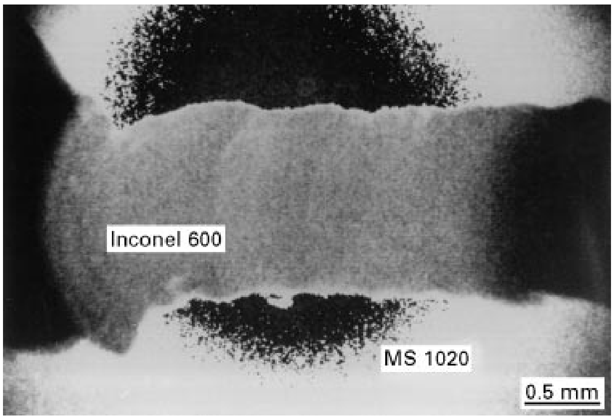

Figure 16 Normal plane X-fluoroscopic image of the inconel/mild steel interface (specimen I4).

shows the interface line clearly, as observed in Fig. 13 (specimen T2). Fig. 14 also shows the layered structure of the coating and the extent of the depth of the layer below the coating surface. This could probably be due to the fact that the surface of the consumable rod of tool steel is always red hot during the friction surfacing, thus facilitating the formation of semi-solid steel at the consumable surface. The shear strength is lower than the interfacial shear strength between the coating and the substrate.

Fig. 15 shows the transverse mask-processed images of the representative friction surfaced sample of tool steel on to the mild steel. It can be clearly seen that the substrate had developed a crack parallel to the coating interface, which indicates that the substrate had failed during the coating process and had developed subsurface cracks. A cohesive failure of the matrix caused by the frictional heat and load had, therefore, occurred, which confirms the inference from the SEM.

Fig. 16 shows the images of the friction surfaced specimen of inconel on to mild steel (specimens I2) using a simple averaging function (Integration) and that of the pseudocolour function, respectively, viewed from the normal plane to the plane of surfacing. A typical layered structure, as observed for the tool steel on mild steel, can be seen. The dark regions around the centre of the coating in the substrate indicate the localized thinning of the substrate due to the load and heat.

Fig. 17 shows the transverse cut section of the friction surfaced specimens with different image processing functions applied to them. Fig. 17 (specimen I4) shows a mask-processed image showing the three-dimensional difference. It can be seen from this image that the coating had a clear interface and the coating had a layered structure at the edge and in between these layers there appears to be no bonding. Fig. 18 (specimen I4) shows the image with pseudocolour function applied. This image also confirms the observation of the interface from Fig. 17, where a black region along the interface shows lack of bonding. A cavity is also seen along the interface in this image, indicating the coating may not be dense along the interface. Fig. 19 shows the transverse X-ray fluoroscopic image of the inconel coating on to mild steel (specimen I2), mask processed using the pseudocolour function. Here again the interface had some defects, which can be seen from the dark region near the centre of the interface. The layered structure is also seen from the dark region along the coating surface. The thickness of the inconel coating can be seen to be larger than the tool steel coating.

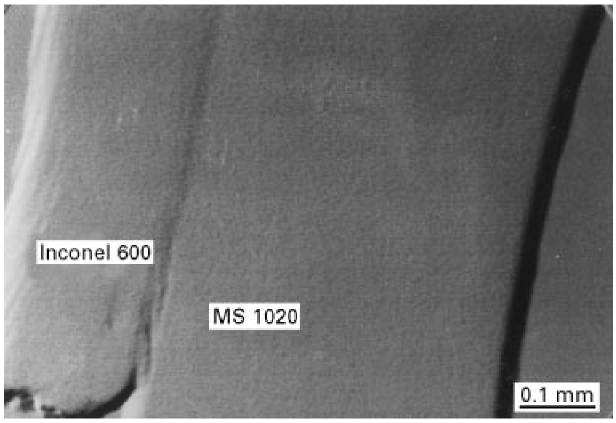

Figure 17 Transverse plane X-fluoroscopic image of the inconel/mild steel interface (specimen I4).

