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Surface Modification through Friction Stir Processing (FSP)

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Abstract

Friction stir processing has paved the way for the fabrication of surface composite in solid-state processing routes wherein desired properties are tailored up to a specified thickness. In the present investigation, surface composite is fabricated on AA5083 alloy using hybrid reinforcements (SiC-Fe-Mn-Sn) and the characteristics of the produced surface composites were explored using thermal analysis and mechanical tests such as micro-hardness and tensile analysis. To observe the distribution of reinforcement across the processed zone, a detailed microstructural examination was carried out. All these characteristics were assessed across all 18 samples but in the present investigation, one of the best results is discussed. Optical micrographs elegantly portray an array of meticulously processed zones, encompassing stir zone, the thermomechanically affected zone, heat-affected zone, and base material. Within these intricate zones, the grain size gracefully transitions from one distinct zone to another. Microhardness and tensile strength experienced a notable augmentation attributable to the refinement of grains and the fortifying influence of the Orowan mechanism while thermal behavior explained the temperature evolution during the process.

Keywords
Friction stir processing, Surface composites, Aluminum alloys, Microstructure, Mechanical properties.

1. Introduction
Aluminum alloys are widely used materials in various industries owing to their virtuous properties like high specific strength, excellent corrosion resistance, and ease with design (Dwivedi et al. 2021; Sharma et al. 2015) while they also possess poor wear properties. Hence, creating a metal matrix composite based on aluminum proves to be a superior choice to instill all the desired properties. Moreover, these metal matrix composites (MMCs) can be manufactured using methods involving both liquid and solid-state processing routes. Challenges related to liquid processing methods include the creation of harmful phases and undesired reactions between the reinforcement and matrix phases at elevated temperatures. To address this concern, a solid-state processing method known as friction stir process (FSP) is recommended for the production of surface composites (SC). SC's are gaining popularity through FSP since it has a powerful application to revolutionize various sectors like aerospace, marine and automobile and it has a newer grade

of MMC wherein excellent surface properties along with retained bulk material properties are present (Rathee et al., 2018a).

In FSP process, a tool with intentionally designed shoulder and pin is plunged into the baseplate and after the defined plunging action, the tool is traveled in the desired direction. As the tool touches the surface, the shoulder creates frictional heat which softens the material and it distributed around the pin. Thereafter material is consolidated behind the pin as a machined surface. The side where tool rotational direction and processing direction are the same is known as the advancing side (AS) and its vice versa is known as the retreating side (RS). Material experiences friction, extrusion and forging action during its travel from advancing side AS to RS as well as intense plastic deformation takes place while processing. FSP is mainly used in the fabrication of surface composites, modifying the local microstructure of the surface layer and grain refinement (Mishra and Ma 2005). While Friction Stir Process (FSP) offers numerous advantages, it does have certain drawbacks. For instance, the inhomogenous distribution of reinforcement particles can lead to a decline in the mechanical properties of the composites. Hence, the incorporation of metallic powder plus ceramic particles is used to assist in multiple aspects. Such as metallic powders with a low melting point can undergo melting at processing temperatures, facilitating homogenous particle distribution and enhancing the desired properties of SC.

