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Surface Modification by Friction Based Processes

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1. Introduction

The increasing need to modify the surface's properties of full components, or in selected areas, in order to meet with design and functional requirements, has pushed the development of surface engineering which is largely recognised as a very important field for materials and mechanical engineers.

Surface engineering includes a wide range of processes, tailoring chemical and structural properties in a thin surface layer of the substrate, by modifying the existing surface to a depth of 0.001 to 1.0 mm such as: ion implantation, sputtering to weld hardfacings and other cladding processes, producing typically 1 - 20 mm thick coatings, usually for wear and corrosion resistance and repairing damaged parts. Other deposition processes, such as laser alloying or cladding, thermal spraying, cold spraying, liquid deposition methods, anodising, chemical vapour deposition (CVD), and physical vapour deposition (PVD), are also extensively used in surface engineering. Hardening by melting and rapid solidification and surface mechanical deformation allow to change the properties without modifying its composition [1].

Friction based processes comprise two manufacturing technologies and these are: Friction Surfacing (FS) and Friction Stir Processing (FSP). The former was developed in the 40's [2] and was abandoned, at that time, due to the increasing developments observed in competing technologies as thermal spraying, laser and plasma. Specially laser surface technology has largely developed in the following years in hardening, alloying and cladding applications and is now well established in industry. However, FS as a solid state processing technology, was brought back for thermal sensitive materials due to its possibility to transfer material from a consumable rod onto a substrate producing a coating with a good bonding and limited dilution.

The patented concept of Friction Stir Welding in the 90's [5] opened a new field for joining metals, specially light alloys and friction stir processing emerged around this concept.

FSP uses the same basic principles as friction stir welding for superficial or in-volume processing of metallic materials. Applications are found in localized modification and microstructure control in thin surface layers of processed metallic components for specific property enhancement. It has proven to be an effective treatment to achieve major microstructural refinement, densification and homogenisation of the processed zone, as well as, to eliminate defects from casting and forging [6-8]. Processed surfaces have enhanced mechanical properties, such as hardness, tensile strength, fatigue, corrosion and wear resistance. A uniform equiaxial fine grain structure is obtained improving superplastic behaviour. FSP has also been successfully investigated for metal matrix composite manufacturing (MMCs) and functional graded materials (FGMs) opening new possibilities to chemically modify the surfaces [9].

However, FSP has some disadvantages, the major of which is tool degradation and cost, which limits its wider use to high added value applications. Therefore, friction surfacing (FS) emerged again.

This chapter will focus on the mechanisms involved in both FSP and FS and their operating parameters, highlighting existing and envisaged applications in surface engineering, based on the knowledge acquired from ongoing research at the author's institutions.

2. Friction stir processing

2.1. Fundamentals

Friction Stir Processing (FSP) is based on the same principles as friction stir welding (FSW) and represents an important breakthrough in the field of solid state materials processing.

FSP is used for localized modification and microstructural control of surface layers of processed metallic components for specific property enhancement [6]. It is an effective technology for microstructure refinement, densification and homogenisation, as well as for defect removal of cast and forged components as surface cracks and pores. Processed surfaces have shown an improvement of mechanical properties, such as hardness and tensile strength, better fatigue, corrosion and wear resistance. On the other hand, fine microstructures with equiaxed recrystallized grains improve superplastic behaviour of materials processing and this was verified for aluminium alloys [7]. More recently the introduction of powders preplaced on the surface or in machined grooves allowed the modification of the surfaces, producing coatings with characteristics different from the bulk material, or even functionally graded materials to be discussed later in this chapter. The process has still limited industrial applications but is promising due to its low energy consumption and the wide variety of coating / substrate material combinations allowed by the solid state process.

A non-consumable rotating tool consisting of a pin and a shoulder plunges into the workpiece surface. The tool rotation plastically deforms the adjacent material and generates frictional heat both internally, at an atomic level, and between the material surface and the shoulder. Localized heat is produced by dissipation of the internal deformation energy and interfacial

friction between the rotating tool and the workpiece. The local temperature of the substrate rises to the range where it has a viscoplastic behaviour beneficial for thermo-mechanical processing. When the proper thermo-mechanical conditions, necessary for material consolidation are achieved, the tool is displaced in a translation movement. As the rotating tool travels along the workpiece, the substrate material flows, confined by the rigid tool and the adjacent cold material, in a closed matrix like forging manufacturing process. The material under the tool is stirred and forged by the pressure exerted by the axial force applied during processing as depicted in Figure 1.

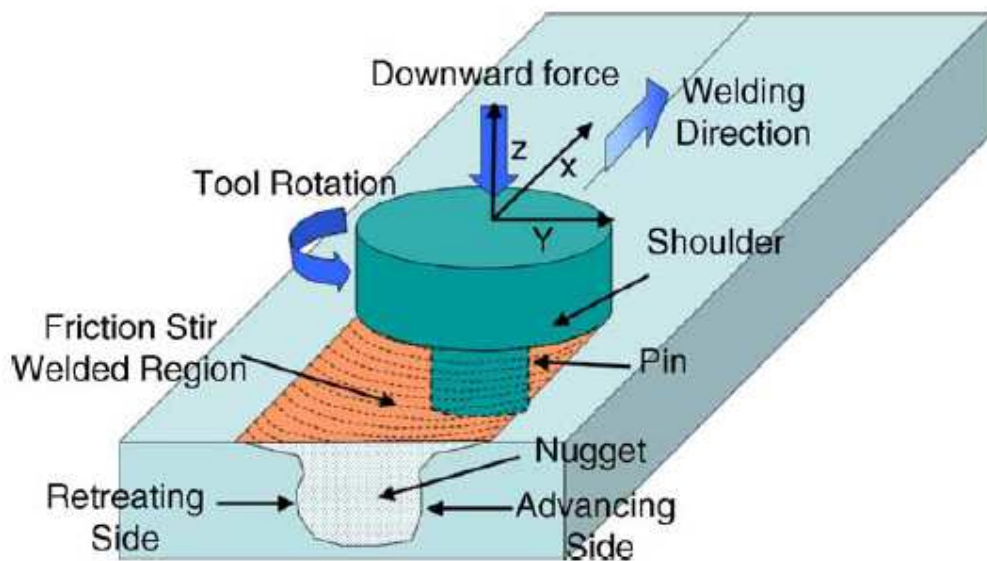


Figure 1. Schematics of friction stir processing.

The material structure is refined by a dynamic recrystallization process triggered by the severe plastic deformation and the localised generated heat. Homogenization of the structure is also observed along with a defect free modified layer of micrometric or nanometric grain structure.

