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FRICTION SURFACING USING CONSUMABLE TOOLS- A REVIEW

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ABSTRACT

The friction surfacing technique is a new variation of friction stir welding process for modification of the surface properties of the substrate. There is a growing body of literature dealing with friction surfacing by consumable tool. This is a metallic deposition technique in which a rotating consumable tool deposits material onto a solid substrate. Friction surfacing has many applications in welding, coating, repair of defective components, hard surfacing and corrosion protection. This process does not generate high temperatures; therefore this technique is a suitable coating method capable of joining low melting point alloys. This review paper studies the basic principles and the use of friction surfacing as well as a survey of the latest researches and applications with emphasis on superficial and microstructural characterization, tensile, bending, effects of the different process factors such as axial force, rotation and travel speed, material deposition rate, energy consumption and different tool types. This review shows there are a few investigations dealing with novel tool/workpiece configurations for adding material for purposes other than coating, such as keyhole filling or dissimilar material joining. Also, the possible future directions for development and application of this technique are presented.

Keywords: Friction Surfacing, Solid State Coating, Deposition, Consumable Tools, Characterization

INTRODUCTION

Friction surfacing (FS) process is a thermo-mechanical solid-state method that can be utilized to create metal coatings. The deposition is possible due to frictional heat generated between the rotating consumable rod and substrate. There has been a developing interest in employing the FS process within the recent years. This technique can be utilized for many purposes in industry, including welding, coating, repair of defective components, hard surfacing and corrosion protection. FS is a relatively new variation of friction stir welding (FSW) process, a joining technique invented by Wayne Thomas at TWI Ltd in 1991, overcomes several difficulties experienced by using traditional joining techniques [1]. FSW is an appropriate technique to produce solid-state joints using a rotating rod which is pressed onto the workpiece surface with an axial loading force. This technique creates high quality joints or deposition, suitable for wide range of thicknesses and materials.

In the FS coating process, the rotating consumable tool is forced against the substrate surface, which generates frictional heating and shear forces at the interface between tool and substrate. A layer of tool material can be transferred from the rod to substrate surface as the consumable tool moves across, as shown in Figure 1. There are many process parameters which have impact on the results. The effect of the travel and rotation speed of the rod, pressing force and the consumable tilt angle have been considered as important parameters of this process [2]. The results can be examined by different methods such as hardness testing, image processing techniques and optical microscopy. It is proved that tilting the tool along the desired passing direction can increase the efficiency of the joint up to 5% [3]. Creating flash is another important issue which should be investigated. It is reported that in some experimental tests, flashes can result in material loss of about 40-60% of the total rod consumed [3].

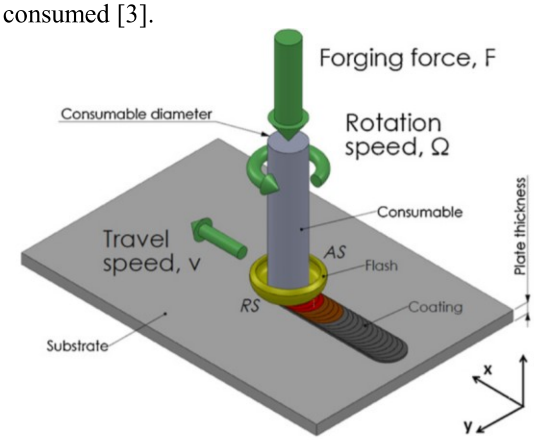

Figure 1. Schematic representation of the FS process, with identification of the main process variables [3]

The (FS) process has made it possible to produce thick coating layer over substrate with fine grain for improved

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mechanical properties of the substrates. In this technique, the heat is generated by frictional shearing at the contacting interfaces and internally in the material flow. The relative speed between the materials in the viscoplastic layer on the rod, which is rotating with the rod at V_{xy}, and the substrate ($V_{xy}=0$), enable the transfer of deposited layer from the consumable tool onto the surface of the substrate, as shown in Figure 2. The most significant portion of heat energy in this process is generating by the viscous shearing friction between the base and deposited material of the consumable tool [4]. FS could be used as an advanced surface modification technique, so it is of great importance to study the different mechanisms of material transfer in this process for controlling and improving the deposit's quality. Many researchers have studied FS processing based on different points of views. There are many investigations about viability of employing the FS process on various materials [4-10]. Table 1 presents the different tool and substrate materials as well as the processes have been used in FS.

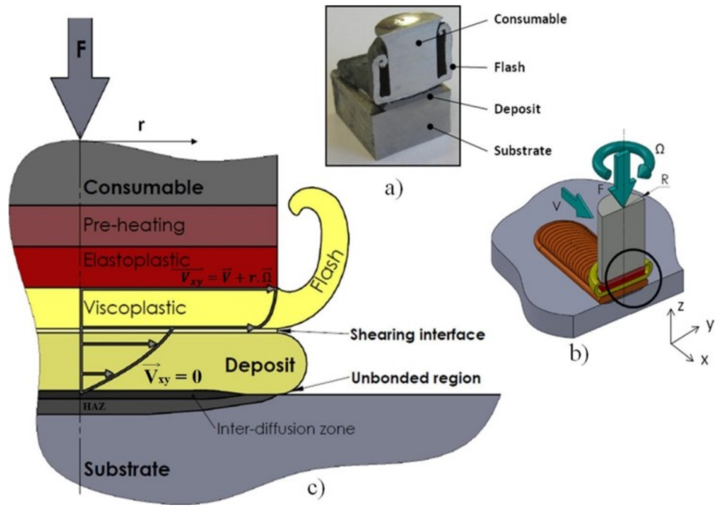

Figure 2. Schematic picture of different zones and important parameters in FS: a. Real cross section, b. Process parameters, c. Different zones and speed profile. (F: axial force, V_x travel speed, Ω tool rotation speed, V_{xy}: rod tangential speed in XY plane [3]

Table 1. Materials and processes used in FS

Tool Material	Substrate Material	Process	References
Aluminum	Aluminum	Consumable Rod	[22],[25],[26],[45],[49],[68],[72]
	Aluminum	Reinforcing Particles	[18],[20],[67]
	Aluminum	PMAFS	[17]
	Aluminum	RFSSW	[29],[39],[41],[42]
	Copper	Filling Friction Stir Welding (bit)	[37]
	Steel	Consumable Rod	[5], [7],[13],[23],[27],[33],[35],[50],[69]
	Steel	Spot Welding (bit)	[43],[44]
Steel	Aluminum	Consumable Rod	[12],[30],[70],[71]
	Steel	Consumable Rod	[2],[3],[4],[9],[11],[13],[14],[16],[24],[28] [31],[33],[34],[50],[51],[52],[53],[56],[57] [58],[59],[60],[61],[62],[63],[64],[73]
	Steel	Reinforcing Particles	[19]
	Steel	Spot Welding (bit)	[43]
	Copper	Consumable Rod	[12]
Titanium	Steel	Consumable Rod	[13]
	Titanium/Aluminum	FS-HFSW	[6]
	Titanium	Consumable Rod	[46],[54],[55]
	Titanium	Reinforcing Particles	[21]
Brass	Steel	Consumable Rod	[33]
Inconel	Steel	Consumable Rod	[13],[65]
Zinc	Aluminum	Consumable Rod	[32]
	Aluminum	RFSSW	[38]
	Steel	Consumable Rod	[32]
Copper	Copper	Consumable Rod	[12],[14]
	Steel	Consumable Rod	[10],[14]
Monel	Steel	Consumable Rod	[36]
Stellite6	Steel	Consumable Rod	[8]
NiAl-Bronze	Steel	Consumable Rod	[66]
Chromium-Nickel	Chromium-Nickel	Consumable Rod	[47]
Magnesium	Magnesium	Consumable Rod	[48]

PMAFS: Powder Metallurgy Assisted Friction Surfacing, RFSSW: Refill Friction Stir Spot Welding, FFSW: Filling Friction Stir Welding, FS-HFSW: Friction Surfacing Assisted Hybrid Friction Stir Welding

This paper focuses on the literature review of FS process with consumable tools. In section 2, recent research on FS of dissimilar materials using consumable tools and their results are discussed. Section 3 is devoted to the influence of process parameters in FS. Filling keyholes through FS using consumable bits is presented in Section 4. Characterization and mechanical properties in FS process are presented in Section 5. Finally in Section 6, the conclusions of this study and a summary of advantages of this process are presented.

