Materials and Design 32 (2011) 82–87

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Microstructural evolution during friction surfacing of tool steel H13

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A R T I C L E I N F O

Article history:
Received 12 April 2010
Accepted 17 June 2010
Available online 22 June 2010

Keywords:
C. Coatings
E. Wear
F. Microstructure

A B S T R A C T

Coatings of AISI H13 tool steel were made on low carbon steel by friction surfacing. Detailed microstructural studies and microhardness tests were carried out on the coatings. Studies revealed defect-free coatings and sound metallurgical bonding between the coating and the substrate. In addition, mechanical interlocking on a very fine scale was observed to occur between the coating and the substrate. Coatings exhibited martensitic microstructure with fine grain size and with no carbide particles. Coatings in as-deposited condition showed very high hardness (58 HRC) compared to the mechtrode material in annealed condition (20 HRC). Based on these findings, microstructural evolution during friction surfacing of H13 tool steel is discussed. The current work shows that friction surfaced tool steel coatings are suitable for use in as-deposited condition. Further improvements in coating microstructure and properties are possible with appropriate post-surfacing heat treatment.

1. Introduction

Friction surfacing is an emerging surface engineering technology, developed on the basic principle of friction welding, for depositing wear and corrosion resistant metallic coatings. A rotating consumable rod is fed against a substrate which moves in *X–Y* plane. Due to intense frictional heating followed by severe plastic deformation, a thin layer of plasticized metal is deposited over the moving substrate. A schematic of friction surfacing process is shown in Fig. 1. Fine-grained wrought microstructure, zero dilution, absence of porosity, narrow heat affected zone, and high deposition rate are amongst the most important advantages of friction surfacing in comparison with conventional fusion welding based surfacing methods. While friction surfacing was patented way back in 1941, there is renewed interest in this process mainly because of its repair and reclamation capabilities [1].

Tool steels are commonly used for manufacturing moulds, dies and other components because of their high strength and wear resistance. When tool steel dies get damaged during service, processes such as gas tungsten arc welding (GTAW), submerged arc welding (SAW), plasma transferred arc surfacing (PTA) and laser cladding are commonly used to rebuild the worn part. A typical repair operation involves first gouging out the damaged portion by milling or grinding and then filling the missing volume with appropriate filler material [2]. Repair welding of tool steels is a daunting task due to hot cracking and/or cold cracking. Pre-heating can be used to overcome the cracking problems, but it reduces the cooling rates and adversely affects the coating microstructure. Such problems do not arise in friction surfacing as it does not involve melting.

Earlier studies on friction surfacing dealt with stainless steel [3], tool steel, inconel [4], and aluminum [5] coatings on mild steel substrates. Tokisue et al. [6] reported multilayer friction surfacing of aluminum alloys AA5052 and AA2017 on AA5052 substrate. Aluminum matrix composites were also successfully friction surfaced on aluminum [7] and titanium substrates [8]. While these studies clearly demonstrate the capabilities of friction surfacing, more work is needed in order to mature friction surfacing as an alternative to established conventional fusion welding based surfacing processes. In particular, it is necessary to understand microstructural evolution during friction surfacing. Accordingly, the present study focuses on microstructural aspects of friction surfaced H13 grade tool steel coatings on a low carbon steel substrate.

2. Experimental work

AISI H13 tool steel rods, with a chemical composition of 0.37 C, 0.37 Mn, 0.7 Mo, 0.9 Si, 0.8 V, 5.56 Cr, and balance Fe (in wt.%), were used in the present study. The material was supplied in annealed condition with a hardness of 20 HRC, which can be heat treated to higher hardness levels in the range of 46–60 HRC, depending on application requirements. Rods of 18 mm diameter and 100 mm length were prepared for friction surfacing experiments. Rod ends were faced to ensure flatness. A low carbon steel plate (150 mm × 100 mm × 8 mm) was used as the substrate. The substrate was milled and surface ground to obtain a flat, even surface, free from oxide scales. Just before surfacing, both the rod

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doi:10.1016/j.matdes.2010.06.031

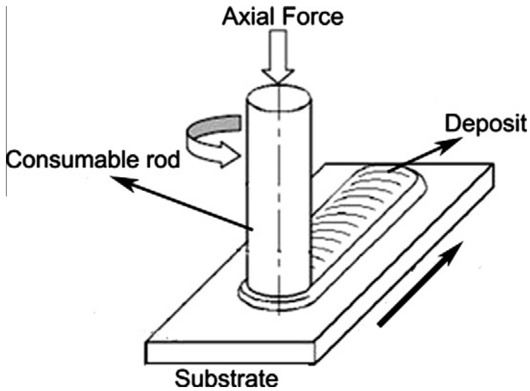

Fig. 1. Schematic of friction surfacing.

