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A Comprehensive Study of Friction Stir Processing Technique

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ABSTRACT

Friction Stir Processing technique is a surface modification method that transforms heterogeneous microstructures into homogeneous ones, enhancing the mechanical properties of metal sheets. This single-step process, introduced by The Welding Institute (TWI) in 1991, offers advantages such as superior strength and formability, especially in aluminum alloys. FSP's simplicity, cost-effectiveness, and environmental friendliness make it preferable over traditional methods. Despite challenges in aerospace and transportation applications, FSP shows promise for forming lightweight alloys at room temperature. However, producing ultrafine grain sheet metals remains a challenge. Overall, FSP presents a viable solution for improving material properties and processing efficiency in various industrial applications. This study includes the literature review of research publications from different researchers to develop the understanding regarding friction stir processing technique.

Keywords: Friction Stir Processing, Surface Modification, Grain Refinement, Mechanical Properties

1. Introduction

Friction stir processing (FSP) method is a materials processing technique based on the principle of friction stir welding process (FSW). In this process, a non-consumable rotating tool with shoulder and pin is inserted into the workpiece surface and moved forward perpendicular to the insertion. The Welding Institute (TWI) of the United Kingdom introduced it in 1991. FSP serves as a surface modification technique and has recently emerged as an efficient method for homogenizing and refining the grain structure of metal sheets [1]. Friction stir processing transforms a heterogeneous microstructure into a more homogeneous and refined one. Various methods are available for application to different material shapes and sizes. In many instances, reprocessed areas exhibit superior strength and formability compared to the parent material. For example, aluminum castings can undergo processing to consolidate voids, and extrusions can be enhanced in highly stressed areas. When combined with super plastic forming, FSP enables the formation of complex-shaped parts at higher strain rates and section thicknesses not achievable through conventional super plastic processing. [1, 2]

Friction stir processing represents a novel microstructural modification technique, increasingly recognized for its efficacy in homogenizing and refining metal sheet grain structures. It holds promise in the realm of super plasticity, with reported enhancements in many aluminum alloys. Compared to conventional and other newer techniques, FSP offers numerous advantages. Notably, it is a single-step process, unlike others requiring multiple steps, rendering it more efficient and less time-consuming. Moreover, FSP employs a simple, inexpensive tool, with readily available machines such as milling machines suitable for conducting the process. Additionally, FSP's suitability for automation and its environmentally friendly nature, devoid of gases or chemicals, further contribute to its appeal over other processing methods.[2]

In various industrial applications, particularly in aerospace and transportation, identifying materials with specific properties is crucial. However, conventional processing techniques often pose limitations in terms of cost and production time. Materials with fine and homogeneous grain structures can achieve high strength coupled with high ductility. Several processing techniques, including FSP and Equal Channel Angular Extrusion (ECAE), are being developed to address these challenges. FSP, in particular, holds promise for forming lightweight alloys at room temperatures for aerospace and automotive applications, albeit presenting significant challenges. Refining and homogenizing the microstructure, along with employing advanced forming techniques like superplastic forming, can improve formability. Recent findings indicate that fine-grained sheet metals exhibit superior formability at moderate temperatures, underscoring the importance of grain size reduction. However, the difficulty in producing ultrafine grain sheet metals impedes the widespread adoption of lightweight alloys in the transportation industry. [3]

