Wear Resistance Increase by Friction Stir Processing for Partial Magnesium Replacement in Aluminium Alloys

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Abstract. In this paper, the influence of friction stir processing (FSP) was evaluated as a way of increasing mechanical properties and a way of replacing the magnesium content in aluminium alloys. FSP was done on AA5754 H111 aluminium alloy, containing 3 % Mg, by using various types of tools and different welding speeds, rotational speeds and tilt angles. Wear test was done against SiC abrasive papers. SiC was used to simulate extreme abrasive wear conditions. The wear test was done on untreated AA5754 specimens, processed AA5754 specimens and untreated AA5083 H111 specimens, the latter containing 4.5 % Mg. AA5083 was chosen as an alternative to AA5754, but with a significantly higher Mg content. Base material microhardness was 60 HV1 and 80 HV1 for AA5754 and AA5083 alloys respectively. To find the effect of FSP on AA5754 alloy, microstructures were studied, mainly grain size in the stir zone. It was found, that an elevated processing and rotational speed, without tilt angle and the tool without a reservoir resulted in an increase in hardness of the AA5754 to 70 HV1, but with the occurrence of tunneling defect and the wear rate of 79.3 mg. Lower FSP parameters and a tilted tool with a reservoir resulted in microhardness of 68 HV1 and wear rate of 68.2 mg without tunneling. These wear values are lower than those obtained with unmodified Al-alloys: AA5754 97.2 mg and AA5083 86.3 mg. An increased wear resistance can be attributed to the combined effect of grain boundary strengthening mechanism and solid solution strengthening, versus only the latter in untreated alloys.

1. Introduction
The relatively high specific strength and particularly specific stiffness of aluminium and its alloys due to low density make them suitable for a significant number of applications in aerospace and automotive industries. There has been a tendency to improve these properties even more, because of increasing need of high strength to weight ratio. However, in increase in demand for aluminium alloys is in contrast to the most common alloying elements availability. Namely, one of the most common alloying elements is magnesium, which is considered to be a critical raw material (CRM) for European Union [1]. One of the accepted methods for improving mechanical properties alloys is grain refinement strengthening mechanism through friction stir processing (FSP). It has several advantages: it can be used to fabricate metal matrix composites; microstructure and mechanical properties of the processed zone can be accurately controlled by optimizing the tool design and process parameters, providing good mechanical properties in the as-processed condition [2]. It can be used for superplastic forming (SPF) by achieving
the high-strain rate superplasticity (HSRS) at lower temperatures [3]. Also, it can be easily automated on specialized or simple universal milling machines, with a relatively low environmental impact [4, 5].

The FSP is a variation of friction stir welding (FSW), a solid state joining process invented at The Welding institute (TWI), UK in 1991, as a technique for joining Al alloys. However, instead of FSW the FSP was developed to modify the microstructure of metallic parts. [6-11]. The FSP has been successfully applied to modify the microstructure of various cast metal, to improve the mechanical properties [11-15]. For example, in [12] after FSP, yield and tensile strength were improved by thirty percent over the base aluminium 2285 alloy. In casts A319 and A356, FSP was applied to reduce porosity and to create more uniform distributions of second-phase particles. As result, the ultimate tensile strengths, ductilities, and fatigue lives of both alloys were increased [13]. In [14], the hardness and tensile strength of the friction stir-processed 1050 aluminum alloy increased significantly. However, since the technique is relatively new there is certainly a need for a better scientific understanding.

The aim of this paper is to study the influence of different tool geometries and process parameters on mechanical properties and microstructure of Al-Mg alloy. The main aim is to develop fine-grained microstructure by the FSP, which reflects an increase in hardness and wear resistance, compared to a Al-Mg alloy with a higher Mg content in order to provide a reduction of Mg which is a CRM.

2. Experimental
In this study, the specimens used for the friction stir processing were made of EN AW 5754 H111 plates, 8 mm thick, having the dimensions 130 mm × 100 mm. The chemical composition of the aluminum alloy was determined by using ARL 3580 optical emission spectrometer, Table 1. In Table 1, the chemical composition of the comparative EN AW 5083 H111 is shown. The specimens were placed into a steel fixture within a 130 mm groove and secured in place by several clamps. The fixture was fitted onto an adapted Prvomajska UHG universal milling machine. The tools used were made of H11 hot-work tool steel, with the hardness of 62±2 HRC. Tool geometry is shown in Figure 1. Three types of tool geometries were used: a) with a flat shoulder and cylindrical pin with a thread, b) with concave shoulder and square pin and c) with three concentric reservoirs with a square pin. The FSP parameters are shown in Table 2. The plunge depth of tool shoulder was 0.2 mm for all FSP samples.

