Power System Technology
ISSN:1000-3673

Received: 10-09-2018 *Revised: 02-12-2018* *Accepted: 15-12-2018*

Research Methodologies that can be used for surface modifications of non-ferrous alloys in Friction Stir Processing – A Review

Kulbir Singh Sandhu*
Department of Mechanical Engineering, Punjabi University, Patiala, Punjab, INDIA.
**Corresponding author: kulbirsandhu@pbi.ac.in*

Abstract: *Friction Stir Processing (FSP) is an innovative solid-state processing technique that holds significant promise for the enhancement of non-ferrous alloys, particularly aluminum and magnesium. Unlike traditional methods involving melting and casting, FSP operates at temperatures below the material's melting point, preserving its inherent properties and mitigating defects associated with liquid-state processing. The technique employs a non-consumable, specially designed tool with a rotating pin and shoulder, which is plunged into the material and traversed along the surface. This action generates intense frictional heat, leading to plastic deformation and subsequent recrystallization. In non-ferrous alloys, FSP results in refined microstructures, improved mechanical properties, and enhanced wear resistance. The process has found widespread applications in aerospace, automotive, and other industries where lightweight and high-performance materials are crucial. Various approaches like numerical modelling, taguchi and analytical modelling can be followed while processing for optimization of processing parameters. The microstructural modifications induced by FSP contribute to grain refinement, reducing porosity and enhancing the overall integrity of the material. Furthermore, FSP enables the incorporation of reinforcing particles, leading to the formation of surface composites with tailored properties.*

Keywords: *Surface modifications, Friction stir processing, Aluminium alloys, Magnesium alloys.*

1. Introduction

Friction Stir Processing (FSP) stands as a recent solid-state processing technique, stemming from the adaptation of Friction Stir Welding pioneered by The Welding Institute (TWI) in Cambridge, UK. Unlike its welding counterpart, FSP focuses on the localized modification of the microstructure in monolithic specimens to attain specific and desired properties through surface microstructure modification (M.S. Weglowski, 2018). This method employs a non-consumable rotating tool to generate frictional heat, inducing severe plastic deformation and processing the material in the solid state. The key advantages of FSP, as a solid-state process, include minimal distortion, grain refinement, improved mechanical properties, and the induction of superplasticity, even in alloys challenging to process through conventional methods, such as Aluminum alloys and Magnesium alloys (Padhy et al., 2018). Additionally,

Power System Technology
ISSN:1000-3673

Received: 10-09-2018 **Revised: 02-12-2018** **Accepted: 15-12-2018**

Friction Stir Processing is extensively employed for the fabrication of surface Metal Matrix Composites (MMCs), aiming to enhance tribological properties and hardness by incorporating reinforced second-phase particles (Sharma et al., 2015). In the Friction Stir Processing (FSP) procedure, a specifically designed rotating tool with both a shoulder and a probe or pin is employed. This tool is firmly secured in a fixture affixed to the machine table bed. As the tool traverses the predetermined direction, its shoulder comes into contact with the base material. The rotation of the tool's shoulder, subjected to an applied load, induces heating in the surrounding metal due to the generation of frictional heat (M.S. Weglowski, 2018). The processed zone exhibits two distinct sides in relation to the centerline. The side where the rotational motion of the probe aligns with its traverse motion is termed the "advancing side," while the side where the rotational motion opposes the traverse motion is known as the "retreating side" (see Figure 1). The rotation of the tool contributes to severe plastic deformation, facilitated by the mechanical (solid-state) mixing of materials beneath it (Yan et al., 2005). The tool, equipped with a probe, is affixed to the vertical spindle of a Milling Machine, rotating at a constant rate. The operational mechanism involves the generation of frictional heat through the interaction between a rotating tool composed of a material harder than the workpieces under processing (Elangovan and Balasubramanian, 2008). The tool configuration incorporates a larger-diameter shoulder and a smaller-diameter specifically profiled probe or pin. The depth of penetration is governed by the length of the probe situated beneath the shoulder of the tool, with the probe length intentionally kept slightly shorter than the thickness of the workpiece (Singh and Arora, 2010). The primary function of the tool's shoulder is twofold: firstly, to impart additional frictional heat to the processed region, and secondly, to prevent the expulsion of highly plasticized material during the operation (Abassi et al., 2006).

