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

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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 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, 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	Year	Author	Title of paper	Work-Piece/ Tool and groove size	Input parameters	Output parameters	Finding
1	2004	C.I. Chang et al.	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 4) tilt angle- 3 degree	➢ RS range- 1000-1800 rpm ➢ TS range- 6-24 mm/min	➢ Strain rate ➢ grain size ➢ Temperature range	➢ The temperature rise during FSP was observed and maximum temperature can reach 250–450 C, depending upon tool rotation speed ➢ The results of X-ray diffraction showed that dynamically recrystallized zone, the (0002) basal plane tends to lie on the transverse plane at lower TRS, and at higher TRS approaches to nearly random orientation.
2	2006	Morisada. Y.,et al	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 Dimeter - 4 mm, ➢ Probe length - 1.8 mm ➢ Tool rotating speed - 1500 rpm ➢ Tool travel speed - 25 to 200 mm/min	➢ Microstructure and micro-hardness ➢ Effect of SiC particles on grain size ➢ Grain growth at elevated temperatures	➢ The grain refinement of SiC particles by the FSP. And the micro-hardness of the stir zone increases upto 80 HV. ➢ The fine grain structure was unstable above 300^0C and maintained at the elevated temperatures (~400^0C).
3	2006	A.H. Feng and Z.Y. Ma	Enhanced mechanical properties of Mg–Al–Zn cast alloy via friction stir processing	Mg–Al–Zn cast alloy		➢ UTS ➢ %EL	➢ The result after FSP showed an ultimate tensile strength of 337 MPa and %elongation of 10%. ➢ FSP combined with aging is a simple and effective approach to improve the mechanical properties of cast Mg–Al–Zn.
4	2007	Chang.C.I ., et al	Microstructure and Mechanical Properties of Nano-ZrO2 and Nano-SiO2 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/mn	➢ Microstructures ➢ XRD Results ➢ Hardness Measurement ➢ Mechanical Properties	➢ The distribution of Nano particles measuring ~20 nm was observed satisfactorily uniform after four FSP passes. ➢ The tensile properties and hardness were appreciably improved at room temperature of the AZ31 composites after FSP. ➢ The crystalline ZrO2 phase is very stable due to no reaction held between Mg and ZrO_2 during the FSP mixing ZrO2 into Mg-AZ31 matrix.

5	2007	Darras. B.M., et al	Friction stir processing of commercial AZ31 magnesium alloy	AZ31B-H24 Mg-alloy Thickness - 0.125 in. Tool Material -H-13 tool steel	➢ Tool Shoulder diameter - 0.5 in ➢ Tool pin diameter 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	➢ The results showed the grain refinement and homogenous microstructure after a single pass of FSP. ➢ The thermal histories presented in these studies give useful results on the peak temperature, heating and cooling rates which are critical to control and optimize the process
6	2007	C. J. Lee et al.	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	➢ Multipass-4 ➢ TRS-800 rpm ➢ TS- 45-90mm/min	➢ Microstructure ➢ Strain rate ➢ True stress-true strain	➢ The FSP with multi-pass could cure the onion premature splitting effectively by accumulating a higher degree of strain to fully recrystallize the initial grains and to improve homogeneity of the inhomogeneous microstructure.
7	2009	Chen Ti-jun et al.	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	➢ Microstructural evolution of the thixoformed AZ9 is slower compared with the PMC alloy because of low the operation efficiency of the grain refinement mechanisms. ➢ An Al-rich surface layer can be produced on the thixoformed alloy by FSP and improves the corrosion resistance is observed in NaCl aqueous solution.
8	2010	Faraji.G., et al	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	Al_2O_3 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 ➢ Pass number - 1, 3 ➢ Shoulder diameter -15 mm. ➢ Tool pin dia 5 mm ➢ pin height-1.8 mm ➢ Tool tilt angle - 3°	➢ Microstructure ➢ Micro hardness Study ➢ X-ray Diffraction	➢ Grain structures had equiaxed and fine grains due to the recrystallization in the SZ while Nano-sized alumina particles distributed differently because of different stirring action. ➢ The cluster size and grain size in the sample produced by the triangular tool is smaller than that of square tool. ➢ The hardness of the sample made by triangular tool is higher than that of square tool and increasing the number of passes.

9	2010	Azizieh.M., et al	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 Al2O3 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-2º	➢ Material flow in the stir zone. ➢ Microstructure of the stir zone. ➢ Hardness measurement	➢ The result showed that probe profile, TRS and the number of FSP passes effects the nanoparticle distribution and matrix microstructure. ➢ On increasing no. of passes the grain refinement of matrix and improved distribution of nanoparticles were obtained. ➢ Increasing TRS results greater heat input, grain size of the base alloy increased and simultaneously more shattering effect of rotation, cause a better nanoparticle distribution.
10	2012	Asadi.P., et al	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	1) Tool shoulder diameter (mm) - 15 2) Tool square pin diameter - 5 3) Tool square pin length (mm) - 2.5 4) Tool rotating speed (rpm) - 900 5) Welding Feeds (mm/min) - 63 6) Tilt angle -3 º	➢ Microstructure ➢ Hardness ➢ Tensile properties ➢ Wear properties	➢ Water cooling improves the hardness and reduces grain size, while the oxide particles amount in the processed area increases. ➢ The oxide particles reduce the final grain size because of limiting grain growth due to pinning of the grain boundaries. ➢ The grain size reduces on changing the RD in each pass, because of creating more suitable sites for nucleation during DRX, and increases the tensile strength and hardness considerably.
11	2013	Zheng.F. Y.,et al	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. ➢ Threaded cylindrical pin length - 8 mm ➢ Tool pin length - 6mm ➢ Tool rotation speed - 800 rpm ➢ Tool traverse speed - 200 mm/ min ➢ Tool tilt angle - 2.8 °	➢ XRD patterns analysis. ➢ SEM images & EDS analyses	➢ The friction stir processed alloys with different passes: single-pass, three-pass and five-pass, under TRS of 800 rpm and a TS of 200 mm/ min were obtained. ➢ The average grain size in the SZ is first decreases and then increases with the increase of pass. ➢ The Vikers hardness of SZs improved after on comparing with the base material. ➢ Tensile strengths of the SZ along advancing direction are slightly lower than those of base material.