FRICTION SURFACING OF DISSIMILAR MATERIALS USING CONSUMABLE TOOLS

Friction Surfacing of Dissimilar Tools and Substrates

Much research has been done to assess the FS process of dissimilar materials. Huang, Y., et al. studied a new technique of hybrid FSW assisted by FS for joining dissimilar titanium and aluminum alloys, as shown in Figure 3. In this method, a consumable rod which has concave end and enlarged head was used to enhance the material flow and increase the lap width [6].

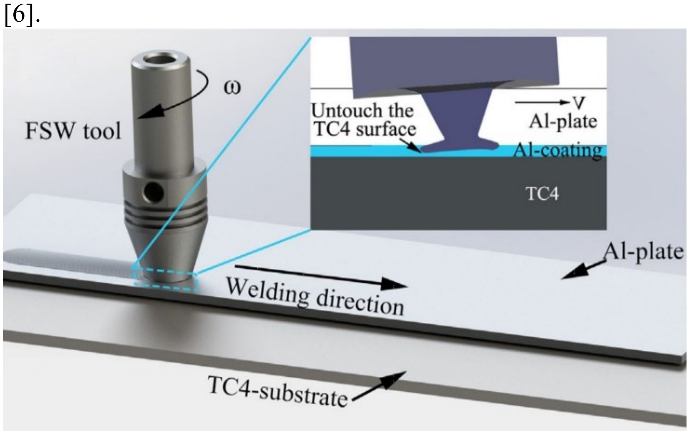

Figure 3. The friction stir lap welding [6]

The viability assessment of FS process of aluminum 6351 T6 consumable rod with several diameters over steel substrate was studied by Badheka and Badheka [7]. The best deposited coating layer was obtained using 22 mm rod based on visual appearance. In this process, the highest reported temperature on advancing side ($421°C$) was higher than highest temperature measured on the retreating side ($375°C$). In another investigation, the deposited coating of Stellite6 over steel substrate using FS process has been studied [8], and compared to deposition by gas tungsten arc and plasma transferred arc welding processes. The FS coating layers showed finer and well distributed carbides compared to gas tungsten arc joining and plasma transferred depositions. Also, the FS coating layers presented higher level of hardness.

The coating process of stainless steel over spheroidal graphite iron using FS process has been investigated by [9]. In this study, various combinations of process factors such as rotational speed, traverse speed and axial pressing load were considered. The microstructure revealed a strong joint between stainless steel and ductile iron and no cracks were observed in the HAZ. Bending tests and corrosion tests confirmed that this technique is suitable to manufacture pumps for chemical, petrochemical vessels and other corrosion resistant applications. The feasibility of using FS process in depositing copper onto mild steel with various process parameters has been studied [10]. A better copper deposition was produced on rough surfaces created by rough milling. Macedo, M.L.K.D., et al. studied the coating layers of three different type of tool materials (ABNT 4140, ABNT 8620, and AISI 310 steel tool) onto an ABNT 1070 carbon steel substrate. The results showed that FS can be employed to repair the surfaces of high carbon steels and produce coatings on similar and dissimilar materials [11].

Shariq, M., et al. examined the feasibility of FS coating process on several combination of consumable tools and substrates by using conventional universal milling machine FNU2213. In this study, AISI 304 and commercially pure copper have been utilized as consumable tools and mild steel, AISI 304, copper and aluminum (AA1050A) have been utilized as substrates. FS deposition of stainless steel onto commercially pure copper substrate, and commercially pure copper onto commercially pure copper were not successful. FS process of stainless steel (AISI 304) on aluminum (AA 1050A) resulted in an acceptable and successful deposition using mild steel as a start-up plate. The start-up plate of mild steel was clamped and welded to the aluminum substrate, to make a continuous surface, as presented in Figure 4. The maximum generated temperature during the investigation was 1415ºC [12].

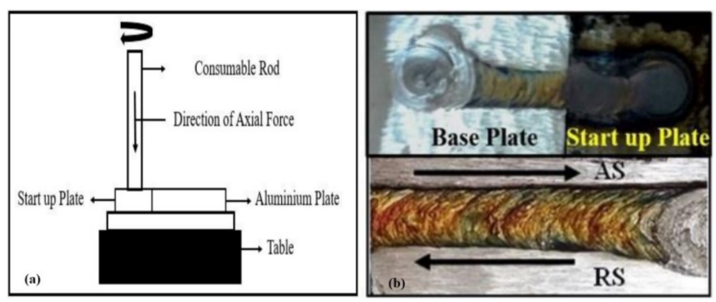

Figure 4. (a) Schematic diagram of the test setup; (b) FS of stainless steel onto aluminum substrate using start-up plate [12]

FS of different materials such as aluminum, mild steel, stainless steel, titanium and inconel as the consumable rods over mild steel and aluminum have been studied [13]. It was observed that steel and inconel rods were coated onto steel successfully, while aluminum rod was only coated successfully under high contact pressure. Mild steel, inconel and stainless steel were coated onto aluminum substrates successfully, but deposition of titanium was not possible.

In the FS of consumable tools, thermal processing analysis has an important role in the successful employment of the deposition process. Rao, K.P., et al. [14] considered the thermal profiles of several sets of tool materials and substrates include copper/copper, steel/steel and copper/steel. Also, infrared thermography technique was utilized to record the thermal profiles during FS process. Liu, X., et al. [15] attempted to model the temperature field of a consumable tools during the FS process using applied finite difference method. As shown in Figure 5, the results were consistent with experiments and provides theoretical guidance for technical parameters in FS. A thermal analysis was done during the FS of 1Cr18Ni9Ti (321) rod on mild steel 1020 substrate. In this investigation, a thermocouple was used to measures the temperature changes at important points on the consumable tool. The results exhibited a high rate of temperature change at the friction interface initially during the process. Once the friction process approached to a quasi-steady state, the rate of temperature change decreased and gradually became stable around the melting point of the consumable tool [16].

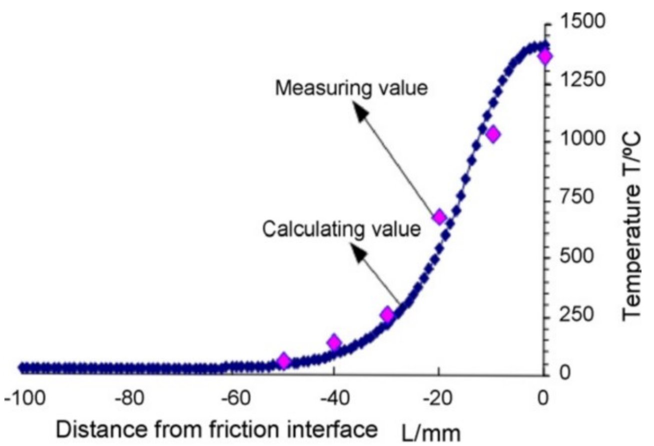

Figure 5. The simulation and experimental results of temperature analysis (force:4000 N; rotating speed:1825 rpm; time:37 s) [15]

In a recent investigation, the characterization and fabrication of aluminum-graphene surface composites were studied [17]. The impregnation of graphene nano platelets in aluminum substrate by modified FS process with a tool composed of powder metallurgy technique was carried out in two stages. First, an aluminum-graphene composite tool was made by powder metallurgy. Then, this consumable tool was used to create a deposition coating layer on aluminum substrate through FS process. The produced surface composite was shown to have impregnated graphene in aluminum substrate.

Friction Surfacing Using Reinforcement Particles

Oliveira, P.H.F., et al. [18] investigated AA6351-T6 deposition onto AA5052-H32 substrate, reinforced with aluminum oxide (Al_2O_3) particles. In this study, the consumable tool was drilled with holes that were filled with aluminum oxide particles. The Al_2O_3 particles had a significant impact on increasing the hardness values of generated deposition [18]. In a recent study, stainless steel 316L/TiB2 coating was successfully fabricated using FS technique onto the stainless steel 304 substrate [19]. A few blind holes were created on the cylindrical 316L consumable tools to encapsulate TiB2 powder which was used as reinforcement in the deposition process. The friction depositing process was successfully applied on an aluminum matrix composite which was reinforced using titanium particles. This process resulted in a multilayer composite deposition with well-bonded layers and uniformly distributed Ti particles [20].