FSP is considered an environmentally friend technology due to its energy efficiency and absence of gases or fumes produced. Table 1 summarizes the major benefits of FSP considering technical, metallurgical, energy and environment aspects.

Technical	Processed depth controlled by the pin length One-step technique No surface cleaning required Good dimensional stability since it is performed under solid state Good repeatability Facility of automation
Metallurgical	Solid state process Minimal distortion of parts No chemical effects Grain refining and homogenization Excellent metallurgical properties No cracking Possibility to treat thermal sensitive materials
Energy	Low energy consumption since heat is generated by friction and plastic deformation Energy efficiency competing with fusion based processes as laser
Environmental	No fumes produced Reduced noise No solvents required for surface degreasing and cleaning

Table 1. Major benefits of friction stir processing

Analysing the cross section of a friction stir processed surface, three distinct zones can be identified and these are: the nugget or the stirred zone (SZ), the thermomechanically affected zone (TMAZ) and the heat affected zone (HAZ) as shown in Fig. 2.

The nugget, just below the pin and confined by the shoulder width, is the area of interaction where severe plastic deformation occurs. The raise in local temperature due to internal friction and the generated friction between the shoulder and the surface along with the high strain, promotes a dynamically recrystallized zone, resulting in the generation of fine homogeneous equiaxial grains in the stirred zone and precipitate dissolution. Though this is a solid state process, the maximum temperature can be of about 80% of the fusion temperature. Ultrafine-grained microstructures with an average grain size of 100-300 nm in a Mg-Al-Zn alloy were observed in a single pass under cooling [8]. These micro and nano structures are responsible for increases in hardness and wear behaviour reported by several researchers studying different types of alloys under different processing conditions.

The thermo-mechanically affected zone (TMAZ) is immediately adjacent to the previous and, in this zone, the deformation and generated heat are insufficient to generate new grain formation, thus, deformed elongated grains are observed with second phases dispersed in the grain boundaries. Though new grain nucleation may be observed, microstructure remains elongated and deformed. The hardness is higher than in the heat-affected zone due to the high dislocations density and sub-boundaries caused by plastic deformation.

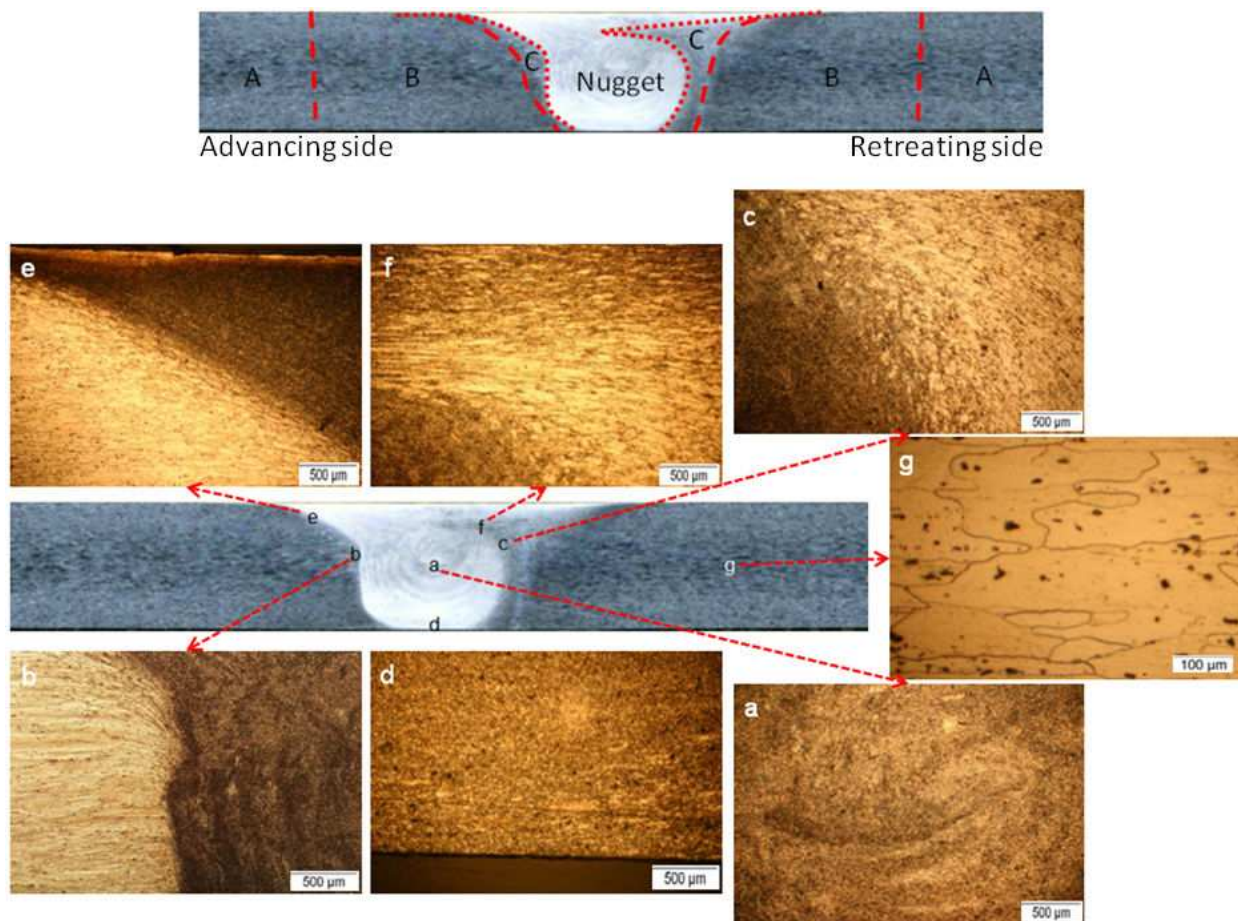


Figure 2. A typical macrograph showing various microstructural zones in FSW of AA2024-T351

In the heat affected zone (HAZ) no plastic deformation is experienced but heat dissipated from the stirred zone into the bulk material can induce phase transformations, depending on the alloys being processed, as precipitate coarsening, localized aging or annealing phenomena.

The non symmetrical character of the process is also evident (Fig. 2). The advancing side is usually referred to the one where the rotating and travel movements have the same direction, while in the retreating side these have opposite directions. On the advancing side, the recrystallized zone is extended and the nugget presents a sharp appearance. The relative velocity between the tool and the base material is higher due to the combination of tool rotation and translation movement. As such, plastic deformation is more intense, thus, the increase in the degree of deformation during FSP, results in a reduction of recrystallized grain size, extending the fine-grain nugget region to the advancing side. Hardness can be higher than in the thermo-mechanically affected zone, but typically lower than in the base material, whenever it is a heat treatable alloy hardenable by aging. The Hall Petch equation establishes a relation between grain size and yield strength and states that these vary in opposite senses [10]. So, in the nugget yield strength is seen to be much higher than in the base material and this is a major result from this process.

