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Friction stir processing of magnesium alloys used in automobile and aerospace applications

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Abstract

A new microstructural modifications technique was developed by the Welding Institute (TWI) of United Kingdom in 1991 is known as friction stir processing (FSP). The FSP is a newer technique used for refining and homogenizing the grain structure of metal sheet. Friction stir processing is a great potential in the field of super-plasticity and metal matrix composites. Many investigators observed that the FSP greatly enhances super plasticity in many Al alloys. It is a solid-state processing technique based on friction stir welding technique in which a specially designed rotating cylindrical tool that comprises of a probe and shoulder. The probe of the tool is inserted into the sheet material while rotating and the shoulder moves over the surface of the sheet, and then traverses in the desired direction. The contact between the rotating probe and the sheet material generate heat due to friction which softens the material and the mechanical stirring caused by the probe, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure.
This paper mainly deals with friction stir processing of magnesium alloys with different reinforcement and different input parameters. The study consist of the effect of different reinforcement addition methods that i.e. groove method and drill hole method on tribological and mechanical properties. The result shows that the addition of reinforcements improves the ultimate tensile strength, strain rate and wear resistance.

Keywords: Friction Stir Processing (FSP), Tool Rotation Speed (TRS), Transverse Speed (TS).

1. Introduction

Friction stir processing is a novel technique used for improving material properties with the help of a rotation tool by plastic deformation. Friction stir processing is used to make the grain structure homogenous that enhance the properties of material. Friction stir processing is totally based on the friction stir welding technique in which there is a rotating tool consists of a shoulder and a probe. The probe of the tool plunged into the material and produces heat due to friction with the work material. The shoulder produces the additional heat and also capped the material extruded out during the process. Friction stir processing is mostly used for making surface composite, bulk composite and super-plasticity

2. Literature Review

The literature consists of the work conducted on various magnesium alloys by friction stir processing. The study consist of various parameters, tool materials, tool dimensions, response parameters and results obtained by various researchers on magnesium alloys by friction stir processing. The literature in the tabular form is given below:

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S.N	Author	Title of paper	Work-Piece/ Tool and groove size	Input parameters	Output parameters	Finding
1	C.I. Chang et al. (2004)	Relationship between grain size and Zener–Holloman parameter during friction stir processing in AZ31 Mg alloys	AZ31B billets ➢ Tool Pin length- 6 mm. ➢ Pin dia- 6 mm ➢ Shoulder dia- 18 mm ➢ Tilt angle- 3 degree	➢ RS range- 1000-1800 rpm. ➢ TS range- 6-24 mm/min	➢ Strain rate. ➢ grain size ➢ temperature range	(1) The temperature rise during FSP is traced, and the maximum temperature can reach 250–450^0 C, depending on the FSP pin rotation speed. (2) X-ray diffraction results show that, in the FSP dynamically recrystallized zone, the (0002) basal plane tends to lie on the transverse plane at lower pin rotation speeds, and approaches to nearly random orientation at higher rotation speeds.
2	Morisada. Y.,et al (2006)	Effect of friction stir processing with SiC particles on microstructure and hardness of AZ31	SiC powder was filled into a groove (1mm×2 mm) on the AZ31 plate SKD61 has a columnar shape	➢ Probe Diameter 4 mm. ➢ Probe length 1.8 mm. ➢ Tool rotating speed 1500 rpm ➢ Tool travel speed - 25 to 200 mm/min. ➢ Tool tilt angle 3◦	➢ Microstructure and micro hardness. ➢ Effect of SiC particles on grain size. ➢ Grain growth at elevated temperatures	(1) The SiC particles lead the grain to be refined by the FSP. (2) The micro hardness of the stir zone with the SiC particles increases to about 80 Hv. (3) The fine grain structure of the AZ31 fabricated by the FSP is unstable above 300 ◦C. (4) The fine grain fabricated by the FSP with the SiC particles is maintained at the elevated temperatures (∼400 ◦C).
3	A.H. Feng and Z.Y. Ma (2006)	Enhanced mechanical properties of Mg–Al–Zn cast alloy via friction stir processing	Mg–Al–Zn cast alloy		➢ UTS ➢ % EL	(1) The FSP Mg–Al–Zn sample exhibited an ultimate tensile strength of 337 MPa and an elongation of 10%. (2) FSP combined with aging is a simple and effective approach to enhance the mechanical properties of Mg–Al–Zn casting.
4	Chang. C.I ., et al (2007)	Microstructure and Mechanical Properties of Nano-ZrO2 and Nano-SiO_2 Particulate Reinforced AZ31-Mg Based Composites Fabricated by Friction Stir Processing	10~20 vol% nano-sized ZrO2 and 5~10 vol% nano-sized SiO2 particles into an Mg-AZ31 alloy Thickness - 10 mm	➢ Tool Shoulder diameter 18 mm. ➢ Tool pin diameter 6 mm. ➢ Tool pin length - 6 mm. ➢ Tool rotation speed - 800 rpm. ➢ Tool traverse speed - 45 mm/min	➢ Microstructures. ➢ XRD Results. ➢ Hardness ➢ Measurement ➢ Mechanical Properties	(1) The distribution of Nano particles measuring ~20 nm after four FSP passes resulted in satisfactorily uniform distribution. (2) The hardness and tensile properties at room temperature of the AZ31 composites with nano-fillers were appreciably improved, as compared with the AZ31 cast billet (3) The crystalline ZrO2 phase is very stable, no reaction between ZrO2 and Mg occurred during the FSP mixing ZrO2 into Mg-AZ31 matrix.

