Friction Stir Processing of Magnesium Alloys- Review

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ABSTRACT

Recently, Friction stir processing (FSP) is one of the solid state surface processing techniques used to produce surface composites. The FSP which doesn't affects the bulk properties of the material but improves the surface properties of the material concern such as hardness, strength, ductility, corrosion resistance and formability etc. Magnesium alloy is one among the major raw materials used due to their low density and high strength-to-weight ratio. Alloys of magnesium are processed successful by FSP which are difficult by other processes. The review offers better understanding of Friction Stir Processed alloys of Magnesium. This article reviews the various mechanical and metallurgical properties along with analysis of microstructure on different magnesium alloys and FSP magnesium alloys for better understandings.

KE YWORDS: Magnesium Alloys, Friction Stir Processing (FSP), Scanning Electron Microscope (SEM), Mechanical properties, Microstructure, Hardness, Wear properties.

1. INTRODUCTION

Magnesium alloys: Magnesium with mixture of other metals is called as magnesium alloys. The major alloying elements are aluminium, zinc, manganese, silicon, copper, rare earths and zirconium. Magnesium alloys have a hexagonal lattice structure and is the lightest structural metal Cast alloys of magnesium are used in components of automobiles, bodies of camera and lenses. Heat treatment is used to harden alloys of magnesium containing 0.5% to 3% zinc. Sand castings mostly use alloys AZ92 and AZ63, die castings use AZ91 magnesium alloy and permanent mold castings generally use AZ92 alloy. Alphabets represent major alloying elements, for instance A represents Aluminium, Z represents Zinc, M represents Manganese, S represents Silicon and so on. For example AZ91 represents alloy of magnesium with 9 weight % of aluminium and 1 weight % of zinc.

Friction Stir Processing: Friction stir processing (FSP) is the recent available techniques for fabricating surface composites and modifying its micro structural features (Mishra, 2003; Ni, 2014). Friction Stir Processing (FSP) was introduced as an adaptation technique from Friction Stir Welding (FSW) by UK Mishra in 1991. FSP was first used to produce high grain boundary orientations and ultrafine grain super plastic aluminum alloys (Mishra 1999; Ma, 2008). Friction Stir Processing is a solid state welding process which modifies the microstructure of welds due to the compressive force contact of work pieces which are either rotating or moving relative to one another (Advanced Welding Processes Lecture:4). In friction processing the heat required to produce the process is generated by friction heating at the interface. The tool is mounted in a chuck driven by a motor which is rotated in high speed against the work piece which is mounted stationary. A low contact pressure may be applied initially to permit cleaning of the surfaces by a burnishing action. This pressure is increased and contacting friction generates heat to raise the surfaces to the welding temperature. Friction Stir Process can improve properties such as strength, hardness, corrosion resistance, ductility and formability without affecting the bulk properties of the material.

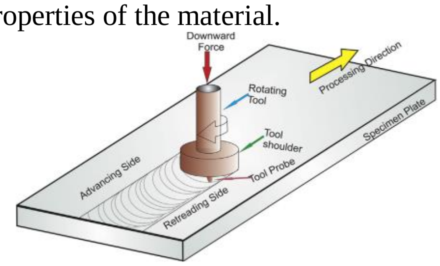

Figure.1. Schematic illustration of FSP (Vipin Sharma, 2015)

2. MECHANICAL PROPERTIES

Hardness: Hardness of a material has many definitions but according to materials handbook it can be defined as the Resistance of material to plastic deformation, usually by indentation. The ability of the material to resist permanent deformation like bend, change of shape or breakage when certain loads are applied is called as hardness of the material. The greater the resistance of a material to deformation is equivalent to its hardness. The processing parameters are very sensitive to hardness of the processed sheets (Darras, 2007). By different combinations of translational speeds and rotational speeds, higher hardness values can be achieved than the original hardness of the material. It is important to couple the microstructure results with temperature measurements (Darras, 2007). There will be increase in hardness when the temperature decreases from the surface to the bottom of sheet. The grain growth and softening are due to higher temperature. This result is supported by the smaller grain size at the bottom of the processed zone which was observed by Sutton (2002). In Asadi (2010), investigation, in cast AZ91 magnesium alloy, SiC particles are added and nano grained structure of AZ91/SiC surface nano composite layer was produced through Friction Sir Processing. As the rotational speed increases the grain size of the layer also increases with the decreases in micro hardness of the layer (Asadi, 2010). In addition, increasing Friction Stir Process pass numbers will lead to better distribution of Silicon Carbide particles in the AZ91 matrix resulting in higher hardness and refined grains. Changing the direction of rotation of the tool result in higher distribution of SiC particles uniformly (Asadi, 2010).

