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Advancement in friction stir processing on magnesium alloys

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Abstract. This review paper gathers information on the current trend of friction stir processing (FSP) that had been utilized to alter the surface metal that offers greater properties on magnesium alloys. However, inconsistent results due to changing parameters and different pin profile designs used previously was a challenge in this process. Hereby, discussing on FSP parameters, tool properties and impacts on magnesium (Mg) alloys to improvise the process. Rotational speed and traverse speed were set beforehand. Tool was plunged onto the material and moved in the traverse direction along certain length. The microstructure and microhardness properties of FSPed material were observed. AZ series of magnesium alloys mostly used in FSP. Most significant review was that the fixed rotational speed and feed rate made the grains became coarser. Finer grains were found when rotational speed was constant while feed rate increases. The higher the traverse speed, the higher the hardness of specimens. Setting up rotational speeds in between (900-1400) rpm could minimize defects effectively. Traverse speeds were set in between (25-40) mm/min to prevent pin holes and tunnel defects. Rotational speed affects the grain refinement level and the width of stirred zone while traverse speed influences the material flow rate.

1. Introduction

Friction stir processing (FSP) is a new approach developed based on the principle of friction stir welding process [1-3]. Then it emerges into an effective process by using tool for enhancing metallic sheets and plates through the modification in microstructure [4]. FSP is another mechanical procedure to produce great execution with less cost in a base time and it is likewise accomplishing microstructure and mechanical properties demands [5].

Based on previous studies, major part of the automotive and aerospace industries also maritime always demand for lightweight material. Recently, aluminium-based alloys have been the popular materials used in cars to reduce weight [6] but magnesium-based alloys have become well known for years because of their good advantages such as strength to weight ratio and its low density when compared to aluminum alloys [7]. Magnesium and its alloys have recently been evaluated as excellent material as it has high specific strength (158kN-m/kg), responsive cast-ability, weld-ability, strong damping and superior machinability.

Choices of procedure parameters such as applied power, traverse speed and rotational speed as well as material flow can yield an adjusted microstructure of material. The latest parameters used during FSP are tool traverse speed (v) and the rotational speed of tool (ω) which must be in conjunction with the probe and shoulder diameter. The hardware parameters in FSP tool that are traverse speed (v) and the rotational speed of tool (ω) become related to the pin and shoulder diameter which guarantees essential measure of quality of friction stir processing on the workpiece during experiment [8-9]. As the tool rotates, it moves forward to cover the processed region. The tool parameters specifically determined to ensure the amount of heat required on the workpiece.

The principle of FSP applied is for alteration of material's surface after embedding a cylindrical-shaped rotating tool with small probe at the tip of the tool. Then, tool was plunged into the material so that there is contact between the shoulder of the rotating tool and the material's sheet surface along the required length in the traverse direction by applying a suitable load [1-2]. Heat will be generated from the contact and softens the material underneath melting temperature while the mechanical stirring induced by the probe leads to strongly plastic deformation. FSP also enable alloying with categorical components as well as make improvement of eight welded joints element [10-11].

The aim of this review paper is to gather information on the FSP parameters and conditions that can be implemented during FSP experiments as there were inconsistency among the final results obtained due to changing parameters and different pin profile designs used in previous researches. In this review paper, it was found that various FSP parameters can be applied throughout the experiments. Moreover, its subsequent impacts on different magnesium alloys were discussed in order to improve the FSP development in manufacturing industry.

Section 2 justified the development of FSP which includes some methodology and flow of experiment whereas section 3 listed the FSP parameters that could assist in choosing the right parameters to be implemented during experiment. Details in section 4 is mainly about types of magnesium alloys that had been used for FSP, section 5 will be focusing on development of FSP tools such as type of material used to fabricate tool and their dimensions. Other than that, section 6 explained the enhancement of magnesium alloy mechanical properties via FSP. Lastly, section 7 concludes this whole review paper. A table was constructed under each of the following sections to summarize all the information collected.

2. Current development of friction stir processing (FSP)

FSP enhances specific properties thermo-mechanically of prepared metallic parts in close surface layers when processing some particular areas on the surface and depth of a structure. In addition, FSP is an alternative method in altering fabrication of surface layer composites and grain refinement [12-13]. Generally, FSP ends with a huge plastic deformation resulting in a dynamic recrystallized fine grain structure within the processed zone on material. This phenomenon showed there were refined grains in the mixed area with irregular disorientation of grain limits as well as mechanical blending between surface and subsurface layers. FSP also present fashioned microstructure in cast parts by dispensing porosity.