2.2. Processing parameters

Operating or processing parameters determine the amount of plastic deformation, generated heat and material flow around the non-consumable tool.

The tool geometry is of major relevance as far as material flow is concerned. Two main elements constitute the tool and these are the pin and the shoulder. Geometrical features such as pin height and shape, shoulder surface pattern and diameter, have a major influence on material flow, heat generation and material transport volume, determining the final microstructure and properties of a processed surface. Several tools have been designed and patented for both FSW and FSP.

The pin (Fig. 3) can be cylindrical or conical, flat faced, threaded or fluted to increase the interface between the probe and the plasticized material, thus intensifying plastic deformation, heat generation and material mixing. The pin length determines the depth of the processed layer. However, since FSP usually aims to produce a thin fine-grained layer across a larger surface area, pinless tools with larger shoulder diameters can also be used.

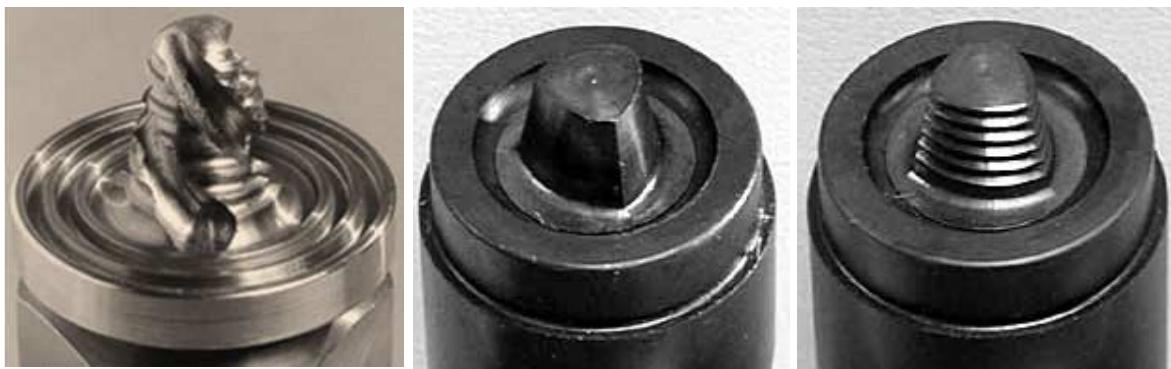


Figure 3. Example of tool geometries

Shoulder profiles aim to improve friction with the material surface generating the most part of frictional heat involved in the process. Shoulders can be concave, flat or convex, with grooves, ridges, scrolls or concentric circles as depicted in Figure 4.

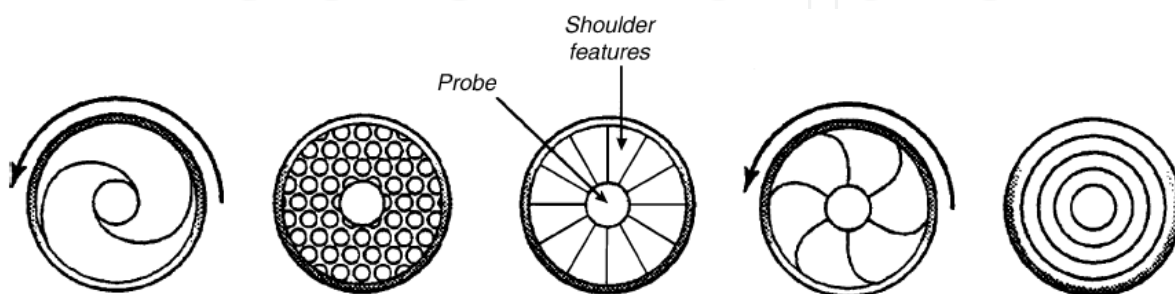


Figure 4. Examples of shoulder geometries

The major processing parameters are the tool rotation and traverse speeds, the axial force and the tilt angle:

- Tool rotation and traverse speeds

These parameters, individually or in combination, affect the plastic deformation imposed onto the material and, thus, the generated heat. An empirically accepted concept divides processing into two main classifications: “cold” and “hot”. Cold processing is the one where the ratio between rotating and traverse speed is below 3 rpm/mm and hot processing when this ratio is above 6. Though there is no scientific basis for this border line, it is, however, noticeable that increasing this ratio, the SZ is larger and a very fine structure is observed, while under “cold” conditions the SZ is not well defined since the heat generated is insufficient to promote grain recrystallization. So, increasing the tool rotation speed, plastic deformation is more intense and so is generated heat enabling more material mixing. Therefore, it is possible to achieve a smaller grain size of equiaxial homogeneous grains with precipitate dissolution.

Transverse speed mostly affects the exposure time to frictional heat and material viscosity. Low traverse speeds result in larger exposure times at higher process temperatures.

- Tool axial force

This parameter affects friction between the shoulder and the substrate surface generating and promoting material consolidation. High axial force causes excessive heat and forging pressure, obtaining grain growth and coarsening, while low axial forces lead to poor material consolidation, due to insufficient forging pressure and friction heating. Excessive force may also result in shear lips or flashes with excessive height of the beads on both the advancing and retreating sides, causing metal thinning at the processed area and poor yield and tensile properties. So, surface finishing is much controlled by the axial or forging force.

- Tilt angle

The tilt angle is the angle between the tool axis and the workpiece surface. The setting of a suitable tilting towards the traverse direction assures that the tool moves the material more efficiently from the front to the back of the pin and improves surface finishing.

The effect of the different process parameters has been widely documented by several authors and they are all unanimous that plastic deformation and consequent heat generation are essential to establish the viscoplastic conditions necessary for the material flow and to achieve good consolidation. Thus, a tilt angle of 2-4° is usually used in practice.

Insufficient heating, caused by poor stirring (low tool rotational rates), a high transverse speed or insufficient axial force, results in improper material consolidation with consequent low strength and ductility. Raising heat will cause grain size to decrease to a nanometric scale improving material properties. However, a very significant increase in tool rotation rate, axial force or a very low transverse speed may result in high non desired temperature, slow cooling rate or excessive release of stirred material with property degradation.

2.3. Multiple passes

In order to process large areas in full extent, multiple-passes are used. These can be run separately or overlapped. An overlap ratio (OR) was defined to characterize the overlap between passes and defined by equation 1 [7].

$$OR = 1 - \left[\frac{l}{d_{pin}} \right] \tag{1}$$

Where l is distance between centres of each pass and d_{pin} is the maximum diameter of the pin. From this equation, fully overlapped passes have an OR=1 and OR decreases, when increasing the distance between passes. For an OR<0 no overlap of the nuggets exists.