2. Literature Review

In this experimental analysis metallic (Fe-Mn-Sn) and ceramic (SiC) reinforcement were used to enhance the multiple properties of the composite. Therefore literature related to these reinforcements were highlighted. SC was fabricated via FSP using SiC as reinforcement on aluminum alloy (AA5083) wherein good intermixing of particles with substrate having 50-200μm composite layer were found. Micro-hardness was double when increasing the amount of SiC (Mishra et al.2003). Effect of tool plunge depth on reinforcement (SiC) distribution during FSP was investigated and found that optimum plunge depth can give uniform distribution of reinforcement and hence mechanical properties. Low plunge depth causes less contact area between shoulder and workpiece which causes less heat generation results less material flow and cavity formation at the centre of SZ (Rathee et al., 2017).In investigated on AZ91/SiC composite by FSP route, uniform distribution of reinforcement was observed with enhanced mechanical properties (Asadi et al.2010). Effect of Fe particles on aluminum matrix with reverse in tool direction in every pass was studied and concluded that improvement in mechanical properties and better distribution of particle were observed using these particles (Eftekhari et al. 2017). Relationship among microstructure, mechanical behavior in Al-Fe_3O_4 nanocomposite processed by FSP was established (Khorrami et al., 2015).The idea behind using Mn powder and Sn powder was to increase the corrosion resistance of the processed material and to act as distributor facilitator during processing respectively. Addition of Mn in AZ91 alloy formed independent phase like Al_6Mn.Electrode potential of Mg can enhanced as this phase became solution in solid solution of Mg and hence improved the corrosion resistance of the alloy (Xiaoyan et al., 2014).Sn powder is employed as a phase change material that regulate the process temperature during the process as it absorbs the latent heat (Confalonieri et al. 2020). Furthermore many researches has been studied separately on these reinforcements but no research has been conducted on the collected response of these reinforcements. Therefore, the present study is an attempt to enhance the multiple properties of material which are not obtained by adding the single reinforcement.

3. Material and Methods

The SCs have been fabricated on AA5083 plate having a dimension of 200×80×6 mm with a chemical composition of Mg 4.59%,Mn 0.55%, Fe 0.294%,Si 0.129%,Zn 0.109%,Cu 0.068%,Cr 0.066% ,Ti 0.018% and Al 94.176% by weight. Metal powder (Fe-Sn-Mn) and ceramic powder (SiC) are filled as reinforcement in an appropriate proportion. The reinforcement was filled with the help of groove method wherein 2.5×2mm groove is cut in the center of the plate and a packing run was performed to avoid the spattering of reinforcement during processing. Retrofitted FSW machine was used to perform FSP. Present investigation shows the result of a single experiment as it is the typical presentation of overall result. Process parameters that were used in this experimentation was depicted in table 1.HSS material tool with cylindrical threaded profile pin was used for experimentation.

Samples are cutout from the processed plate for microstructural and mechanical analysis in transverse direction. Standard metallographic procedures are used for sample preparation. Modified poulten reagent is used to etch the sample for microstructural analysis. Micro-hardness was calculated on Vickers hardness machine at 1N load with a dwell time of 15 s. The K-type thermocouples are used for temperature measurements that are located at the centre line of the processed plate (three each at 2.5 mm center-to-center distance on AS and RS).For tensile test, specimens are cut from wire electric discharge machine along transverse direction as per ASTM E8M standard and this test was performed on computer controlled Tensometer with a crosshead speed of 2mm/min (Figure 1, Table 1).