5	Darras. B.M., et al (2007)	Friction stir processing of commercial AZ31 magnesium alloy	AZ31B-H24 magnesium alloy Thickness - 0.125 in Tool Material -H-13 tool steel	➢ Tool Shoulder diameter - 0.5 in. ➢ Tool pin dia 0.25 in. ➢ Tool pin length - 0.12 in. ➢ Tool rotation speed - 1200–2000 rpm ➢ Tool traverse speed - 20–30 in./min	➢ Temperature ➢ Microstructure ➢ Hardness	(1) The preliminary results on FSP of AZ31 magnesium alloy are promising; grain refinement and homogenization of the microstructure are achieved in a single FSP pass. (2) The thermal histories presented in these studies give useful results on the peak temperature, cooling and heating rates which are critical to control and optimize the process
6	C. J. Lee et al. (2007)	Using Multiple FSP Passes to Cure Onion Splitting of Mg Alloys Deformed at Elevated Temperatures	AZ61A Mg (130*60*10) tool: Shoulder dia.18mm Pin dia.-6mm pin lenth- 6mm	➢ Multi-pass (4) ➢ TRS-800 rpm ➢ TS- 45-90mm/min	➢ Microstructure ➢ Strain rate ➢ True stress- true strain	The multi-passes FSP could effectively cure the onion premature splitting by accumulating a higher degree of strain to fully recrystallize the initial grains and to improve the inhomogeneous microstructure.
7	Chen Ti-jun et al. (2009)	Friction stir processing of thixoformed AZ91D magnesium alloy and fabrication of Al-rich surface	thixoformedAZ91D magnesium alloy 100 mm×40 mm×15 (Al powder) GROOVE- 4.2 mm in depth and 1.25 mm in width	➢ TRS-450 RPM. ➢ TS-60 mm/min	➢ Corrosion resistance ➢ Microstructure ➢ grain size and distribution	(1) Compared with the PMC alloy, the microstructural evolution of the TF alloy is slower because the operation efficiency of the grain refinement mechanisms is relatively low. (2) An Al-rich surface layer can be produced on the thixoformed alloy by FSP and the corrosion resistance in NaCl aqueous solution is obviously improved.
8	Faraji.G., et al (2010)	Effect of Process Parameters on Microstructure and Micro-hardness of AZ91/Al2O3 Surface Composite Produced by FSP Effect of Process Parameters on Microstructure and Micro-hardness of AZ91/Al2O3 Surface Composite Produced by FSP	Al2O3 powder with three different sizes (ranging from nanometer to micrometer scale) 3000, 300, and 30 nm, and 99.9% pure & as-cast AZ91 plate Groove - 0.8 mm (width) & 2 mm (depth) Tool Material - H13 tool	➢ Tool type - Square & Triangular ➢ Particle size - 0.03 , 3 ➢ Pass number - 1, 3 ➢ Tool Shoulder diameter - 15 mm ➢ Tool pin diameter - 5 mm ➢ Tool pin height - 1.8 mm ➢ Tool tilt angle - 3° ➢ Tool rotation speed - 900 rpm	➢ Microstructure ➢ Micro-hardness ➢ X-ray diffraction	(1) Grain structures in the SZ had fine and equiaxed grains due to the recrystallization, while nano-sized alumina particles distributions were different because they received a different stirring action. (2) Grain size and cluster size in the specimen produced by the triangular tool is smaller than that of square tool. (3) Decreasing the particle size leads to increase in the hardness. (4) Hardness of the specimen produced by triangular tool is higher than that of square tool and increasing the number of passes leads to monotonous hardness curve.