There are two types of material modification by Friction Stir Processing, the in-volume FSP (VFSP) consisting on the modification of the full thickness of the processed materials and the surface FSP (SFSP) which consists in the surface modification up to depth of about 2 mm.

Figure 5 depicts the effect of OR in two Al alloys, a heat treatable (AA7022-T6) and a non heat treatable one (AA5083-O) with different number of passes and overlap ratios.

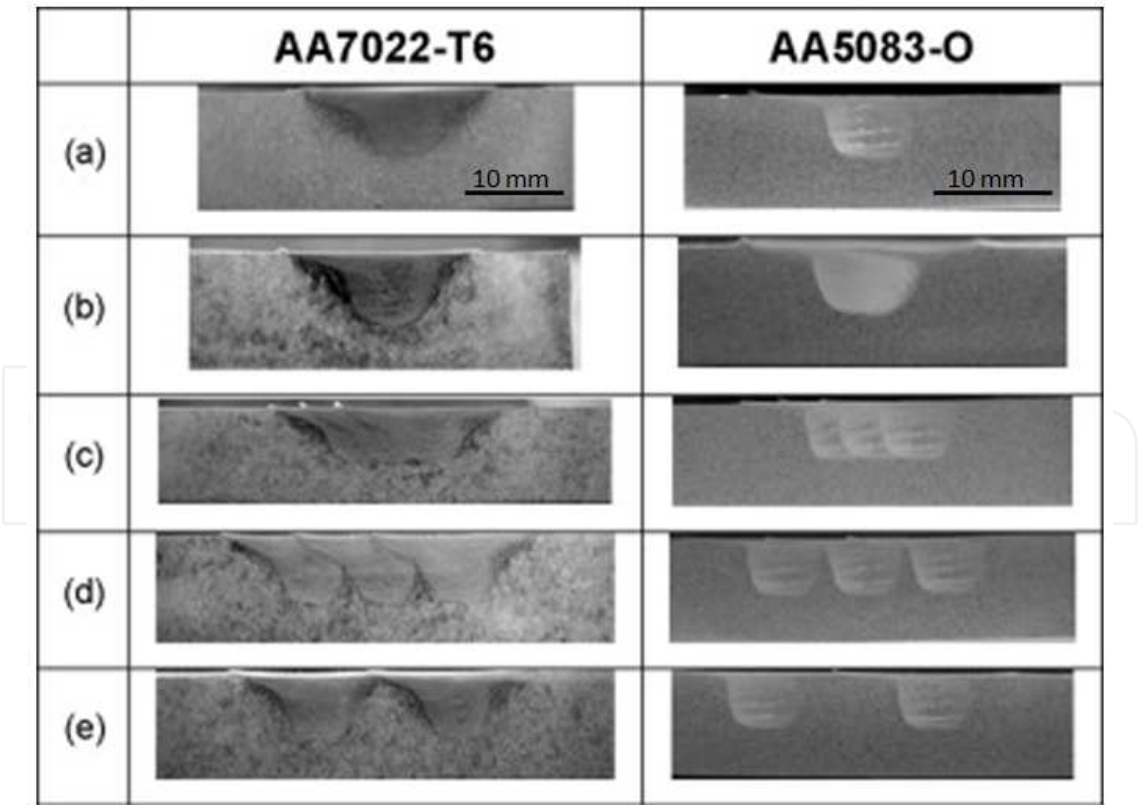


Figure 5. Cross sections of the samples processes with different treatments a) one pass with OR=1; b) four passes with OR=1; c) three passes with OR=1/2; d) three passes with OR=0 and e) two passes with OR=-1 [7]

In this study [7] the authors showed that AA5083-O alloy needed at least three passes in the same location to produce a homogeneous processed area, while the AA7022-T6 alloy only needed one pass, since this is a heat treatable alloy. Grain size reduced from 160 μm (AA7022-T6) and 106 μm (AA5083-O) to an average grain size of about 7.1 and 5.9 μm , respectively. The highest hardness value was located in the nugget due to a significantly decrease in the grain size. This results that in AA7022-T6 alloy the hardness is lower in the nugget than in the base material because it is a heat treatable aluminium alloy and in the AA5083-O alloys the hardness in the nugget is higher than in the base material which is a typical behaviour of non-heat treatable alloys. A significant increase in the formability of the materials was observed due to the increase of the materials ductility resulting from the refinement of the grain size, increasing the maximum bending angle in four times for the SFSP treatment and twelve times for the VFSP treatment in the AA7022-T6 samples. In AA5083-O samples an increase in the maximum bending angle around 1.5 times for the SFSP treatment and about 2.5 times for VFSP treatment was observed.

The overlapping direction in multipass Friction Stir Processing (FSP) was also seen to have a major influence on the surface geometrical features [11]. Structural and mechanical differences were observed in a AA5083-H111 alloy when overlapping by the advancing side (AS) direction or by the retreating side (RS) one. Overlapping by the retreating side was found to generate smoother surfaces, while overlapping by the advancing side led to more uniform thickness layer (Fig. 6). This result is quite relevant from a practical point of view since when the aim of processing large areas in multiple passes procedure is to increase the depth of the processed zone, overlapping of successive passes should be performed by the advancing side of the previous pass. If surface finishing is to be maximised to prevent finishing operations, overlapping on the previous pass in the retreating side produces very low rough surfaces.

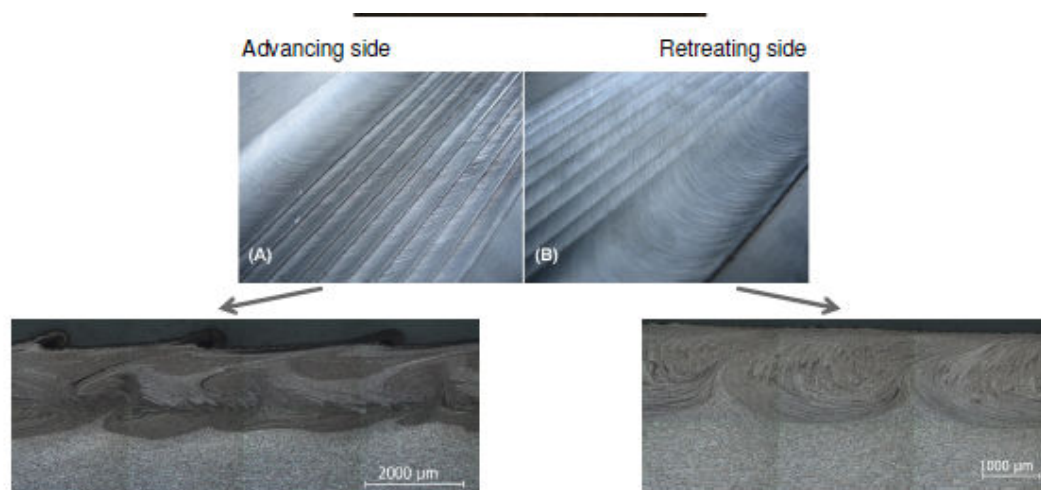


Figure 6. Macro and micrographs of cross sections in friction stir processed surfaces when overlapping by the advancing and by the retreating sides [11]

Hardness within the processed layer increased by 8.5 % and was seen to be approximately constant between passes. The mechanical resistance and toughness under bending were improved by 18 % and 19 %, respectively.

