Solid state surface deposition by friction surfacing: A review

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Abstract. Developing surface coatings and depositions for imparting specific properties at the surface of materials is an important strategy in surface engineering. Several processing routes are widely used in surface engineering which involve melting the coating materials and deposition on the substrate. On the other hand, surface coatings by solid state routes eliminate complex issues associated with liquid based processes. Friction surfacing is one of such potential solid state processes in which a consumable rod made of coating material is used to deposit a layer on the substrate. Several material systems have been used to produce surface coatings by friction surfacing. In this present review, the state of the art in developing several non-ferrous based coatings by friction surfacing is discussed. The role of process parameters and material properties influenced by the coatings are summarized and presented.

Keywords: friction surfacing, coatings, solid state, non-ferrous metals, surface engineering

1. Introduction

Surface engineering is a useful approach to improve the surface properties of a bulk structure without affecting the properties of the core of the structure. Developing several modern engineered materials addressed the existing issues in the materials engineering. However, inevitably, altering the surface properties or developing surfaces with special properties is a great demand for various applications where surfaces play very important role. Surface coatings has become an important area of research in recent years due to their significance associated with the surface of components, which needs a wide range of knowledge, including materials engineering, physics, and manufacturing sciences. Most of the components and structures fail or become disbanded due to fatigue, wear, and corrosion during functioning. Various surface modifications were developed to improve the surface qualities and extend the working life of components and structures, thereby decreasing risks associated with un-
programmed delays [1]. Surface engineering encompasses a wide range of techniques that modify the chemistry and properties of a thin layer of the substrate's surface, which include cladding process, laser treatment, cold spraying, liquid deposition methods, thermal spraying, anodizing, chemical and physical vapour deposition etc [2, 3]. Most of the liquid state processes results in several other complications such as cast microstructure, oxidation, development of unwanted intermetallics etc. On the other hand, several viable and novel alternatives to conventional techniques were developed in surface engineering such as friction stir processing (FSP) and friction surfacing (FS) [4].

Friction surfacing (FS) was first patented in 1941 and has now developed into a well-established machine tool-based technology that utilizes a single consumable tool that can produce a large variety of coating combinations over a substrate. Among surface engineering technologies, the FS process is becoming increasingly important that works on friction manufacturing principles. The expansion of those concepts resulted in one of the most substantial developments in the history of surface engineering [5]. A few combinations of dissimilar materials were processed in friction surfacing along with similar alloys with different combinations of process parameters and the results were promising [6- 8]. Wide range of materials such as steels, aluminium alloys, copper, inconel, sterlite etc have been used to develop surface coatings by FS as reported in the literature [9 - 12]. Friction surfacing of alloy steels on low carbon steel is the subject of majority of the reported research. Various commercial applications for friction-surfaced steel coatings are currently being considered. Additionally, the practicality of generating coatings by friction surfacing on various nonferrous substrates using a range of consumable rods is of significant interest due to the inadequate response of some nonferrous metals to greater loads and temperatures. In this present review, state of the art in developing several nonferrous based coatings such as aluminium, magnesium, copper, and Inconel 800 by friction surfacing is discussed. These combinations hold promise for making bimetallic strips for a variety of industrial applications. The role of process parameters and material properties influenced by the coatings are summarized and presented

2. Friction surfacing

Friction surfacing (FS) is a solid-state deposition technique that utilizes the plastic deformation of a consumable rod. As illustrated in Fig.1, an axial load is applied to a revolving rod that is forced on the substrate. At the rod tip, frictional heat creates a viscoplastic boundary layer. Pressure and temperature conditions result in an interdiffusion process between the plasticized material and the base metal, forming a metallic connection [13]. As a result, the heat conducted into the base metal and the layer consolidates along with the contact, forming the connection between viscoplastic shearing and the revolving consumable rod and the deposited layer. The viscoplastic shearing contact slides away from the substrate surface as heat conduction increases the layer thickness. The viscoplastic material is deposited continuously onto the substrate surface by a transverse action. Notably, FS heats materials primarily by interfacial friction and plastic deformation, enabling processing at temperatures below the fusion. Due to the thermo-mechanical process, a continuous layer of fine-grained microstructures is deposited as the rod is consumed [14]. Additionally, the process is recognized by the formation of a revolving flash of material at the rod tip, which imparts a mushroom-shaped geometry to the rod as shown in Fig 1[15].