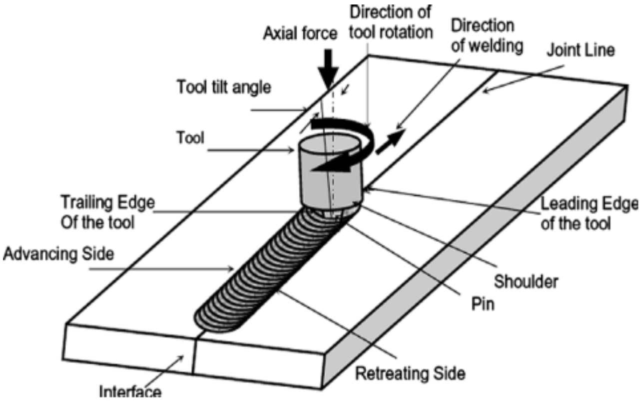

Figure 1: Setup of FSW/P(Kumar and Kales, 2008)

The parameter denoting the velocity of tool rotation is termed tool rotation speed and is quantified in revolutions per minute (rpm). Concurrently, the rate at which the tool advances in the forward direction is termed traverse speed, measured in millimeters per minute (mm/min). Both of these parameters are pivotal in the process and necessitate meticulous selection to ensure a successful and efficient processing outcome. While the relationship between these parameters is intricate, it can be posited that an augmentation in rotational speed, coupled with a reduction in transverse speed, engenders elevated temperatures, thereby exerting a significant influence on material properties. Conversely, insufficient material temperature may result in the presence of voids or other anomalies in the stir zone, potentially leading to tool fracture in extreme cases. The plunge depth is defined as the measure of the lowest point of the shoulder below the material surface and is identified as a critical parameter in the process. Submerging the shoulder beneath the plate surface results in an augmentation of pressure beneath the tool, facilitating adequate material forging at the rear of the tool. Tilting the tool at an angle ranging from 2-4 degrees, where the rear is positioned lower than the front, has been identified as a beneficial strategy to enhance this forging process. Precise adjustment of the plunge depth is imperative, serving both to ensure the requisite downward pressure and to guarantee full penetration of the tool into the material (Singh and Arora, 2010).

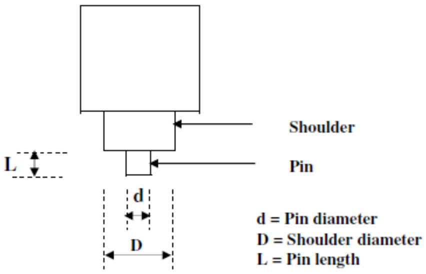

Figure 2: Design of FSP Tool(Elangovan and Balasubramanian, 2008).

The configuration of the tool holds paramount importance, as an adeptly designed tool can enhance both material surface characteristics and the maximum attainable traverse speed. For an effective Friction Stir Processing (FSP) tool, a material exhibiting ample strength, toughness, high-temperature wear resistance, oxidation resistance, and low thermal conductivity is imperative. Notably, hot-worked tool steel has demonstrated suitability for processing low-density materials such as Aluminum and magnesium (Elangovan and Balasubramanian, 2008).

The FSP tool comprises a shoulder and a probe, which may be integral with the shoulder or exist as a separate insert, potentially composed of a different material [see Fig 2]. The design intricacies of the shoulder and probe significantly influence the weld's quality. The probe, responsible for generating heat and stirring the processed material, works in conjunction with the shoulder. The shoulder, beyond contributing additional heat treatment, plays a crucial role

Received: 10-09-2018 **Revised: 02-12-2018** **Accepted: 15-12-2018**

in preventing the escape of plasticized material from the processed region, as previously discussed. It is evident that diverse materials and thicknesses necessitate distinctively profiled probes. Various tool pin/probe profiles, including straight cylindrical, threaded cylindrical, tapered cylindrical, square, and triangular profiles, can be employed [see Fig 3].