Bending test curves are presented in Figure 7. The processed surfaces were tested under tensile and compression loads. Different behaviours were observed for each bending specimen. Surface modification by multi-pass FSP resulted in an increase of the maximum load supported for all samples and up to a maximum of 18 % for the compression solicitation of the sample produced when overlapping by the RS (Fig. 8). FSP produced a thin layer of a fine equiaxial recrystallized grain structure and homogeneous precipitation dispersion, enhancing material strength.

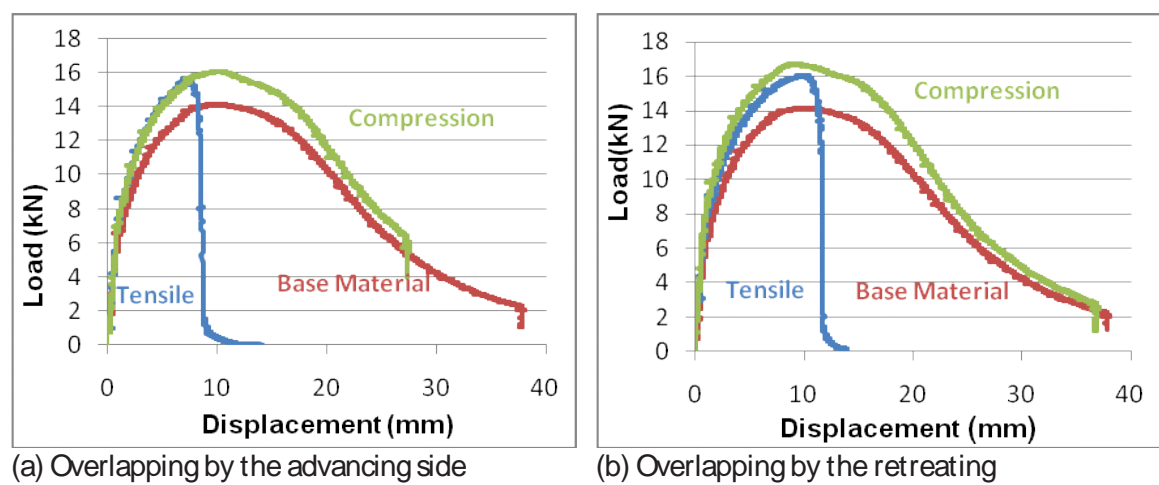


Figure 7. Load vs. displacement plot of the bending tests of the FSP samples produced when overlapping by (a) AS and (b) RS [11].

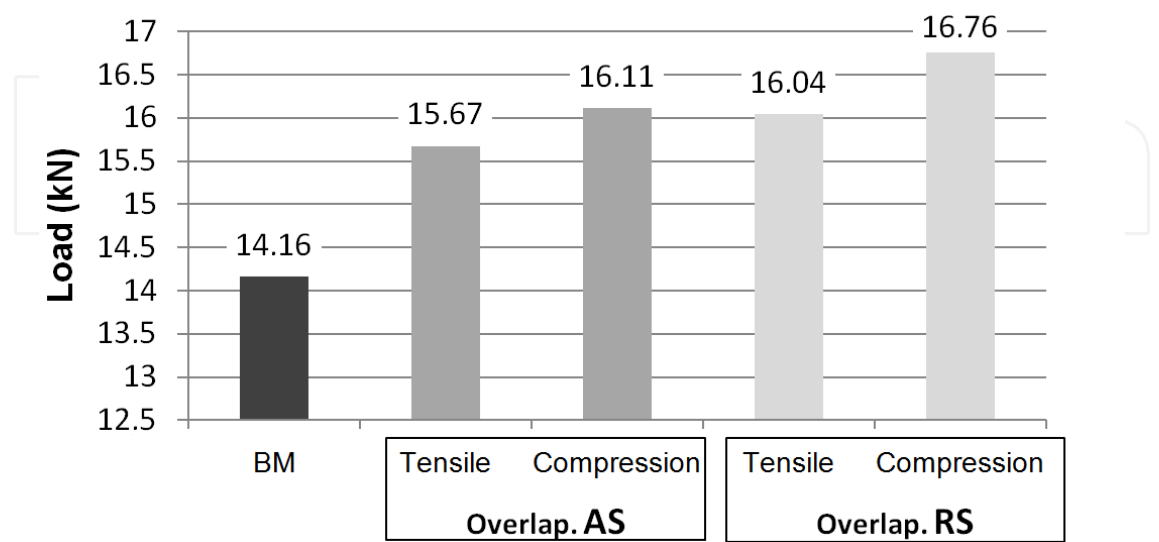


Figure 8. Maximum load attained by FSP samples under different test conditions relatively to the base material [11].

2.4. Applications and performance

Friction stir processing can be used to locally refine microstructures and eliminate casting defects in selected locations, where property improvements can enhance component performance and service lifetime. For instances, aluminium castings contain porosities, segregated phases and inhomogeneous microstructures which contribute to property degradation. Microstructural casting defects, such as: coarse precipitates and porosities increase the possibility of rupture due to the intragranular nucleation of micro-cracks during material deformation. Precipitates are less capable of plastic deformation than the matrix, so cavity nucleation is very frequent, whether caused by a disconnection from the matrix or the rupture of precipitates.

Friction stir processing allows the breakage of large precipitates and their dispersion in a homogeneous matrix, increasing the material capability to withstand deformation, since it results in a higher level of crack closure. Additionally, mechanical properties such as ductility, fatigue strength and formability, are improved.

On the other hand, a large number of small precipitates increases the material resistance to deformation and hence its strength, as they act as barriers or anchorage points to dislocations movements. A uniform equiaxial fine grain structure is also essential to enhance material superplastic behaviour. Friction stir processing generates fine microstructure and equiaxed recrystallized grains which leads either to an increase in strain rate or a decrease in the temperature at which superplasticity is achieved.