N. Singh et al. [7] stated that readily available computer numerical control (CNC) vertical milling machine as well as a simple tool were the main features in FSP. A specially designed fixture made of EN-8 material was utilized to perform FSP. At the top surface of the fixture, cavity with 80 × 50 × 2.5 mm dimension was machined. Several 2 mm-diameter holes were drilled and then filled with three different particle sizes of boron carbide powder (B4C) which are 20 µm, 50 µm and submicron. Those reinforcement particles were added for the microstructure refinement and improving the properties of material.

From previous research, AZ31 magnesium alloy was used as the base material with length of 240 mm, width of 60 mm and thickness of 5 mm. In butt joint configuration, Ugender [16] found that the rotational speed had influenced the grain refinement of AZ31 Mg alloy plates.

SiO_2 particles with grain size of 10 nm were inserted into the holes of 1 mm x 2 mm machined on the specimen beforehand. To proceed with the microstructural studies, the standard metallographic methods must be followed. Later, Khayyamin et al. [17] cut the stirred zone, those specimens were etched for 2 seconds using etching solution which contains 5 ml of acetic acid and HCl each, 7 g picric acid, 8 ml nitric acid, 15 ml water and 120 ml ethanol. Then, their microstructures were observed using optical microscopy (OM) and scanning electron microscopy (SEM). For microhardness, all of the specimens were measured at certain points by using a Vickers microhardness testing machine applied for 20 seconds long using load of 200 g.

3. FSP parameters

FSP is a moderately confounded approach in the fact that the surface of adjusted material depends upon numerous parameters. Various conditions that were found among the latest development of FSP which can be comparable as FSW transforms. The primary innovative specifications of the FSP procedure are rotational speed, traverse speed, tilt edge and infiltration intensity of the apparatus. The properties of the tool that were emphasized in FSP are length and width of pin, state of the pin, distance across and state of the shoulder [11, 14].

There are many parameters which can influence the quality of the subsequent weld such as the adequacy and recurrence of vibration as well as weld weight and pace. FSP tool parameters always play an imperative work in acquiring predominant mechanical properties [7]. To be specific, geometry of tool pin as well as the tool rotational and traverse speeds were known as the main specifications for regulating the material flow. Other than the specifications listed, the profile of tool's pin also has a significant job in enhancing the substance strength or adaptability of microstructure in the particular range of Mg alloys.

K. Singh et al. [15] studied the microstructure and mechanical properties when friction stirred 4 mm-thick AZ61. The experiment was conducted by using the parameter, 1400 rpm for rotational speed and 25 mm/min for traverse speed. It was stated that the existence of finer grains in the stir zone the joint had been increased. The results displayed that microhardness at the base metal was higher than the thermo-mechanically influenced zone but lower than the stirred zone. The test also showed the friction stirred zone's width was about 6 mm indicates the diameter of tool pin.

Ugender [16] investigated the rotational speed on the formation of friction stirred zone using AZ31. AZ31 magnesium alloy with thickness of 5 mm was used as the base material for this work. Different rotational speeds such as (900, 1120 and 1400) rpm and traverse speed of tool which are (25-75) mm/min were implemented during the study. There were significant influences on grain refinement of a material. It was also reported that when the rotational speed is below 900 rpm, the worm hole defect was found due to inadequate heat generation and insufficient metal filling. In addition, a tunnel defect was found due to excessive heat generation when the rotational speed is higher than 1400 rpm. The result showed that pin holes were detected when the traverse speed is below 25 mm/min due to excessive heat generation. When the traverse speed used was greater than 40 mm/min, a tunnel defect was detected due to insufficient heat inputs induced by inadequate metal flow. The optimum values for tool rotational speed and traverse speed to enhance the mechanical properties of Mg AZ31 was at 1120 rpm and 40 mm/min respectively.

N. Singh et al. [7] set the rotational speed and traverse speed at 900 rpm and 45 mm/min respectively before plunging the tool until 0.3 mm deep into AZ91 specimen. It came out with outcomes which displayed the grain refinement that also increased the hardness of AZ91. Khayyamin et al. [17] applied the rotational speed at 1250 rpm and three different traverse speeds which were (20, 40 and 63) mm/min on 8 mm-thick AZ91 magnesium alloy throughout the experiment. The important findings in FSP parameters investigations are summarized in Table 1.