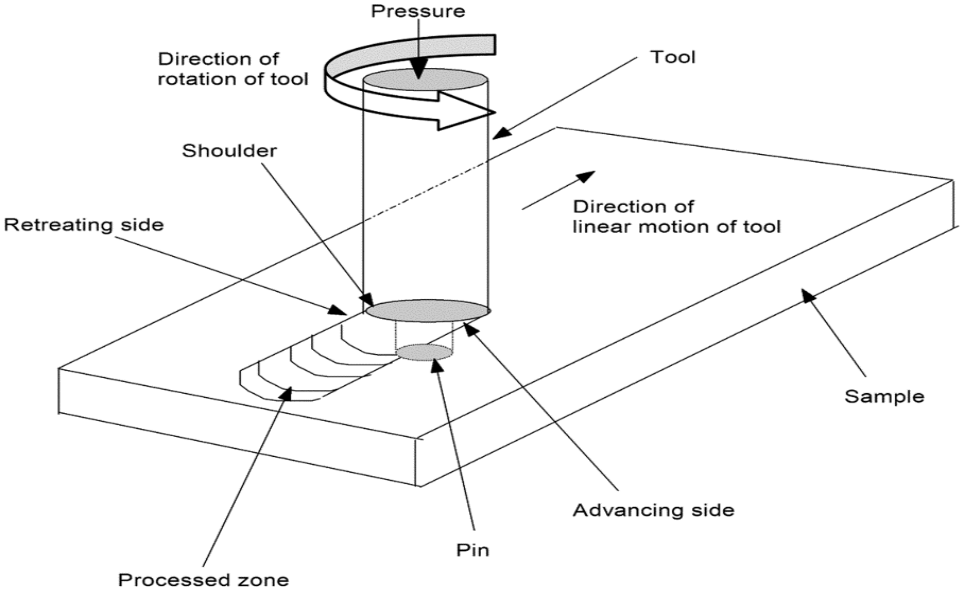

Fig 1 Working principle of FSP [4]

2. Literature Review

J Kwon et al. (2003) studied the effect of tool rotational speed (900, 1300 and 1600 rpm) and concluded that with increase in rotational speed, tensile and hardness increase. In this study 1050 aluminum alloy was used to enhance mechanical properties with the help of Friction Stir Processing. This results when these characteristics increased and grain refinement also goes up to 37% to 46% as compared to the starting material. Optimum result is obtained at 1300 rpm. [5]

B.M. Darras (2005) study the impact of tool travel speed during friction stir processing on material composites was examined. It was revealed that the grain size becomes more uniform, with significantly smaller grains in the nugget region compared to other regions. Furthermore, it was detected that the heat affected zone was larger at 800 rpm compared to 600 rpm. At 600 rpm and 2.5 in/min, the average grain size reduced to approximately 1.67 µm, while at 1000 rpm and 2.5 in/min, it increased to 4.49 µm. Furthermore, the hardness was found to be greater at the center compared to the edges. The resulting grain size fluctuated from 0.1 to 18 micrometers, indicating a fine grain structure. Moreover, about 80% of the yield stress was attained in the parent metal. [6]

C.I. Chang (2007) found that Friction Stir Processing effectively produced ultrafine grain sizes in a Mg–Al–Zn alloy. Utilizing this technique, ultrafine-grained (UFG) microstructures averaging 100–300 µm in grain size were achieved in a solution-hardened AZ31 Mg–Al–Zn alloy. This process employed friction stir processing with a rapid heat sink. The resultant UFG region demonstrated a mean hardness of 120Hv, which exceeded that of the AZ31 matrix by more than double. [7]

M.K. Khraisheh et al. (2007) investigated the impact of tool rotational speed (ranging from 1200 to 2000 rpm) and transverse speed (ranging from 20 to 30 in./min) on AA6061/SiC through friction stir processing. Their findings reveal that the microstructure of FSP samples exhibits greater homogeneity compared to the as-received material. Notably, FSP refines the microstructure, reducing the average grain size to approximately 6. Furthermore, the study highlights the significant influence of processing parameters on the hardness of the resulting sheets. [8]

Sudhakar et al. (2008) investigated the impact of tool travel speed (20 mm/min, 50 mm/min, and 70 mm/min) and transverse speed (925-1000 rpm) on Al-7075 through friction stir processing. Higher rotational speeds (>1200 rpm) induced significant plastic deformation, leading to surface cracks and voids in composite A's transverse section. Optimal results were achieved with a tool feed rate of 50 mm/min, a rotational speed of 960 rpm, and a plunging speed of approximately 30 mm/minute, with a tilt angle of approximately 2.50. EDX analysis affirmed the effectiveness of friction stir processing, revealing intact boron carbide particles without dissolution. This study successfully demonstrated the fabrication of surface metallic matrix composites (SMMC) incorporating boron carbide particles onto AA7075 for wear-resistant applications, with optimal outcomes observed at 50 mm/min and 960 rpm. [9]