9	Azizieh. M., et al (2010)	Effect of rotational speed and probe profile on microstructure and hardness of AZ31/Al2O3 nanocomposites fabricated by friction stir processing	AZ31 billets Three kinds of Al_2O_3 particles with mean diameters of 35 nm , 350 nm and 1000 nm Thickness - 10 mm Tool Material = H13 Steel Groove- 1.2 mm * 5 mm	➢ Shoulder dia. (mm) – 18 ➢ pin dia. – 6 ➢ pin length (mm) - 5.7 ➢ TRS (rpm) - 800, 1000 and 1200 rpm ➢ Welding Feeds (mm/min) - 45 ➢ Tilt angle-2 ^{0}	➢ Material flow in the stir zone ➢ Microstructure of the stir zone ➢ Hardness measurement	(1) The effects of probe profile, rotational speed and the number of FSP passes on nanoparticle distribution and matrix microstructure were studied. (2) The grain refinement of matrix and improved distribution of nanoparticles were obtained after each pass. (3) By increasing the rotational speed, as a result of greater heat input, grain size of the base alloy increased and simultaneously more shattering effect of rotation, cause a better nanoparticle distribution.
10	Asadi.P., et al (2012)	On the role of cooling and tool rotational direction on microstructure and mechanical properties of friction stir processed AZ91	AZ91 Magnesium alloy Thickness - 5 mm Tool material - 2344 hot working steel	➢ Tool shoulder diameter (mm) 15. ➢ Tool square pin diameter – 5 ➢ Tool square pin length (mm) - 2.5 ➢ Tool rotating speed (rpm) – 900 ➢ Welding Feeds (mm/min)- 63 ➢ Tilt angle -3 ^{0}	➢ Microstructure ➢ Hardness ➢ Tensile properties ➢ Wear properties	(1) Water cooling enhances the hardness and reduces the final grain size, while the amount of oxide particles in the processed area increases. (2) The oxide particles reduce the final grain size because of limiting grain growth due to pinning of the grain boundaries. (3) Changing the RD in each pass reduces the grain size noticeably, because of creating more suitable sites for nucleation during DRX, and increases the hardness and tensile strength considerably.
11	Zheng.F. Y.,et al (2013)	Microstructures and mechanical properties of friction stir processed Mge2.0Nde0.3Zne1.0Zr magnesium alloy	NZ20K (nominal Mge2.0Nde0.3Zne1.0Zr, wt.%) alloy Thickness - 7 mm Tool Material - Steel	➢ Tool Shoulder diameter - 16 mm ➢ Tool pin length - 6mm ➢ Tool rotation speed - 800 rpm ➢ Tool traverse speed - 200 mm/ min	➢ XRD patterns analysis ➢ SEM images & EDS analyses	(1) The alloy was friction stir processed with different passes: single-pass, three-pass and five-pass, under a tool rotation rate of 800 rpm and a traverse speed of 200 mm/ min. with the increase of pass, the average grain size in the stir zone (SZ) is decreased firstly and then increases. (2) The Vikers hardness of SZs in all FSPed samples is higher than that of the parent material (3) Tensile strengths of the stir zones along the FSP advancing direction are slightly lower than those of PM.
12	Lee.W., et al (2013)	Joint properties of friction stir welded AZ31B– H24 magnesium alloy	AZ31B –H24 alloy Thickness – 4 Tool material- D2 (SKD11)	➢ Tool shoulder diameter (mm) - 20 ➢ Tool rotating speed (rpm) - 1250 - 2500 rev/ min ➢ Welding Feeds (mm/min) - 87 - 507 ➢ Tilt angle - 3 ^{0}	➢ Change of top surface roughness ➢ Macrostructure ➢ Microstructure ➢ Grain size distribution ➢ Hardness distribution	(1) The microstructure of the weld zone was composed of +ve regions: base metal, HAZ, thermomechanical affected zone, stir zone I & stir zone (2) Stir zones I and II were characterized by partial dynamic recrystallization and full dynamic recrystallization, respectively. (3) The hardness of the weld zone was lower than that of the base metal owing to grain growth. (4) The maximum tensile strength was 240 MPa, which was ~85% of the base metal value.