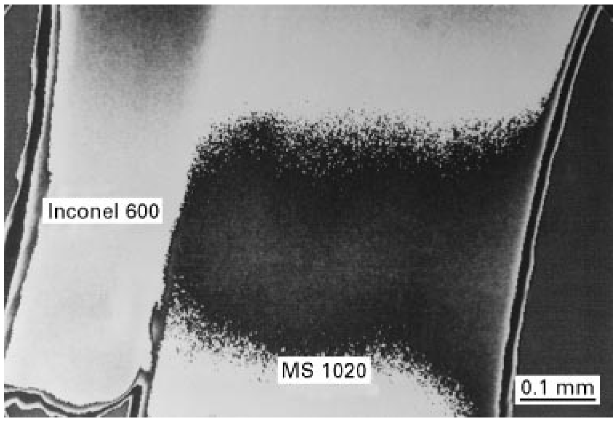

Figure 18 Transverse plane X-fluoroscopic image of the inconel/mild steel interface (specimen I4).

4. Discussion

Friction surfacing is effected by the interlocking of the heat-affected zone (HAZ) in both the consumable and

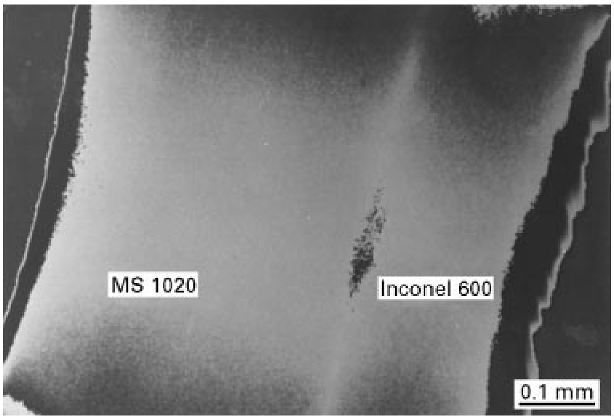

Figure 19 Transverse plane X-fluoroscopic image of the inconel/mild steel interface (specimen I6) at a magnification of 100x.

the substrate under the influence of nominal contact pressure. During friction surfacing, a distinct heat-affected zone appears to form both in tool steel and inconel consumables and the substrate. Seizure and localized softening of the HAZ of consumable and substrate seem to cause friction surfacing to occur due to the transverse feed of consumable. This leads to the formation of a thick deposit on the substrate by propagation of a shear crack in the consumable, as the shear strength of the HAZ in the consumable tends to be lower than the stress, due to interlocking of HAZ.

The consumable rotational speed and nominal contact load on the consumable are observed to control the quality of the coating obtained. Good coatings of tool steel and inconel on mild steel substrate could not be obtained at lower speeds and loads. The reason for poor adhesion of tool steel as compared to earlier works [8] is due possibly to the loading restriction of the milling machine. At higher speeds and loads, good adhesion was observed for inconel 600 coatings. The bend angle of 85° was obtained for inconel as compared to the bend angle of 8° for the tool steel coated under identical conditions. Both the inconel and tool steel coatings were found to have cracks propagating from the interface towards the surface (Figs 4 and 7). Both the inconel and tool steel required a minimum load of about 21.8 MPa for obtaining good coatings. The inability to obtain a good coating of inconel and tool steel consumables at lower loads and speeds (of about 2500 r.p.m.) could be due to insufficient frictional heat generated to initiate reactions leading to the formation of softer phases and the initiation of plastic flow of the material. This enhanced adhesion obtained with inconel coatings as compared to the tool steel, could be due to the formation of soft nickel compounds at the surface due to the frictional heating. Coating–substrate bonding would have occurred by atomic transfer across the interface with the mild steel substrate. The finding that inconel could be coated at comparatively lower loads and higher feed rates as compared to the tool steel, may be due to the higher reduction in hardness with frictional heating than tool steel. This would have facilitated flow of material once the softening point of inconel is obtained. It can be observed from the X-ray images that the inconel coatings as observed in the cross-section exhibit good bonding by adhesion. It can also be seen that mild steel had deformed below the centre of the coating to accommodate the frictional loading during the deposition of the coatings. This indicated that the axial pressure of the consumable was high enough to cause a plastic flow below the coating in the substrate.