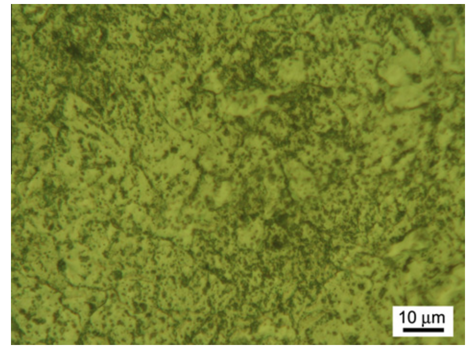

Fig. 2. Microstructure of H13 tool steel rods.

and the plate were thoroughly cleaned with acetone to minimize contamination.

Friction surfacing experiments were carried out using an indigenously developed friction surfacing machine. The parameters used were: traverse speed – 4 mm/s, rotational speed – 800 RPM and axial load – 10 kN. These parameters were arrived at based on the results from earlier experiments.

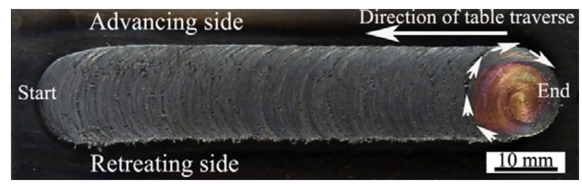

Fig. 3. Photograph of a typical friction surfaced tool steel coating.