12	2013	Lee.W., et al	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 º	➢ Change of top surface roughness ➢ Macrostructur ➢ Microstructur ➢ Grain size distribution ➢ Hardness distribution	➢ The hardness was lower of the weld zone than that of the base metal owing to grain growth. ➢ The maximum tensile strengh was 240 MPa, which was ~85% of the base metal value of 293 MPa. The fracture location was close to the stir zone.
13	2015	Gupta.A ., et al	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. ➢ Cylindrical pin	Defects	➢ Less tunnel defect was produced by Truncated conical tool as compare to the cylindrical tool. ➢ Tunnel defect increases along the weld length towards the retreating side of the weld in all the specimens as the welding proceeds. ➢ Negligible tunnel defect was found at the TRS of 2000 rpm and TS of 40 mm with the truncated conical tool. ➢ Excessive flash was observed at the feed rate of 50 mm/min with the cylindrical tool.
14	2016	Azizieh M.et al.	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 rpm.	➢ Material flow ➢ Hardness	➢ The best material flow and the least cavities was produed by Threaded pin tool. ➢ The hardness increased in the FSP specimens compared with the received pure Mg castings.
15	2017	Husain Mehdi et al	Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy- A Review		➢ 2100 rpm and travel speed of 2.33 mm/s ➢ 650 rpm and a traverse speed of 203 mm/min ➢ Tool rotation rate of 300,700, 900 and 1100 rpm.	➢ UTS ➢ XRD ➢ Microstructure ➢ Micro-Hardness	➢ Grain structures had equiaxed and fine grains due to the recrystallization in the SZ while Nano-sized alumina particles distributed differently because of different stirring action. ➢ An average grain size as low as 1.46 µm was obtained for a particular process parameters setting.

16	2017	Husain Mehdi et al	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
17	2017	Husain Mehdi et al	Influences of Process Parameter and Microstructural Studies in Friction Stir Weldingof 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.	➢ 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.
18	2014	Li.J., Chai.F., et al	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 diameter - 15 mm	➢ Microstructure of BM and FSP samples. ➢ X-ray diffraction patterns of WE43 samples ➢ Mechanical properties of BM and FSP samples	➢ Fine grain microstructures, fundamental break-up and dissolution of the coarse second phases was observed FSP. ➢ The mechanical properties of the WE43 alloy are improved significantly after FSP. ➢ High temperature tensile tests revealed that the FSPed WE43 alloys shows excellent HSRS, with a large elongation of 631% at 748 K with a strain rate.
19	2013	Morishige .T., et al	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 20mm	➢ Microstructures of as cast and homogenized Mg–Y–Zn alloys and die cast AZ91D alloy. ➢ Microstructures ➢ Hardness	➢ Fine grain refinement, higher hardness of 120 HV and finer structure was observed after. 2) The hardness and grain refinement level in the stir zone in AZ91D alloy, were less than Mg–Y–Zn because of the partly dissolved second phase particles.

20	2013	Ahmadkhaniha.D., et al	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 - 63,31.5,12 v/mm /min	➢ Qualification of friction stir processed workpieces. ➢ Micro hardness. ➢ Microstructure	➢ A defect free layer of FSP pure Mg is very sensitive to the processing temperature and friction mode. ➢ TRS and TS play a vital roles in achieving a sound FSPed pure Mg layer. ➢ At constant TRS and TS, when the PD increases, the tool tilt angle must also increase in order to have a defect free workpiece.
21	2013	Jamshidijam.M., et al	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 cylindrical pin diameter 4 mm	➢ Micro hardness profile. ➢ Optical micrographs ➢ Friction coefficient of the FSP AZ31 with the MWCNTs as a function of sliding distance.	➢ Multi-walled carbon Nano-tubes reinforcement was used in the FSP AZ31 and the grain size reduced to less than 0.5μm after FSP. ➢ The micro-hardness was increased due to high interfacial strength and grain refinement at the MWCNT-AZ31 interface. ➢ The wear resistance of the AZ31 alloy containing MWCNTs also doubled under an applied load of 20 N
22	2010	Karthikeyan.L., et al	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 dia18 mm. ➢ Cylindrical pin diameter 6 mm	➢ Thickness Distribution ➢ Microstructures	➢ The sheets subjected to gas forming showed similar behavior to what has been reported earlier alloys processed by other techniques. ➢ The sheets were found to thin by ~53.3% from the outer flange to the bottom portion.
23	2016	Azizieh.M., et al	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 conical pins. ➢ Tool rotational speed -400, 500, 630, 800, 1000, 1250rpm. ➢ Tool travel speed -50 mm/min	➢ Microstructure ➢ XRD results ➢ Hardness measurements	➢ The samples obtained by the threaded pin shows the best material flow and the least cavities. ➢ The temperature rise during the FSP was traced, and the maximum temperature reached 360–550 °C, depending on the FSP TRS. ➢ The grain size was refined to 13.5–35.5 μm, compared with 200 μm in the initial Mg ingot. ➢ The grain growth in high TRS due to the higher temperatures during FSP.

3. Conclusions & Recommendations

1. 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.
2. 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.
3. 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.
4. Water cooling durin 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.

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