The FS deposition process of Ti-6Al-4V composite reinforced by TiC particles onto Ti-6Al-4V substrate was investigated in [21]. TiC particles were added to drilled holes at the tool tip. Different hole placement configurations within the tool affected the deposition efficiency, coating quality, process behaviour and distribution of particles within the coating layer. It was found that axial forces were higher for tools with holes located near to the tool center.

Reddy, G.M., et al. [22] studied the FS coating technique of AA 2124 aluminum alloy composite reinforced with SiCp onto A356 aluminum alloy substrate. This research focused on the corrosion and wear performance of the processed material. The deposited coating was examined by dry sliding wear, metallography and potentiodynamic polarization testing and showed adequate corrosion resistance. The results revealed that FS of aluminum alloys with metal matrix composites is feasible.

EFFECT OF PROCESS PARAMETERS IN FRICTION SURFACING

There are many studies on the influence of different parameters with variations of materials. Optimization of FS process parameters is another important aspect of these investigations [23]. Further improvement in the FS process requires development in mathematical modeling of the process which facilitate the optimization methods for experimental tests [24]. Galvis, J.C., et al. [25] studied the influence of FS process parameters in deposition of AA6351-T6 onto AA5052-H32 with a conventional milling machine. In their research, the rod feed rate was used as a control parameter and the superficial and microstructural characterization of the coating layer was investigated. It was found that a conventional machine can produce homogeneous deposited layers. In this friction deposition, the value of hardness in the central region decreased 15.87% in relation to the substrate material as-received.

Gandra, J., et al. [26] studied the coating of AA6082-T6 onto AA2024-T3 substrate, considering the influence of process parameters including axial pressing force, travel and rotation speed. The results indicated that to increase coating thickness and width, low travel and rotation speeds should be considered. In [27], a study was done to investigate the relations between process factors and dimensions of AA6063 aluminum alloy deposition on IS2062 substrate. Some physical factors such as axial pressing force, tool rotational speed, and table traverse speed were concluded as most important parameters on physical dimensions. Thickness of the deposition decreased as the deposition width increased. Furthermore, at low and high torques, the thickness and width of the depositions were higher.

An investigation was done by Nixon, R.G.S., et al. [28] in order to obtain the deposition of AISI316 stainless steel onto EN24 carbon steel by FS process shown in Figure 6. Again, the tool speed, axial force, and table traverse speed of the FS system were considered as the most effective parameters. The results showed that the depth of the coating layer lessened as the coating width increased. Shen, Z., et al. [29] performed the refill friction stir spot welding technique in a 0.8 mm thick AA7075-T6 considering varying process factors such as plunge depth and welding time. The effect of process factors on mechanical and microstructure features was studied in terms of overlap shear strength, nugget thickness and hardness. It was proved that by increasing the plunge depth and process time, the nugget thickness increases. The shear strength of overlaps increased with the increment of plunge depth and process time due to increased nugget diameter.

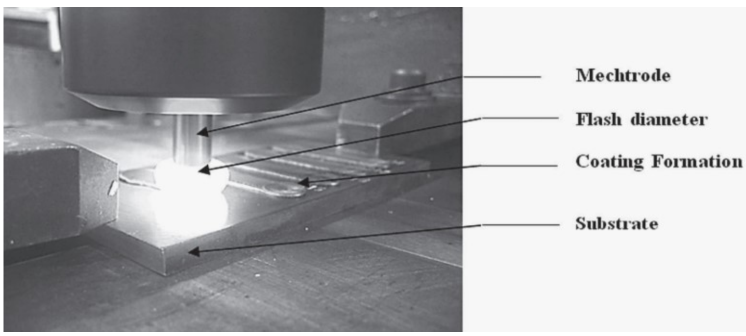

Figure 6. A close sight of investigational arrangement [28].

Casalino, G., et al. [30] studied the influences of geometry and deposition of the tool shoulder on microhardness and microstructure of the 5754H11 aluminum alloy substrate which has 3 mm thick. The weld microhardness profile of all microstructural zones investigated. Shinoda, T., et al. [31] established a method that creates a 1 mm thick hard coating by using FS process. The experimental tests were done to determine the influences of process parameters on the quality of the deposition. It was shown that the rotational speed of the coating material strongly affects on the hardness of the coating layer, and the investigation shows that a harder coating layer can be created when the tool has a lower rotational speed. Kumar, V.A. and Sammaiah, P. [32] improved the corrosion performance of steel & aluminum by creating the deposition of zinc on them. By increasing the friction in the process, the Zinc deposition on aluminum and mild steel increased. It is shown that at a lower feed, lower forward time and higher speed, the smaller crystalline size of the zinc coated on the surfaces. A study was done on different materials, deposition parameters and number of coated layers in FS process [33]. Three consumable materials such as stainless steel, aluminum and brass were deposited onto a mild steel substrate while nitrogen was flowing on the surfaces in the open air. The stainless steel produced a strong thick deposition layer, but this process was not successful with both aluminum and brass. The nitrogen ventilation decreased the quality of the deposition coating because it was cooling the heated layer.

Rafi, H.K., et al. [34] studied the FS process of tool steel H13 on low carbon steel substrates. In this method, the rotational speed of mechtrode (consumable rod) and traverse speed of the substrate were varied, while the axial force was held constant. As is demonstrated in Figure 7, by using the higher tool rotational speeds, the coatings layers were narrower compared to the layers produced at lower tool rotational speeds. Another investigation has been done in [35] to identify the appropriate process parameters for FS process. Analysis revealed that higher axial force results in lower coating thickness and has favorable effect on bend ductility. Recently, the fuzzy logic based on soft computing model has been developed to predict the thickness and width of coatings in the FS process. In the experimental tests, mild steel AISI 1012 was friction surfaced with Monel 500. In the FS process of these materials, it was observed that the increasing the axial load increases the deposition thickness and width [36].

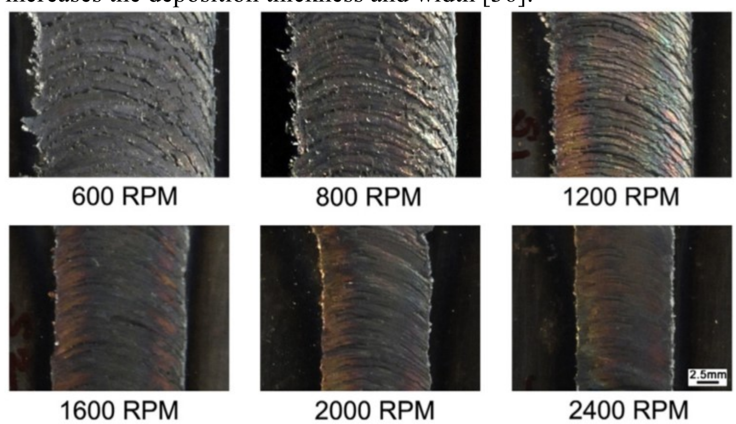

Figure 7. Deposition coatings created by using different mechtrode rotational speeds [34].

FILLING KEYHOLES THROUGH FRICTION SURFACING USING CONSUMABLE BITS

In [37] a new method for filling friction stir welding (FFSW) of lap joints to remove the remained exit holes in the friction stir welding of AA5456 sheets was studied, as shown in Figure 8. In order to fill the holes, tools with steel shoulder and aluminum alloy joining pins with different geometries and several pin applying methods were used. Then, the mechanical properties and structures of the results studied that showed the resulting joints were 7% stronger than the joints with the non-filled exit hole. Zhang, G., et al. [38] filled a keyhole created by friction stir weld bead on 1060 aluminum substrate using a pin tool equipped with a T shaped filler bit, as shown in Figure 9. In comparison with the case of employing a cylindrical filler bit, the experimental result shows improvement in filling quality and small gaps were created at the lower periphery and bottom interface.

