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# Formation of Surface Metal Matrix Composites with Reinforcement Particles in Aluminium Alloys by FSP-A Review

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**Abstract:**

Friction Stir Processing (FSP) is an advanced solid-state technique developed to enhance surface properties of aluminium alloys by in-situ surface metal matrix composites (SMMCs) through the incorporation of reinforcement particles into the substrate material. In contrast to FSP, conventional techniques like powder metallurgy and surface coatings often suffer from inherent limitations, including porosity and non-uniform distribution or segregation of reinforcement particles within the metal matrix, which can compromise the mechanical and functional properties of the final composite. Different type of ceramic reinforcement particles like $TiO_2$ (titanium oxide), SiC(Silicon carbide), $Al_2O_3$(aluminium oxide), and $B_4C$(boron carbide) may be used to form SMMC's of aluminium alloys. The incorporation of reinforcement particles through FSP has proven to be an effective method for enhancing the surface properties of metallic materials. These reinforcement particles are introduced into the stirred zone, where intense plastic deformation and dynamic recrystallization occur. This results in a refined grain structure and a uniform dispersion of particles within the alloy's surface layer. As a result, significant improvements are observed in surface hardness, wear resistance, and corrosion resistance of soft aluminium alloys. The solid-state nature of FSP eliminates common defects associated with fusion-based methods, such as porosity or interfacial reactions between the matrix and reinforcement. These improvements make FSP an attractive technique for developing surface metal matrix composites (SMMCs) tailored for demanding applications in aerospace, automotive, and marine industries.

***Keywords:*** *FSP, Metal Matrix Composites, Surface Properties*

## 1. Introduction

Aluminium (Al) and its alloys are widely used in automotive applications due to their high strength-to-weight ratio, good thermal conductivity, and excellent corrosion resistance. However, their major limitation is low surface properties like wear resistance and strength (Singh J., 2016). Surface Metal Matrix Composites (SMMCs) are of soft lightweight alloys increasingly utilized in modern engineering applications, representing an advanced class of materials that integrate metallic matrices with ceramic reinforcements. These basically constitute soft metallic materials like aluminium and magnesium infused with reinforcement particles of small sizes, micro or nano, for enhancing properties at the surface only (Sunil B.R., et al., 2016). The particles may be of glass, natural/synthetic fibres, ceramics, fly ash, bio-compatible hydroxyapatite(HA) etc. Nowadays, ceramics are in great use due to their certain properties and applications. Ceramic materials exhibit exceptional hardness, superior thermal and electrical insulating properties, high compressive strength, and outstanding chemical as well as thermal stability. $Al_2O_3$, SiC, $TiO_2$ and $B_4C$ are key ceramic reinforcements commonly employed in the fabrication of surface composites through friction stir processing. (Raju and Kumar, 2014). The primary limitation of ceramic materials lies in their inherently low tensile strength and fracture toughness, which restricts their applicability in bulk structural forms. However, when incorporated in powder form into metallic matrices, these ceramics serve as reinforcements to significantly enhance the mechanical properties of the base metals. The matrix, typically metallic in nature, embedded with ceramic reinforcement particles, forms a composite material that enhances the mechanical performance of the base metal (Das, et al., 2014). MMCs formed by FSP improves wear resistance, hardness, and tensile strength (Balakrishnan M. et al., 2015).

Friction Stir Processing (FSP) was developed as an extension of Friction Stir Welding (FSW) by The Welding Institute (TWI) in the UK in the late 1990s (R.S. Mishra and Z.Y. Ma, 2005).

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While FSW was primarily designed for joining materials in the solid state, FSP was introduced as a surface modification technique aimed at altering the microstructure and improving surface properties without melting the base material and was first used on aluminium alloy by Mishra et al.(Mishra et al., 2003). FSP utilizes a non-consumable rotating tool that plunges into the material and generates localized heat through friction and plastic deformation. This leads to dynamic recrystallization and grain refinement in the processed zone (Chang, et al., 2011). Over the years, FSP has evolved to enable the fabrication of Surface Metal Matrix Composites (SMMCs) by incorporating ceramic reinforcement particles into the substrate, significantly enhancing hardness, wear resistance, and corrosion performance. The process has found growing interest in aerospace, automotive, marine, and defense industries due to its ability to locally tailor material properties with minimal distortion and without the need for post-processing.