Chen Z. W. et al. (2009) conducted a study on the strain and strain rate during Friction Stir Processing (FSP) of AL-7Si-0.3Mg alloy. Despite previous efforts, understanding the maximum strain and strain rate encountered during FSP has remained elusive. Knowledge of these parameters is crucial for comprehending the subsequent grain structure evolution and serves as a foundation for validating various models. In this study, the researchers facilitated the breaking and embedding of the pin into the cast AL-Si-Mg alloy workpiece during FSP to obtain "frozen" samples for analysis. Metallographic evidence revealed a rapid increase in strain gradient in the leading transitional zone before entering the thread space. Analysis of deformed dendrites suggested a strain of 3.5 and a strain rate of approximately 85 S-1 upon entering the thread space. As the heavily deformed material formed a rotational zone within the thread spaces, the strain decreased considerably along with the strain rate. [10]

Jun Qu et al. (2010) investigated the impact of silicon particle reinforcement on the tensile strength and hardness during friction stir processing (FSP). They employed FSP to mix sub-micron-sized Al2O3 and SiC particles into the surface of a 5 mm thick aluminum 6061-T6 alloy plate, forming a composite layer up to 3 mm thick. The use of ceramic particles, like silicon carbide and aluminum oxide, for reinforcing aluminum matrix composites has been extensively studied. Recent research indicates that smaller particles tend to result in stronger and harder composites, leading to the exploration of nano or sub-micro-particle reinforced aluminum composites through methods such as casting or powder metallurgy. The FSP tool utilized had a 19.05 mm diameter shoulder and a threaded pin measuring 6.35 mm in diameter and 4 mm in length. Depending on the particle size and concentration, the tool's spinning speed ranged from 1000 to 1800 rpm, while the feed rate varied from 0.1 to 1.0 mm/s. The Vickers hardness of the composite surfaces was evaluated via microindentation under a 1.96 N load. Wear testing was performed under specific conditions, revealing that the composite surfaces were over 20% harder than the original alloy, with improved stability and lower friction coefficients compared to the untreated aluminum 6061-T6 alloy.

Additionally, the worn composite surface exhibited less adhesive wear and was primarily affected by abrasive wear and plastic deformation. These findings underscore the significant enhancement in wear performance achievable with aluminum-based materials. Optimal values of hardness (65 HV) and tensile strength (190 MPa) were attained at 950 rpm and 30 mm/min, representing a substantial improvement over the base metal properties. [11]

M. Salehi et al. (2011) studied effect tool travel speed (20 mm/min, 40 mm/min and 60 mm/min) rotational speed (900 rpm, 1600 rpm and 1900 rpm) and pin profile (cylindrical threaded and square tool pin) on AA6061/Sic nanocomposites produced by friction stir processing. The FSP process parameters were optimized to maximize the tensile strength of ASNCs. The optimum condition of the rotational speed, transverse speed, tool penetration depth, and pin profile were found to be 1600 r/min, 40 mm/min, 0.30 mm and threaded type respectively. [12]

X. Weiping et al. (2011) investigated the fabrication of carbon nanotubes (CNTs) reinforced aluminum matrix composites through friction stir processing (FSP). They examined the influence of CNTs content on the wear performance and hardness of the composite. The results demonstrated that FSP effectively dispersed CNTs within the AA1100 and AA6101 aluminum matrices, facilitating a strong interface between the CNTs and the matrix. This interface exhibited smoothness and lacked defects, representing a robust mechanical bonding interface. Additionally, the presence of CNTs led to a significant enhancement in the hardness of the composites, as well as improved wear performance. Furthermore, an increase in CNTs content correlated with further improvements in wear performance of the matrix composites. [13]

T. Kanimozhi et al. (2011) conducted friction stir processing on AA6082 alloy with varying proportions of Silicon-Graphite composite. They measured the hardness values and found that the maximum hardness achieved was 140 BHN. This occurred at a processing speed of 60 mm/min and 500 rpm. The composite consisted of 8% Si and 0.5% Gr hybrid composite. Throughout the experiment, defect-free and sound surface composites were successfully fabricated within the specified parameters. [14]

S. Jerome et al. (2012) studied the effect of rotational speed on surface composite developed by single pass FSP with groove design, the average hardness along the top surface was found to increase by 22.72% as compared to that of the base metal whereas the in case of surface composite developed by double pass FSP in same and opposite direction, the average hardness along the top surface was found to increase by 25% and 27.27% respectively, as compared to that of the base metal. Parameters used are 1400 rpm, 1120 rpm and 900 rpm with 6 mm/min transverse speed. The maximum average depth of surface composite was found to be 250 µm in hole-design. It is observed that with increasing rotational speed hardness also increases and optimum value is 108 Hv at 1400 rpm. [15]