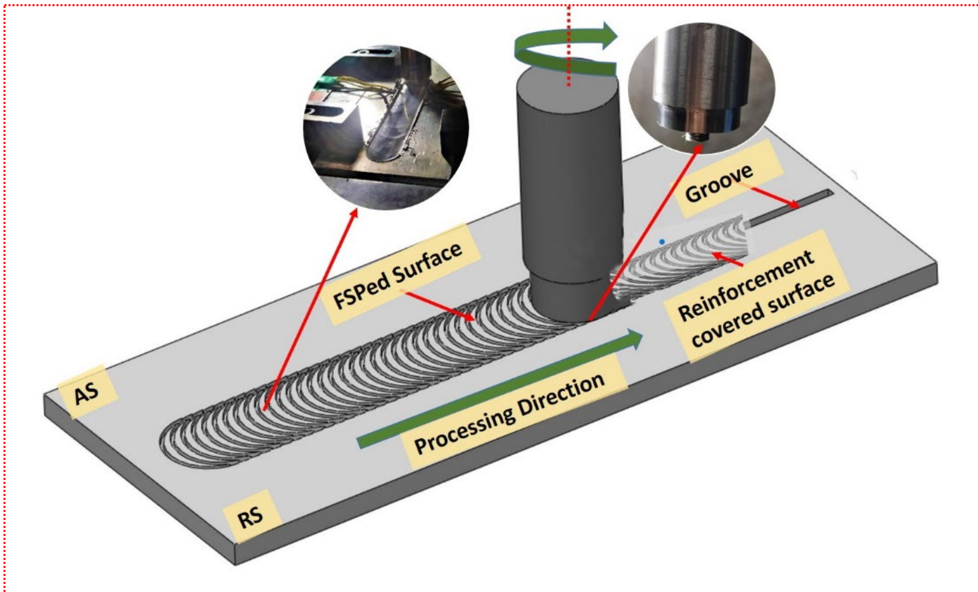

Figure 1. FSP Illustration

Table 1.Process parameter for FSP run

Process Parameter	Value
Tool Shoulder	21mm
Tool Rotational Speed	900rpm
Tool Traverse Speed	50mm/min
Tool Tilt Angle	2°
Pin Length	5mm
Pin Diameter	6mm

4. Results and Discussion

In this section macro and microstructural analysis, microhardness, thermal and tensile testing were done to examine the effect of process parameters on properties of FSPed material.

4.1. Macro and microstructure

Particle distribution plays a vital role for measuring mechanical properties. Figure 2 depicted the optical macro cum micrograph of fabricated SC. Figure 2(a) shows macrograph which has a basin shaped processed bead with a broad upper layer which is because of high frictional heat input due to shoulder contact with processed surface. Distinguishable regions, such as stir zone (SZ), shoulder affected stir zone (SASZ), pin affected stir zone (PASZ), thermos-mechanically affected zone (TMAZ), heat affected zone (HAZ),base material (BM) in AS and RS can be seen. In HAZ, grain are coarse as this zone only experiences heat cycle without any plastic deformation and dynamic recrystallization (Dwivedi et al.2022) .Whereas TMAZ grains are elongated in an upward direction around SZ due to plastic deformation and partial recrystallization. SZ consists of equiaxed, fine and recrystallized grains because of dynamic recrystallization that indicates significant grain refinement as comparison to base material. Furthermore, the stirring actions by shoulder and pin also result in the formation of subzones in SZ, namely, SASZ and PASZ. The thickness of the SASZ is varying from AS to RS because of the material flow. Due to thermal gradient and change in stirring action, the grain size reduces from SASZ to PASZ. SASZ has the smallest grains, as the stirring rate is higher due to higher tangential velocity away from the centre of shoulder (Khan et al., 2015). Figure 2 shows the SEM micrograph of SZ wherein reinforcements are uniformly distributed (Gangil et al. 2018b).