The properties of the FSP samples were determined using microhardness testing, metallographic examination and wear testing. Microhardness was determined with Wilson Tukon 1102, with a 1-kg load. To obtain the microhardness profiles the microhardness measurements were done using a 0.5 mm distance between the indentations and 1 mm from the surface as shown on Figure 2. The metallographic examination was done after the standard preparation procedure: grinding with sandpapers (grit 220 to 2000), polishing with diamond suspensions (6, 3, 1 and 1/4 μm abrasive-grain sizes) and etching with Keller’s reagent (2 mL HF, 3 mL HCl, 5 mL HNO3, 190 mL H2O). The metallographic samples were examined with a Leitz Orthoplan light microscope. The wear testing was conducted on a pin-on-disc method, with the following parameters: sample size 10×10 mm; SiC grinding paper with grit size P600 for 1 min under 1kg load. The specimen followed the path 70 mm away from the abrasive paper center, with water flow maintained at 10 ml/min. Testing specimens followed the same wear path. Spindle speed was 250 min⁻¹, providing 110 mm wear path. Before testing, each specimen was ground up to 2000 grit abrasive paper, to the surface Ra of 0.07 μm. Each wear test was conducted on three specimens and the average mass loss was reported.

Table 1. Chemical composition of aluminium alloys (in weight %)

| Alloys     | Cu  | Mn  | Mg  | Si  | Fe  | Zn  | Ti  | Cr  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| EN AW 5754 | 0.05| 0.33| 3.10| 0.33| 0.37| 0.06| 0.025| 0.039|
| EN AW 5083 | 0.07| 0.57| 4.10| 0.26| 0.32| 0.07| 0.026| 0.10|
Figure 1. FSP tools: a) cylindrical profile with a flat shoulder with tread (type I), b) feature shoulder with three concentric circles with the overall-volume-to-pin ratio of 0.5 (II-type) and c) concave shoulder with the shoulder-to-pin volume ratio of 0.5 (III-type).

Table 2. Friction stir processing parameters

| Specimen designation | Rotational speed [min⁻¹] | Processing speed [mm/min] | Tool tilt [°] | Tool type |
|----------------------|--------------------------|---------------------------|---------------|-----------|
| 1                    | 710                      | 40                        | 0             | I         |
| 2                    | 710                      | 20                        | 0             | I         |
| 3                    | 560                      | 40                        | 0             | I         |
| 4                    | 560                      | 20                        | 0             | I         |
| 5                    | 560                      | 40                        | 3             | I         |
| 6                    | 560                      | 20                        | 3             | I         |
| 7                    | 450                      | 40                        | 3             | I         |
| 8                    | 450                      | 20                        | 3             | I         |
| 9                    | 450                      | 20                        | 3             | II        |
| 10                   | 450                      | 20                        | 3             | III       |

Figure 2. Hardness measurement distribution scheme
3. Results and discussion

3.1 Macro imagery

The metallographic images of samples processed with tool I and the processing speed of 40 mm/min are presented in Figure 3. In Figure 3 a,b samples without tilt angle and with rotational speed of 710 min⁻¹ and 560 min⁻¹ are depicted. Samples with tilt angle 3° and with rotational speeds 560 min⁻¹ and 450 min⁻¹ are shown in Figure 3 c,d. It can be seen that the tunnel-like defects occur in all samples in Figure 3. The defects become smaller as the rotational speed is reduced and the tilt angle is introduced. These defects are typical for FSW/P samples if the processing conditions i.e. processing speed, tool rotation etc. fail to generate the required heat for bonding, inadequate material mixing and stirring can occur, resulting in the formation of tunnel defects [16, 17]. In [17], it has been shown that most notable influence on the size and shape of the defects have rotational and processing speed and plunge downforce. A similar trend can be seen in Figure 4, where macro images of samples processed tool type I and 20 mm/min processing speed. In Figure 4 a,b samples without tilt angle and with rotational speeds 710 min⁻¹ and 560 min⁻¹ are given while in Figure 3c,d, samples with tilt angle of 3° and with rotational speeds 560 min⁻¹ and 450 min⁻¹ are shown, respectively.

![Figure 3](image-url)

Figure 3. Macrographs of samples processed with tool type I; processing speed 40 mm/min and different rotational speeds (ω): a) with ω=710 min⁻¹ and without tilt angle; b) with ω=560 min⁻¹ and without tilt angle; c) with ω=560 min⁻¹ and with tilt angle 3°; d) with ω=450 min⁻¹ and with tilt angle 3°.

In all samples tunnel-like defects occur in bottom section of the NZ (nugget zone). The macrostructures of the HAZ (heat affected zone) and TMAZ (thermomechanical zone) zones are similar in all samples processed with tool type I. Also in all samples the NZ has finer grain structure compared to basic material.

In Figure 5, samples processed with 20 mm/min, 450 min⁻¹, tilt angle 3° and tool type II (Figure 5a) and type III (Figure 5b) are shown. In both samples, no tunnel-like defects are present. Microstructure in the NZ is also finer compared to the basic material.
Figure 4. Macrographs of samples processed with tool type I; processing speed 20 mm/min and different rotational speeds: a) $\omega=710 \text{ min}^{-1}$ and without tilt angle; b) with $\omega=560 \text{ min}^{-1}$ and without tilt angle; c) with $\omega=560 \text{ min}^{-1}$ and with tilt angle $3^\circ$; d) with $\omega=450 \text{ min}^{-1}$ and with tilt angle $3^\circ$.