R. Sathiskumar et al. (2012) investigated the impact of parameters on the microstructure and micro hardness of copper surface composites reinforced with boron carbide particles. They achieved defect-free and sound surface composites at a transverse speed of 40 mm/min. Various transverse speeds ranging from 20 mm/min to 60 mm/min and rotational speeds of 1000 rpm, 1100 rpm, and 1200 rpm were utilized. The surface composite area expanded with higher rotational speed but decreased with increased processing speed due to elevated frictional heat generation. Moreover, enlarging the groove width reduced the surface composite area. The distribution of B4C particles was influenced by the tool, yielding a micro hardness of 132 Hv at 1200 rpm. [16]

Davidson et al. (2012) examined how varying rotational speeds during Friction Stir Processing (FSP) of Mg AZ31B alloy sheets affected both microstructural changes and mechanical properties. FSP was conducted within rotational speed ranges of 900 to 1400 rpm while maintaining a constant traverse speed of 32 mm/min. Their findings indicate a substantial correlation between rotational speed and both microstructural evolution and mechanical properties of the processed material. It was concluded that optimizing rotational speed led to the attainment of superior mechanical properties. [17]

D. Dharmpal et al. (2013) investigated the impact of incorporating reinforced particles via friction stir processing on a 6 mm thick plate. They prepared an AL5083/SiC surface composite using FSP and conducted mechanical characterization. Their findings indicate that introducing hard SiC particles into 5083 Al via FSP results in a notable increase in hardness. However, despite the higher hardness achieved, the wear resistance of the FSP-treated sample is lower compared to untreated 5083Al, particularly at 1200 rpm and 40 mm/min. [18]

P. Cavaliere (2013) conducted a study examining the influence of tool travel speed (20 mm/min, 40 mm/min, and 60 mm/min) on friction stir processing outcomes. The research observed that higher travel speeds led to the development of a finer and more stable grain structure. The investigation specifically targeted the friction stir processing of a 6 mm thick AM60B magnesium alloy. This alloy showcased improved tensile properties at room temperature, attributed to the consolidation of casting defects facilitated by the stirring action. SEM observations highlighted regions where grain boundary sliding occurred, particularly in areas exhibiting higher strain rate sensitivity during friction stir processing. [19]

V.K. Gupta et al. (2013) investigated the fabrication of a surface composite using AL5083 matrix reinforced with nano-sized silicon carbide particles through Friction Stir Processing (FSP). They examined the microstructure, hardness, and wear behavior of the composite and compared it with pure AL5083 alloy. The study revealed a significant increase in hardness of the FSP-produced surface composite due to the incorporation of hard SiC particles. The highest hardness (155 HV) was observed at the center of the processed zone, achieved at a rotational speed of 500 rpm and a transverse speed of 60 mm/min. However, the wear resistance of the FSP-produced sample was found to be lower than that of pure AL5083 due to detachment of SiC particles during wear testing. [20]

F. Khodabakhshi et al. (2014) investigated the impact of varying tool travel speeds (70 mm/min, 85 mm/min, and 100 mm/min) on the fabrication of aluminum matrix nanocomposites through friction stir processing of Al-Mg alloy sheets preloaded with TiO2 particles. This process induced the in-situ formation of MgO and Al3Ti nanophases with an average size of 50 nm. The inclusion of TiO2 particles expedited the grain refinement process within the aluminum matrix during friction stir processing. [21]

K Rajesh et al. (2014) examined the impact of tool travel speed (ranging from 20 to 60 mm/min) on 6 mm thick aluminum 6016 plates. They incorporated varying proportions of alumina and aluminum nitride powders, compacted within grooves on the aluminum plates. Utilizing a high carbon high chromium tool with a cylindrical pin featuring a threaded profile, the study explored FSP parameters including rotational speed, axial load, and tool travel speed. Optical micrographs revealed a well-bonded surface composite layer without interface defects, while also highlighting the refinement of the aluminum alloy's grain size through FSP. Interestingly, hybrid surface composites exhibited greater hardness compared to those fabricated using single ceramic particles, irrespective of the composition of the reinforcement material. [22]

A. Thangarasu et al. (2014) AA1050/TiC SMMC was fabricated using FSP. The fabricated AA1050/TiC composite layer was well-bonded to the aluminum substrate. TiC particles were distributed homogeneously in the FSP zone. The hardness of the FSP zone was increased by 45% higher than of the alloy. TiC particles enhanced the hardness of aluminum alloy. The average hardness of FSP zone is 45% higher as compare to base metal at 1200 rpm and 60 mm/min with axial force 10 KN. [23]

