Investigation on the Effect of Machining Parameters on Mechanical Properties of Friction Stir Processed Mg–Al-Micro Al_2O_3 Metal Matrix Composites

Zuhairah Zulkfli, M. Faris Zaidi, Nanang Fatchurrohman, and Zamzuri Hamedon

Abstract Low density of magnesium makes it an ideal choice as it is lighter than steel and aluminium alloys. Combination of cast magnesium alloys component can be used widely in the automobile sector and factories but were restricted. Friction stir processing is an infinite machining operation used to enhance the structural workpiece in solid-state strengthening. By using a straight cylindrical tool pin profile which will be used throughout this study, the effects of FSP parameters on magnesium AZ91A can be investigated. Variation of feed rates, (10–58) mm/min with a fixed rotational speed, 1208 RPM were applied for each single FSP pass. Mg alloy will be plated with Al6061 sheets and reinforced with Al_2O_3 particles before running FSP. Mechanical properties and metallographic requirements are the characterizations in investigating the effects of machining parameters of FSPed workpiece. Both characterizations can be gained via Rockwell hardness test and optical microscopy. Finally, this study discovered that the average hardness of FSPed Mg–Al-Micro Al_2O_3 was reduced significantly with the increment of feed rates. Next, improved hardness at HAZ points as well as reduced surface roughness at three distances from FSP starting point were detected.

Keywords Friction stir processing (FSP) · Machining parameters · Magnesium AZ91A · Al6061 · Metal matrix composite (MMC) · Hardness · Surface roughness

1 Introduction

Increasing demand for functional properties of production components as well as the need to reduce the mass of a system reflect the functional properties required

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in developing material engineering surface layers. Surface spraying or re-melting using laser beam are the most widely used technique in surface layer processing which reported for years [1]. Matrix composites exhibit higher mechanical properties than unreinforced alloys. It had been used for broad range of applications due to high specific strength, stiffness, wear resistance, good damping capacities, dimensional stability and machinability [2]. Friction stir processing (FSP) of surface layers is a modernized technique nowadays. Friction created between the spinning tool and workpiece helps to heat and soften the material under FSP tool surface [3]. The FSP approach is mainly used for microstructure modification of refined metal components and produce a surface layer of composite to improve the material's mechanical properties [4]. Therefore, better grain construction, surface composite, microstructure change of casting composites, blending with rare components and rise the stability of welded joints can be produced by this process [5].

Due to low strength properties of magnesium (Mg) AZ91A, FSP experiment has been carried out using different machining parameters in order to alter the mechanical properties of the workpiece. Moreover, this study analyses the effects of different machining parameters applied on the Mg AZ91A workpiece mainly on mechanical properties and microstructure as the output characterizations.

The interaction between the FSP machining parameters and comparative results on FSPed magnesium AZ91A concentrating on the mechanical properties of Mg–Al-Micro Al_2O_3 before, during and after the process were considered. FSP parameters involved were the cutting depth [6], rotational speed and traverse speed [7, 8]. These parameters were intended to investigate the relationship between the different processing parameters and hardness. Secondly, to analyse the surface roughness and microstructure of the machined workpiece. The samples will be observed using the LEXT™ OLS5000 Laser Scanning Microscope to examine the surface roughness and microstructure of FSPed workpiece while utilizing the Rockwell hardness tester for hardness testing.

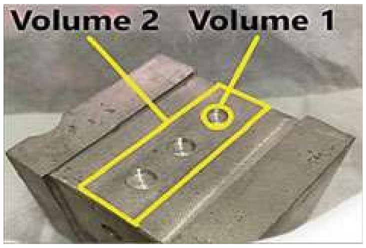
2 Methodology

2.1 *Material Preparation*

Before starting the FSP process, materials were prepared using the procedures as follows: (1) Starting with a primary machining using horizontal and vertical band saw, the raw magnesium AZ91A block was cut. (2) Then, the blocks undergo squaring process using milling machine. (3) The squared blocks will be slotted 30 mm-width and 1.2 mm-depth. (4) Then, three 6 mm-diameter holes were drilled until 3 mm deep. (5) Al6061 sheets were bent.