FS generates and processes a viscoplasticized solid-state region into a new layer on the surface. While this area remains solid, it exhibits a three-dimensional substantial flow pattern similar to a liquid, allowing for simple blending of various metals [16]. The concept of the 'third-body region' is usually used to represent this phenomenon. Mechanically, this third-body zone contains relatively lower flow stress and temperatures that are higher than the material recrystallization temperature but lower than its melting point [5]. Heat is generated by friction at the contacting surfaces and internally throughout the material flow in this solid-state process, which is purely governed by mechanical energy input
Since frictional heat dissipates to zero as the material approaches to fusion temperature, the maximum temperature reached inside the treated zone is physically restricted by the fusion temperature. As a result, all deformation is limited to the solid-state condition.

Fig. 1. Friction surfacing Process (a) Rotation start, (b) initial contact, (c) initial deformation stage and (d) deposition stage [Source: Gandra et al., [15]]

Fig. 2. Thermo-mechanics of friction surfacing. (a) Sectioned consumable, (b) process parameters and (c) thermo-mechanical transformations and speed profile (Source: P. Vilaça [5])

Depending on the metallurgical changes outlined, Fig 2 displays a possible model for the thermal and mechanical processes that are involved in FS [5]. The speed difference between the rotating viscoplastic material with the rod and the material that is successfully adhered to the substrate allows the deposit to detach from the consumable rod. During the operation, the primary source of heat is the viscous shearing friction between the deposition and the consumable [18]. Due to the lack of restraint at the lower end, the highly plasticized material flows outside the consumable rod diameter, producing in a rotating flash connected to the consumable rod end and poorly adhered coating edges. Additionally, unbounded patches correlate with greater rotation speeds at the consumable rod outer radius. At the deposit’s relative speed, the substrate breaks the bonding contact and disrupts the ongoing diffusion bonding process. Nonetheless, flash and unbounded zones contribute significantly
to the joining process by serving as temperature and pressure border conditions [4, 19]. The flash generated during the transitory starting phase of the FS process will expand and harden when the viscoplastic material transitions to the solid-state. This increases the necessary forging pressure into the viscoplastic layer, effectively closing the rod's viscoplastic zone. From then on, the flash will only raise because of excessive mechanical energy (through forging force and/or torque) imparted to the rod during the stationary phase of the operation. Thus, the flash formation rate along the process can be used to monitor the correct parameter selection.

3. Process parameters

Coatings are rated for thickness, appropriate bond width/extension, and bond strength for a particular consumable rod and substrate material, all of which are dependent on controlled process parameters [5]. The important process parameters, which influence the success of developing surface coatings by FS are given below.

   i) Axial Force
   ii) Rotational speed
   iii) Travel speed
   iv) Consumable rod diameter.

The bonding interface is subjected to shear by the relative speed of the deposit layer and the substrate and affects the bonding process during FS. As a result, excessive rotation and travel speeds can damage the joining by reducing the cross section's bonded width [14, 20]. It is reasonable to assume that increasing the rotational speed results in increased friction, which always has a beneficial effect on bonding efficiency. However, at lower rotational speeds, the slower relative speed of the coated material to the substrate can occasionally promote an effective diffusion process and enhance the contact area between the deposit and the rod [1, 4]. Process parameters have a complex and nonlinear impact on the end results, as they are highly dependent on the used material combination. However, the literature has established several general tendencies and effects [4, 20].

Axial force promotes bond extension, resulting in broader and thin deposits [21, 22]. However, severe loads lead to an irregular deposition in the center of the material discharged from the consumable rod's tail zone. Inadequate forging forces result in suboptimal interface consolidation [4]. The increased axial force is also shown to result in deeper heat-affected zones in the substrate. The adherence of the deposit increases proportionately, resulting in a decrease in the region of the cold lap. On the other
side, increasing the applied force decreases the deposit thickness, thus increasing their width [20, 21]. As illustrated in Figure 3, the increase in forging force decreases the deposit layer thickness.

Rotational speed has an effect on the adherence quality, coating width, and roughness as illustrated in Figure 4. Good bond quality is obtained with slow to moderate speeds, but flatter and regular deposits are produced at higher speeds with significant forging action. Coating width often reduces as rotation speed increases. Heat distribution between the substrate and consumable rod is controlled by both rotation speed and HAZ depth. At the same time, faster rotations were resulting in a deeper HAZ. This occurs because the contact area is reduced as the consumable rod rotates at high speed and the substrate advance speed increases [22, 23].