The processing of lightweight Non-ferrous alloys with FSP leads to a change in Microstructure without disturbing much of the metallurgy of the base material. There is a wide application of non-ferrous materials like aluminum and magnesium alloys in bridges, highway structures, frames and seat racks of automobiles, hull materials of ships, exterior panels of trains, pressure vessels and pipelines in the petroleum industry.

FSP emerged as a promising technique to improve surface properties and also make surface metal matrix composites (SMMCs) in comparison to conventional surface improvement techniques (Sharma et al., 2015). FSP technique can be used with single pass or multi pass and with embedment of strengthening particles such as SiC, $Al_2O_3$, etc (Sahraeinejad et al., 2015). As these reinforcement particles improve their surface properties, they refine the grains and thus improve mechanical properties.

Mazaheri et al. (2011) developed the A356/Al2O3 surface nano composite by FSP. In this A356-T6 alloy was taken as the substrate. A356 chips, micro $Al_2O_3$ and nano $Al_2O_3$ powder particles were deposited individually and duo by High Velocity Oxy Fuel spraying. After successful coating of A356 and $Al_2O_3$ particles on substrate friction stir processing was done. A thorough analysis was done by the authors for base alloy, coated alloy and FSPed alloy. It was found that the FSP with $Al_2O_3$ particles increased the microhardness of substrate in comparison with FSP without $Al_2O_3$ particles. The results obtained by nanoindentation technique showed better microhardness and elastic modulus. The better mechanical properties of A356/$Al_2O_3$ surface nanocomposite attributed to the presence of nanosized $Al_2O_3$ particles.

Lee et al. (2011) studied the particle-reinforced aluminium matrix composites produced from powder mixtures via FSP. Sintered billets was formed with 10, 20, 30 % of Si in Al. FSP with selected parameters was carried out with two to four passes of tool as four passes completely eliminates porosity in billet and refines the microstructure. After multiple passes of FSP it had been found by the authors that the composites are characterized by fine microstructure in which the Si particles are uniformally dispersed in the aluminium matrix which has a fine-grained structure ~2µm. Significant refinement of Si particles from the original size of 40µm to an average of 1.5µm has been achieved by FSP. All the Al-Si composites show compressive yield strength higher than the tensile strength and the strength difference increases with the Si content. It indicates that the strength of the composites results from the strengthening due to the substructure in the matrix.

Zhang et al. (2012) studied the reactive mechanism and mechanical properties of in situ composites fabricated from an Al-$TiO_2$ system by FSP. In situ $Al_3Ti$+$Al_2O_3$/Al composites were fabricated from powder mixtures of Al and $TiO_2$ using hot pressing, forging and subsequent multiple pass FSP. Four pass FSP was done to obtain defect free microstructure. During FSP Al-$TiO_3$ reaction produced $Al_2O_3$ and Ti atoms then $Al_3Ti$ precipitated from the Al matrix when Ti was supersaturated in Al decreasing the size of $TiO_2$ from 450 to 150 nm resulted in the formation of more $Al_3Ti$ and α- $Al_2O_3$ .The formation mechanisms of $Al_2O_3$ and $Al_3Ti$ are considered to be deformation assisted interfacial reaction and deformation assisted solution precipitation, respectively. The microhardness, young's modulus and tensile strength of the FSPed composites are substantially enhanced compared with those of FSPed pure al and increased with a decrease in the $TiO_2$ size from 450 to 150 nm.

Aruri et al. (2013) studied the wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites (SiC+Gr) and (Si+$Al_2O_3$)

fabricated by FSP at different tool rotation speed. The average size of reinforced particles kept as 20µm. It was reported by the authors that with the increase in tool rotation speed microhardness decreases due to high heat generation that causes matrix softening as this softening resulted in coarsening and dissolution of strengthening precipitates in the aluminum matrix which occurs especially in heat treatable aluminum alloys. The wear rate increases with tool rotation speed. Also the wear rate increases in the Al-SiC/$Al_2O_3$ surface composites compared to Al-SiC/Gr surface hybrid composites. The presence of SiC and $Al_2O_3$ particles increases the wear rate due to pulled out of hard SiC particles from the composite pin during the wear process. These particles formed on steel disc which acts as a barrier and further converts the adhesive wear to abrasive wear, resulting in greater amount of material worn out from the composite pin. The presence of Sic particles serves as load bearing elements and Gr particles acted as solid lubricant. Tensile properties are decreased as compared to the base material due to presence of reinforcement particles which make the matrix brittle.