Reinforcement Volume Fraction. The volume fraction measurement was done to ensure the FSP reinforcement of aluminum oxide (Al_2O_3) particles efficiency is between 20% and 40%. The reinforced Al_2O_3 particles with ($\leq$ 10 μm average

Fig. 1 Volume area for measurement



particle size) was used in this study. The area considered for volume fraction measurement calculation was selected (see Fig. 1).

$$\begin{aligned} &= \frac{\mathbf{Volume}\,1}{\mathbf{Volume}\,2} \times 100\% \\ &= \frac{3\left(\pi r^2 \mathbf{h}\right)}{\mathbf{W} \times \mathbf{D} \times \mathbf{H}} \times 100\% \\ &= \frac{3\left(3.142 \times 3\,\mathbf{mm}^2 \times 3\,\mathbf{mm}\right)}{22\,\mathbf{mm} \times 18\,\mathbf{mm} \times 3\,\mathbf{mm}} \times 100\% \\ &= 21.42\% \end{aligned} \tag{1}$$

2.2 *Tool Preparation*

Tools were prepared using the procedures: (1) H13 steel rod was cut into 100 mm length using Way Train horizontal band saw machine. (2) Straight cylindrical tools were fabricated into dimension using ROMI C 420 CNC lathe machine which mainly consists of a shoulder diameter (D): 18 mm, pin diameter (d): 6 mm and pin length (L): 3 mm (see Fig. 2).

2.3 *Friction Stir Processing Experimental Setup*

The experiment setup proceeded with the FSP of Mg–Al-Micro Al_2O_3 metal matrix composites with the variation of feed rates chosen to boost the strength of base material (BM) of magnesium. Based on literature review [9], the optimum machining parameter that enhanced mechanical properties for FSP of magnesium alloy AZ91 were between 10 and 58 (mm/min) at fixed 1208 RPM rotational speed. Six FSP samples were processed by a single pass with feed rate variations listed in Table 1.

To summarize, subsequential FSP experiment setups were as follows: (1) The Mg workpiece holes were filled with Al_2O_3 powder. (2) Then, Mg workpiece was plated with aluminium sheet, Al6061 and clamped together to avoid slipping during high-speed machining. (3) Start running FSP using manual mode. (4) To proceed, the

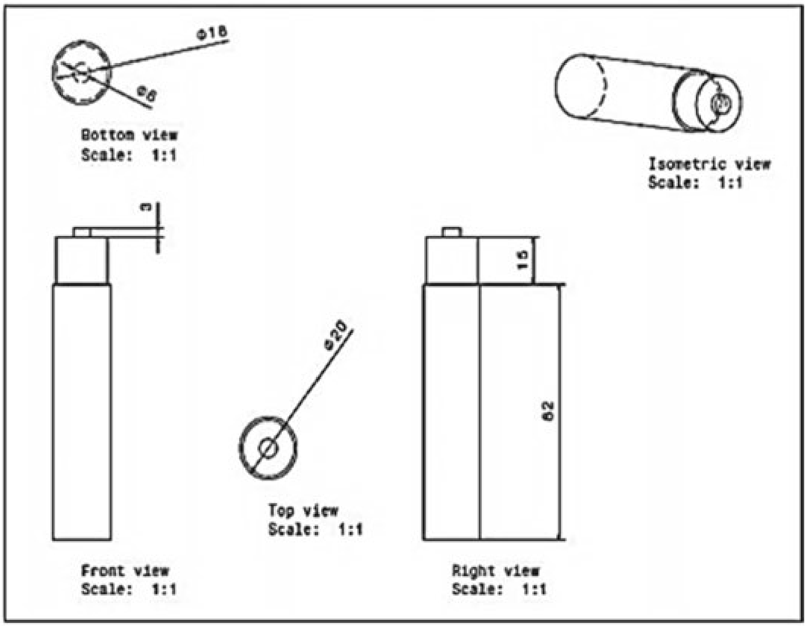


Fig. 2 FSP tool dimension for cylindrical pin profile

Table 1 FSP machining parameters for magnesium alloy AZ91

Feed rate (mm/min)	Rotational speed (RPM)	Depth of tool pin (mm)
10	1208	3.3
17	1208	3.3
25	1208	3.3
34	1208	3.3
46	1208	3.3
58	1208	3.3

samples need to be faced mill again as both materials, Mg–Al were bounded together after FSP to obtain flat surface area. (5) The samples were ready to be used for data collection of hardness test, surface roughness test and microstructure observation.