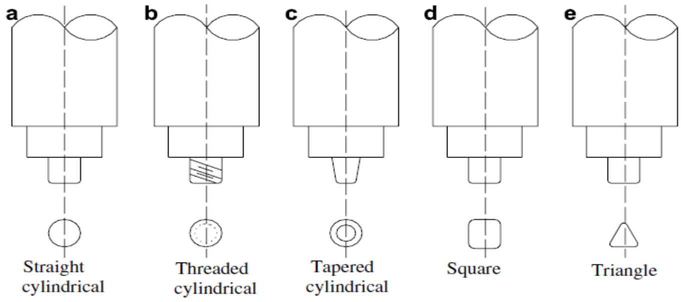

Figure 3: FSW/P tool pin profiles (Padamanban and Balasubramanian, 2009).

The inherent solid-state nature of the Friction Stir Processing (FSP) procedure, coupled with its distinctive tool configuration, gives rise to a highly distinctive microstructure. Typically, FSP manifests itself in four discernible regions [see Fig 4].

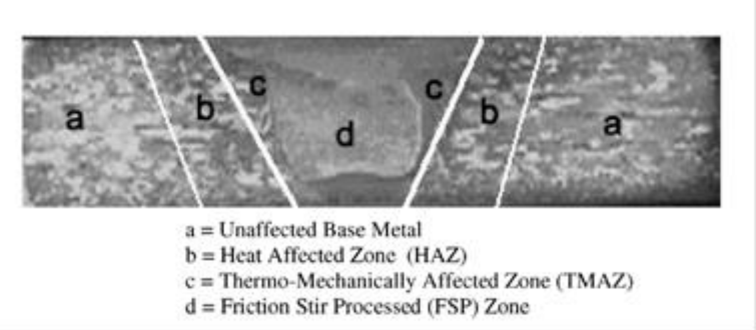

Figure 4: Different Zones of FSP/W(Singh and Arora, 2010).

The Stir Zone, also known as the nugget or dynamically recrystallized zone, constitutes a region of highly deformed material that aligns with the approximate location of the pin during processing. Within the stir zone, the grains exhibit a roughly equiaxed morphology and are often an order of magnitude smaller than those found in the parent material. A distinctive characteristic of the stir zone is the frequent presence of several concentric rings, commonly referred to as an 'Onion ring' structure. Adjacent to the stir zone, on both sides, is the Thermo-Mechanically Affected Zone (TMAZ). In this region, both the strain and temperature are lower compared to the stir zone, resulting in a proportionately smaller impact on the microstructure. Unlike the stir zone, the microstructure in the TMAZ is readily recognizable as that of the parent material. The Heat-Affected Zone (HAZ) undergoes a thermal cycle but remains undeformed during processing. While temperatures in the HAZ are lower than those

Power System Technology
ISSN:1000-3673

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

experienced in the TMAZ, they may still exert a significant effect, especially if the microstructure of the material is thermally unstable (Singh and Arora, 2010). The applied load that compels the tool to engage with the stationary plates is a critical parameter requiring careful consideration. It is imperative that the applied load is judiciously chosen, as an excessive load can lead to a substantial generation of frictional heat, resulting in elevated temperatures. Conversely, if the load is insufficient, proper mixing of the plasticized material may not be achieved. For the processing of soft alloys, it is generally recommended to employ an axial load within the range of 4-6 kilonewtons (KN). This load range is deemed preferable to strike a balance, ensuring effective mixing of the plasticized material without generating excessively high temperatures in the process.