You et al. (2013) studied In-situ formation of $Al_2O_3$ nanoparticles during friction stir processing of Al-$SiO_2$ composite. A billet of Al-$SiO_2$ was prepared using conventional pressing and sintering route. A set of processing parameters like tool rotation speed (500-2000 rpm) and traverse speed (15-90 mm/min) were used to carry out friction stir processing. The rotating tool in FSP fragmented both Al and $SiO_2$ which increased the contact area between them and promoted the reaction. Alumina exists in a number of metastable transition phases as well as the thermodynamically stable α- phase. The different amount of heat generated during processing at different parameters responsible for the reaction between Al-$SiO_2$ composite. Quantitative phase analysis indicated that the extent of the Al-$SiO_2$ reaction increased in conjunction with an increasing tool rotation rate and a decreasing tool traverse speed in FSP. With the processing condition 500-15-4 the composite produced possesses enhanced tensile modulus and tensile strength as well as a tensile ductility of approximately 13%. The major contributions to the high composite strength are the ultra fine grained structure of the aluminum matrix.

## 2. Materials and Methods

### 2.1 Substrate Materials

The substrate material studied in this review are non–ferrous alloys like aluminum alloys and magnesium alloys.

### 2.2 Reinforcement particles

Ceramic particles like $Al_2O_3$, SiC, $TiO_2$ etc may be used. The particle size also plays an important role in surface properties. Different particle sizes may be used for desired surface properties.

### 2.3 Processing Parameters

Processing parameters play very important role in microstructure evolution and mechanical properties. These parameters are responsible for heat generation and fragmenting of coarse grains into finer grains. Heat generation during FSP is mainly due to the friction between tool and workpiece and intense plastic deformation around rotating tool pin (Cartigueyen et al., 2014). The heat generation during FSP strongly depends on rotational and traverse speed, where the peak temperature depends upon tool rotation speed and heat depends upon traverse speed (Barmouz et al., 2011). l Generally processing parameters taken are as following.

**Table1 Friction Stir Processing parameters**

| | |
|---|---|
| Tool Rotation Speed | 800-1600 rpm |
| Traverse speed | 40-120 mm/min |
| Shoulder Diameter | 16-20 mm |
| Pin Diameter | 3-6mm |
| Pin Length | 2.5-4 mm |
| Tilt angle | $2^0$-$5^0$ |

## 3. Lacuna

Non-ferrous alloys like aluminum and magnesium alloys are widely used these days due to their high strength to weight ratio, good castability and corrosion resistance etc. There is wide application of aluminum and magnesium alloys in bridges, highway structures, frames and seat racks of automobiles, hull materials of ships, exterior panels of trains, pressure vessels and pipelines in petroleum industry. The surface modification of these alloys to attain the desirable properties is becoming a challenging task these days. Improving surface properties by various ways with the application of FSP is reported by various authors as discussed in the literature survey. FSP emerged as promising technique to improve surface properties and also making of metal matrix composites (MMCs) in comparison to conventional surface improvement techniques. Some researchers had used direct FSP technique with single pass or multi pass and few had invented it with addition of strengthening particles such as SiC, $Al_2O_3$, Gr (Lee et al., 2011, Mazaheri et al., 2011). As these reinforced particles improves their surface properties, refines the grains and thus improving mechanical properties (Huang et al., 2018). Still there is lot of scope to fabricate and characterize the MMC of Al and Mg alloys using various reinforced powder particles to institute the outcomes without disquieting substrate.

## Conclusions

Surface metal matrix composites of friction stir processed aluminum alloys with reinforcement particles may show the following characteristics:

- Higher wear resistance, high hardness, and strength.
- Uniform and dense microstructure compared to base alloys.
- These improved surface properties are due to the addition of ceramic particles and the formation of Al/Ceramic Metal matrix composites. The formation of surface composites by friction stir processing method attracts a lot of attention, as by this method only surface properties are improved, retaining properties of the base material.

## References


[1] Guoqiang Huang, Jie Wu, Wentao Hou, Yifu Shen, 2018, Microstructure, mechanical properties and strengthening mechanism of titanium particle reinforced aluminum matrix composites produced by submerged friction stir processing, Materials Science and Engineering: A, 734, 353-363.