2.4 Characterization

Hardness Test. Hardness test is one of effective techniques to measure the strength of a structured material. Using Rockwell Hardness Tester, the hardness readings were taken in seven different areas along the traverse FSP line with 3 mm interval difference between each location. The hardness for heat affected zone (HAZ) were taken from point 1–4 with 1 mm interval difference between points from FSP zone.

The hardness measurement procedures were repeated for all the samples. The average hardness values will be calculated after testing completed.

Surface Roughness Test and Microstructure Observation. The surface roughness testing and microstructure of FSPed samples were measured and observed, respectively using the LEXT™ OLS5000 3D Laser Scanning Microscope. The surface roughness test was fixed at three different FSP traverse location on each sample which distanced 10 mm, 20 mm and 30 mm from the starting point. This step was performed to observe the different characteristics on surface after FSP.

3 Results and Discussion

Present analysis focusing on hardness test, surface roughness test and microstructure observation after processing Mg–Al-Micro Al_2O_3 with different feed rates which were (10, 17, 25, 34, 46 and 58) mm/min.

3.1 Hardness Test

The effect of feed rate on the resulting average hardness was illustrated (see Fig. 3). The average hardness decreased from 49.71 HRB to 29.71 HRB. The increment of feed rates will limit the processed area's exposure time to the temperature generated from the rotating tool, hence can rise the temperature attained during the operation. Further refinement can be achieved as the feed rate increases which leads to decrement of the average hardness. However, the average hardness values are higher than as-received Mg AZ91A hardness value which is 29.14 HRB. Hence, this experiment was acceptable since the hardness of FSPed workpiece increased than the hardness of as-received Mg AZ91A.

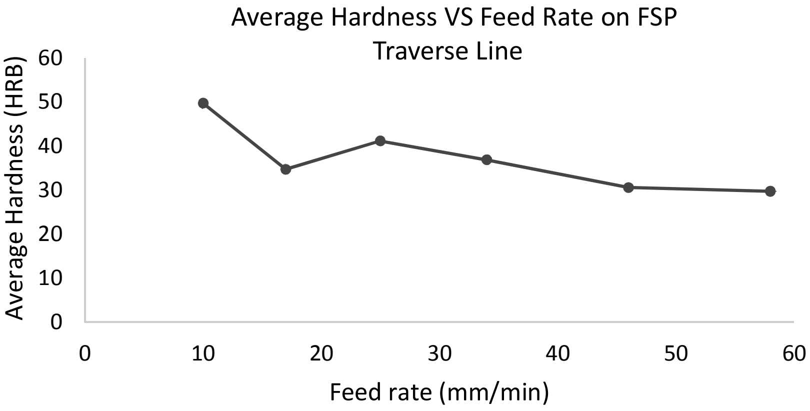


Fig. 3 Average hardness of FSPed Mg–Al-Micro Al_2O_3 against feed rate on FSP traverse line

By increasing the feed rate also reduce the hardness of heat affected zone (HAZ) which distanced 1 mm interval from FSP traverse area. The HAZ hardness values were always lower than FSP traverse area. The hardness values of HAZ points were lower than the average hardness on FSP traverse line for each feed rate. For example, HAZ 1, HAZ 2, HAZ 3, HAZ 4 has hardness values of (8, 20, 38, 46) HRB, respectively which lower than 49.71 HRB average hardness on FSP traverse line at 10 mm/min (see Fig. 4). This was caused by failure of mechanical deformation (stirring) in HAZ although the maximum temperature reached, it is adequate for the material to be softened and weaken the hardness around the nugget zone.