In the FSP of an aluminium cast alloy ADC12, Nakata et al. [12] applied multiple-passes to increase tensile strength to about 1.7 times that of the base material. The hardness profile of processed layer was uniform and about 20 HV higher than that of the cast material. The observed increase in tensile strength was attributed to the elimination of the casting defects such as porosities, an homogeneous redistribution of fine Si particles and a significant grain refinement to 2–3 μm . Santella et al. [13] investigated the use of friction stir processing to homogenise hardness distributions in A319 and A356 cast aluminium alloys. Hardness and tensile strength were increased relatively to the cast base material.

Similar results were also reported in the friction stir processing of magnesium based alloys. A.H. Feng and Z.Y. Ma et al. [14] combined FSP with subsequent aging to enhance mechanical properties of Mg-Al-Zn castings

Chang et al. [8] obtained a significant improvement of mechanical properties as the mean hardness measured at the ultrafine-grained zone reached approximately 120HV (twice the base material hardness).

Several investigations have been conducted to study the enhancement of superplasticity behaviour in friction stir processed alloys. In the FSP of Al-8.9Zn-2.6Mg-0.09Sc, Charit and Mishra et al. [15] reported a maximum superplasticity of 1165% at a strain rate of $3 \times 10^{-2} \text{ s}^{-1}$ and 310 °C with a grain size of 0.68 μm . More recently, F.C. Liu [16] reported a fine-grain microstructure of 2.6 μm sized grains by applying FSP to extruded samples of an Al-Mg-Sc alloy, achieving a maximum elongation of 2150% at a high strain rate of 1×10^{-1} and a temperature of 450 °C.

A ultrafine-grained FSP Al-Mg-Sc alloy was also reported [17] with a grain size of $0.7\ \mu\text{m}$ exhibited high strain rate superplasticity, for a low temperature range of 200 to 300 °C with a single pass. For a strain rate of $3 \times 10^{-2}\ \text{s}^{-1}$ at a temperature of 300 °C, a maximum ductility of 620% was achieved. However, for a temperature of 350 °C, abnormal grain growth was observed, as grain size increased and the samples no longer presented superplasticity, thus confirming that grain size is essential for the existence of a superplastic behaviour. García-Bernal et al. [18] conducted a study to evaluate the high strain rate superplasticity behaviour during the high-temperature deformation of a continuous cast Al-Mg alloy, having reported that the generation of a fine grain structure and the breaking of cast structure led to a significant improvement in its ductility up to 800% at 530 °C and a strain rate of $3 \times 10^{-2}\ \text{s}^{-1}$.

The fine-grained microstructure generated by FSP can also prevent fatigue crack initiation and propagation due to the barrier effect of grain boundaries. For example, Jana et al. [19] friction stir processed a cast Al-7Si-0.6Mg alloy, widely used for its good castability, mechanical properties and corrosion resistance, but characterized by poor fatigue properties. The authors succeeded to improve fatigue resistance by a factor of 15 at a stress ratio of $R = \sigma_{\min} / \sigma_{\max} = 0$ due to a significant enhancement of ductility and a homogeneous redistribution of refined Si particles.

Intense plastic deformation and material mixing featured in the FSP of A356 aluminium casting also resulted in the significant breakage of primary aluminium dendrites and coarse Si particles, creating a homogenous distribution of Si particles in the aluminium matrix and eliminating casting porosity [7]. This led to a significant improvement of ductility and fatigue strength in 80%, proving that FSP can be used as a tool to locally modify the microstructures in regions experimenting high fatigue loading.

Friction surfacing of AA6082-T6 over AA2024-T3 evidenced a significant improvement of wear performance in about 25 %, compared to the consumable rod in as-received condition (Table 1). This enhancement in wear behaviour is also due to a finer equiaxed grain microstructure within the coating, compared to the rod anisotropic microstructure which is more prone to delamination under wear loads.

AA2024-T3 substrate plates exhibited the best tribological properties, presenting the lowest weight loss, frictional force and friction coefficient. This is most likely due to both its higher surface hardness and its lower ductility, which make this material less prone to suffer plastic deformation under abrasive wear, in comparison with the AA6082 coating and the rod in as-received condition. Due to the fine grain structure observed, the coatings present high frictional force and coefficient (10.9 N and 0.56, respectively).

2.5. Surface composites

FSP has been also investigated to produce layers of hard materials on soft substrates, as aluminium based alloys. Most of the published work is focused on the effect of processing parameters on surface characteristics and techniques to evaluate the performance of modified surfaces. Nevertheless, the reinforcing particles deposition method is relevant in terms of

Material	Weight lost [mg]	Volume lost [mm ³]	Volume rate [10 ⁻² mm ³ /m]	Wear rate [mg/m]	First stage		Second stage	
					Run-in wear		Steady state wear	
					Frictional force [N]	Friction coefficient	Frictional force [N]	Friction coefficient
Substrate	12.6 ± 3	4.54	1.51	0.042	4.9 ± 0.97	0.25 ± 0.05	7.5 ± 0.33	0.38 ± 0.017
ARCR	30.2 ± 5	11.19	3.73	0.101	-	-	7.1 ± 1.14	0.36 ± 0.059
Coatings	23.2 ± 3	8.59	2.86	0.077	-	-	10.9 ± 0.58	0.56 ± 0.029

Table 2. Weight loss due to wear (average values).

structural and chemical homogeneity and depth of the modified layer which influence the final surface performance. Different methods for depositing reinforced particles have been reported. A main reinforcing method consists of mixing reinforcing particles or powders with a volatile solvent such as methanol or a lacquer, in order to form a thin reinforcement layer, preventing reinforcing powders to escape. Another method consists of machining grooves in the substrate, pack these with reinforcing particles and process the zone with a non consumable FSP tool in a single pass or in multiple passes.

An enormous diversity of materials is used for surface reinforcements, the majority being hard ceramic particles as SiC, Al₂O₃ and AlN to improve surface properties as hardness, superplasticity, formability, corrosion and wear resistances.

The particle size is relevant since small particles lead to higher concentration along bead surface and to smooth fraction gradients both in depth and along the direction parallel to the surface, while the thickness of the reinforced layer decreases with increasing particle size and is, typically, below 100 micron [20].