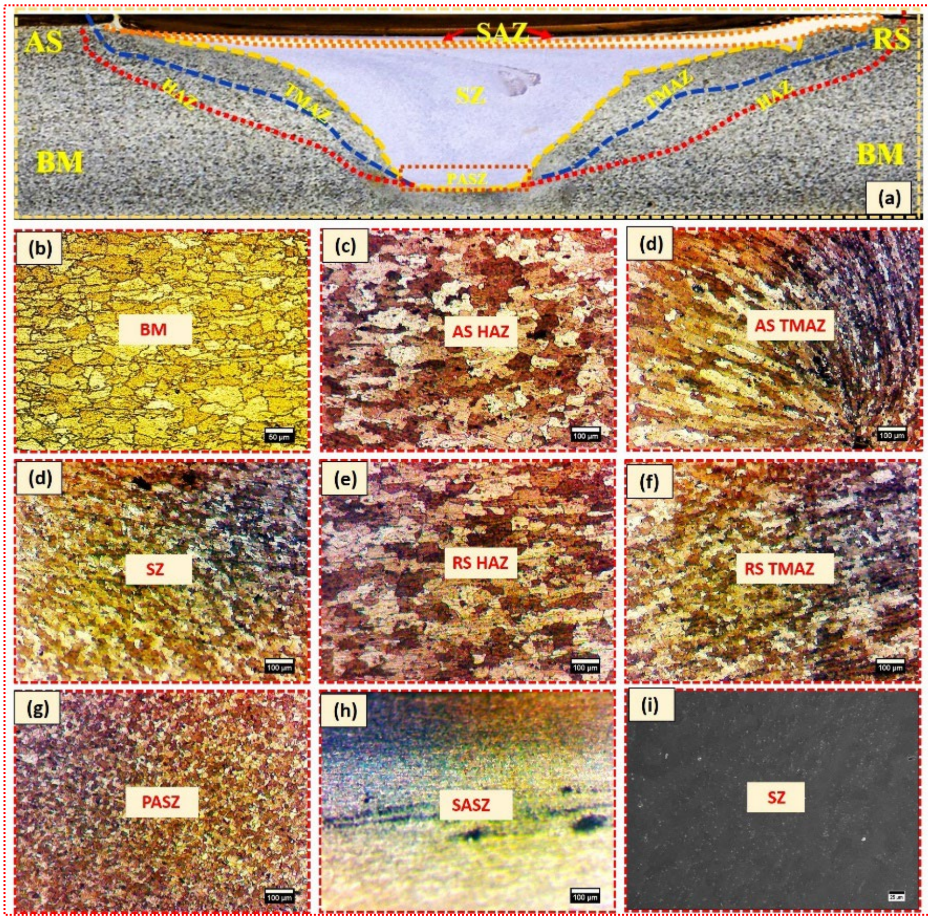

Figure 2. Detailed macro cum microstructure of processed plate

4.2. Micro-hardness Measurement

Micro hardness testing was performed along the width of the processed sample at 0.5 mm equidistant point which is illustrated in Figure 3. The maximum micro-hardness of the processed sample is achieved as 102 HV at AS. Variation in the micro-hardness throughout the processed zone has been observed owing to distribution of reinforcement. Increase in hardness is achieved due to two mechanisms namely by grain refinement in stir zone and by orowan strengthening. As grain refined, number of grain boundary increases which hinder the dislocation motion. Higher hardness in AS may be attributed to the fact that the material on this side of the processed zone is picked-up and rotates around the pin, undergoes extrusion and subsequently forged behind the tool. The materials on AS and RS sides get transported from ahead of the tool and deposited on the similar locations behind the tool. Thus, the material on the AS undergoes greater deformations (Gangil et al., 2018a,Rathee et al., 2018b) (Figure 3).