Table 1. Significant findings in FSP parameters investigations

Authors, Year	Findings
K. Singh et al., (2018)	Rotational speed: 1400 rpm and traveling speed: 25 mm/min increases the existence of finer grains in the stir zone.
Ugender (2018)	Worm hole defect was found when implement the rotational speed below 900 rpm. Tunnel defect was found when the rotational speed is higher than 1400 rpm while traverse speed greater than 40 mm/min. Pin holes were detected when the traverse speed is below 25 mm/min.

N. Singh et al., (2018)	Rotational speed and traverse speed at 900 rpm and 45 mm/min respectively before plunging the tool until 0.3 mm deep into AZ91 specimen.
Khayyamin et al., (2013)	Using rotational speed: 1250 rpm and three traverse speeds: (20, 40 and 63) mm/min on AZ91

4. Magnesium and its alloys

Magnesium (Mg) with a blend of different metals is called magnesium alloy. In the current alloying development, the major alloying components are zinc, manganese, aluminum, zirconium, silicon, phenomenal earths and copper. Magnesium compounds have a hexagonal grid structure which made them as the main metal casted alloys applied in parts of vehicles or groups of camera and lenses. In order to solidify compounds of magnesium containing 0.5% to 3% zinc, heat treatment was utilized. Mostly, sand casting parts use combinations of AZ92 and AZ63. AZ91 magnesium composite usually famous in die casting parts while the major parts of perpetual form castings use AZ92 compound.

As reported in the literature, pure magnesium and other magnesium alloys have been utilized to acquire surface metal matrix composites (MMCs) by FSP. Recent studies were carried out using AZ series (aluminum and zinc) of magnesium alloys. Example of the alloys are AZ31, AZ61, AZ91 and ZM21. AZ31 Mg alloy is widely used to develop surface composites by FSP while AZ91-SiC/Al2O3 composites are groups of widely produced by FSP [1,16]. The letter sets speak to the alloying components. For example, letter A refers to Aluminum, Z to Zinc, M to Manganese whereas S refers to Silicon. For instance, AZ91 has a combination of magnesium with the ratio of 9:1 percent weight of aluminum and zinc, respectively [18]. Aluminum provides strength and improves the castability while zinc improves the oxidation resistance of the alloys [7].

Magnesium composites are known as the lightest basic metallic materials that can be accessed economically [19] and mostly applied into various fields such as hardware and electronic building. Magnesium composites are characterized into 13 by extremely constrained flexibility joined at room temperature because It have hexadic close-packed (hcp) characteristic, such a precious metal and fixed accessible structure [3].

5. Latest development of FSP tool

There are some descriptions and parameters that required for each part of the FSP tool developed currently which were listed as shown below:

i. Pin/Probe: is a device inserted into the abutting edge and move along the sheet after produce sufficient heat.
ii. Shoulder: generates heat during FSP due to the larger contact between its surface and material plates.
iii. Hub: works as a holder that connects to the arbor of the milling machine.
iv. Rotational speed: is the tool speed when rotating in order to produce adequate heat by friction.
v. Traverse speed: is the tool's travel speed from one point to another point.
vi. Axial force: is the downward pressure onto the workpiece in creating tolerable heat during FSP.

A cylindrical tool made up of mild steel was used with 4 mm-diameter pin, 4 mm length and 12 mm-diameter shoulder [7]. Ugender [16] utilized tools that were made of stainless steel with 18 mm-diameter nominal shoulder and pin with length of 4.8 mm and diameter of 6 mm. Another review about tool was Khayyamin et al. [17] used two H13 (DIN 2344) hot working steel tools. The first tool was designed without pin and had been utilized to cover the top of the holes to prevent the powder from being scattered during FSP. After the surface of material was prepared using the first tool, the procedure of FSP was completed using another squared pin tool with dimensions of 4.54 mm x 4.54 mm and length of 4 mm.

The geometry of tool gives impact on heat generation, distribution of reinforcement as well as mechanical and microstructural properties. The heat generation emerges from the friction contact between the rotation of tool and material. During material plastic deformation, heat generation occurred. The higher the increment of the rotational speed, the higher the temperature leading to the increment of heat input. Low cooling rate of material flow detected which produces fine grain structure in the friction stirred zone after high heat generated. Major factor that ensures FSP to work effectively was the rotating round shoulder with a pin heating the workpiece by friction [20].