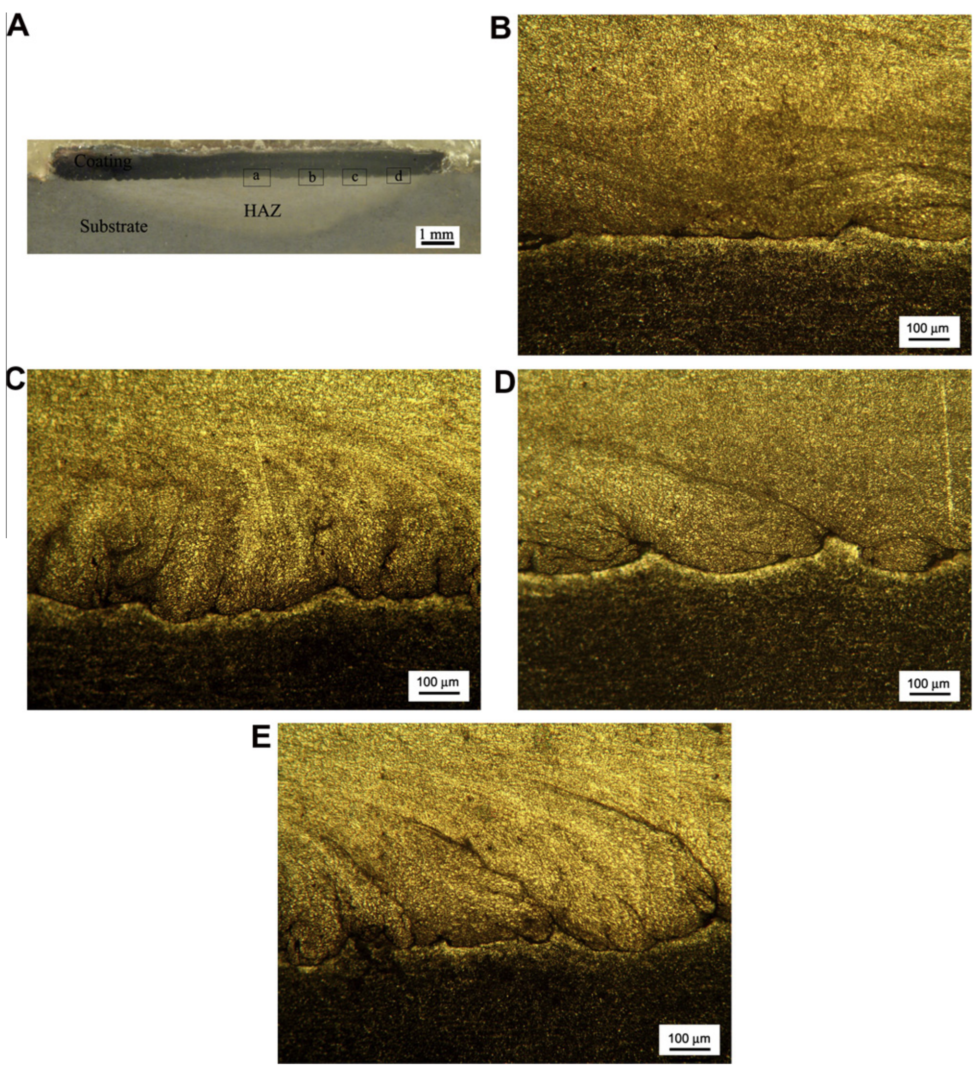

Fig. 4. (A) Macrostructure of tool steel coating (transverse section) and (B–E) interface microstructures corresponding to locations a–d in (A).

Microstructural studies were carried out on friction surfaced coatings using optical microscopy (OM) and scanning electron microscopy (SEM). Specimens for microstructural examination were prepared following standard metallographic procedures. Vickers microhardness tests were carried out on coating top surface and transverse sections. Coatings were also characterized using X-ray diffraction (XRD).

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the microstructure of H13 tool steel rods in annealed condition, consisting of fine carbides particles of $M_{23}C_6$ and M_7C_3 dispersed in the matrix [9]. A typical friction surfaced tool steel coating is shown in Fig. 3. The top surface of the coating is rough due to formation of ripple-like features, which is an inherent characteristic of friction surfaced coatings. Ripple formation is related to the nature of material transfer from the consumable rod to the substrate. The plasticized metal 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 [10].

During friction surfacing, a large amount of heat is generated due to friction. This results in substantial heating at the contact region between the rod and the substrate. The temperature distribution in the contact region is strongly dependent on a variety of factors like contact pressure, mechtrode rotational speed, geometry of contact, substrate traverse speed, thermal conductivities of rod and substrate materials. On the mechtrode side, energy gets dissipated during the process so quickly that there is no time for substantial heat flow into the regions outside the contact zone. This results in intense localized heating at the tip of the consumable rod facilitating smooth plastic flow. On the substrate side, however, the larger plate dimensions result in rapid heat conduction, which prevents the substrate from plasticizing. This is a very desirable condition, which needs to be ensured for satisfactory coating formation.

Fig. 4 shows the coating/substrate interface microstructures at four different locations from center to edge of the tool steel deposit. No decarburized layer or oxide inclusions were observed in the interface region. During friction surfacing, considerable amount of the plasticized metal at the tip of the mechtrode gets extruded out in the form of flash. This helps avoid problems such as oxide entrapment and internal oxidation in friction surfaced coatings. At the deposit center, the interface was observed to be relatively straight with good coating integrity. Away from the deposit center, the interface was observed to be wavy, characterized by "Paw" like features, which act as mechanical anchoring points. These differences in interface morphology arise due to variations in mechtrode