13	Gupta.A ., et al (2015)	Effect of Tool rotation speed and feed rate on the formation of tunnel defect in Friction Stir Processing of AZ31 Magnesium alloy	AZ31 magnesium thickness - 6 mm Tool Material - H-13	➢ Tool Rotational speed (RPM) – 2000 ➢ Feed rate (mm/min.) 40,50 ➢ Tool Shoulder dia. -18 mm ➢ Tool pin dia. 6 mm ➢ Tool pin length 5.36 mm. ➢ Tool tilt angle 1.8°	Defects	(1) Truncated conical tool produced much less tunnel defect as compare to the cylindrical tool. (2) Tunnel defect increases along the weld length as the welding proceeds and it was inclined towards the retreating side of the weld in all the specimens. (3) Negligible tunnel defect was found during FSP with the truncated conical tool at the rotational speed of 2000 rpm and welding speed of 40 mm (4) Excessive flash was observed during FSP with the cylindrical tool at the feed rate of 50 mm/min.
14	Azizieh M.et al.(2016)	Effect of friction stir processing on the microstructure of pure magnesium castings	pure magnesium (110*70*10) Tool: Shoulder dia.-18mm Pin dia.-6mm pin lenth-6mm	➢ Cylindrical non-threaded pin, a cylindrical threaded pin and a conical pin. ➢ TRS- 400, 500, 630, 800, 1000, 1250 and 1600 rpm ➢ TS- 50 mm/min.	➢ Material flow ➢ Hardness	(1) Threaded pin produced the best material flow and the least cavities. (2) The hardness measurements demonstrated increase in the FSP specimens compared with the initial pure Mg castings.
15	Li.J., Chai.F., et al (2014)	Influence of processing speed on microstructures and mechanical properties of friction stir processed Mg–Y–Nd–Zr casting alloy	Cast WE43 magnesium alloy plates (6 mm)	➢ Tool angle - 2.5° ➢ Tool rotational speed -800 rev/ min ➢ Tool travel speed -30, 60, 90 and 120 mm/ min. ➢ Tool concave shoulder dia - 15 mm	➢ Microstructure of BM and FSP samples ➢ X-ray diffraction patterns of WE43 samples ➢ Mechanical properties of BM and FSP samples	(1) Friction stir processing results in the generation of fine grained microstructures and fundamental break-up and dissolution of the coarse second phases. (2) Owing to much finer microstructure, the mechanical properties of the WE43 alloy after FSP are significantly improved. (3) High temperature tensile tests show that the FSP WE43 alloys exhibit excellent HSRS, with a large elongation of 631% at 748 K with a strain rate.
16	Morishige .T., et al (2013)	Microstructural modification of cast Mg alloys by friction stir processing	Mg–Y–Zn cast alloys Thickness - 10 mm AZ91D die cast	➢ Tool angle - 2° ➢ Tool rotational speed -450,600 rpm ➢ Tool travel speed -50,100 mm/min ➢ Tool shoulder diameter -20 mm.	➢ Microstructures of as cast and homogenised Mg–Y–Zn alloys and die cast AZ91D alloy ➢ Microstructures 3) Hardness	(1) For Mg–Y–Zn cast alloy, FSP was a very efficient method for grain refinement, higher hardness (.120 HV) and finer structure (grain size of y1 mm) than that of AZ91D was achieved. (2) In AZ91D alloy, the grain refinement level and hardness in the stir zone were less than Mg–Y–Zn because of the partly dissolved second phase particles.