Maximum temperature increased when there were changes in rotational speed on the stirred zone. Furthermore, the shorter time period taken for the material to reach high temperatures. However, there were voids appearance on the surface if the value of tool's rotational speed is too high which can produce defects in the stirred zone due to the material released to the top [21]. The latest development in FSP tool study is summarized in Table 2.

Table 2. Significant findings in latest development of FSP tool

Authors, Year	Findings
N. Singh et al., (2018)	Material: mild steel Dimension: 4 mm-diameter pin, 4 mm length and 12 mm-diameter shoulder
Ugender (2018)	Material: stainless steel Dimension: 18 mm-diameter nominal shoulder, pin length of 4.8 mm and diameter of 6 mm.
Khayyamin et al., (2013)	Material: H13 (DIN 2344) hot working steel The first tool was designed without pin. Second tool was a squared pin tool with dimensions of 4.54 mm x 4.54 mm and length of 4 mm.

6. Enhancement of Mg alloy mechanical properties via FSP

Nowadays, studies on friction stir process only focusing on the investigation of mechanical properties and microstructure of magnesium alloys when the parameters were adjusted alternately. Microstructural studies can be acquired using several methods such as optical microscopy, Scanning Electron Microscopy (SEM), Orientation Imaging Microscopy (OIM) and Transmission Electron Microscopy (TEM). Mechanical properties were also investigated through numerous mechanical tests which are tensile, hardness and microhardness.

N. Singh et al. [7] stated that there was significant grain refinement observed in Mg alloy after FSP. This grain refinement increased the hardness of material as grain size and hardness are inversely proportional to each other. As the results, B4C particles were smoothly distributed along the nugget zone. This situation improved the tribological and mechanical properties of the materials. Microhardness along with B4C particles as well as the wear resistance of the specimens had been improved.

Ugender [16] explained that using lower rotational speed at which 900 rpm, the microstructure showed larger grains in the stirred zone (SZ) due to lesser heat generation causing inadequate flow of the metal. At higher rotational speed of 1120 rpm, it was observed a mixture of coarse and fine grains. There was inferior tensile strength occurred because of increment in temperature from the heat input of the joint as the tool speeds faster. Due to higher heat input, excessive flash was formed at the extreme ends. Fabrication using traverse speed at 40 mm/min produced fine grains. Improvement in tensile strength of the joints can be identified from the existence of well equiaxed grains in the SZ.

Furthermore, Khayyamin et al. [17] stated the consequences of process parameters applied when fabricating AZ91/Sio2 composite by FSP. The findings exposed that when the traverse speed of FSP tool in higher value, the hardness profile of the cross sections of the FSPed specimens improved into greater condition. The specimen's microhardness will be affected by the traverse speed set up during the FSP work. The action of rising the traverse speed had made grain size in the stirred zone decreased hence the strength increased significantly due to exposure time of the metal to heat was shortened.

P. Sevvel and V. Jaiganesh [22] studied on the microstructural properties of AZ80A magnesium alloy with the influence of FSP parameters and the tool profile. It was found the emergence of coarse grains containing intermetallic compounds of Al12Mg17 through SEM image. No uniform distribution of intermetallic compounds in the base metal displayed via SEM image and those intermetallic compounds are fairly coarse. In the nugget area (NZ), the micrographs outcome clearly indicated that the large-size coarse grains are transformed into equidistant fine-sized grains in the base metal after FSP. It can be seen that by maintaining a constant feed rate and tool's rotational speed made the grains became coarser in the NZ. On the other side, finer grains in the NZ were observed by setting up the rotational speed at constant value while simultaneous feed rate increases.

In addition, Seifiyan et al. [23] explained the microstructural findings of the effect of FSP conditions on magnesium alloys AZ31B. SEM has been utilized for the grain structure testing after FSP. It was revealed that the microstructure of base metal came out with combination of coarse and fine grains while the stirred zone did not have distributions of uniform grain size. The grain size was slightly decreased after single-pass of FSP. However, the grain size reduced to one-third of their amount from the original condition of the alloy significantly after the third pass of FSP.