In Figure 6, it can be seen that the microstructure in the NZ in samples processed with tool type I is finer than that of tool types II and III. Furthermore, the microstructure of sample processed with tool type II is slightly finer than microstructure obtained with tool type III.

All samples processed with the tool with a flat shoulder Figure 1a developed a tunnel-like defects. This phenomenon is the result of the tool-shoulder geometry and, therefore, its influence on the material flow. Even a relatively small reservoir Figure 1c and d provides a more convenient material flow. This allows the material to move not only perpendicularly to the tool axis, as forced by the pin, but also in parallel to the tool axis, eliminating the tunnel-like defect at a lower processing and rotational speed [9, 11, 15]. At a constant rotational speed, a relatively low processing speed causes an increase in the stirring-impulse frequency at a given processed length, leading to a more effective filling and defect avoidance. These results support the findings from [18], where the influence of a tunneling-type defect on the mechanical and metallurgical properties of an Al-Mg alloy friction stir welded was studied.

Figure 5. Macrographs of samples processed with rotational speed 450 min$^{-1}$; processing speed 20 mm/min; tilt angle $3^\circ$: a) tool type II; b) tool type III.
Figure 6. Microstructure of processed samples at locations shown in Figures 4 and 5 indicated by white arrows at processing speed 20 mm/min, rotational speed 450 min⁻¹: a) base material; b) tool type I; c) tool type II d) tool type III

3.2 Hardness profiles

Hardness profiles of FSP specimens are presented in Figures 7 and 8. Hardness profiles of samples processed with tool type I are shown in Figure 7. Hardness profiles have a similar shape, with the maximum attained hardness values at the middle of the chart, that is, in the NZ. These results are supported by the microstructural analysis which indicates that in the stir zone (NZ), the highest refinement was observed. Also, the hardness in the NZ is higher for the samples processed at smaller processing speeds. Finally, the decrease in the rotational speed and the introduction of tilt angle causes a drop in hardness.
Figure 7. Microhardness profile of samples processed with tool type I; processing speed: a) 20 mm/min and b) 40 mm/min and different rotational speeds, tilt angle 3°

Hardness profile of samples processed with tool types II and III are depicted in Figure 8. There are generally slightly lower hardness values in sample processed with tool geometry II. The hardness values in Figure 8 are lower than profiles in Figure 7 for the same processing and rotational speeds. Most notably, the area with increased hardness is wider, due to a wider shoulder in type I tool. This, together with a shallower pin, with a longer travel of material in vertical plane, results in a more uniform hardness distribution in tool types II and III.

Figure 8. Microhardness profile of samples processed with tool type II and III; processing speed 20 mm/min, rotational speed 450 min⁻¹ and with tilt angle 3°
3.3 Wear testing

Wear testing results are shown in Table 3. Wear testing was done on the base metal (EN AW 5754), the comparative material with increased Mg content (EN AW 5083). Also, wear rate was measured on two of the processed specimens. Firstly, the specimen 10, without tunneling defect, obtained with tool type III, as the one having a higher hardness in the majority of areas compared to the specimen obtained with tool type II. Finally, the wear rate was determined on specimen 2, processed with tool type I, rotation speed 710 mm\(^{-1}\) and processing speed of 20 mm/min. This particular specimen is of interest, since the tunneling defect is the most pronounced. Tunneling of this extent could be of interest for compact heat exchangers [19].

Wear rates in terms of mass loss of selected specimens is shown in Table 3. It can be seen that the highest wear rate, that is, the lowest wear resistance has the EN AW 5754 base metal, followed by the harder EN AW 5083 alloy. Friction stir processed specimens 2 and 10 performed the best, although their hardness does not exceed the hardness of the EN AW 5083 alloy. The lowest mass loss was measured in specimen 10, obtained with polygonal tool with reservoir without the tunneling. This relatively high wear resistance compared to unprocessed specimens can be the result of the combined work hardening, grain boundary strengthening mechanism originated from the friction stir process and solid solution strengthening from the alloy itself, compared only to solid solution strengthening in the untreated alloys.

| EN AW 5754 | EN AW 5083 |
|------------|------------|
| Base material; 60 HV1 | Specimen 2; 70 HV1 | Specimen 10; 68 HV1 | Base material; 80 HV1 |
| Mass loss [mg] | 97.2±5 mg | 79.3±6 mg | 68.2±5 mg | 86.3±6 mg |

4. Conclusions

According to the presented results and within the limitations of the experiment setup, the following conclusions can be drawn:

- An elevated processing and rotational speed, without tilt angle and the tool without a reservoir resulted in an increase in hardness of the AA5754, but with the occurrence of tunneling defect and wear rate of 79.3 mg.
- Lower FSP parameters and a tilted tool with a reservoir resulted in microhardness of 68 HV1 and wear rate of 68.2mg without tunneling.
- These wear values are lower than those obtained with unmodified Al-alloys: AA5754 97.2 mg and AA5083 86.3mg.
- An increased wear resistance can be attributed to the combined effect of grain boundary strengthening mechanism and solid solution strengthening, versus only the latter in untreated alloys.

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