V. Yadav et al. (2014) studied the impact of reinforced particles on AL6082/Cu with a plate thickness of 6 mm was examined. The ultimate tensile strength (UTS) of the base metal decreased from 314 MPa to a range of 133-152 MPa after processing without a composite. Notably, samples processed using a cylindrical threaded tool profile exhibited a higher UTS of 152 MPa compared to 133 MPa for those processed with a square profile. When a copper composite was employed with the threaded cylindrical tool pin profile at 1000 rpm and 16 mm/min, the UTS reached 161 MPa, while it measured 156 MPa with a square profile tool and composite. Plates processed with a composite also showed improved hardness values (77 HRB - 84 HRB) compared to those without (64 HRB - 70 HRB). Additionally, specimens without a composite exhibited a higher percentage elongation (30.9%-33.4%) than those with a composite. The study suggests potential applications for Al-6082-Cu MMC in fields requiring high surface hardness, particularly for treating machine components prone to wear. Moreover, non-composite Friction Stir Processed Al-6082 shows versatility in automotive, aerospace, and metal forming sectors, albeit requiring careful selection of process parameters to avoid compromising tensile properties. [24]

C. Langlade et al. (2014) investigated the impact of transverse speed and tool rotational speed on the stirred layers of 316L steel produced through Friction Stir Processing (FSP). Utilizing parameters of 1000 rpm and 710 rpm for rotational speed, along with transverse speeds of 20 mm/min, 40 mm/min, and 56 mm/min, the study explored the attractive properties exhibited by nanostructure materials, particularly in mechanical applications where high hardness is desirable. FSP, a recent surface engineering technique derived from Friction Stir Welding (FSW), was evaluated on 316L austenitic stainless steel. The treated layers were assessed for hardness and microstructure, with findings correlated to FSP operational parameters, revealing an optimum hardness of 130 Hv at a transverse speed of 40 mm/min. [25]

H.S. Arora et al. (2014) investigated the control of length scale and distribution of the ductile phase in metallic glass composites using Friction Stir Processing (FSP). Their research showcased the refinement and uniform distribution of the crystalline dendritic phase through FSP in a titanium-based in situ ductile-phase reinforced metallic glass composite. The average dendrite size decreased by nearly fivefold, from 24 µm to 5 µm, at the highest tool rotational speed of 900 rpm. Interconnected dendrites became more fragmented with increased circularity post-processing. Changes in thermal characteristics were assessed using differential scanning calorimetry. FSP led to increased hardness and modulus in both the amorphous matrix and crystalline phase. The study elucidated the interaction of shear bonds in the amorphous matrix with the strain-hardened dendrite phase, proposing a novel microstructure design approach for metallic glass composites. [26]

3. Conclusions

The studies mentioned yield the following conclusions:

1. The mechanical properties and microstructure of materials undergoing friction stir processing (FSP) are notably influenced by various process parameters like rotational speed and travel speed.
2. Friction stir processing (FSP) has proven effective in improving mechanical characteristics like tensile strength, hardness, and resistance to wear across a range of materials, encompassing aluminum alloys, magnesium alloys, and steel.
3. Friction stir processing leads to grain refinement in treated material, resulting in improved mechanical properties because of more homogeneous microstructure.
4. Optimization of FSP parameters such as spindle speed, travel speed, and tool profile is crucial for achieving the desired mechanical properties also microstructure in the processed materials.

5. Friction stir processing method enables the creation of composite materials with enhanced properties by incorporating reinforcing particles such as SiC, TiO2, carbon nanotubes, and boron carbide into the matrix material.
6. Friction stir processing method can be efficiently used for surface modification of materials, leading to improved mechanical properties, wear resistance, and hardness of treated surface layer.
7. Friction stir processing technique offers the ability to control the microstructure of materials, including the distribution and size of reinforcing particles, dendritic phases, and grain sizes, leading to tailored material properties.
8. Friction stir processing holds significant potential for various applications, including aerospace, automotive, wear-resistant coatings, and the fabrication of advanced materials with improved mechanical properties.

Disclosures Statement

The author proclaims that there is no dispute on subject of publication of this paper.

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