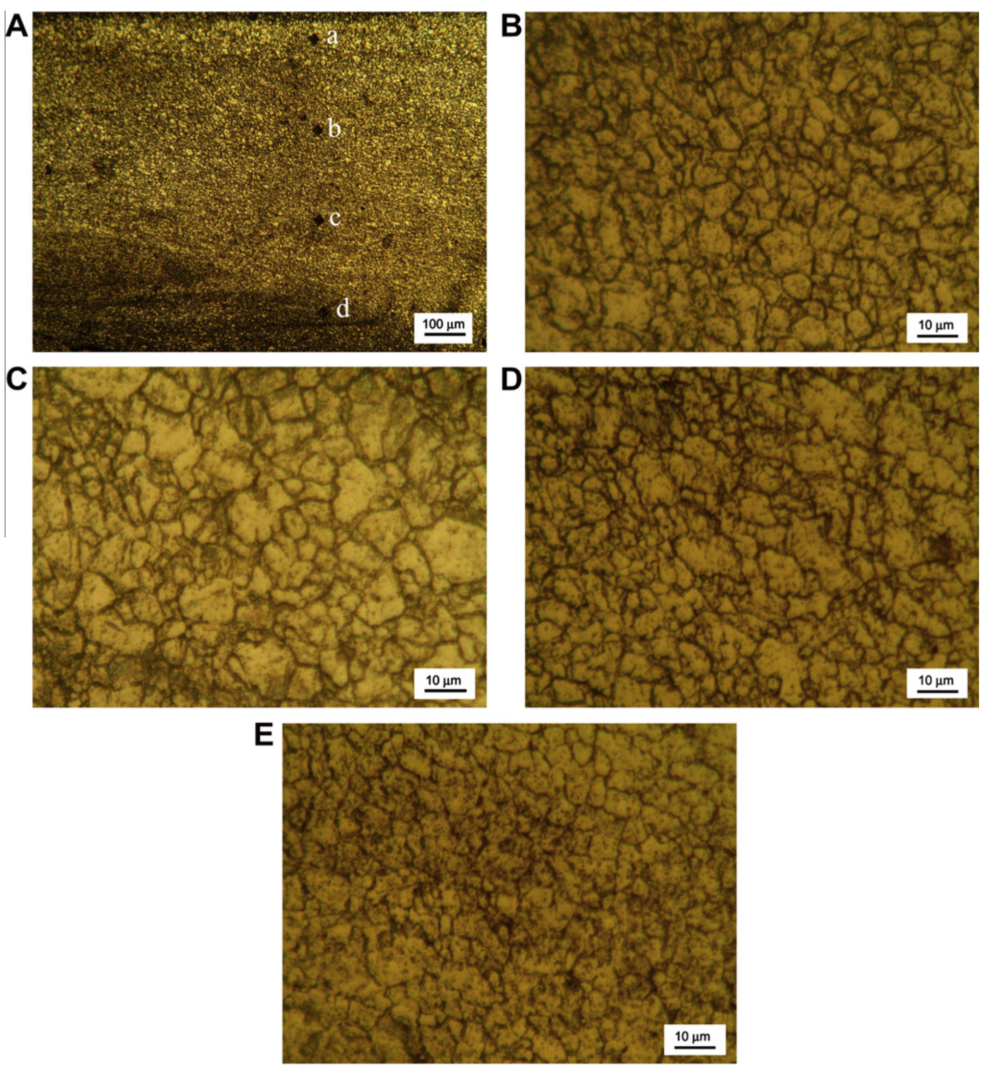

Fig. 5. (A) Low magnification microstructure of the coating and (B–E) microstructures corresponding to locations a–d in (A).

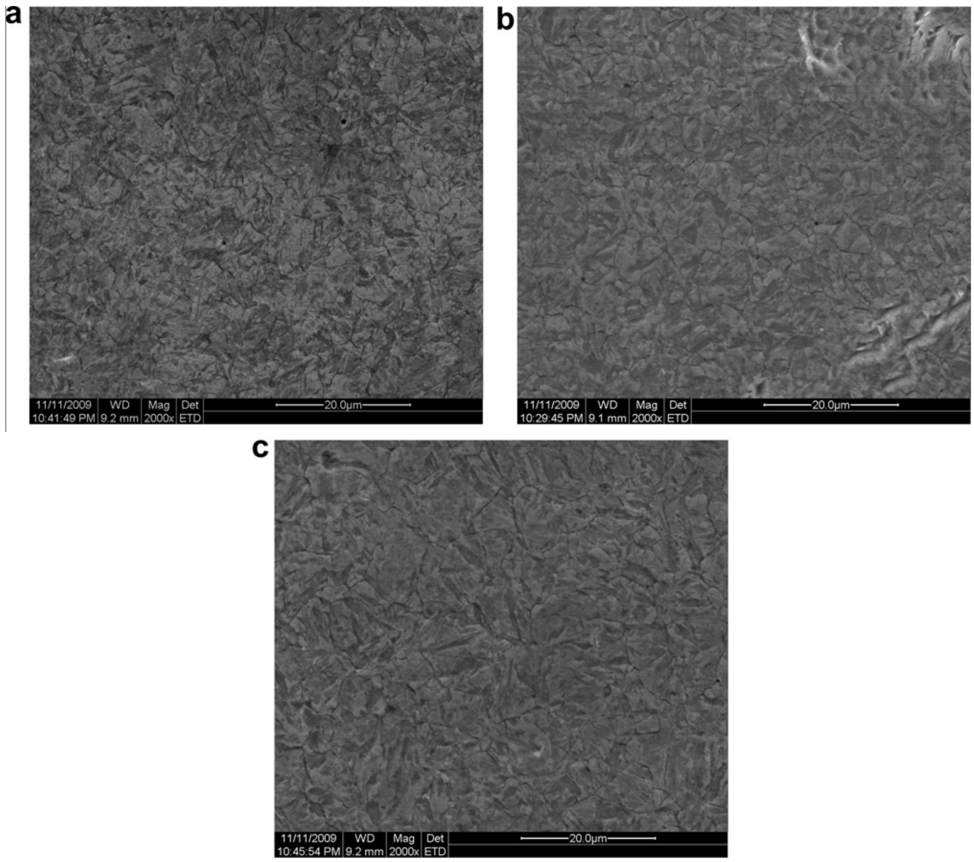

Fig. 6. SEM-SE images of coating top surface: (a) advancing side, (b) retreating side, and (c) center.

linear velocity from its center to periphery. It is known that the velocity at mid-center is zero and maximum at the periphery when a solid cylindrical rod rotates about its axis [11].