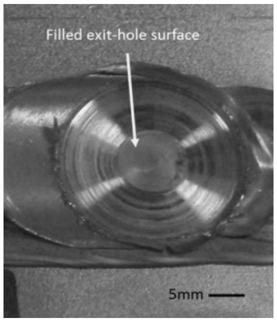

Figure 8. Surface of filled exit hole by FFSW (K2T1D8L8a11) [37]

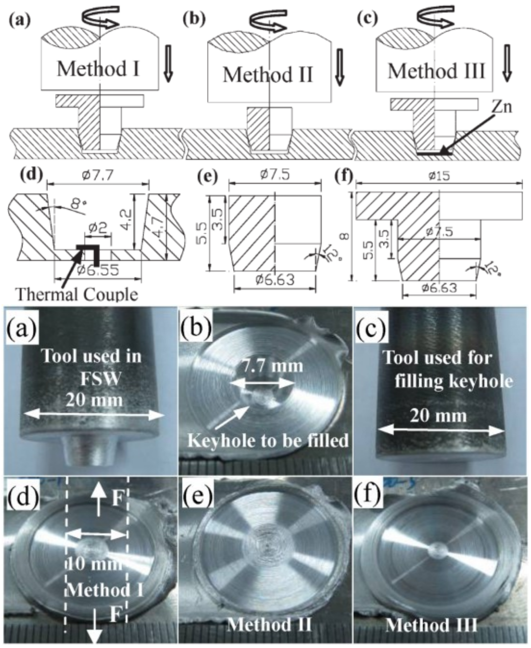

Figure 9. Top: schematic diagrams of filling keyhole processes using filler bits, a–c: filling processes, d: keyhole size, e and f filler bit sizes; Bottom: The test results before and after filling keyhole processes, mechanical test illustration and used tools [38]

Huang, Y., et al. [39] studied the FFSW technique using semi-consumable joining tool to repair and fill the keyholes. In this method, a semi-consumable joining tool which includes alloy steel shoulder and aluminum alloy joining bit has been designed to produce a solid-state joint, as shown in Figure 10. Another investigation has been done to study the application of FS process to repair the aged structural materials in nuclear plants [40]. Huang, Y., et al. and Han, B., et al. [41-42] investigated the FFSW of AA2219 rolled plates using a semi-consumable rod equipped with an alloy steel shoulder, and AA2219 and AA7075 bits, respectively (Figure 11). The effects of the bit's geometric factors and plunge speed on the interface, ductility, hardness distributions and fracture features were studied. Miles, M., et al. [43] evaluated using a consumable bit on dual phase 980 steel and a dissimilar combination of 5754-O aluminum alloy and dual phase 980 steel through FS. In [44] a consumable bit was employed to make a spot joint between high strength steel and AA5754 sheets. The metallurgical and mechanical evaluation of the result shows that this technique can be applied successfully between very hard and very soft alloys, light metals like AA5754 and dual phase like 590 and DP 980.

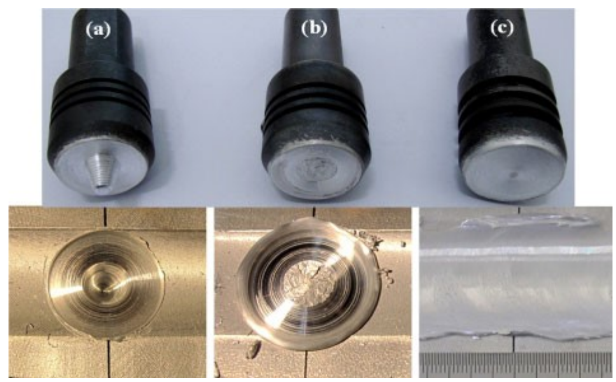

Figure 10. joint and corresponding tool: a keyhole created in friction stir welding process; b after FFSW; c after friction stir processing [39].

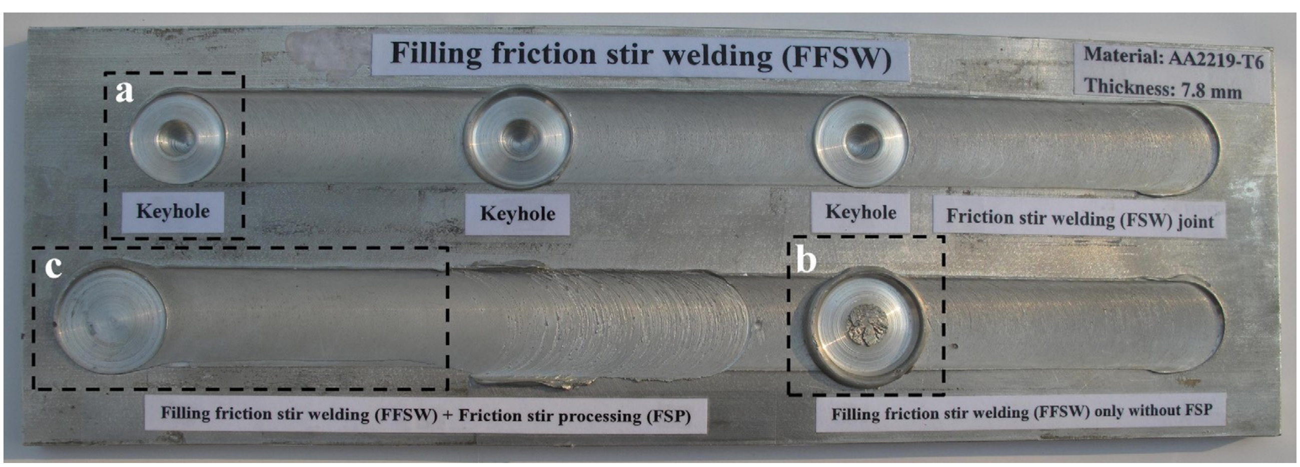

Figure 11. AA7075 bit for repairing AA2219 keyhole through FFSW process with (a) friction stir welding with keyhole defects, (b) filled keyhole, (c) repaired keyhole using friction stir processing [42].

CHARACTERIZATION & MECHANICAL PROPERTIES

Surface modification is an essential step in the manufacturing process for improving the service properties of produced components. Investigation of mechanical properties and characterization of coating layers are considered in many of the studies to evaluate the result of the experimental tests. The FS is a process which can improve the properties and has repair applications. This technique works at temperatures below the melting point followed by high cooling rates, therefore this process has been studied for producing fine-grained depositing layers with better wear and corrosion properties. In the multi-layer FS deposition process, this is important to know that how microstructures develop in heat-treatable aluminum alloys. It is shown in [45] that the procedure invariably results in overaging of strengthening precipitates in different materials. For such a problem, a solution treatment can be used but it can cause other problems such as abnormal grain growth. The microstructural evolution through FS of an aluminum alloy 6082-T6 consumable tool onto aluminum alloy 2024-T351 substrate has been evaluated using the electron backscatter diffraction technique. In this study, crystallographic data obtained from several different regions in the tool and coating material. By using textural analysis, it was explored that the material flow is close to simple-shear deformation and the FS process was found to result in significant grain refinement. Depositing with the high deformity rates results in microstructure grain refinement, which increases the mechanical properties of the deposition coating [46]. The process parameters associated with deposition of Ti-6Al-4V lead to defect free coatings and flash have been studied. In this process, the tool consumption rate mode was utilized as an efficient control mode for deposition. Achieving a low energy input using appropriate deposition and rotational speeds during the FS process can control the flash formation [46]. Hanke, S., et al. [47] studied FS of Cr60Ni40 alloy on Nimonic 80A substrates. In this study, microstructural evaluation of the coating was compared to the cast state. The amount of wear resistance of all coatings was near to that of cast state but a little smaller, the result of finer microstructure.

Monolayer FS AZ91 magnesium alloy casting tool onto AZ31 magnesium alloy studied by Nakama, D., et al. [48]. Monolayer and multilayer FS process of 2017 aluminum alloy rod on 5052 aluminum alloy plate was also studied [49]. The influences of process parameters on mechanical properties and structure of both multilayer and monolayer coating were explored. In both multilayer and monolayer coatings, microstructures showed finer properties than those of the consumable rod and substrate. It was revealed that the monolayer coating tends to incline toward the retreating side (right side), and the second surfacing of multilayer coatings inclined toward the first deposition side, as shown in Figure 12.