1.1 Advantages of Friction Stir Processing

- The key advantages of Friction Stir Processing are given in Table 1

Metallurgical benefits	Environmental benefits	Energy benefits
Solid-state processing	No shielding gas required	Less energy required
Minimal distortion of workpiece	Green Process no hazardous gases/fumes	Decreased material loss
Dimensional stability and repeatability	Eliminate solvents required for degreasing	
No loss of alloying elements	Non- Consumable tool	
Excellent metallurgical properties in the processed area		
Fine grain structure		
Absence of cracking		

Table 1. Advantages of Friction stir Process (R.S.Mishra and Z.Y.Ma, 2005)

1.2 *Limitations of Friction Stir Processing*

- The elevated pressures inherent in the friction stir processing (FSP) necessitate the use of rigid clamping mechanisms to ensure precise positional accuracy throughout the procedure (Singh and Arora, 2010).
- In comparison to other techniques involving liquid states, the friction stir processing operates at relatively slower speeds, reflecting a distinctive characteristic of the method.
- The conclusion of the processed zone results in the formation of a tool exit hole at

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

both the starting and ending points, necessitating subsequent steps for refilling after the completion of the friction stir processing.
- The applicability of the process is restricted when dealing with intricate shapes, posing a limitation in its effectiveness for complex geometries.

1.3 Applications of Friction Stir Processing

- The friction stir processing (FSP) technique finds application in the fabrication of components such as airframes, fuel tanks, and thin alloy skins within the aerospace sector (W.M. Thomas and E.D. Nicholas, 1997).
- Within the automotive industry, FSP is employed for the creation of sheet bodywork and engine support frames, exemplifying its adaptability in the production of structural components (W.M. Thomas and E.D. Nicholas, 1997).
- FSP offers an opportunity to manufacture lightweight assemblies, leading to pervasive cost savings particularly within the aerospace industries (R.S. Mishra and Z.Y. Ma, 2005).
- The process facilitates the creation of metal matrix composites, showcasing its versatility in developing advanced materials with enhanced properties.
- Friction stir processing is routinely employed for the production of aluminum railway stock and in the construction of aluminum ships, emphasizing its widespread application in the manufacturing of transportation-related structures.

2. Aluminium alloys

Aluminum, characterized by its atomic number 13 and chemical symbol Al, presents as a silvery-white metal. It stands as the most abundant metal within the Earth's crust and holds the position as the third most prevalent element, succeeding oxygen and silicon in abundance. Preparation methods for aluminum include extraction from bauxite or electrolysis of alumina dissolved in molten cryolite. Noteworthy properties of aluminum encompass its density, which is approximately one-third that of steel and brass. Beyond its lightweight nature, aluminum exhibits excellent electrical conductivity and heightened resistance to corrosion compared to many other metals. This superior corrosion resistance arises from the formation of a thin yet robust oxide film on its surface upon exposure to air. The film further thickens with heating. Aluminum is recognized for its ductility and non-magnetic characteristics. In its pure form, aluminum is soft and corrosion-resistant, making it extensively utilized for applications such as foils and conductor cables. However, alloying with other elements becomes imperative to impart the requisite strength for diverse applications. The pure aluminum compound possesses a melting point of 650ºC, while the fusion range of most

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

aluminum alloys varies between 520ºC and 650ºC. These characteristics collectively contribute to the diverse applications of aluminum in various industries. Aluminum alloys are composite materials with aluminum as the base element, incorporating alloying elements such as Mg, Zn, Cu, Ti, Si, Fe, among others. These alloying elements play a crucial role in augmenting and refining the mechanical properties of the alloy. The classification of aluminum alloys is contingent upon the composition of these alloying elements, leading to categorizations into casting and wrought alloys, further stratified into distinct series and categories, including heat-treatable and non-heat-treatable alloys. These alloys find widespread application in engineering structures and components, particularly in scenarios where lightweight construction and resistance to corrosion are paramount. The versatility of aluminum alloys stems from their distinctive properties, including low density, a high strength-to-weight ratio, commendable corrosion resistance, proficient electrical and thermal conductivity, non-magnetic attributes, and ductility retention at low temperatures. These properties render aluminum alloys extensively utilized in critical industries, notably aerospace and automotive sectors (Elongovan and Balasubramanian, 2008; Singh and Arora, 2010).Presently, the automotive industry is witnessing a shift towards the utilization of lightweight aluminum alloys, displacing traditional steel. This transition is driven by the benefits of reduced automobile weight, leading to enhanced fuel efficiency and diminished CO2 emissions into the environment. Table 3 delineates various series of aluminum alloys, providing insight into their composition based on alloying elements.