The friction surfaced coatings exhibited fine equiaxed grain structure. The grain size in the coating, from top surface to the interface, lies between 2 and 10 µm when compared to 50–60 µm of the original rod microstructure in annealed condition. Fig. 5a–e shows the cross-sectional microstructures from the top surface to the interface at the center of the deposit. Although the rod material was subjected to severe plastic deformation, no distorted grains in the coating were observed. The fine equiaxed grains observed in the coating suggest that dynamic recrystallization occurs during friction surfacing. Carbide particles which were originally present in the mechtrode were not observed in the deposit microstructure. This can possibly be due to the higher temperatures and strains involved in the process. It was reported that when high speed steel rods were friction surfaced, the temperatures attained were higher than 1100 °C [10]. Similar temperatures are expected to during friction surfacing of tool steels. At such high austenizing temperatures, carbide particles present in the mechtrode material can get dissolved in the matrix [4,12]. Faster cooling rates involved in the process prevent re-precipitation of carbides in the coating.

SEM pictures in Fig. 6 show the coating top surface microstructure. Very fine martensitic features can be seen. Fig. 6a and b shows the deposit microstructures on advancing and retreating sides. The side where direction of mechtrode rotation and direction of bead formation are same is referred to as advancing side and the side where direction of mechtrode rotation and direction of bead formation are opposite is referred to as retreating side. While some microstructural differences are likely between advancing and retreating sides (due to material transfer from advancing side to retreating side), no differences between advancing and retreating sides were evident in the coatings produced in the current study. However, the microstructure at the center of the coating surface (Fig. 6c) was found to be more homogenous when compared to advancing and retreating sides. A high magnification SEM image is shown in Fig. 7, which reveals fine intra-granular lath martensitic features.

3.2. Microhardness

Fig. 8 shows the microhardness values across the interface from the coating surface to the unaffected substrate. The as-received

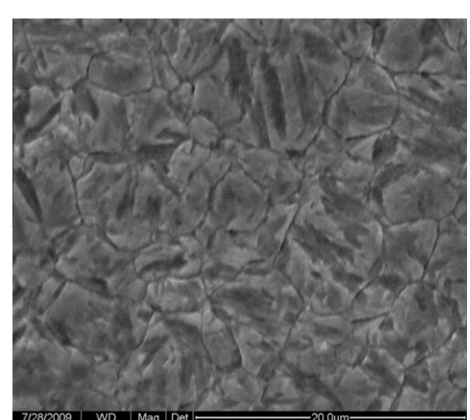

Fig. 7. High magnification SEM-SE image showing lath martensitic features in the coating.

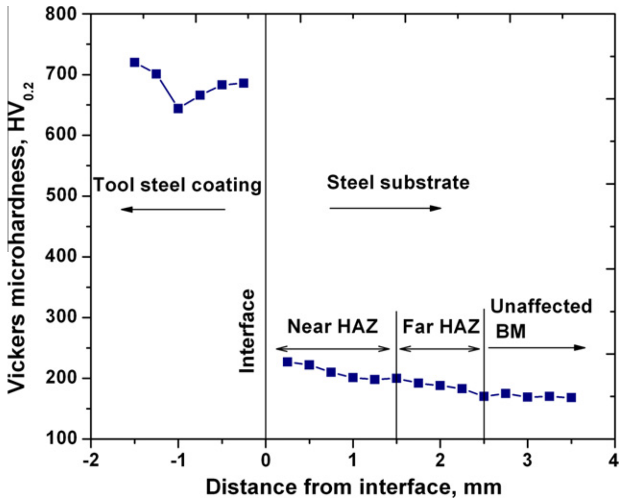

Fig. 8. Vickers microhardness profile across the coating/substrate interface.

tool steel rod showed a hardness of was 220 HV. In contrast, the as-coated tool steel deposit showed a significantly higher hardness of 740 HV (around 58 HRC). A similar increase in hardness was reported in tool steel after friction stir processing [12]. This increase in hardness can be attributed to the martensitic microstructure in the coating. Towards the top surface and towards the interface, the coating exhibited higher hardness when compared to the mid-thickness region. Grain size differences across the deposit thickness (Fig. 5) can account for this.