More recently, nanostructured layers have been produced and less common reinforcements were studied successfully. Two examples are: the incorporation of multi-walled carbon nanotubes (MWCNT) into a number of metallic materials as reinforcing fibres is a topic of recent interest due to the unique mechanical and physical properties of this material, namely very high tensile strengths [21]. FSP was tested to produce a composite of an aluminium alloy with MWCNT. Nanotubes were embedded in the stirred zone and the multi walled was retained. With tool rotational speeds of 1500 and 2500 rpm the distribution of nanotubes

increased. Aiming at weight reduction of vehicles, FSP MWCNT/AZ31 surface composite were produced by Morisada et al. [22] and succeeded to disperse MWCNT into a AZ31 matrix. The microhardness increased to values of about 74 HV and the addition of MWCNT was seen to further promote grain refinement by FSP.

Another example is the incorporation of Nitinol (NiTi) that is a shape memory alloy with superelastic behavior and good biocompatibility. These alloys are widely used in orthodontics, but also in sensors and actuators. The possibility of incorporating wires, ribbons or powders into metallic matrixes opens up new applications for shape memory alloys. Studies report on the use of NiTi wires, but few have been made in the dispersion of NiTi powders in a metal matrix. Dixit et al. [23] produced a NiTi reinforced AA1100 composite using FSP and the particles were uniformly distributed. Good bonding with the matrix was achieved and no interfacial products were formed. The authors suggest that under adequate processing, the shape memory effect of NiTi particles can be used to induce residual stress in the parent matrix, of either compressive or tensile type. This study showed that samples had enhanced mechanical properties such as: Young modulus and micro hardness. A more recent work showed the possibility to introduce 1x2 mm ribbons of NiTi in AA1050 alloy by FSP showing a good vibration and damping capacity of the composite [24].

Shafei-Zarghani et al. [25] used multiple-pass FSP to produce a superficial layer of uniformly distributed nano-sized Al₂O₃ particles into an AA6082 substrate. Hardness was increased three times over that of the base material. Wear testing revealed a significant resistance improvement. Researchers also found that the increase of the number of passes leads to more uniform alumina particle distributions with a significant increase of surface hardness. The nano-size Al₂O₃ powder was inserted inside a groove with 4 mm depth and 1 mm width, which was closed by a tool with a shoulder and no pin.

3. Friction surfacing

3.1. Principles and process parameters

Friction surfacing (FS) was first patented in the 40's and is now well established as a solid state technology to produce metallic coatings. While FSP modifies the microstructure of a surface by simply deforming, recrystallize and homogenise the grain structure, FS modifies its chemistry. In friction surfacing a consumable rod under rotation is pressed under an axial load against the surface as depicted in Fig. 9. Heat generated in the initial friction contact promotes viscoplastic deformation at the tip of the rod. As the consumable travels along the substrate, the viscoplastic material at the vicinity of the rubbing interface flows into flash or is transferred over onto the substrate surface, while pressure and heat conditions triggers an inter diffusion process that soundly bonds the deposit. As the material undergoes a thermo-mechanical process, a fine grain microstructure is also produced by dynamic recrystallization.

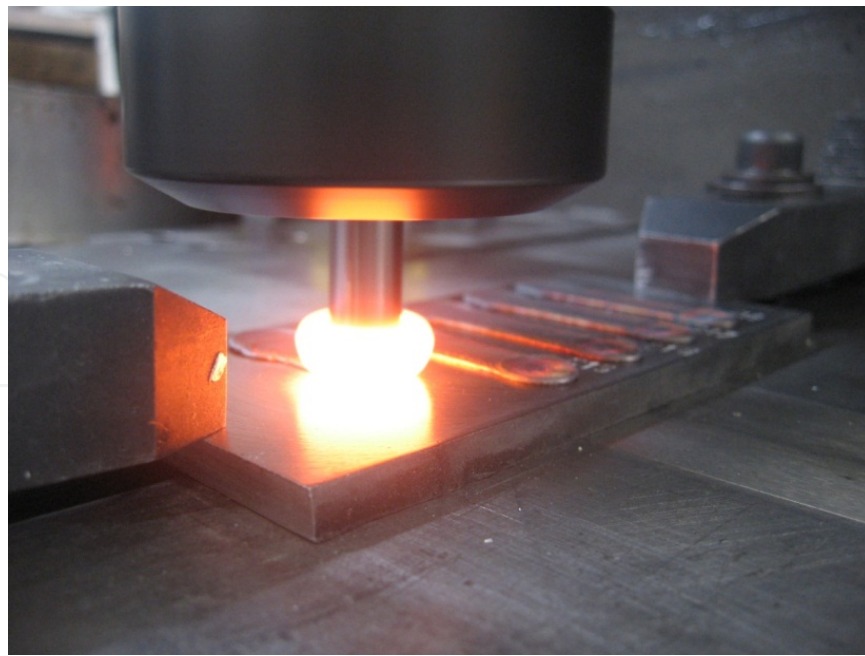


Figure 9. Metallic coating of steel substrate by FS

Gandra et al [20] proposed a model for the global thermal and mechanical processes involved during friction surfacing based on the metallurgical transformations observed when depositing mild steel over mild steel and is shown in Fig.10.

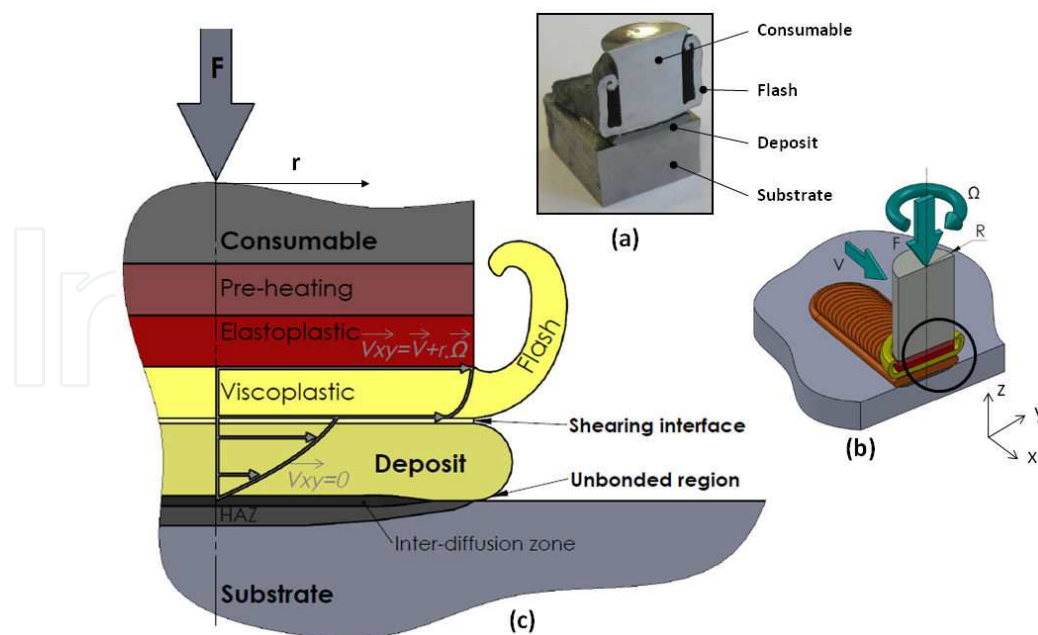


Figure 10. Thermo-mechanics of friction surfacing. (a) Sectioned consumable, (b) Process parameters and (c) Thermo-mechanical transformations and speed profile. Nomenclature: F – Forging force; Ω – rotation speed; v – travel speed; V_{xy} – rod tangential speed in-plan xy given by composition of rotation and travel movements [20]