The presence of a thermal gradient along the length of the consumable allows transformation of near-surface layers to the semi-solid state during friction surfacing. This results in staggered flow of material from the consumable rod as the transverse feed is started, because the subsurface of the consumable does not transform into a semi-solid state to facilitate continuous flow of material over the substrate. This results in the formation of a layered structure of the coating. This plastically flown material is compressed under the action of normal force and extrudes under the consumable. This results in a smoother coating whose surface is less rough in comparison to the substrate at the interface.

The mechanisms of coating deposition observed when tool steel and inconel were friction surfaced on mild steel, are described below.

During rotation of the consumable over the stationary substrate, the deposition of inconel involved the formation of nickel compounds of manganese and cobalt. Fig. 20 shows the EDX analysis of the inconel/MS interface. This indicates the presence of nickel, manganese, cobalt and oxygen, which indicates some oxide compounds have formed. The inconel also loses its strength rapidly above 1000 °C [14–16], i.e. the temperatures required for friction surfacing. This temperature of 1000 °C or more, and the high normal load, cause the substrate to deform and produce a wavy surface. The inconel coating appears to have

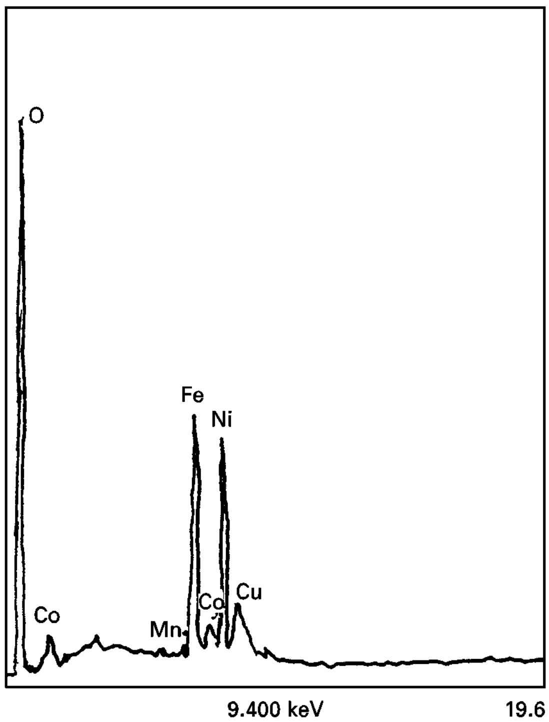

Figure 20 EDX spectrum of the inconel/mild steel interface.

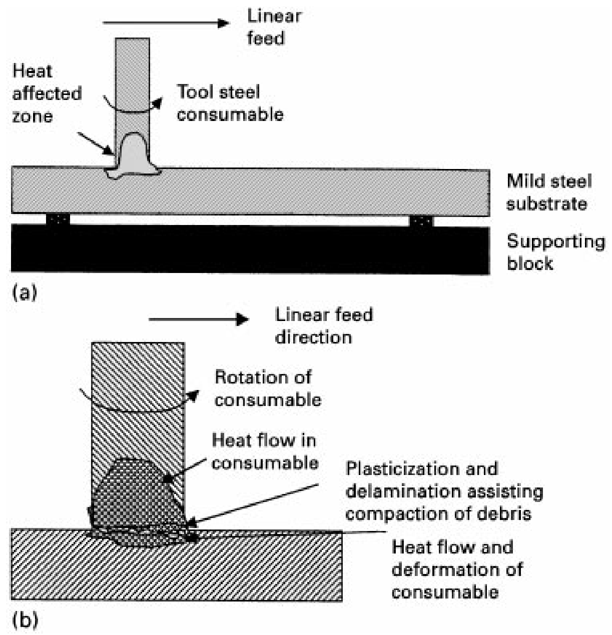

Figure 21 (a, b) Mechanism of friction surfacing of tool steel on mild steel.