Arora (2012) have done Micro hardness testing at bulk hardness at 5 kgf load and 50 gf load. The bar chart shows the average micro hardness as well as average bulk hardness values of all the investigated cases (Figure.2). It can be observed from this figure that bulk hardness as well as micro hardness got enhanced after Friction Stir Processing (Arora, 2012).

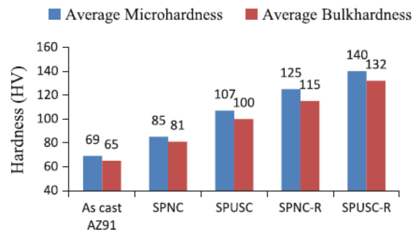

Figure.2. Bar chart showing average micro hardness and bulk hardness (Arora, 2012)

Parviz Asadi (2010), studied and proved that the microhardness was increased in the Stir Zone because of (a) Severe grain refinement during dynamic recrystallization, (b) The SiC particles which are the harder phase and were distributed ordery in the magnesium matrix and made a particle reinforced composite and (c) Quench hardening resulted from the dislocations has made a differential thermal contraction between the reinforcing particles and the matrix. The decrease in grain size is due to increase in the traverse speed. So, the hardness of the Stir Zone increases according to Hall-Petch relationship (Parviz Asadi, 2010).

Abbasi (2015), observed that by increasing the number of passes, the grains size decreases and there will be improvement in distribution of second-phase particles and due to that the hardness value increases. Increase in hardness represents an increase in the ability of material to resist the deformation (Callister, 2007). The smaller size of grains and second-phase particles result in higher hardness values (Callister, 2007; Ma, 2008). The average micro hardness of the as-cast alloy can be observed to be 62.5 HV which got increased after Friction Stir Processing (Arora, 2013). FSP has resulted in uniform enhancement through the depth of the specimen as revealed by slight variation in the microhardness value with increase in distance from the top surface (Arora, 2013). Grain boundary strengthening in relation with Hall-Petch equation is believed to be the major phenomenon that contributed towards enhanced hardness of the Friction Stir Processed alloy (Arora, 2013).

Ganta Venkateswarlu (2014), studied the relationship between the hardness in the grain size and stirred zone. Increase in rotation speed resulted in decrease in the impact energy and is higher for lower rotational speed. The micro hardness values at the region away from the nugget zone are found to be nearly same to the parent material hardness. This is due to the thermal exposure in thermo-mechanical affected zone (TMAZ) and insufficient deformation on advancing side (AS) and retreating side (RS) side. This tendency suggests that the increase of hardness is mainly because of the grain refinement. Tool rotational speed has the highest influence on variation of hardness of the material (Ganta Venkateswarlu, 2014).

Asadi (2006), studied Micro hardness profile of the specimen produced by one Friction Stir Process pass at the rotational speeds and traverse speeds of 900rpm and 63mm/min respectively. Because of the very fine grains of SiC particles and high hardness, the hardness of Stir Zone increases. The micro hardness of the layer decreases with increase in rotational speed and the grain size increases with increase in rotational speed. As the traverse speed increase the grain size decreases whereas there will be increase in the micro hardness of the layer (Asadi, 2006). Increasing the number of passes, as grains size decreases and the distribution of second-phase particles improves, the hardness value increases (Abbasi, 2014).

Wear Studies: Arora (2013), examined wear behavior of Magnesium AE42 alloy under as-cast and FSPed conditions. Wear tests were performed in pin on disc setup using Universal Tribometer. The load range was varied from 5N to 20 N and sliding velocity from 0.33 to 3 m/s. During low load conditions, wear mechanism were found to be changed from abrasive and oxidation wear at low sliding velocity to delamination of composite at high sliding velocity. At intermediate loads, abrasion and oxidation characterized the worn surface at low velocity, and plastic deformation and delamination were found to be major wear mechanisms at high velocities. At high loads, severe plastic deformation and delamination were observed at high velocities, whereas delamination, plastic deformation and abrasion were observed at low velocity. It was found that maximum wear rate occurred at highest load and lowest velocity. Additionally, the wear rate was found to decrease with decrease in load and increase in sliding velocity.