Nevertheless, increasing feed rates have an equal effect as increasing rotational speed on hardness FSPed Mg–Al-Micro Al_2O_3 which greater strength can be achieved with hardness value of (up to 49.71 HRB) compared to FSPed Mg AZ91A with hardness value of 30.33 HRB at 10 mm/min feed rate. As the FSP experiment carried out without measuring the temperature, the workpiece assumed to be over-heated during the machining resulting from rising axial load during feed rate increment between (10 and 58) mm/min. The workpiece was refined hence, hardness was increased.

On the contrary, past study on AZ31 Mg alloy conducted by Darras et al. [9] discovered that the refinement of average grain size was observed from 6 μm to an average size of 3–4 μm. Generally, the established Hall–Petch relationship proved that the hardness is inversely proportional to grain size. Grain refinement increased the hardness from 62 to 72 HV when using increasing feed rate of (20–30) in/min at 1200 rpm.

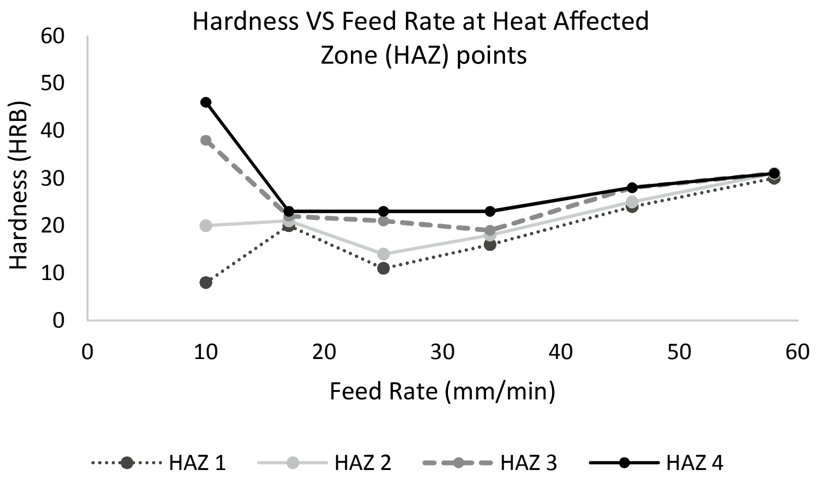


Fig. 4 Hardness of FSPed Mg–Al-Micro Al_2O_3 against feed rate at four HAZ points

3.2 Surface Roughness Test and Wear Characteristics

The correlation between feed rate and surface roughness were investigated by Ramezani et al. [10]. The study critically examined the surface quality and product life via surface roughness. Components with a high surface roughness tends to break easily and have a shorter lifetime due to smaller stress concentration and larger surface roughness. The relationship between feed rate and surface roughness was found (see Fig. 5). As the feed rate increases, the average surface roughness calculated declined from 31.948 to 5.603 µm. This shows that the FSPed Mg–Al-Micro Al_2O_3 have lower tendency to break which leads to longer lifetime as the feed rate increases.

An increase in sliding distances in the traverse motion led to lower surface roughness related from increasing feed rate (see Fig. 6). The graph shows the same trend of surface roughness values for each distance except the surface roughness at 34 mm/min. Furthermore, it shows that lowest surface roughness values (14.044, 6.838, 13.853, 8.613, 4.575 and 3.118) HRB for (10, 17, 20, 34, 46 and 58) mm/min feed rates, respectively at distance 10 mm where the surface mapping at the same position was the roughest, whereas the highest surface roughness values (52.616, 16.699, 22.621, 35.009, 8.698 and 8.584) HRB for (10, 17, 20, 34, 46 and 58) mm/min feed rates, respectively at distance 30 mm where the surface mapping was the smoothest.

Table 2 consists the surface mapping of FSPed samples at different feed rates. From the surface mapping results, there were several significant adhesive wears approaching to the end of traverse line FSP. Severe adhesive wears were validated by the surface damage with crates or ploughs of rough area [11]. It was shown that the surface mapping at 30 mm from starting point for each feed rate variations contain the biggest size of harsh debris. Debris formed on the surface shows that adhesive mechanism dominates from high feed rate at a longer sliding distance.