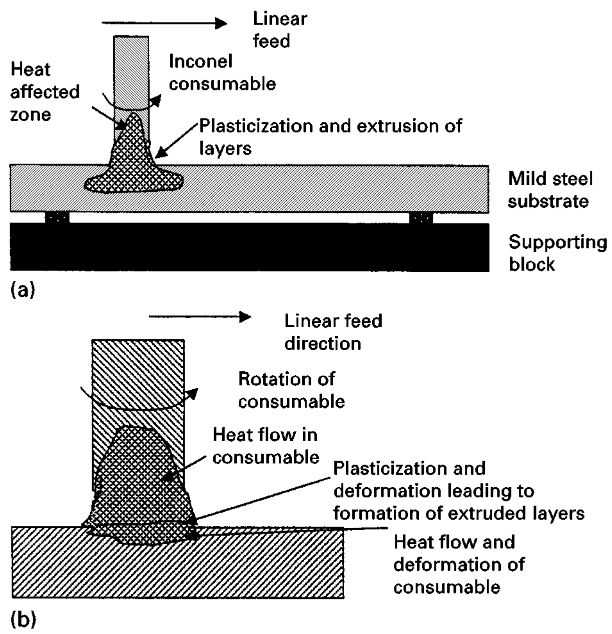

Figure 22 (a, b) Mechanism of friction surfacing of inconel steel on mild steel.

extruded to form a thick layer of inconel and flow over the substrate. For tool steel, the coating appears to be formed by delamination and rolling of delaminated tool steel surface on the substrate. The models of the coating mechanism of tool steel on MS are illustrated in Fig. 21a and b and inconel on MS are shown schematically in Fig. 22a and b. For inconel, the frictional heat generated between the surfaces caused localized softening and tearing of the mild steel substrate and the formation of soft nickel extrudates on the inconel surface with lowering of shear strength of the near-surface region. As the heat flow to the atmosphere is blocked by the plasticized consumable rod (which acts as a barrier for flow of heat to the sides), the heat conducts through the consumable to cause further softening of the consumable rod, thereby facilitating downward flow of material and consumable rod. This effect, combined with the linear feed of the consumable, leads to the formation of soft nickel compounds, which plastically flow over the mild steel surface.

The tool steel consumable surface appears to delaminate and the delaminated layers are compressed together before attaining the necessary plasticity for flow over the substrate under the action of external linear feed. This leads to the coalescence of flakes of tool steel which, under the action of friction surfacing pressure and heat, bond together forming a coating over the mild steel. The evidence for this model can be seen from poor bonding between the substrate and coating material with a low bend angle of about 8 °.

5. Conclusions

1. The above study indicates that friction surfacing could be used as a method for obtaining coatings of dissimilar materials.
2. Inconel 600 is more effectively deposited on mild steel by friction surfacing than tool steel. Tool steel (AISI 01) fails cohesively at a much lower bend angle than the inconel. This difference in behaviour appears to be due to the formation of soft nickel-based compounds with inconel and this forms homogeneous extrudates under the action of normal load and frictional heat that bond well with mild steel by atomic transfer. The oxide layer then bonds with the coating to bind coating to substrate.
3. No interfacial compound formed in the case of tool steel coating, resulting in poor adhesion to the substrate as opposed to reports on tool steel coatings. The tool steel appears to be deposited from flakes of a delaminated layer of material trapped between the consumable and the substrate.

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