Series	Major Alloying Element/Elements	Uses
1xxx	Al, Fe, Si	Aluminum Wires and Pipings
2xxx	Al, Cu	Aerospace and Marine Applications
3xxx	Al, Mn	Heat Exchangers for Vehicles and Power
4xxx	Al, Si	Plants
5xxx	Al, Mg	As Filler Materials
6xxx	Al, Si, Mg	Decorative and Architectural Applications
7xxx	Al, Zn, Mg	Aerospace and Automobile Applications
8xxx	Al, Lithium	Aerospace and Marine Applications
		Special Alloy Applications

Table 3. Classification of Al alloys (Terry Khaled, 2005)

2.1 Applications of Aluminum Alloys

- Aluminum alloys are extensively employed in various transportation sectors, including trains, trucks, buses, cars, and airplanes, specifically for body

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

panels. This application aims to reduce the overall weight of automobiles, contributing to increased fuel efficiency.

- Commonly utilized in the aerospace industry, aluminum alloys play a crucial role in the fabrication of aircraft and other aerospace structures, as highlighted by Lakshminarayanan et al. (2009).
- Aluminum alloys find utility in overhead conductors and components of heat exchangers, demonstrating their efficacy in electrical and thermal applications.
- Within the food industry, aluminum alloys serve diverse roles, functioning as materials for food preparation equipment such as pans. Additionally, they are employed in the production of shipping containers and storage containers.
- Aluminum alloys are also utilized domestically in the fabrication of items like mangles and wafflemolds, showcasing their versatility in various consumer applications.

3. Magnesium And Its Alloys

Magnesium, characterized as the lightest among engineering metals, exhibits a density of 1.74 g/cm³. Its exceptional lightweight nature is underscored by being 35% lighter than aluminum (2.7 g/cm³) and over four times lighter than steel (7.86 g/cm³). Abundant in the Earth's surface, magnesium is among the most prevalent elements, with essentially limitless reservoirs in oceanic sources. The industrial output of magnesium alloys has witnessed a notable surge, experiencing an approximately 20% increase in recent years, surpassing the growth rates of other metals. The production of magnesium involves either the metallothermic reduction of magnesium oxide with silicon or the electrolysis of magnesium chloride using seawater. Each cubic meter of seawater contains approximately 1.3 kg (0.3%) of magnesium. Alloying magnesium with elements such as aluminum, manganese, rare earths, thorium, zinc, among others, enhances its strength-to-weight ratio. This characteristic renders magnesium alloys crucial in applications prioritizing weight reduction and the necessity to mitigate inertial forces. The superior strength-to-weight ratio of magnesium-based alloys has led to their substitution for denser materials, including not only steel, cast iron, and copper-based alloys but also aluminum alloys. This transition is emphasized by Mustafa K. Kulekci (2008). Table 4 provides an overview of common magnesium alloys, detailing their alloying elements and applications.

Power System Technology
ISSN:1000-3673

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

Alloy Designation	Alloying Additives	Uses	Basic Properties and Applications
AZ91	9%Al, 0.7%Zn, 0.13%Mn	General Casting alloy	Good Castability, Good Mech. Properties T<423K.
AM60	6%Al, 0.15%Mn	High Pressure Die Casting alloy	Greater toughness and ductility than AZ91, Slightly lower strength.
AM50	Mg-Al System	General Casting Alloy	Good strength, ductility, energy absorption properties.
AZ31	3%Al, 1.0Zn, 0.2%Mn	Wrought Mg Products	Good Extrusion Alloy.
AS21	Mg-Al-Si System	Casting Alloy	For Use at temp. in excess of 393K.