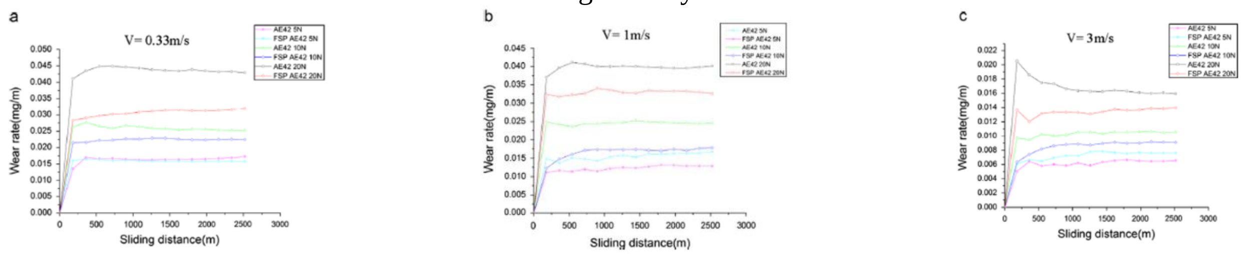

Figure.3. Wear rate plots for as-cast as well as FSPed AE42 alloy at (a) 0.3 m/s sliding velocity, (b) 1 m/s sliding velocity and (c) 3 m/s sliding velocity and different normal loads (Arora, 2013)

Abbasi (2014) studied, "The effect of FSP tribological behavior of composite layer developed on magnesium AZ91 alloy surface". Wear rate of base metal is greater than other samples, and as pass number increased the wear rate decreased. The distribution of nanoparticles in surface became homogenized as the pass number increases. Based on Archad relation, hardness increases when wear rate decreases. Increase of pass number up to four passes modified the microstructure property and with respect to that the tribological behavior and mechanical properties enhance and corrosion resistance increases.

Specific wear of alloys tends to increase with increasing friction load and difference of specific wear values between the materials was obtained (Dai Nakama, 2008 &Huang, 2006). Although Friction Stir Process in different conditions changes the mechanical properties of the AZ91 alloy (Asadi, 2012).

The higher hardness of the Friction Stir Processed specimens with SiC and Al2O3 particles will lead to higher wear rates (Asadi, 2011).

3. MICROSTRUCTURAL RESULTS

Friction stir processing is done for AZ31 magnesium alloy (Darras, 2007). The micro structural results were obtained using optical microscope showed grain refinement, additionally, Friction Stir Process produced more homogenous microstructure. Fig. 4 shows the grain structure of the base material and Friction Stir Processed samples at 1200 rpm rotational speed and 22 and 25 in./min translational speeds, respectively. The distribution of grain size is evidently changed which indicates equiaxed homogeneous structure and increase in refinement.

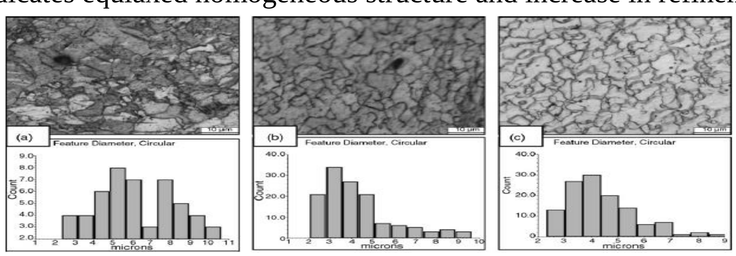

Figure.4. Microstructure of (a) as-received, (b) FS processed sample at 1200 rpm and 22 in/min, and (c) FS processed sample at 1200 rpm and 25 in./min

There is uniform dispersion of Titanium Carbide particles in magnesium matrix with no development of clusters. Fig. 5 shows TiC particles at 1000x magnification. When the volume fraction is increased, the number of particles increases and also the spacing between particles reduces. The uniform distributions of TiC particles are due to adequate generation of frictional heat, stirring and plasticized material flow across the FSPed zone.