![Fig. 4. Tool steel (H13) coatings on low carbon steel: Change of width and coating surface roughness due to rotating speed [Source: Rafi et al., [22]](image)

![Fig. 5. Tool steel (H13) coatings on low carbon steel: a) The effect of travel speed on coating width and b) mechtrode rotational speed on coating width. [Source: Rafi et al., [22]](image)

Travel speed has a significant effect on coating width and thickness, as it regulates material deposition rate. As a result, faster travel speeds produce thinner deposits. The heat exposure is short because of the increased travel speeds, resulting in less grain formation and fine microstructures [23]. The HAZ on the substrate diminishes with increasing travel speed. Increased travel speed has the potential to cause bonding at the edges of the deposition to degrade [21, 22]. In general, the required coating thickness is to maximize bonded width (with minimal deviations between the deposited and bonded widths) and decrease the under fill. Fig 5 demonstrates the decreased coating width by increasing the mechtrode travel speed and rotational speed while depositing tool steel (H13) coatings on low carbon steel [22]. Consumable rod diameter can be said to determine the deposit width; that is, larger the
diameter of the rod, the larger the deposit. Consequently, when the diameter of this rod is larger, the deposit equipment potential will be greater. As a result, the equipment's potential is depending on consumable rod diameter [5].

4. Material systems

Several steels, aluminium, copper and their alloys are the important material systems used in friction surfacing in addition to some high entropy alloys. The coating phenomena, level of bonding between the surface coating and the substrate, coated layer characteristics are completely different for different combination of materials. For example, compared to steels, because of their fast softening, copper cannot sustain a high-temperature range. Furthermore, the parameter range is too limited narrowed for achieving better coatings of steel over a copper substrate [22]. Therefore, the balance between mechanical and thermal stability should be established. Prasad Rao et al., [18] conducted extensive study on the feasibility of different combinations of materials as compared in Table 1.

Table 1 Feasibility of surface coatings in FS as demonstrated by Prasada Rao et al., [23]

| Substrate                  | Consumable rod                                      |
|----------------------------|-----------------------------------------------------|
|                            | Low carbon steel | Copper | Aluminium Alloy(AA 6063) | Commercially Pure Titanium |
| Commercially Pure Aluminium| Not possible due to drilling effect of steel consumable rod, but can be done by using startup plate. | Not Possible; Heat generation not sufficient to deform copper, hence copper rod deformed Al | Possible; Same Properties, Sufficient heat concentration at the contact surface | Not Possible; Both the materials are softer |
| Commercially Pure Copper   | Possible Higher thermal conductivity of copper cause heat concentration on steel side | Intermittent Coating; Limited heat concentration at the contact surfaces | Very thin Coating; Lack of heat concentration at the interface | Not Possible; Large difference in deformation Characteristics |
| Inconel 800                | Possible; Comparable mechanical and thermal properties | Not Possible; Softens very fast due to its high ductility at elevated temperatures | Not Possible; Aluminium softened very fast due to high thermal conductivity | No continuous coating; It is highly instable at elevated temperature |
| Mg Alloy [ZM21]            | Not Possible; Steel rod ploughed through Mg surface | Not Possible; Friction not sufficient to cause heating | Not Possible; Large difference in deformation behaviour | Not Possible; Titanium rod skids over Mg surface |
| Ti-6Al-4V                  | Not Possible; Insufficient friction and oxide formation | Not Possible; Insufficient friction and oxide formation | Very thin coating; Forms more flash than coating due to faster softening | Intermittent Coating; Instability of Ti at elevated temperature prevents from continuous coating. |
Friction surface coating of flow carbon steel over a copper substrate showed that the coated layer is uniform in thickness and free of gaps. At first, part of distortion is visible in a substrate, but this subsides as the coated layer progresses. The process of coating is separated into two stages: the immobile dwell period and the deposition phase, during which the substrate moves. During the dwell phase, friction between the consumable rod and the substrate generates heat. In the beginning, the frictional heat produced results in a localised softening of the copper substrate, as indicated by material displacement on either side. However, heat concentration on the interface increases. The steel rod preferentially heated due to dimensional difference and thermal conductivity between the substrate and the steel rod. This severely plasticizes the consumable rod's rubbing surface and the viscoplastic substance is transferred into the copper substrate to produce a layer of coating. It is resulting in simply a difference in the coating width or thickness. The substrate travels at a steady speed during the deposition phase. Consequently, no direct contact at this stage between the steel rod and the copper substrate. Rather than that, the previously applied coating is in touch with the deformed steel rod. As a result, a regular coating is formed on the copper substrate with minimum distortion during the deposition phase. The coating-substrate interface is found to be fault-free and continuous. A physical interface of steel and copper suggests that the substrate underwent micro deformation during the deposition phase. Microhardness measurements across the coating-substrate interface reveal a rise in coating hardness relative to the substrate material. This occurs as a result of grain refinement of grains and is caused by dynamic recrystallization [24].