Many types of inspection such as optical microscopy, scanning electron microscopy and X-ray diffraction testing and different techniques such as strength and tensile tests, microstructure and hardness distribution have been done to examine the deposited coatings quality. The literature shows that FS can be utilized as an alternative method to produce coatings of dissimilar materials using vertical milling machine [50]. Govardhan, D., et al. [51] discussed different process parameters and factors involved in FS process to optimize them to approach high quality deposits and joints. In order to find the suitability of the deposits for many applications in different industrial sections of engineering fields such as defense, aerospace, automobile, pressure vessels, chemical pumps, corrosion tests were carried out. The metallography of the coatings exhibited dense, clear and fine microstructure and no cracks observed in the HAZ. In another investigation, the process was developed to produce a defect free deposition coating of D2 tool steel onto a low carbon steel substrate [52]. Then, optical microscopy, X-ray diffraction and scanning electron microscopy were used to evaluate the microstructural characterization.

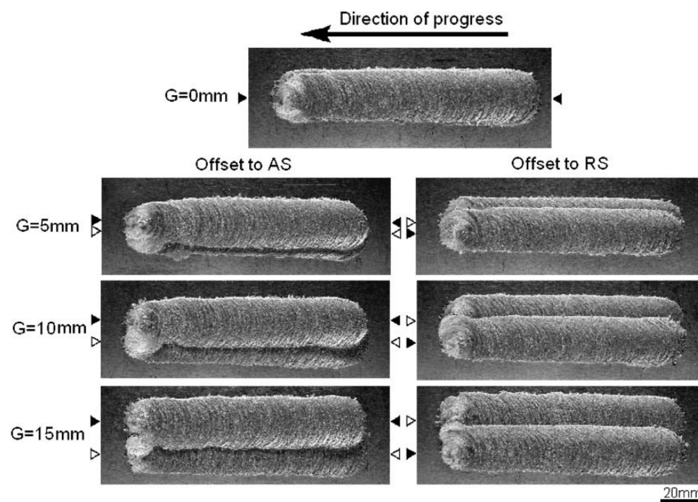

Figure 12. Multilayer deposition coatings, rotational speed 20.0 s^{-1}, friction pressure 30 MPa, and travel speed 9mm.s^{-1}
△: Center of the first coating rod, ▲: Center of the second coating rod.

In [53], it was proven that under moderate Zener-Hollomon parameter conditions during the FS process, the austenitic stainless steel AISI 316L experiences discontinuous dynamic recrystallization. The deposited layer of alloy 316L showed an increase in the grain size from the interface of coating and substrate to the top surface of the coating which was the result of decreasing cooling rate form the interface to the top surface of the coating. In [54] an attempt was carried out to understand the influence of rotational speed of consumable tool on microstructure, grain size evolution and mechanical properties of Ti-6Al-4V during the FS process.

Dovzhenko, G., et al. [55] studied the relationship between the travel speed of the stud and the residual stress of the deposited 2 mm thick Ti-6Al-4V substrates through FS process using synchrotron diffraction. Furthermore, the effect of the residual stress on creating fatigue cracks was studied. The results revealed that higher stud travel speeds create high values of residual stress peak, as shown in Figure 13. Also, the thickness of the deposited layer had an effect on the residual stress propagation.

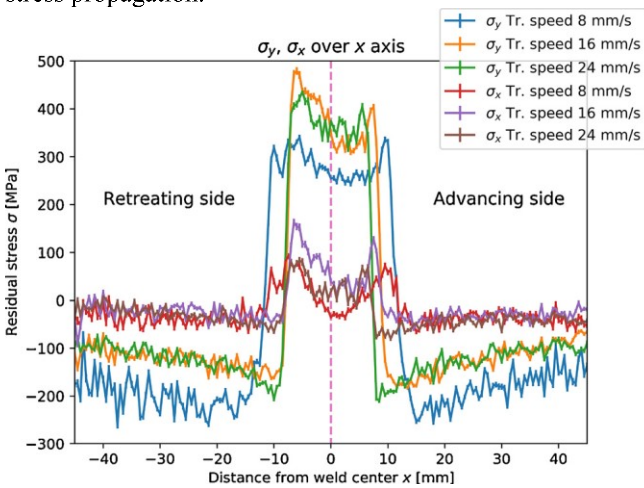

Figure 13. Distribution of deposition residual stress along the scan line: longitudinal (σ_x) and transverse (σ_y) [55]

AISI 410 deposition coating onto low carbon steel sheets was created by FS and manual metal arc welding technique, and the microstructures of the deposited layers, wear and corrosion properties were evaluated in detail [56]. In the FS technique, the deposited layers exhibit no dilution, unlike the result of manual metal arc coating technique. Also, the results of FS of alloy 410 present comparable corrosion and wear behavior to alloy 410 in the tempered and hardened situation. Puli, R., et al. [57] studied the deposition of martensitic stainless steel AISI 410 onto mild steel substrate. The results indicated fully martensitic microstructures which were quite hard, average hardness was 460 HV. Also, shear and bend tests show excellent coating/substrate bonding. In another investigation, 440C stainless steel alloy was friction surfaced onto low carbon steel successfully [58]. Shear and bend tests on deposited layers show excellent coating/substrate bonding. The result of the FS process showed superior corrosion resistance, while its wear performance was somewhat inferior. In a recent study, stainless steel was deposited onto mild steel using FS technique [59]. The peak joint strength of the deposition layers was 502 MPa evaluated by ram tensile test. The corrosion performance of the coating layers was found to be inferior to that of tool material and greater than the substrate. Pereira, D., et al. [60] performed FS process to create multi-layer deposition coating of AISI H13, AISI 1024 and AISI 1045 onto mild steel substrates. The major goal of this investigation was to examine which material combination was more wear-resistant. As is shown in Figure 14, the analysis reveals that AISI 1024 presents the least wear rate and wear friction coefficient. Figure 15 presents a comparison between the coating microstructure and the consumable tool original condition. The deposition shows martensitic and bainitic microstructures, which reveals that the coated layer has experienced full austenitization.

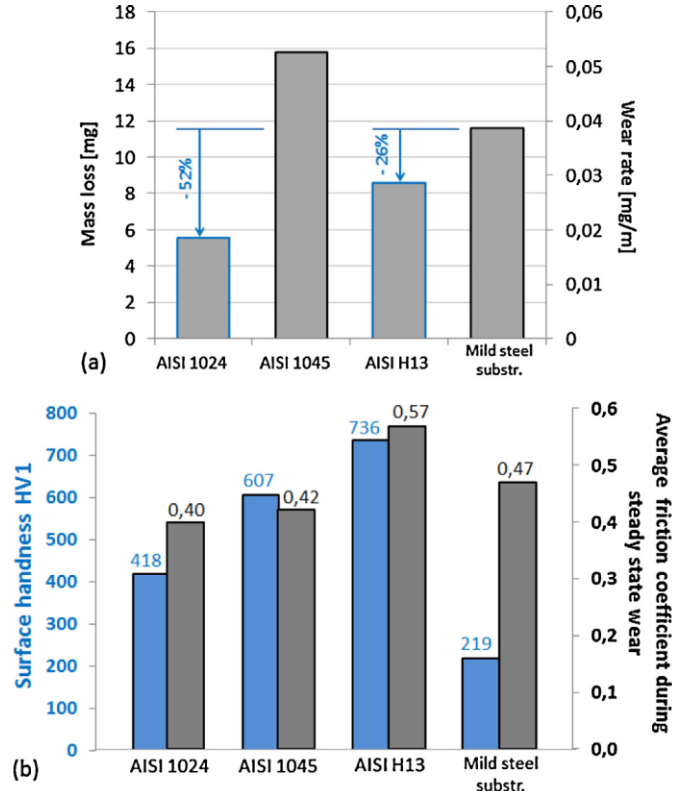

Figure 14. (a) Mass loss calculated by pin-on-disc wear evaluation, (b) surface hardness and average friction coefficient through steady state wear [60]