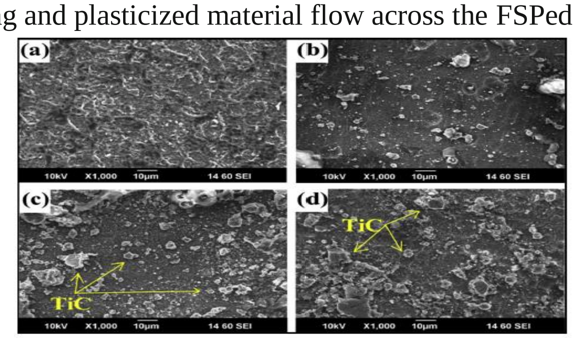

Figure.5. SEM Micrograph of AZ31/TiC MMC containing TiC; (a) 0 vol.%, (b) 6 vol.%, (c) 12 vol.% and (d) 18 vol.%

Fang Chai (2015), investigated Microstructure analysis and tensile properties of submerged friction stir processed AZ91 magnesium alloy. The intermediate grain size of magnesium grains is about 72 ± 3 μm. During FSP, dynamic recrystallization took place which resulted in refinement of the microstructures. The intermediate grain size of the NFSP AZ91 alloy is about 8.4 ± 1.3 μm. Darras (2007) also described that increase in grain refinement was accomplished under submerged condition, and they associated to two main factors: (1) submerging in water reduced the maximum temperature; (2) the time spent by the processed material above certain temperature was reduced.

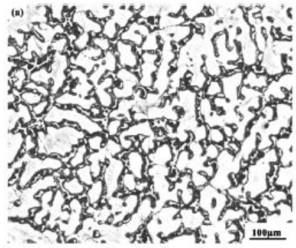

Figure.6. Microstructures of AZ91 magnesium alloy

Behzad Hassani (2016), investigated "Effect of Friction Stir Processing on Microstructure and Mechanical Properties of AZ91C Magnesium Cast Alloy Weld Zone". In this study Micro structural investigation of the material was performed using optical microscope and the phases in the microstructure were found by x-ray diffraction. The microstructural results showed that FSP deface the coarse dendritic microstructure. Additionally, it dissolves the brittle b-Mg17Al12 phase and secondary hard existing at grain boundaries of the TIG welded zone. Behzad Hassani, 2016 observed that there is decrease in amount of porosities with the elimination of the cracks in the microstructure.

The micro structure of AZ91 magnesium alloy consists of primary α-phase in which aluminium rich β-phase (Mg17Al12) is precipitated along the grain boundaries (Asadi, 2012).

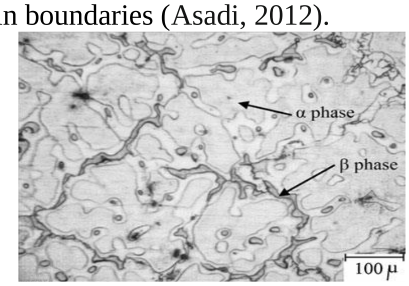

Figure.7. Microstructure of AZ91 magnesium alloy (P. Asadi et al., 2012)

Parviz Asadi, 2010 done friction stir processing at different process parameters i.e. rotational speed and transverse speed and corresponding microstructures have been arrived. It is shown in figure 8

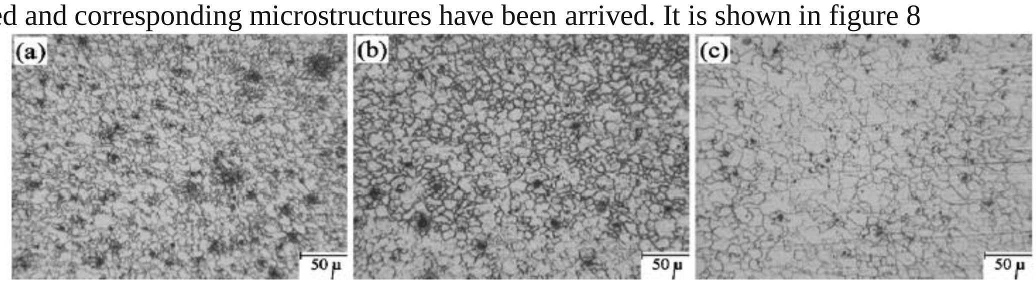

Figure.8. Microstructure of stirred zone in the FSPed specimens with the rotational speed of (a) 900 rpm (b) 1,120 rpm (c) 1,400 rpm. The transverse speed was 63 mm/min (Parviz Asadi, 2010)