The high thermal strength of Inconel 800 makes it a good option as substrate and consumable for friction surfacing applications [25]. Due to the high thermal stability of both Inconel 800 and steel, it has been proven that coating is feasible. The interface micrograph of friction-surfaced layer of low-carbon steel on an Inconel substrate revealed a strong connection between the steel coating and the Inconel 800 substrate. There was no evidence of intermixing of the coated layer and the substrate. Due to its resilience to deformation, the Inconel 800 substrate exhibited no deformation in comparison with copper at high temperatures. When the thermomechanical properties of aluminium and magnesium were considered, the surfaces on both copper and Inconel 800 substrates could support friction surfacing. However, the surfaces on aluminium and magnesium substrates did not react well to the surfacing. All other consumable rods have left a cavity in the substrate in commercially pure aluminium except AA 6063. The rubbing surface of the consumable rod was undamaged because of low heat generation, indicating that the generated friction heat was minimum. AA6063 consumable rods were coated. The reason is that the materials have similar characteristics and a relatively high coefficient of friction between aluminium. Similarly, no coating was achieved on the magnesium substrate using any of the consumable rods [23].

A steel start-up plate with the same thickness as the aluminium substrate was secured close to the aluminium substrate, resulting in the plates forming a continuous surface. Consumable rod was initially in connection with the start-up plate and rotated until an adequate quantity of plasticized material was produced (dwell stage). After that, the table was permitted to move against the rotating consumable rod. When the steel rod reaches the aluminium substrate, the process becomes steady by developing a satisfactorily thick plasticized layer (deposition stage). When a thick layer of material begins to form, contact is established between the rod and the previously deposited coating. As a result, there is no direct contact between the rod and the substrate when the consumable rod reaches the aluminium substrate. The coating is created in this case by the simultaneous action of both forwarding motion and spreading action of the plasticized material due to relative movement between the consumable rod and the substrate and rotational movement of the consumable rod, respectively. Consolidation of the coating happens as the result of the continual action of axial force. A regular bead with no discontinuities was obtained.
FS can also be performed under water or any fluid to produce surface layers on immersed structures [26]. If the mechtrode is made of composite materials, FS can develop a composite surface layer on the substrates [27]. FS Fundamentals of FS have led to develop friction assisted additive manufacturing processes where the objective is to produce three-dimensional components by depositing number of overlapping layers [28, 29]. Several properties particularly at the surface were enhanced by producing surface layers through FS, which include mechanical, wear, corrosion etc [30 - 33]. It can be summarized that FS offers several advantages to develop solid-state coatings of similar and dissimilar materials with superior surface properties.

5. Concluding remarks

Among the available friction based processing routes, FS is a promising technique to develop solid state surface coating layers with enhanced mechanical, tribological and surface properties. FS has several advantages over conventional coating techniques. FS is environmentally friendly and reduces metallurgical flaws in the produced coating. FS eliminates or reduces the ill effects of intrinsic fusion-based procedures and limits HAZ. FS can be used to develop surface composite layers by using a composite rod as mechtrode. However, the technique has some drawbacks, including a high equipment cost, thin layers (0.5–6mm at most), and the removal of deposit borders that do not attach to the substrate (cold lap). On the other hand, developing coatings on the surface with complex geometries is difficult with FS. The reported literature also suggests the need of selecting feasible combination of materials to successfully develop surface coatings by FS. The process is new and still in its infant stage compared with several well-established surface-coating techniques. However, the solid-state nature and the superior properties exhibited by the surface coatings developed by FS make this process as a potential tool in near future for surface engineering applications.

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