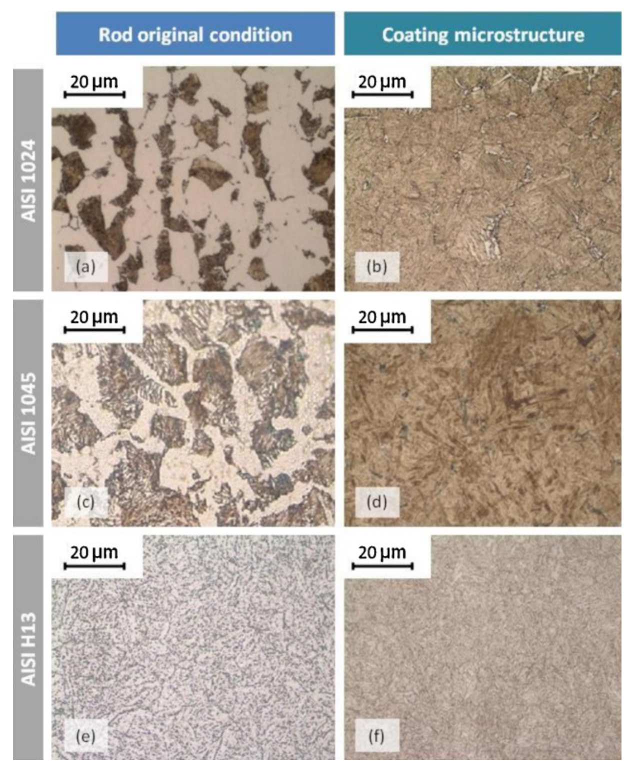

Figure 15. Comparison between different consumable tool original condition and deposition coating microstructure [60].

FS of stainless steel as consumable tool on low carbon steel as substrate has been studied [61]. It is an attempt to study the influences of process parameters during FS technique on different combinations of materials, surface roughness, and shear strength. Also in another investigation, Rafi, H.K., et al. studied the deposition of AISI H13 tool steel onto low carbon steel through the FS process [62]. Microstructural and microhardness evaluations were carried out on the deposition coatings in details which reveal defect free coating layers. The deposition coatings exhibited significantly higher level of hardness (58 HRC) comparing to the consumable tool material when it is in annealed condition (20 HRC). Figure 16 presents the microhardness profile from the deposition coating layer to the unaffected substrate.

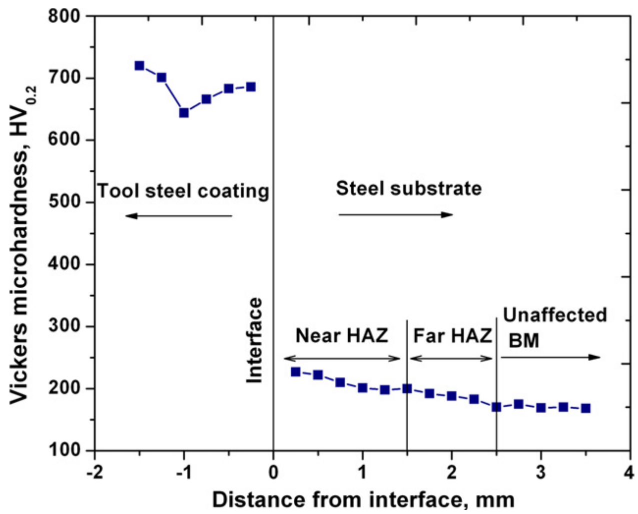

Figure 16. The values of Vickers microhardness across the coating/substrate interface [62].

AISI 304 (austenitic stainless steel) was deposited onto high strength low alloy (HSLA) steel substrate [63]. The FS coating and substrate were tested for pitting corrosion by potentiodynamic polarization technique. Pitting resistance of the deposited coating was less than that of tool material and superior to that of the substrate. In another investigation, it was proven that AISI 304 stainless steel coatings created by FS process shows superior corrosion resistance in various environments [64]. In a recent investigation, Ni-based alloy 625 was friction surfaced onto 42CrMo4 substrate, appropriate for corrosion protection layers [65]. The result shows that the thermal cycle and dynamic recrystallization determine the final microstructure. Hanke, S., et al. [66] studied the deposition coating of NiAl-bronze deposited on self-mating substrates through the FS process. In order to examine the wear performance of the result, cavitation evaluations were performed. The single deposited layer of NiAl-bronze on the same substrate material shows a fine grained, and homogeneous microstructure. The cavitation erosion behaviour of the deposited layers was in a higher level than that in cast material [66].

Many investigations have been done on properties and microstructural characterization aluminum alloys subjected to FS. Miranda, R.M., et al. [67] studied the production of aluminum based FGM composites using alumina and SiC reinforcements through FS process. Gandra, J., et al. [68] studied the application of the FS process to deposit AA6082-T6 onto AA2024-T3 considering bending, tensile and wear characterization. The produced coatings reveal that the ultimate tensile strength was 25 % less than that in the substrate material, while the strain at break points was improved in 42 %. In [69], commercial pure aluminum in the form of the consumable tool was friction surfaced over medium carbon steel through the FS process. Coated aluminum consisted of small Fe particles dispersed in it. The result shows a smooth interface between the deposition coating and substrate.

An experimental setup is prepared in [70] to investigate the FS process parametric relationships in the classical approach to FS with the addition of inductive heating. The analysis indicates that high joint strength values for both shear and push-off test will be possible at 3000 rpm and 8 bar in which the minimum amount of flash material being generated. FS process of stainless steel 1.4301 onto the aluminum substrate AlMgSi0.5 has been explored in [71]. In order to produce the specimens, the application of inductive heating and utilizing a flash-reducing tool have been considered and the result has been compared with those achieved through the classical method. Utilizing the inductive heating approach improved the shear strength of the deposition coating compared to flash-reducing tool approach and classical process. Also, the microstructural evolution of the coating during FS of alloy 6082-T6 onto alloy 2024-T351 have been studied by employing the electron backscatter diffraction technique [72]. In another investigation, the deposited coating of tool steel (H13) and austenitic stainless steel (AISI 310) over mild steel substrates carried out in order to study the wear and corrosion protection, respectively. The result of this investigation was analyzed using optical and scanning electron microscopy and by doing shear and bend tests. The analysis shows that the tool steel coating is not good in bending situation, and cracks showed up after five degree of bending which is due to the inherent brittleness of the tool steel. On the other hand, the stainless steel coating was bent 90 degrees without any cracks [73].

CONCLUSION

There is a growing body of literature within friction stir welding dealing with friction surfacing with a consumable tool. The tool is made of the material to be coated or deposited onto the substrate. The precursor to this was friction stir surface modification, where the non-consumable friction stir welding tool was used to modify material properties on the surface of the substrate by refining the grain structure and/or mixing in external particles. This new direction is transfer of material for coating and dissimilar material joining applications. This new solid state friction stir based process has much potential as an alternative means of dissimilar material joining, an area of growing interest.

The literature review here is organized into four different sub areas of importance dealing with material combinations, process parameters, keyhole filling, and property characterization. This review shows that this new research direction is still in early stage, as majority of the research is still experimental and metallurgical in nature, and rightly so because the results suggest there are improvements to be made in terms of deposition quality and consistency for this process to be legitimately viable in industry. There are many papers on process parameter variations for different tool and substrate materials. Most of the literature details FS process with mechanical transfer of material from a rotating consumable tool enabled by elevated force and temperature. There are a few papers dealing with novel tool/workpiece configurations for adding material for purposes other than coating, such as keyhole filling or dissimilar material joining. The possible future directions for this research are:

- analytical and finite element modeling of the process
- studying all the process parameters in order to control the quality of the product
- further development of adding material for structural, joining, or cavity filling purpose as well as corrosion resistance
- further investigation of different tool shapes in order to achieve the best result in different processes
- process scale up
- deeper understanding and control of material transfer

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REFERENCES

[1] Thomas, W. M., Nicholas, E. D., Needham, J. C., Murch, M. G., Temple-Smith, P., Dawes, C.J. (1991) Friction stir butt welding, International Patent Application, No. PCT/GB92/02203.

[2] Liu, X. M., Zou, Z. D., Zhang, Y. H., Qu, S. Y., and Wang, X. H. (2008) Figuration Control of Deposit in Friction Surfacing, In Key Engineering Materials 373 806-810.

[3] Gandra, J., Miranda, R. M., and Vilaça, P. (2012) Performance analysis of friction surfacing, Journal of Materials Processing Technology 212(8) 1676-1686.