Polishing of Magnesium Alloys: A number of procedures have been published for mechanical polishing of magnesium and magnesium alloys. The most commonly used practice uses SiC paper to grind the work pieces using a number of different grade abrasive papers which ranges from P40, P80 upto P1500 or even more fine grids. The use of wax coated in SiC surfaces is used by some metallographies in order to decrease the embedment of abrasive particles.

Chemical etchants that can be used:

Table.1. Chemical etchants

Name	Composition	Comments
Glycol	24 mL Water, 1 mL HNO3 75 mL Ethylene Glycol	Rinse and immerse for 2-3 seconds

Acetic Glycol	20 mL Acetic acid, 1 mL HNO3 60 mL Ethylene Glycol, 20 mL Water	1-3 secs for Immersion-casting alloys
Acetic-Picral	5 mL Acetic Acid 4.2 g Picric Acid 10 mL Water 100 mL Ethanol	Immersion- till brown surface film forms
Phospho-Picral	0.7 mL H3PO4 4-6 g Picric Acid matrix; 100 mL Ethanol	Immersion for 10-20 secs
Hydrofluoric Acid	10 mL 90 mL Water	Rinse and immerse for 2-3 seconds.

Machining variables: Major machine variables include tool rotating speed and tool traverse speed. These two parameters plays a major role in determining the amount of heat genetarted in the specimens (Dolatkhah, 2012). Interaction of tool that is rotating with work-piece generates heat due to friction and plastic deformation. The heat input in Stir Zone influences microstructure evolution and material flow which affects mechanical and tribological properties of the material.

Morisada (2006) investigated the role of traverse speed in MWCNTs reinforced AZ31 alloy surface composites. As traverse speed decreased to 25 mm/min, an improved dispersion of the Multi Wall CNTs was achieved without aggregated Multi Wall CNTs. At a low traverse speed more viscosity in AZ31 alloy was attributed. Figure 9 shows the tool probe geometry of commonly used tools in FSP and figure 10 shows the various machining parameters.

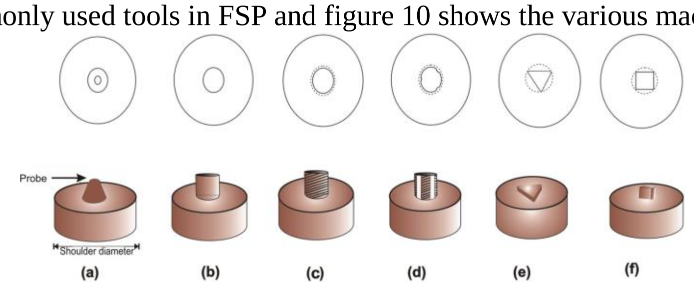

Figure.9. The tool probe geometry of commonly used tools in FSP (a) conical round bottom probe (b) columnar probe (c) threaded columnar probe (d) threaded columnar probe with flutes (e) triangular probe (f) square probe. (Vipin Sharma, 2015)