3.3. XRD

X-ray diffraction patterns of the tool steel rod and the friction surfaced coating are shown in Fig. 9. In the tool steel rod, only ferrite (α) peaks were observed. Carbide peaks were absent probably due to the low carbide volume fraction. In the friction surfaced coating, peaks were observed to shift a little bit, indicating martensite (α') formation. These observations corroborate well with the findings of microstructural examination. During friction surfacing, the ferritic tool steel rod gets austenitized, which, up on rapid cooling, transforms into martensite, resulting in a hard tool steel coating.

The current study shows that friction surfacing can produce defect-free tool steel coatings on low carbon steel substrates with fine equiaxed martensitic grains and high coating hardness. Friction surfacing can be regarded as a thermo-mechanical process. Considering the similarities in microstructural characteristics between the coatings produced in this study and the friction stir processed tool steel SKD61 (Japanese equivalent to AISI H13) samples produced by Chen and Nakata [12], it appears the basic thermo-mechanical phenomena that govern microstructural evolution in friction surfacing are not different from those in friction stir processing.

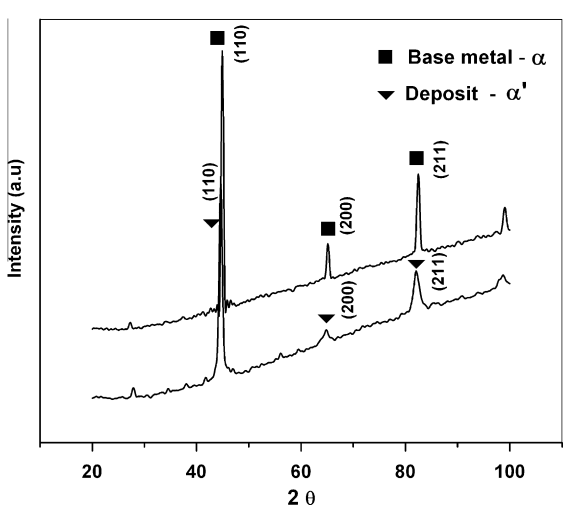

Fig. 9. XRD patterns of tool steel rods and friction surfaced coatings.

Austenitization temperature is a key variable in heat treatment of tool steels. An increase in austenizing temperature results in increased hardness and strength levels due to better dissolution of carbides [13]. However, it also results in grain growth, leading to inferior toughness. During friction surfacing, temperatures attained in the contact region are in the range of 1100–1200 °C, which is the temperature range in which tool steels are usually austenitized. Thus, during heating, the tool steel rod gets effectively austenitized with the carbide particles more or less completely dissolved. 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. In conventional heat treatments of tool steels, use of an austenitization temperature in the range of 1150–1200 °C results in an austenite grain size of 10–20 μm [14]. In contrast, a much finer austenite grain size is expected in friction surfacing due to dynamic recrystallization. The final martensite plate size is a function of grain size. Finer grain size with smaller martensite plate size provides for stronger and tougher coating [15]. Overall, friction surfaced tool steel coatings appear to be suitable for use in as-deposited condition. Further improvements in coating microstructure and properties are possible with appropriate post-surfacing heat treatment, which will temper martensite and facilitate carbide precipitation.

4. Conclusions

Sound metallurgically bonded H13 tool steel coatings can be produced on mild steel substrates using friction surfacing. Thermal cycles in friction surfacing are potent enough to cause complete austenitization and effective dissolution of carbides. The combined effects of deformation and temperature result in dynamic recrystallization leading to formation of fine equiaxed austenite grains. Cooling rates in friction surfacing are adequate to prevent carbide precipitation and to cause austenite to martensite transformation. Consequently, friction surfaced H13 tool steel coatings exhibit a fine-grained martensitic microstructures with no carbides. Coatings in as-deposited condition show very high hardness (58 HRC) due to their martensitic microstructure. Friction surfaced tool steel coatings are suitable for use in as-deposited condition. Further improvements in coating microstructure and properties are possible with appropriate post-surfacing heat treatment.

Acknowledgement

The authors gratefully acknowledge Naval Research Board (NRB), Government of India for the financial support and permission to publish this work.

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