Some microhardness of FSPed specimens were studied by Kumar et al. [24] which focusing on the effect of tool's rotational speed and pin profile on micro hardness of friction stirred aluminum alloys. It was reported that Vickers microhardness was high at 1800 rpm and the value was 97.67 HV. Furthermore, it was also observed the microhardness turned out lower which is at 1400 rpm. The value of hardness of the specimen became not uniform due to the changing pin profile design of tool.

Besides, Venkataiah et al. [25] completed a research on the microstructural and mechanical properties of FSP on magnesium alloy. They explained the structure of fine grain after FSP was considered the key point to the increment of hardness of a specimen. Both, the width of the stirred region and the rate of material flow was observed to decrease as machine rotational speed and traverse speed were increased. Among the results, the specimen fabricated using higher rotational speed and lower traverse speed came out with the higher grain density and hardness. Using other parameter combinations, it showed the width of the stirred zone is bigger than the non-defect stirred zones on the same specimen. The researchers believed that tool's rotational speed affects the grain refinement level and the width of stirred zone whereas the material flow rate influenced by the tool's traverse speed during the FSP. The important research on the enhancement of Mg alloy mechanical properties via FSP is summarized in Table 3.

Table 3. Significant findings in enhancement of Mg alloy mechanical properties via FSP

Authors, Year	Findings
N. Singh et al., (2018)	The grain size was decreased considerably consequently, the microhardness was improved. Increased microhardness along with B4C particles improved the wear resistance of the specimens. Microhardness was increased with the increase in particle size.
Ugender (2018)	Improvement in tensile strength of the joints can be identified from the existence of well equiaxed grains in the SZ.
Khayyamin et al., (2013)	For AZ91, when traverse speed of FSP tool in higher value, the hardness profile of the cross sections of the FSPed specimens increased.
Sevvel et al., (2016)	Constant feed rate and tool's rotational speed made the grains on AZ80A became coarser in the NZ. Finer grains were observed at constant rotational speed while simultaneous feed rate increases.

Seifiyan et al., (2019)	Grain size was slightly decreased after single-pass of FSP. Grain size reduced to one-third of their amount from the original condition of the AZ31B significantly after the third pass of FSP.
Kumar et al., (2017)	Focusing on the effect of tool's rotational speed and pin profile on micro hardness of friction stirred aluminium alloys.
Venkataiah et al., (2019)	Width of the stirred region and the rate of material flow was observed to decrease as machine rotational speed and traverse speed were increased. Higher rotational speed and lower traverse speed came out with the higher grain density and hardness. Rotational speed affects the grain refinement level and the width of stirred zone. Traverse speed influences the material flow rate.

7. Conclusion

This paper presents a review on latest development of friction stir processing of magnesium alloys. Even though with different composition, surface of magnesium composites and its alloys were discovered to be easily processed using FSP. The machining parameters such as rotational and traverse speeds are the main factors to produce defect free stir zone in FSW of magnesium alloys. It is need to be optimized for every material system to alter the micro structure and mechanical properties based on our preferences since fabrication of surface composites by FSP is greatly influenced by these parameters.

As there are no standards yet for running the FSP, the option to try and error is to get the best parameter that can produce good FSP quality. The most important is to make sure there is sufficient heat generation by setting up the suitable and convenient rotational speed of the tool and traverse speed. The difference of tool's pin profile also gives impact to the FSP outcome. Grain refinement, hardness improvement and mechanical behavior are the common findings among the magnesium-based composites from FSP experiment.

To improve the mechanical properties of magnesium alloys, it can be concluded that by maintaining a constant tool's rotational speed and feed rate made the grains became coarser in the NZ. Finer grains were found by setting up the rotational speed at constant value while feed rate increases simultaneously. The higher the traverse speed of FSP tool, the higher the hardness of the cross sections of the FSPed specimens. The condition leads to better condition of profile. To be accurate, rotational speeds must be in the range of 900-1400 rpm so that no defects can be detected. Besides, traverse speeds must be in the range of 25-40 mm/min to prevent pin holes and tunnel defect on material. Researchers believed that tool's rotational speed affects the grain refinement level and the width of stirred zone but the material flow rate was influenced by the tool's traverse speed.

AZ series magnesium alloys were mostly being applied in FSP work. It is anticipated that other magnesium alloys also will be developed in future for a wide range of applications. To conclude, magnesium alloys are good material for FSP if the usage of parameters are suitable to get great results, therefore the parameters should be further tested.

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