[4] Vilaça, P., Hänninen, H., Saukkonen, T., and Miranda, R. M. (2014) Differences between secondary and primary flash formation on coating of HSS with AISI 316 using friction surfacing, Welding in the World 58(5) 661-671.

[5] Da Silva, M. M., Afonso, M. L. B., Silva, S. L. N., Troysi, F. C. T. D., dos Santos, Í. B., and Brito, P. P. (2018) Application of the friction surfacing process in a CNC machining center: a viability assessment for producing Al-alloy coatings on low carbon steel, Journal of the Brazilian Society of Mechanical Sciences and Engineering 40(1) 1-11.

[6] Huang, Y., Lv, Z., Wan, L., Shen, J., and dos Santos, J. F. (2017) A new method of hybrid friction stir welding assisted by friction surfacing for joining dissimilar Ti/Al alloy, Materials Letters 207 172-175.

[7] Badheka, K., and Badheka, V. (2017) Friction Surfacing Of Aluminium on Steel: An Experimental Approach, Materials Today: Proceedings 4(9) 9937-9941.

[8] Rao, K. P., Damodaram, R., Rafi, H. K., Ram, G. J., Reddy, G. M., and Nagalakshmi, R. (2012) Friction surfaced Stellite6 coatings, Materials Characterization 70 111-116.

[9] Nixon, R., and Mohanty, B. S. (2013) Friction Surfacing of Metal Coatings on Stainless Steel AISI 304 over Spheroidal Graphite Iron Substrate, In Advanced Materials Research 816 271-275.

[10] Jujare, T., Kumar, A., Kailas, S. V., and Bhat, K. U. (2014) Friction surfacing of mild steel by copper: a feasibility study, Procedia Materials Science 5 1300-1307.

[11] Kramer de Macedo, M. L., Pinheiro, G. A., dos Santos, J. F., and Strohaecker, T. R. (2010) Deposit by friction surfacing and its applications, Welding International 24(6) 422-431.

[12] Shariq, M., Srivastava, M., Tripathi, R., Chattopadhyaya, S., and Dixit, A. R. (2016) Feasibility Study of Friction Surfaced Coatings over Non-Ferrous Substrates, Procedia Engineering 149 465-471.

[13] Chandrasekaran, M., Batchelor, A. W., and Jana, S. (1997) Friction surfacing of metal coatings on steel and aluminum substrate, Journal of Materials Processing Technology 72(3) 446-452.

[14] Rao, K. P., Sreenu, A. V., Rafi, H. K., Libin, M. N., and Balasubramaniam, K. (2012) Tool steel and copper coatings by friction surfacing–A thermography study, Journal of Materials Processing Technology 212(2) 402-407.

[15] Liu, X., Yao, J., Wang, X., Zou, Z., and Qu, S. (2009) Finite difference modeling on the temperature field of consumable-rod in friction surfacing, Journal of materials processing technology 209(3) 1392-1399.

[16] Liu, X. M., Zou, Z. D., Zhang, Y. H., Qu, S. Y., and Wang, X. H. (2008) Transferring mechanism of the coating rod in friction surfacing, Surface and Coatings Technology 202(9) 1889-1894.

[17] Sharma, A., Sagar, S., Mahto, R. P., Sahoo, B., Pal, S. K., and Paul, J. (2018) Surface modification of Al6061 by graphene impregnation through a powder metallurgy assisted friction surfacing, Surface and Coatings Technology 337 12-23.

[18] Oliveira, P. H. F., Galvis, J. C., Martins, J. D. P., and Carvalho, A. L. M. (2017) Application of Friction Surfacing to the Production of Aluminum Coatings Reinforced with Al2O3 Particles, Materials Research 20 603-620.

[19] Guo, D., Kwok, C. T., and Chan, S. L. I. (2018) Fabrication of stainless steel 316L/TiB2 composite coating via friction surfacing, Surface and Coatings Technology 350 936-948.

[20] Karthik, G. M., Ram, G. J., and Kottada, R. S. (2016) Friction deposition of titanium particle reinforced aluminum matrix composites, Materials Science and Engineering: A 653 71-83.
[21] Belei, C., Fitseva, V., dos Santos, J. F., Alcântara, N. G., and Hanke, S. (2017) TiC particle reinforced Ti-6Al-4V friction surfacing coatings, Surface and Coatings Technology 329 163-173.
[22] Reddy, G. M., Rao, K. S., and Mohandas, T. (2009) Friction surfacing: novel technique for metal matrix composite coating on aluminium–silicon alloy, Surface Engineering 25(1) 25-30.
[23] Sugandhi, V., and Ravishankar, V. (2012) Optimization of friction surfacing process parameters for aa1100 aluminum alloy coating with mild steel substrate using response surface methodology (RSM) technique, Modern Applied Science 6(2) 69-80.
[24] Vitanov, V. I., and Voutchkov, I. I. (2005) Process parameters selection for friction surfacing applications using intelligent decision support, Journal of Materials Processing Technology 159(1) 27-32.
[25] Galvis, J. C., Oliveira, P. H. F., Hupalo, M. F., Martins, J. P., and Carvalho, A. L. M. (2017) Influence of friction surfacing process parameters to deposit AA6351-T6 over AA5052-H32 using conventional milling machine, Journal of Materials Processing Technology 245 91-105.
[26] Gandra, J., Pereira, D., Miranda, R. M., and Vilaça, P. (2013) Influence of Process Parameters in the Friction Surfacing of AA 6082-T6 over AA 2024-T3, Procedia CIRP 7 341-346.
[27] Kumar, B. V., Reddy, G. M., and Mohandas, T. (2015) Influence of process parameters on physical dimensions of AA6063 aluminium alloy coating on mild steel in friction surfacing, Defence Technology 11(3) 275-281.
[28] Nixon, R. G. S., Mohanty, B. S., and Bhaskar, G. B. (2018) Effect of process parameters on physical measurements of AISI316 stainless steel coating on EN24 in friction surfacing, Materials and Manufacturing Processes 33(7) 778-785.
[29] Shen, Z., Chen, Y., Hou, J. S. C., Yang, X., and Gerlich, A. P. (2015) Influence of processing parameters on microstructure and mechanical performance of refill friction stir spot welded 7075-T6 aluminium alloy, Science and Technology of Welding and Joining 20(1) 48-57.
[30] Casalino, G., Campanelli, S., and Mortello, M. (2014) Influence of shoulder geometry and coating of the tool on the friction stir welding of aluminium alloy plates, Procedia Engineering 69 1541-1548.
[31] Shinoda, T., Li, J. Q., Katoh, Y., and Yashiro, T. (1998) Effect of process parameters during friction coating on properties of non-dilution coating layers, Surface Engineering 14(3) 211-216.
[32] Kumar, V. A., and Sammaiah, P. (2018) Comparison Of Process Parameters Influence On Mechanical And Metallurgical Properties Of Zinc Coating On Mild Steel & Aluminium During Mechanical Process, Materials Today: Proceedings 5(2) 3861-3866.
[33] Batchelor, A. W., Jana, S., Koh, C. P., and Tan, C. S. (1996) The effect of metal type and multi-layering on friction surfacing, Journal of materials processing technology 57(1-2) 172-181.
[34] Rafi, H. K., Ram, G. J., Phanikumar, G., and Rao, K. P. (2010) Friction surfaced tool steel (H13) coatings on low carbon steel: A study on the effects of process parameters on coating characteristics and integrity, Surface and Coatings Technology 205(1) 232-242.
[35] Kumar, B. V., Reddy, G. M., and Mohandas, T. (2014) Identification of suitable process parameters for friction surfacing of mild steel with AA6063 aluminium alloy, The International Journal of Advanced Manufacturing Technology 74(1-4) 433-443.
[36] Murugan, C. B. K., Balusamy, V., Padmanaban, R., and Vignesh, R. V. (2018) Friction surfacing mild-steel with Monel and predicting the coating parameters using fuzzy logic, Materials Today: Proceedings 5(8) 16402-16410.
[37] Pandya, S. N., and Menghani, J. V. (2018) Developments of mathematical models for prediction of tensile properties of dissimilar AA6061-T6 to Cu welds prepared by friction stir welding process using Zn interlayer, Sādhanā 43(10) 1-18.
[38] Zhang, G. F., Jiao, W. M., and Zhang, J. X. (2014) Filling friction stir weld keyhole using pin free tool and T shaped filler bit, Science and Technology of Welding and Joining 19(2) 98-104.
[39] Huang, Y. X., Han, B., Tian, Y., Liu, H. J., Lv, S. X., Feng, J. C., Leng, J. C. and Li, Y. (2011) New technique of filling friction stir welding, Science and Technology of Welding and Joining 16(6) 497-501.
[40] Yamashita, Y., and Fujita, K. (2001) Newly developed repairs on welded area of LWR stainless steel by friction surfacing, Journal of nuclear science and technology 38(10) 896-900.
[41] Huang, Y. X., Han, B., Lv, S. X., Feng, J. C., Liu, H. J., Leng, J. S., and Li, Y. (2012) Interface behaviours and mechanical properties of filling friction stir weld joining AA 2219, Science and Technology of Welding and Joining 17(3) 225-230.
[42] Han, B., Huang, Y., Lv, S., Wan, L., Feng, J., and Fu, G. (2013) AA7075 bit for repairing AA2219 keyhole by filling friction stir welding, Materials & Design 51 25-33.
[43] Miles, M. P., Kohkonen, K., Packer, S., Steel, R., Siemssen, B., and Sato, Y. S. (2009) Solid state spot joining of sheet materials using consumable bit, Science and Technology of Welding and Joining 14(1) 72-77.
[44] Miles, M. P., Feng, Z., Kohkonen, K., Weickum, B., Steel, R., and Lev, L. (2010) Spot joining of AA 5754 and high strength steel sheets by consumable bit, Science and Technology of Welding and Joining 15(4) 325-330.
[45] Dilip, J. J. S., and Ram, G. J. (2013) Microstructure evolution in aluminum alloy AA 2014 during multi-layer friction deposition, Materials Characterization 86 146-151.