17	Ahmadkhaniha.D., et al (2013)	Optimisation of friction stir processing parameters to produce sound and fine grain layers in pure magnesium	10*5* 7 mm were prepared from a pure Mg ingot. H-13 tool steel	➢ Tool angle 2 .5° ➢ Tool rotational speed 1000, 1250, 1600 w/rev /min ➢ Tool travel speed -3,31.5,12 v/mm /min ➢ Tool shoulder diameter -15 mm.	➢ Qualification of friction stir processed workpieces. ➢ Micro hardness ➢ Microstructure	(1) FSP's window process for pure Mg is quite narrower than that of AZ alloys. Achieving a defect free layer of friction stir processed pure Mg is very sensitive to the processing temperature and friction mode. (2) Rotational and traverse speeds play key roles in achieving a sound friction stir processed pure Mg layer. (3) At constant rotational and traverse speeds, when the PD increases, the title angle must also increase in order to have a defect free workpiece.
18	Husain Mehdi et al (2017)	Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy – a review	CY16, W-La, WC-411 tool	➢ 350 rpm and 15 mm/min ➢ 2236 rpm to 1500 rpm	➢ Mechanical Properties ➢ Wear Property ➢ Microstructure ➢ Macrostructure	Welding parameter such as tool rotation, transverse speed and axial force have a significant effect on the amount of heat generated and strength of FSW joints. Microstructure evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameter
19	Husain Mehdi et al (2017)	Influences of Process Parameter and Microstructural Studies in Friction Stir Welding of Different Alloys: A Review	CY16, W-La, WC-411 tool	➢ 2236 rpm and travel speed of 2.33 mm/s ➢ 700 rpm and a traverse speed of 203 mm/min ➢ Tool rotation rate of 300,700, 900 and 1100 rpm and a traverse speed 2 and 8 ipm	➢ Mechanical Properties ➢ Microstructure ➢ Macrostructure ➢ Wear Properties	The mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter.