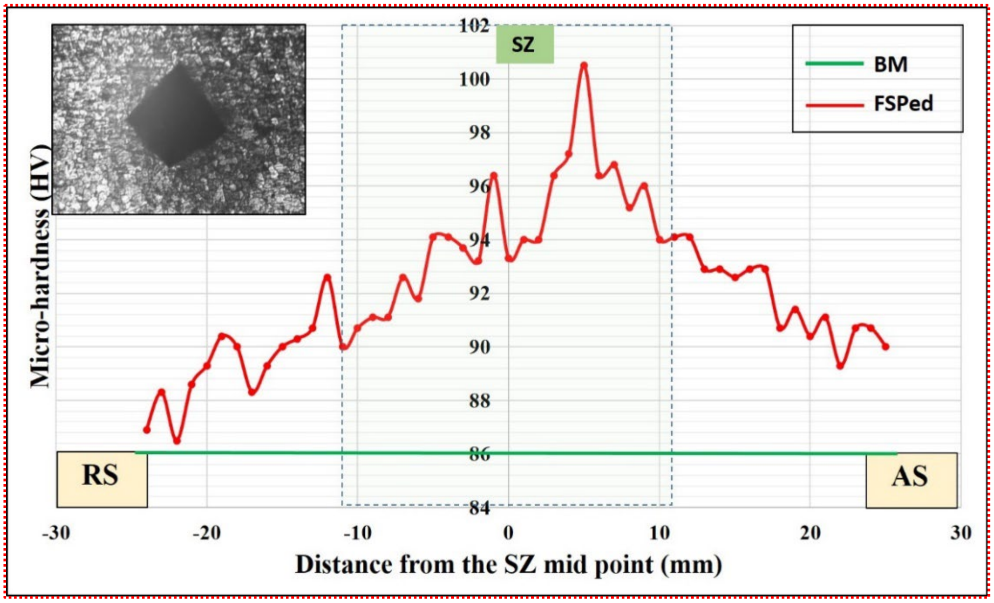

Figure 3. Microhardness distribution of processed plate

4.3. Thermal Analysis

Temperature evolution during FSP is a crucial phenomenon as it governs the material flow during processing.The temperature-time plot shows the thermocouple temperature response over time for the whole FSP run in Figure 4. Initially curve is slowly rising in dwell condition owing to preheating of processed material for proper mixing. Afterthat curve became steep and reached its maximum value. It is observed from the thermocouple data that the highest temperature i.e. 419°C was achieved at the AS as deformation starts from here and it involves lots of heat generation. Slope drops gradually after the maximum temperature due to gradual cooling (Dwivedi et al., 2022) (Figure 4).

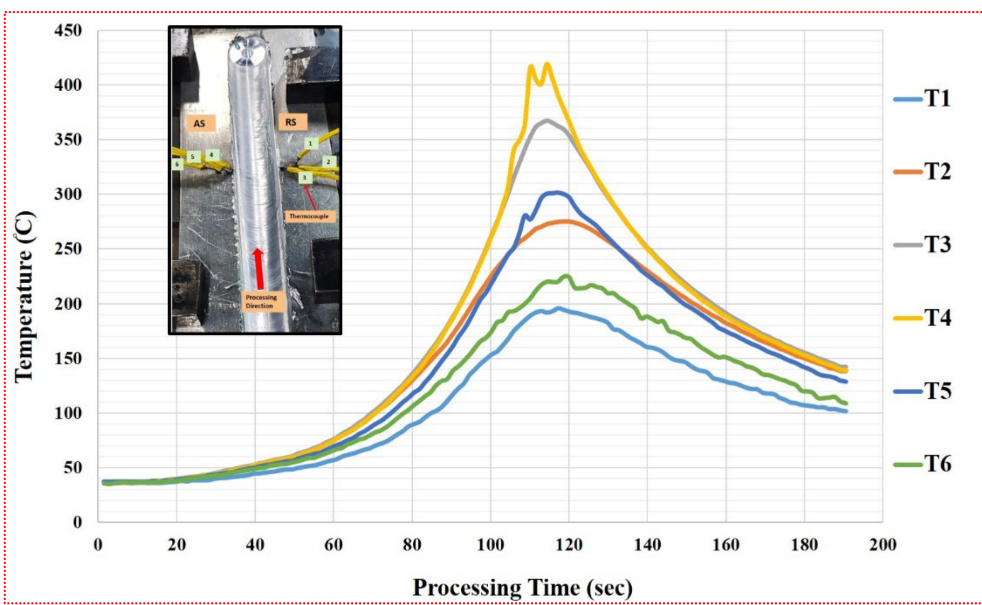

Figure 4. Temperature profile

3.4 Tensile Strength

It is worthwhile to mention that hardness and strength are closely related to each other therefore, reasons of increment in hardness and strength are similar. Figure 5 depicts the comparison of UTS in BM and FSPed sample. In FSPed sample, strengthening occurs due to various mechanisms such as grain size strengthening through Hall Petch effect, solid solution strengthening and strain hardening. Further, as the composite is a mixture of two or more immiscible phases depending on the composition of reinforcement. The rule of mixture-based strengthening is a factor in case of composites (Dwivedi et al.2023) (Figure 5).