Table 4. Classification of Magnesium Alloys (Mustafa K. Kulekci, 2008)

Similar to aluminum alloys, magnesium alloys are categorized into general casting alloys and wrought alloys. Cast magnesium alloys, exemplified by AZ91, demonstrate notable creep behavior at ambient temperatures, specifically under an initial applied stress equivalent to only 39% of its yield stress. Consequently, these alloys, constrained by their creep characteristics, possess a maximum operating temperature of 398 K. This limitation renders them less suitable for applications such as power trains and engine castings, which typically operate at temperatures exceeding 373 K and involve threaded fasteners where creep becomes a critical concern. Conversely, wrought magnesium alloys like AZ31 exhibit a markedly improved combination of strength and ductility when compared to casting alloys. However, the utilization of wrought alloys is presently constrained due to the scarcity of suitable alloys and certain technological limitations imposed by the hexagonal crystal structure inherent to magnesium, as emphasized by Mustafa K. Kulecki (2008).

3.1 Applications of Magnesium Alloys

- Magnesium alloys find application in various components of ground transportation vehicles, including engines, transmission pumps, differentials, floors, and body panels of trucks and cars. This implementation aims to reduce overall weight, thereby enhancing fuel efficiency and reducing CO2 emissions, as discussed by Mustafa K. Kulecki (2008).

Power System Technology
ISSN:1000-3673

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

- Magnesium alloys play a pivotal role in the fabrication of components for aerospace vehicles such as airframes, engines, gearboxes, and seating for airplanes, helicopters, missiles, and satellites.
- Utilization extends to the manufacturing of power tools like electric drills, chain saws, power hammers, showcasing the versatility of magnesium alloys in various industrial applications.
- Magnesium alloys prove useful in the construction of structural elements such as storage tanks, hoppers, ladders, and scaffolds, underlining their applicability in diverse engineering and industrial contexts.

4. Research Methodology that can be used in Fsp

4.1Taguchi technique

Taguchi's orthogonal design proves effective in minimizing errors and identifying significant parameters crucial for optimizing properties in FSP. Design of experiments is applied, typically incorporating parameters such as tool rotation speed, traverse speed, penetration depth, tilt angle, and reinforced particles. The commonly employed Taguchi design for FSP is the L9 orthogonal array, characterized by 3 columns and 4 rows, facilitating the optimization of process parameters. In the Taguchi method, experimental data undergoes analysis through the signal-to-noise ratio (S/N), where a higher S/N ratio signifies superior parameters, aligning with the "higher-the-better" approach. The optimal combination of process parameters is determined by identifying the highest S/N ratio associated with better properties. A detailed Analysis of Variance (ANOVA) framework is employed to assess the significance of process parameters. Calculation of the S/N ratio for each control factor is essential to minimize variance in the property under analysis. Signals represent the influence on average responses, while noises account for deviations from these averages, revealing the experiment's sensitivity to noise factors. The choice of an appropriate S/N ratio depends on prior knowledge, expertise, and an understanding of the process, often guided by the "higher-the-better" criterion. ANOVA tests aid in identifying the most impactful process parameters affecting the properties of FSPed materials. The precision of parameter estimation relies on the degree of freedom (DOF), determined by the number of independent samples of information – calculated as the number of experiments minus the number of additional parameters estimated (D. Ahmadkhaniha et al., 2015).

4.2 Numerical modelling

Numerical simulation serves as a prominent tool for analyzing the thermo-mechanical processes and material flow behavior in Friction Stir Processing (FSP). Its application aims to explore the physical nature of the process and guide tool design. Computational Fluid

Power System Technology
ISSN:1000-3673

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

Dynamics (CFD) and Computational Solid Mechanics (CSM) are commonly employed in modeling FSP, with a prevalent preference for CFD models due to their advantages in simulating material flow, especially in cases involving complex pin shapes. In CFD models of FSP, two primary categories of boundary conditions are employed at the tool-workpiece interface: velocity-based and shear stress-based conditions, as outlined by Sun and Wu (2018). These numerical models are essentially mathematical representations that utilize time-stepping procedures to acquire information about the process over time. By expressing intricate functions through numerical approximations, researchers leverage computers to simulate the FSP. The development of accurate numerical models enables researchers to conduct virtual experiments, reducing the time and cost associated with laboratory work. Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEM) stand out as two pivotal numerical methods used in modeling FSP. These models provide valuable insights into the dynamic nature of the FSP process, as emphasized by Gibson et al. (2014).