[2] Singh, J. 2016, Fabrication characteristics and tribological behavior of Al/SiC/Gr hybrid aluminum matrix composites: A review. Friction, 4, 191–207.

[3] B. Ratna Sunil, G. Pradeep Kumar Reddy, Hemendra Patle, Ravikumar Dumpala. 2016, Magnesium based surface metal matrix composites by friction stir processing, Journal of Magnesium and Alloys, 4(1)52-61.

[4] M. Balakrishnan, I. Dinaharan, R. Palanivel, R. Sivaprakasam. 2015, Synthesize of AZ31/TiC magnesium matrix composites using friction stir processing, Journal of Magnesium and Alloys, 3(1), Pages 76-78.

[5] Vipin Sharma, Ujjwal Prakash, B.V. Manoj Kumar. 2015, Surface composites by friction stir processing: A review, Journal of Materials Processing Technology, 224, 117-134.

[6] S. Sahraeinejad, H. Izadi, M. Haghshenas, A.P. Gerlich, 2015. Fabrication of metal matrix composites by friction stir processing with different Particles and processing parameters, Materials Science and Engineering: A, 626, 505-513.

[7] S.Cartigueyena, O.P.Sukeshb, K.Mahadevanc. 2014, Numerical and Experimental Investigations of Heat Generation during Friction Stir Processing of Copper, Procedia Engineering, 97,1069 – 1078.

[8] Das, D.K., Mishra, P.C., Singh, S. et al. 2014, Properties of ceramic-reinforced aluminium matrix composites - a review. International Journal of Mechanical and Materials Engineering, 9(12).

[9] L. Suvarna Raju, A. Kumar. 2014, Influence of $Al_2O_3$ particles on the microstructure and mechanical properties of copper surface composites fabricated by friction stir processing, Defence Technology, 10(4), 375-383.

[10] Devaraju Aruri, Kumar Adepu, Kumaraswamy Adepu, Kotiveerachari Bazavada. 2013, Wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites

[(SiC+Gr) and (SiC+Al2O3)] fabricated by friction stir processing, Journal of Materials Research and Technology, 2(4), 362-369.

[11] G.L. You, N.J. Ho, P.W. Kao. 2013, In-situ formation of $Al_2O_3$ nanoparticles during friction stir processing of AlSiO2 composite, Materials Characterization, 80, 1-8.

[12] Q. Zhang, B.L. Xiao, W.G. Wang, Z.Y. Ma. 2012, Reactive mechanism and mechanical properties of in situ composites fabricated from an Al–$TiO_2$ system by friction stir processing, Acta Materialia, 60(20), 7090-7103.

[13] Zhang, Y. N., Cao, X., Larose, S., & Wanjara, P. 2012, Review of tools for friction stir welding and processing. Canadian Metallurgical Quarterly, 51(3), 250–261.

[14] Woong-Seong Chang, S.R. Rajesh, Chang-Keun Chun, Heung-Ju Kim. 2011, Microstructure and Mechanical Properties of Hybrid Laser-Friction Stir Welding between AA6061-T6 Al Alloy and AZ31 Mg Alloy, Journal of Materials Science & Technology, 27(3),199-204.

[15] Y. Mazaheri, F. Karimzadeh, M.H. Enayati. 2011, A novel technique for development of A356/Al2O3 surface nanocomposite by friction stir processing, Journal of Materials Processing Technology, 211(10), 1614-1619.

[16] I.S. Lee, C.J. Hsu, C.F. Chen, N.J. Ho, P.W. Kao. 2011, Particle-reinforced aluminum matrix composites produced from powder mixtures via friction stir processing, Composites Science and Technology, 71(5), 693-698.

[17] M. Barmouz, P. Asadi, M.K. Besharati Givi, M. Taherishargh. 2011 Investigation of mechanical properties of Cu/SiC composite fabricated by FSP: Effect of SiC particles' size and volume fraction, Materials Science and Engineering: A, 528(3), 1740-1749.

[18] R.S. Mishra, Z.Y. Ma. 2005, Friction stir welding and processing, Materials Science and Engineering: R: Reports, 50(1–2), 1-78.

[19] R.S. Mishra, Z.Y. Ma, I Charit. 2003, Friction stir processing: a novel technique for fabrication of surface composite, Materials Science and Engineering: A, 341(1–2), 307-310.