The speed difference between the viscoplastic material, which is rotating along with the rod at v_{xy} , and the material effectively joined to the substrate ($v_{xy} = 0$), causes the deposit to detach from the consumable. This viscous shearing friction between the deposit and the consumable is the most significant heat source in the process.

Since the deposited material at the lower end is pressed without lateral confinement, it flows outside the consumable diameter, resulting into a revolving flash attached to the tip of the consumable rod and side unbounded regions adjacent to the deposit. Flash and unbonded regions play an important role as boundary conditions of temperature and pressure for the joining process.

Fig 11 shows typical material combinations tested using FS with successful results.

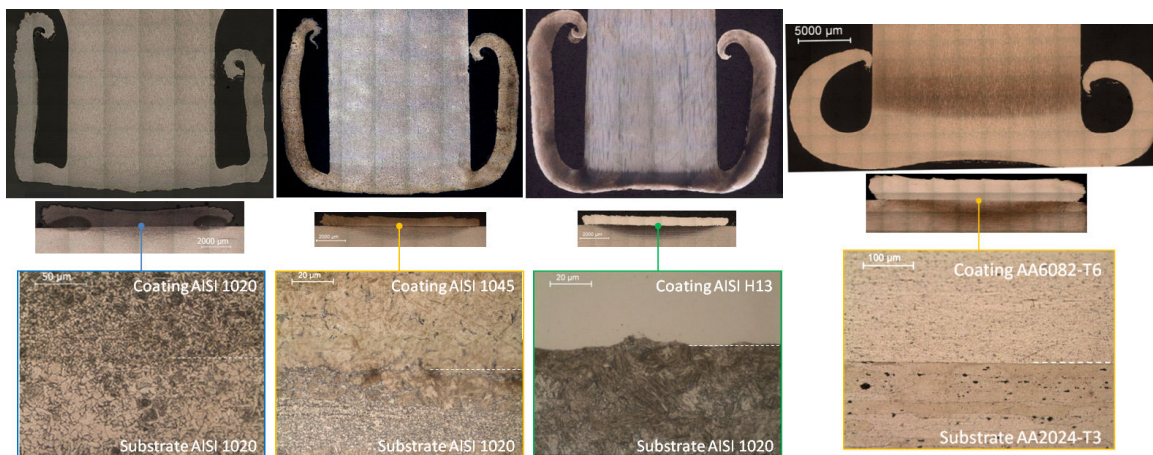


Figure 11. Different coatings/substrates combinations

The process allows the deposition of various dissimilar material combinations as the deposition of stainless steel, tool steel, copper or Inconel on mild steel substrates, as well as, stainless steel, mild steel and inconel consumables on aluminium substrates.

The influence of processing parameters on the deposit characteristics and bonding strength has been studied [26,27] aiming to correlate the resulting coating geometrical characteristics (thickness and bonded width) and mechanical performance with forging force, spindle and travel speeds. The increase of forging force improves the bond strength and reduces the coating thickness. The undercut region decreased when the forging force increased and the travel speed decreased. Higher ratios between the consumable rod feeding rate and the travel speed resulted in superior bonding quality. The applied load on the consumable rod was found to be essential to improve joining efficiency and to increase the deposition rate. Higher rotation or travel speeds were detrimental for the joining efficiency. Tilting the consumable rod along the travel direction proved to improve the joining efficiency up to 5 %. The material loss in flashes represented about 40 to 60 % of the total rod consumed, while unbonded regions were reduced to 8 % of the effective coating section in mild steel deposition. Friction surfacing was seen to require mechanical work between 2.5 and 5 kJ/g of deposited coating with deposition

rates of 0.5 to 1.6 g/s, that is, deposition rates are higher than for laser cladding or plasma arc welding and the specific energy consumption lower than for other cladding processes.

In the friction surfacing of low carbon steel with tool steel H13 consumable rods, Rafi et al. [28] concluded that the coating width was strongly influenced by the rotation speed, while thickness was mostly determined by the travel speed.

This field of exploitation of producing aluminium coatings on aluminium based alloys is very promising. It was seen that friction surfacing enables intermediate mass deposition rates and higher energy efficiency in comparison with several mainstream laser and arc welding cladding processes. The required mechanical work varied between 2.5 and 5 kJ/g of deposited coating with deposition rates of 0.5 to 1.6 g/s. The forging force enhances joining quality while contributing to a higher overall coating efficiency. Faster travel and rotation speeds improved deposition rates and coating hardness, while decreasing energy consumption per unit of mass. Surface hardness increased up to 115 % compared to consumable rod. By adjusting a proper tilt angle, specific energy consumption drops, while slightly improving deposition rate and joining efficiency.

4. Summary and future trends

Friction based processes comprise Friction Stir Processing (FSP) and Friction Surfacing (FS).

Friction stir processing is mostly used to locally eliminate casting defects and refine microstructures in selected locations, for property improvements and component performance enhancement. Aluminium and steel castings are amongst the most common components improved by this technology aiming at eliminating porosities, destroy solidification structures with inhomogeneous segregated phases, refine grain structures improving in-service performance.

The recent advances in adding reinforcing particles to manufacture surface alloys and metal matrix composites is a breakthrough in this technology opening new possibilities to manufacture composites nanostructured with tremendous properties.

Friction surfacing has been used in the production of long-life industrial blades, wear resistant components, anti-corrosion coatings and in the rehabilitation of worn or damaged parts such as, turbine blade tips and agricultural machinery. Other applications feature the hardfacing of valve seats with stellite and tools such as punches and drills.

Since the deposits result from severe viscoplastic deformation, friction surfacing presents some advantages over other coating technologies based on fusion welding or heat-spraying processes, that produce coarse microstructures and lead to intermetallics formation, thereby deteriorating the mechanical strength of the coatings. However, friction surfacing currently struggles with several technical and productivity issues which contribute to a limited range of engineering applications.

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