20	Jamshidijam.M., et al (2013)	Wear Behavior of Multiwalled Carbon Nanotube/AZ31 Composite Obtained by Friction Stir Processing	AZ31 billet AISI-H13 steel tool	➢ Tool angle - 3° ➢ Tool rotational speed -1500 rpm ➢ Tool travel speed -80 mm /min ➢ Tool shoulder diameter -20 mm. ➢ Tool cylindrical pin diameter - 4 mm ➢ Tool cylindrical pin length - 3 mm	➢ Micro hardness profile. ➢ Optical micrographs ➢ Friction coefficient of the FSP AZ31 with the MWCNTs as a function of sliding distance.	(1) Multiwalled carbon nanotubes were used as reinforcement in the FSP AZ31. The grain size of the AZ31 alloy containing MWCNTs reduced to less than 0.5 µm after FSP. (2) The micro hardness was increased due to grain refinement and high interfacial strength at the MWCNT-AZ31 interface. (3) The difference in wear resistance of the specimens was more pronounced under high applied loads. The wear resistance of the AZ31 alloy containing MWCNTs also doubled under an applied load of 20 N due to the low coefficient friction and higher hardness.
21	Karthikeyan.L., et al (2010)	Biaxial Stressing of Sheets of friction Stir Processed Aluminum Alloy A319	A319 aluminum alloy 100mm×100mm×10 mm. High carbon steel	➢ Tool angle -2° ➢ TRS -1200 rpm ➢ TS -40 mm/min ➢ Cylindrical threaded tool shoulder dia-18 mm. ➢ cylindrical pin diameter - 6 mm ➢ cylindrical length -5.7 mm	➢ Thickness Distribution ➢ Microstructures	(1) FSP is a viable technique for inducing at least extended plasticity in materials. (2) The sheets subjected to gas forming exhibited behavior similar to what has been reported earlier in similar alloys processed by other techniques. (3) The sheets were found to thin by ~53.3% from the outer flange to the bottom portion (pole).
22	Azizieh.M., et al (2016)	Effect of friction stir processing on the microstructure of pure magnesium castings	Mg ingot 100 mm3 × 70 mm3 × 10 mm3	➢ FSP tool shapes: a non-threaded cylindrical, b threaded cylindrical and c conical pins ➢ Tool rotational speed -400, 500, 630, 800, 1000, 1250 and 1600 rpm ➢ Tool travel speed -50 mm/min	➢ Microstructure ➢ XRD results ➢ Hardness measurements	(1) The threaded pin produced the best material flow and the least cavities. (2) The temperature rise during the FSP was traced, and the maximum temperature reached 360–550 °C, depending on the FSP pin rotational speed. (3) The grain size of the specimens was refined to 13.5–35.5 µm, compared with 200 µm in the initial Mg ingot. (4) The grain growth in high rotational speed resulted from the higher temperatures in this processing condition.

23	Naser.A.Z et al (2016)	Experimental investigation of Mg/SiC composite fabrication via friction stir processing	Magnesium AZ31B sheets with a thickness of 5 mm groove with a width of 2 mm and a depth of 0.5 mm	➢ Tool angle - 2° ➢ Tool rotational speed - 800–2000 rpm ➢ Tool travel speed -25–200 mm/min ➢ Tool shoulder diameter -15 mm ➢ Tool cylindrical pin diameter -5 mm. ➢ Tool cylindrical pin length - 4 mm	➢ Temperature ➢ Microstructure ➢ Micro hardness	(1) FSP was successfully used to fabricate the Mg/Sic surface composite, and the process was found to be very sensitive to the process parameters (the rotational and translational speeds and the groove geometry). (2) Significant grain refinement was attained by FSP, and an average grain size as low as 1.46 μm was achieved for a specific combination of the process parameters. (3) The addition of the SiC particles tends to slightly increase the peak temperature during processing.

3. Conclusions & Recommendation

- ➢ The surface composite layer of Nano reinforcement particles by friction stir processing on magnesium alloys improves tensile behavior, hardness, corrosion resistance, percentage and wear resistance behavior of the workpiece material.
- ➢ The friction stir processing with multiple passes could effectively cure the onion premature splitting by accumulating a higher degree of strain and the initial grains gets fully recrystallize and to improve the microstructure.
- ➢ Increasing the tool rotational speed results greater heat input and increases grain size of the metal alloy and simultaneously more shattering effect of rotation, results a better distribution of Nano particles.
- ➢ Water cooling during friction stir welding on magnesium MZ91 enhances the hardness and reduces the final grain size, while the amount of oxide particles in the processed area increases.
- ➢ The hardness increases in the FSPed specimens compared with the initial pure Magnesium castings.

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