4.3 Analytical modelling

Analytical modeling of the thermal environment evolution in the Friction Stir Processing (FSP) is of significant interest for two main reasons. Firstly, similar to fusion processes, the stir temperature in FSP profoundly influences the material properties. Secondly, analytical models provide a concise alternative to temperature estimation through Computational Fluid Dynamics (CFD). CFD software, such as FLUENT, can be employed for this purpose, where the boundary conditions in the CFD model play a crucial role in predicting results. The process involves generating a CFD model, incorporating Computer-Aided Design (CAD) geometry and mesh. The CFD model is then solved for the specified parameters. Validation of the predicted data is crucial, followed by estimating the average temperature in the deformation zone. Upon solving the CFD model, a data file can be exported to CFD post software to extract the pressure distribution on the tool surface, representing the pressure profiles. This comprehensive approach is outlined by P. A. Colegrove(2006) Hasan (2019) in the study of FSP, contributing to a deeper understanding of the thermal aspects and facilitating precise temperature estimations.

5. Techniques for fabrication of Metal Matrix composites by FSP

5.1 Sol-gel

The sol-gel process, a wet-chemical technique, involves immersing the metallic substrate multiple times in a gel solution to achieve the desired thickness of the powder coating. Subsequently, a rotating tool is pressed against the top surface. The tool is then traversed, and the process may consist of either a single pass or a double pass, contingent upon factors such as the substrate, reinforcing particles, and the geometry of the tool.

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

5.2 Direct application of powder

In this method, a groove of smaller dimensions is created and subsequently filled with reinforcing powder particles. The groove is meticulously packed with these particles. Following this, a rotating tool, featuring a larger diameter and pin length than the dimensions of the groove, is precisely inserted into the groove. The tool is then traversed along the groove, facilitating the incorporation of reinforcing powder particles into the processed material.

5.3 Number of passes

Numerous studies conducted by various authors emphasize the substantial influence of the number of FSP passes on the microstructure evolution of materials. Single-pass FSP typically results in a coarse grain size, whereas multipass FSP induces the development of a fine and equiaxed grain structure. This recrystallization process contributes significantly to the enhancement of mechanical properties. Reports indicate that multi-pass FSP leads to a reduction in cluster size and a more uniform distribution of reinforcement particles, consequently reducing the grain size of the matrix. The deformation during successive FSP passes generates additional dislocations from various sources. Simultaneously, the stacking fault energy (SFE) of aluminum prompts dynamic recovery and the formation of low-angle sub-grain boundaries.

In the fabrication of surface composites, an increase in the number of FSP passes results in improved distribution of reinforcement particles within the matrix, leading to finer grains and higher levels of hardness, strength, and elongation. Studies, such as those by Sharma et al. (2015), report a nearly doubled ultimate tensile strength in composites after multi-pass FSP. This enhancement is correlated with reduced porosity and improved interfacial bonding.

6. Conclusion and Scope

Friction Stir Processing (FSP) emerges as a highly promising solid-state processing technique, particularly for surface modifications in lightweight alloys such as aluminum and magnesium with low melting points. This method proves advantageous by virtually eliminating defects like porosity inherent in conventional liquid state processing techniques. The improved mechanical properties achieved through FSP result from the processing occurring in the solid state, where material melting is entirely circumvented. FSP holds vast potential for processing specific alloys and forming surface composites through the introduction of second-phase reinforcement particles. Researchers have underscored the importance of processing soft and lightweight alloys to enhance surface properties without adversely affecting the base alloys. The addition of ceramics and rare earth elements during FSP has been explored to enhance the surface properties of composites. To gain deeper

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

insights into surface morphology, various research methodologies, including Taguchi experimentation, numerical simulations, and analytical models, can be employed. These approaches facilitate data simulation and the identification of optimal parameters to achieve superior mechanical properties in the processed materials.