[46] Fitseva, V., Krohn, H., Hanke, S., and dos Santos, J. F. (2015) Friction surfacing of Ti–6Al–4V: Process characteristics and deposition behaviour at various rotational speeds, Surface and Coatings Technology 278 56-63.
[47] Hanke, S., Fischer, A., and dos Santos, J. F. (2015) Sliding wear behaviour of a Cr-base alloy after microstructure alterations induced by friction surfacing, Wear 338 332-338.
[48] Nakama, D., Katoh, K., and Tokisue, H. (2008) Some characteristics of AZ31/AZ91 dissimilar magnesium alloy deposit by friction surfacing, Materials Transactions 49(5) 1137-1141.
[49] Tokisue, H., Katoh, K., Asahina, T., and Usiyama, T. (2006) Mechanical properties of 5052/2017 dissimilar aluminum alloys deposit by friction surfacing, Materials Transactions 47(3) 874-882.
[50] Ravisekhar, S., Das, V. C., and Govardhan, D. (2017) Friction Surfaced Deposits for Industrial Applications, Materials Today: Proceedings 4(2) 3796-3801.
[51] Govardhan, D., Kumar, A. C. S., Murti, K. G. K., and Reddy, G. M. (2012) Characterization of austenitic stainless steel friction surfaced deposit over low carbon steel, Materials & Design (1980-2015) 36 206-214.
[52] Sekharbabu, R., Rafi, H. K., and Rao, K. P. (2013) Characterization of D2 tool steel friction surfaced coatings over low carbon steel, Materials & Design 50 543-550.
[53] Puli, R., and Ram, G. J. (2012) Dynamic recrystallization in friction surfaced austenitic stainless steel coatings, Materials Characterization 74 49-54.
[54] Fitseva, V., Hanke, S., dos Santos, J. F., Stemmer, P., and Gleising, B. (2016) The role of process temperature and rotational speed in the microstructure evolution of Ti-6Al-4V friction surfacing coatings, Materials & Design 110 112-123.
[55] Dovzhenko, G., Hanke, S., Staron, P., Maawad, E., Schreyer, A., and Horstmann, M. (2018) Residual Stresses and Fatigue Crack Growth in Friction Surfacing Coated Ti-6Al-4V Sheets, Journal of Materials Processing Technology 262 104–110.
[56] Puli, R., and Ram, G. J. (2012) Wear and corrosion performance of AISI 410 martensitic stainless steel coatings produced using friction surfacing and manual metal arc welding, Surface and Coatings Technology 209 1-7.
[57] Puli, R., Kumar, E. N., and Ram, G. J. (2011) Characterization of friction surfaced martensitic stainless steel (AISI 410) coatings, Transactions of the Indian Institute of Metals 64(1-2) 41-45.
[58] Puli, R., and Ram, G. J. (2012) Microstructures and properties of friction surfaced coatings in AISI 440C martensitic stainless steel, Surface and coatings Technology 207 310-318.
[59] Nixon, R. G. S., Mohanty, B. S., and Sathish, R. (2018) Friction surfacing of AISI 316 over mild steel: A characteriation study, Defence Technology 14(4) 306-312.
[60] Pereira, D., Gandra, J., Pamies-Teixeira, J., Miranda, R. M., and Vilaça, P. (2014) Wear behaviour of steel coatings produced by friction surfacing, Journal of Materials Processing Technology 214(12) 2858-2868.
[61] Govardhan, D., Sammaiah, K., Murti, K. G. K., and Reddy, G. M. (2015) Evaluation of bond quality for stainless steel-carbon steel friction surfaced deposits, Materials Today: Proceedings 2(4-5) 3511-3519.
[62] Rafi, H. K., Ram, G. J., Phanikumar, G., and Rao, K. P. (2011) Microstructural evolution during friction surfacing of tool steel H13, Materials & Design 32(1) 82-87.
[63] Singh, A. K., Reddy, G. M., and Rao, K. S. (2015) Pitting corrosion resistance and bond strength of stainless steel overlay by friction surfacing on high strength low alloy steel, Defence Technology 11(3) 299-307.
[64] Rafi, H. K., Phanikumar, G., and Rao, K. P. (2013) Corrosion resistance of friction surfaced AISI 304 stainless steel coatings, Journal of materials engineering and performance 22(2) 366-370.
[65] Hanke, S., Sena, I., Coelho, R. S., and dos Santos, J. F. (2018) Microstructural features of dynamic recrystallization in alloy 625 friction surfacing coatings, Materials and Manufacturing Processes 33(3) 270-276.
[66] Hanke, S., Fischer, A., Beyer, M., and Dos Santos, J. (2011) Cavitation erosion of NiAl-bronze layers generated by friction surfacing, Wear 273(1) 32-37.
[67] Miranda, R. M., Santos, T. G., Gandra, J., Lopes, N., and Silva, R. J. C. (2013) Reinforcement strategies for producing functionally graded materials by friction stir processing in aluminium alloys, Journal of Materials Processing Technology 213(9) 1609-1615.
[68] Gandra, J., Pereira, D., Miranda, R. M., Silva, R. J. C., and Vilaça, P. (2013) Deposition of AA6082-T6 over AA2024-T3 by friction surfacing-Mechanical and wear characterization, Surface and Coatings Technology 223 32-40.
[69] Janakiraman, S., and Bhat, K. U. (2012) Formation of composite surface during friction surfacing of steel with aluminium, Advances in Tribology 2012 1-5.
[70] Stegmueller, M. J. R., Schindele, P., and Grant, R. J. (2015) Inductive heating effects on friction surfacing of stainless steel onto an aluminium substrate, Journal of Materials Processing Technology 216 430-439.
[71] Stegmüller, M. J. R., Grant, R. J., and Schindele, P. (2017) Improvements in the process efficiency and bond strength when friction surfacing stainless steel onto aluminium substrates, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 10 1-12.
[72] Suhuddin, U., Mironov, S., Krohn, H., Beyer, M., and Dos Santos, J. F. (2012) Microstructural evolution during friction surfacing of dissimilar aluminum alloys, Metallurgical and Materials Transactions A 43(13) 5224-5231.
[73] Khalid Rafi, H., Janaki Ram, G. D., Phanikumar, G., and Rao, K. P. (2010) Microstructure and properties of friction surfaced stainless steel and tool steel coatings, In Materials Science Forum, Trans Tech Publications 638 864-869.