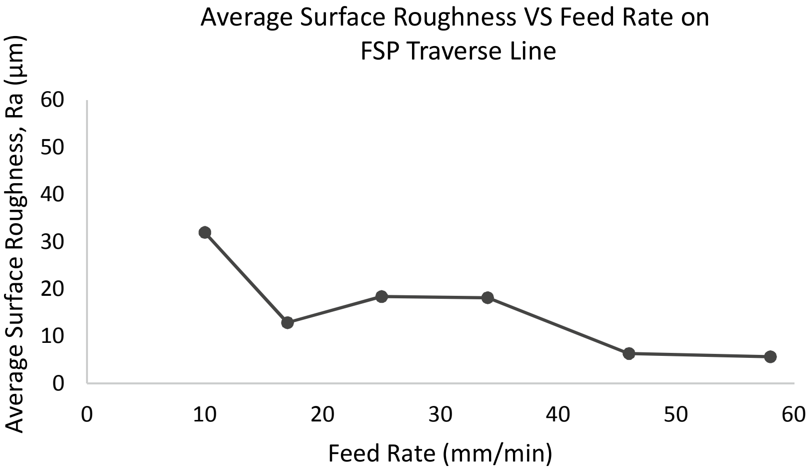


Fig. 5 Average surface roughness of FSPed Mg–Al-Micro Al_2O_3 against feed rate on FSP traverse line

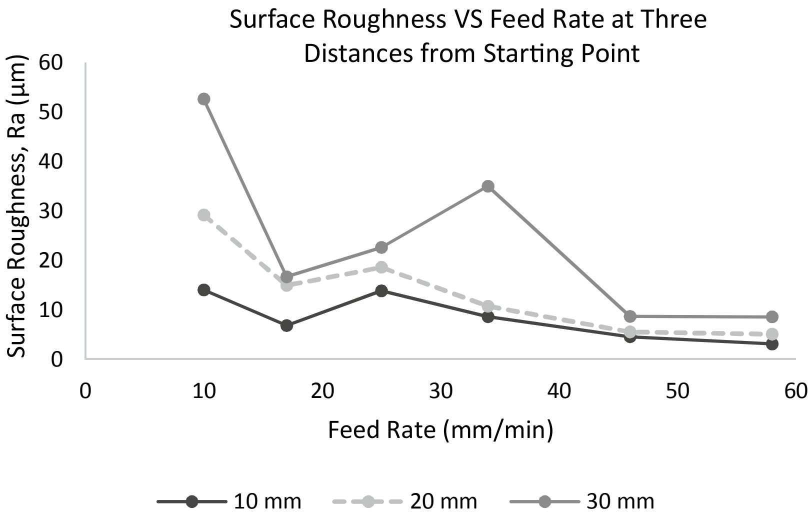


Fig. 6 Surface roughness of FSPed Mg–Al-Micro Al_2O_3 against feed rate at three distances from starting point