References

1. M. S. Weglowski(2018) “Friction Stir Processing - State of the art”, Archives of Civil and Mechanical Engineering, Vol. 18, pp-114-120.
2. G.K. Padhy, C.S. Wu, S. Gao(2018) “Friction stir based welding and processing technologies- processes, parameters, microstructures and applications: A review”, Journal of Materials Science and Technology, Vol. 34, pp1-38.
3. V. Sharma, U. Prakash, B.V.M. Kumar(2015) “Surface composites by friction stir processing: A review”, Journal of Materials Processing Technology, Vol.224, pp-117-134.
4. Terry Khaled (2005) “An outside looks at Friction Stir Welding”, Report#: ANM-112N-05-06, July 2005.
5. G.Padmanaban and V.Balasubramanian (2009) “Selection of FSW tool pin profile, shoulder diameter and material for joining AZ31B Magnesium alloy”, Materials and Design Vol. 30, pp 2647-2656.
6. Jiuchun Yan, Zhiwu Xu, Zhiyuan Li, Lei Li, Shiqin Yang (2005) “Microstructure characterstics and performance of dissimilar welds between magnesium alloy and aluminium formed by friction stirring”, Scripta Materialla Vol. 53, pp 585-589.
7. K. Elangovan and V. Balasubramanian (2008) “Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy”, Materials and Design Vol. 29, pp 362-373.
8. Harpreet singh and H S Arora (2010) “ Friction Stir Welding-Technology and Future Potential”, National Conference on Advancements and futuristic Trends in Mechanical and Materials Engineering. Feb.19-20, 2010.
9. W. M. Thomas and E. D. Nicholas (1997) “Friction stir welding for the transportation industries”, Materials and Design Vol. 18, pp 269-273.
10. M. Abbasi Gharacheh, A.H.Kokabi, G.H.Daneshi, B.Shalchi, R.Sarrafi (2006) “The influence of the ratio of ‘rotational speed/transverse speed on mechanical properties of AZ31 Friction stir welds”, International Journal of Machine Tools & Manufacture Vol. 46, pp 1983-1987.
11. R.S. Mishra and Z.Y. Ma (2005), “Friction stir welding and processing”, Material Science Engineering R 50, pp. 01-78.
12. Mustafa Kemal Kulekci (2008), “Magnesium and its alloy applications in automotive industry”, International Journal of

Received: 10-09-2018 Revised: 02-12-2018 Accepted: 15-12-2018

Advanced Manufacturing Technology 39, pp. 851-865.

13. K. Kumar and Satish V. Kailas (2008), “The role of Friction stir welding tool on material flow and weld formation”, Material Science and Engineering A 485, pp. 367-374.
14. W. M. Thomas and E. D. Nicholas (1997),“Friction stir welding for the transportation industries”, Materials and Design,18, pp. 269-273.
15. D. Ahmadkhaniha, M. H. Sohi, A.Z. Hanzaki, S. M. Bayazid, M. Saba(2015), “Taguchi optimization of process parameters in friction stir processing of pure Mg” , Journal of Magnesium and Alloys, Vol.xx, pp.1-5.
16. Z. Sun, C.S. Wu(2018), “A numerical model of pin thread effect on material flow and heat generation in shear layer during friction stir welding”, Journal of Manufacturing Processes, Vol. 36, pp.10-21.
17. B. T. Gibson, D.H. Lammlein, T.J. Prater, W.R. Longhurst, C.D. Cox, M.C. Ballun, K.J. Dharmaraj, G.E. Cook, A.M. Strauss(2014), “Friction Stir welding: Process,automation, and control”, Journal of Manufacturing Processes, Vol. 16, pp.56-73.
18. P. A. Colegrove & H. R. Shercliff (2006) “CFD modelling of friction stir welding of thick plate 7449 aluminium alloy”, Science and Technology of Welding and Joining, 11:4, 429-441.