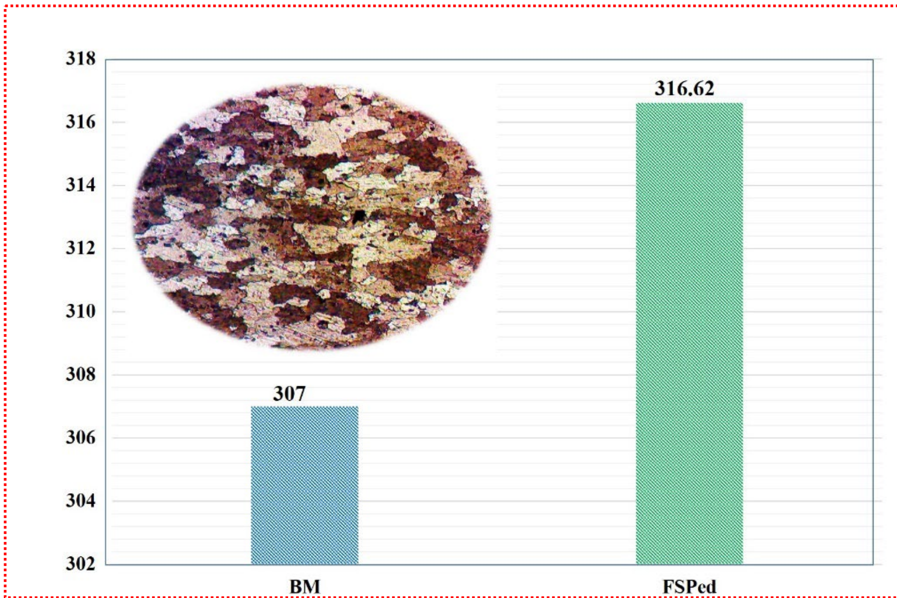

Figure 5.UTS of BM and FSPed sample

5. Conclusion

Surface composite Al5083/ (Sic-Fe-Mn-Sn) was fabricated through FSP using the given process parameters. Detailed macro and microstructural study, micro-hardness measurement, thermal analysis and tensile testing were investigated. Notable conclusions are mentioned below:

- Fine and recrystallized grains are found in SZ due to dynamic recrystallization process. Grain structures are varying from SZ to BM.
- Increase in hardness is achieved due to two mechanisms namely by grain refinement in stir zone and by orowan strengthening.
- Maximum temperature was recorded during processing was 419℃ in AS as flow and deformation starts from this side which generated lots of heat. Tensile strength of the FSPed sample was increased from base material because of grain refinement and adding of reinforcement particles.

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Biographies

Pooja Dwivedi has completed her Ph.D from the division of Manufacturing Processes and Automation Engineering at Netaji Subhas Institute of Technology, New Delhi, India in august 2023. Her PhD work is in the field of fabrication of surface composite through friction stir processing. Her fields of research are friction stir welding/processing, microstructural and mechanical characterization and optimization. She has published some papers in reputed international journals and refereed conferences and also reviewed some papers of reputed journals.

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Dr. Qutubuddin S.M. is presently working as Associate Professor, Industrial and Production Engineering Department, P.D.A.College of Engineering, Gulbarga. He has more than 28 years' experience in teaching and research and has published more than 35 papers in International and National journals and Conferences. He has introduced the course Human Factors and Ergonomics in the curriculum in under graduate engineering and has developed laboratories such as Industrial Engineering Laboratory and Ergonomics Laboratory. He is a life member of professional societies such as ISTE, IIPE, IAENG, and ISE. He is a regular member of various committees' of IEOM Society conferences and continuously involved in promoting the activities of IEOM Society. He has established a IEOM Society student Chapter at PDA College of Engineering. Research interest include Industrial Ergonomics; Human Factors; Occupational Health and Safety; Productivity Improvement Studies; Production/Operations Management; Environmental Ergonomics.