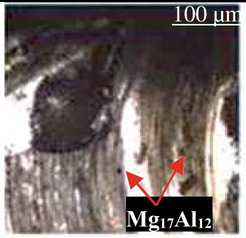
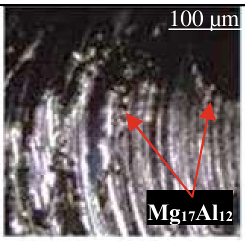
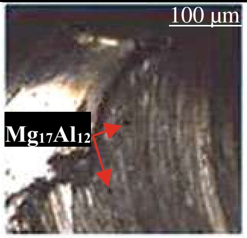
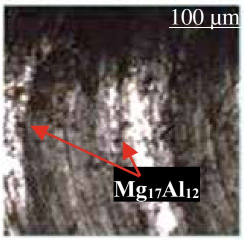
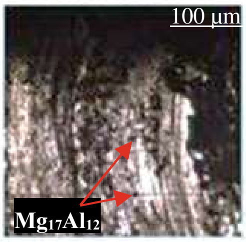
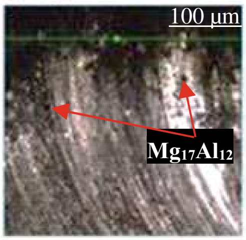
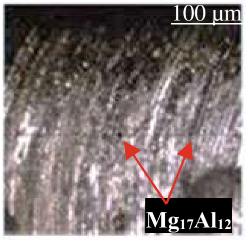
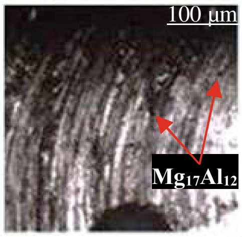
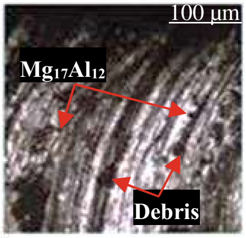
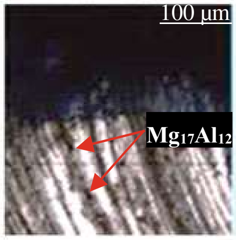
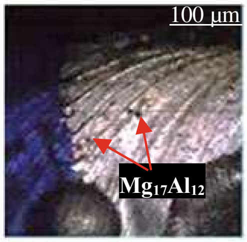
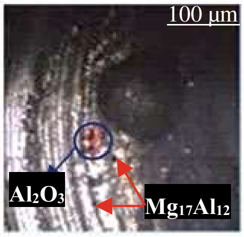
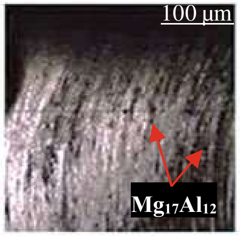
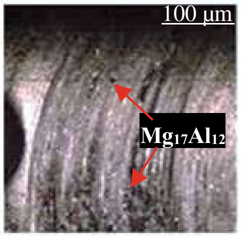
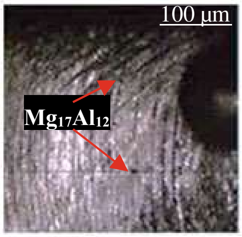
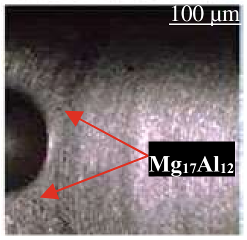
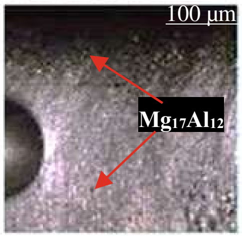
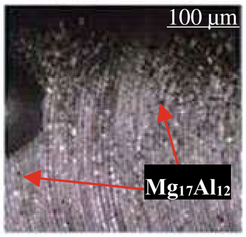
The accumulation and elimination of wear debris occurred when there was feed rate increment with sliding distance. As the distance towards the end point increases, the grooves become deeper which means the abrasive wear increases due to large amount of plastic deformation leading to lower hardness when compared to hardness at starting point for each feed rate.

In addition, abrasive wear is a mechanism of sliding abrasive that ploughs and removes the surface of softened materials outside the groove [12]. The longer the sliding distances, the longer contact time between the surfaces of workpiece and tool. Higher rate of adhesive wear can be produced. Formation in situ of particles from contact with the surface of workpiece emerged as abrasive wear when hardened particles bound together with the moving tool along the traverse motion thus increase the tool's roughness. However, rough tool shoulder gradually softened the workpiece when there is constant contact [11].

4 Conclusion

To conclude, different feed rates (10–58) mm/min were applied. The results clearly show that processing parameters influence the hardness of the processed workpiece. The size of the grain was significantly reduced due to high temperature and improved hardness at HAZ points, thus reduced the surface roughness at three distances from FSP starting point. However, the average hardness of FSPed Mg–Al-Micro Al_2O_3 was reduced significantly with the increment of feed rates. In addition, surface roughness of each FSP tool pin needs to be strictly adjust and control during fabrication as the tool's surface roughness also affect FSP for prospect advancement.

Table 2 Mapping of samples taken by LEXT™ OLS5000 laser scanning microscope

Feed rate (mm/min)	Distance from starting point (mm)		
	10	20	30
10			
17			
25			
34			
46			
58			

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