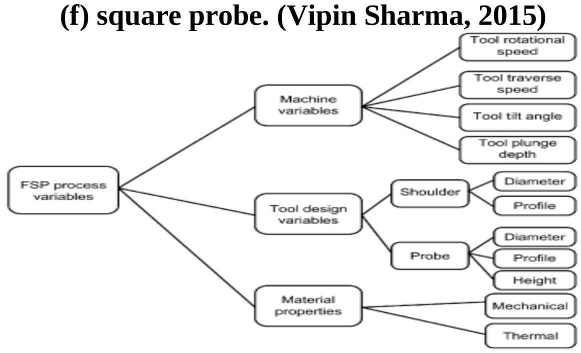

Figure.10. Classification of FSP process Variables

Summary: Friction Stir Processing is a fantastic technique used for processing of surface composites. The grain refinement achieved by FSP is the unique advantage of this process. The corrosion resistance, wear and hardness have been increased by applying Friction Stir Processing to magnesium alloys. A number of reinforcements including metallic and ceramic particles and carbon nano-tubes have been successfully incorporated in metallic matrix by FSP. Surface composites by FSP are defect free without voids and have a homogeneous particle distribution. Hybrid composites of soft and hard reinforcement have been successfully produced with promising properties using FSP. To full potential of nano-composites various methodologies to achieve uniform distribution have been used in FSP. Micro alloying with low melting point metals like tin, lead etc. can be incorporated in the surface composite. Recently Friction Stir Processing of polymers and its composites were initiated and the results were positive, but further more studies were required because of low melting point and polymeric chain structure arrangement. In Friction Stir Processing The tool wear plays an important role specially in materials that possess high melting point temperature like steels, Ceramics particle reinforced composites, Titanium etc.. Tools of polycrystalline cubic boron nitride, tungsten based alloys etc. are recommended for FSP of hard materials. However the usage of these tools will be limited because of their low fracture toughness and high cost. Because of these limitations, FSP technique will be difficult to process hard surface composites. Most of the surface composites fabricated so far is of aluminum based. Surface composites of harder alloys still await the development of cost effective and durable tools.

REFERENCES

Abbasi M, Bagheri B, Dadaei M, Omidvar H.R and Rezaei M, The effect of FSP on mechanical, tribological, and corrosion behavior of composite layer developed on magnesium AZ91 alloy surface, Int J Adv Manuf Technol, 77, 2015, 2051-2058.

Arora H.S, Singh H and Dhindaw B.K, Wear behavior of a Mg alloy subjected to Friction Stir Processing, Wear, 303, 2013, 65-77.

Arora H.S, Singh H, Dhindaw B.K and Grewal H.S, Some Investigations on Friction Stir Processed Zone of AZ91 Alloy, Trans Indian Inst Met, 65 (6), 2012, 735-739.

Asadi P, Besharati Givi M.K, and Faraji G, Producing Ultrafine-Grained AZ91 from As-Cast AZ91 by FSP, Int J Adv Manuf Technol, 51, 2010, 247260.

Asadi P, Faraji G, Masoumi A and Besharati Givi M.K, Experimental Investigation of Magnesium-Base Nanocomposite Produced by Friction Stir Processing: Effects of Particle Types and Number of Friction Stir Processing Passes, Metallurgical And Materials Transactions A, 42, 2011, 2827.

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

Behzad Hassani, Fathallah Karimzadeh, Mohammad Hossein Enayati, Soheil Sabooni, and Rudolf Vallant, Effect of Friction Stir Processing on Microstructure and Mechanical Properties of AZ91C Magnesium Cast Alloy Weld Zone, JMEPEG, 25, 2016, 2776-2785.

Darras B.M, Khraisheh M.K, Abu-Farha F.K and Omar M.A, Friction stir processing of commercial AZ31 magnesium alloy, Journal of Materials Processing Technology, 191, 2007, 77-81.

Del Vallea J.A, Reyb P, Gestob D, Verderab D, Jiméneza J.A and Ruanoa O.A, Mechanical properties of ultra-fine grained AZ91 magnesium alloy processed by friction stir processing, Materials Science & Engineering A, 628, 2015, 198-206

Fang Chai, Datong Zhang and Yuanyuan Li, Microstructures and tensile properties of submerged friction stir processed AZ91 magnesium alloy, Journal of Magnesium and Alloys, 3, 2015, 203-209.

Feng A.H and Ma Z.Y, Enhanced Mechanical Properties of Mg-Al-Zn Cast Alloy via Friction Stir Processing, Scripta Materialia, 56, 2007, 397-400.

Feng A.H, Xiao B.L, Ma Z.Y and Chen R.S, Effect of Friction Stir Processing Procedures on Microstructure and Mechanical Properties of Mg-Al-Zn Casting, The Minerals, Metals & Materials Society and ASM International, 40, 2009, 2447.

Parviz Asadi, Ghader Faraji and Mohammad Besharati K, Producing of AZ91/SiC composite by friction stir processing (FSP), Int J Adv Manuf Technol, 51, 2010, 247-260.

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

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