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Surface Hardening of Aluminium Alloy with Addition of Zinc Particles by Friction Stir Processing

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Abstract: Mechanical alloying can be carried out by a method known as friction stir processing, whereby solid Zn particles in a solution are distributed onto an aluminium alloy plate. The aim of this study was to determine the effects of a volume of Zn particles on the mechanical and physical properties of aluminium 1xxx alloy that had been subjected to friction stir processing. The specimens were plates composed of 1xxx series aluminium. A groove, measuring 12 mm in diameter, was pierced to various depths, and the Zn particles in these containers were then subjected to friction stir processing using a pin-less tool with a diameter of 15 mm. The results showed that the highest hardness was found in the uppermost layer of the workpiece, and this gradually decreased with thickness. An increase in the amount of Zn particles caused an increase in material hardness. The highest hardness of 87.1 HV in the friction stir-processed AA1100 was obtained at the highest volume of Zn compared to the hardness of 44.5 HV, which was obtained for the specimen without the addition of Zn.

Keywords: Friction stir processing; surface hardening; zinc particle addition

1 Introduction

The use of aluminium alloy in vehicle components is very important for improving fuel efficiency. Aluminium alloy has mild strength properties and good formability compared to steel [1]. Efforts to improve the mechanical properties of aluminium can be achieved by several methods including heat treatment, mechanical treatment, coating treatment or surface treatment [2]. Generally, the aim of these treatments is to obtain the desired properties by modifying the microstructure of the material [3]. One such effort to improve the mechanical properties of aluminium is surface treatment. This treatment is aimed at increasing the corrosion resistance, wear resistance, electrical resistance, material strength, and good weldability [4] of the material. Generally, the failure of a component starts from the surface and then, develops into a structural failure [5].

One method of surface treatment is friction stir processing (FSP), which can be used to enhance the mechanical properties and modify the microstructure of a material. Investigation on FSP in laboratory scale has been conducted by some researcher. In FSP, a rotating tool, consisting of a shoulder and a pin, is plunged at a certain rotating speed into the surface of the workpiece so that the pin pierces and the shoulder scrapes the surface of the workpiece. The friction between the tool and the surface of the workpiece will give rise to frictional heat, thereby softening the surface of the workpiece [6, 7]. FSP produces a defect-free material with finer grains [8]. In addition, FSP also improves the processing of solid solutions to enhance the mechanical properties of materials [3].

Additional material particles used in improving mechanical properties in the FSP are ceramics particles such as Al₂O₃, SiC, SiO₂, TiO₂, TiC or alloying elements such as Cu, Ni, Zn [9, 10]. The role of ceramic particles in increasing mechanical strength is as a nucleation sites of solidification so that the grain size to be finer. Whereas the role of alloying elements is to form solid solution of aluminium alloy which causes grain size refinement [11]. The FSP treatment gives an increase in mechanical strength due to grain size refinement and more evenly distributed of additional material particles, thereby giving rise to the dispersion strengthening and eliminating casting defects. Although the result of the investigation on FSP got attractive mechanical properties and modified micro structure of materials, on the other hand it is quite a few successful
Table 1: Parameters of friction stir processing.

| No | Specimen | Tool Rotation Speed (RPM) | Hole Thickness (mm) | Tool Diameter (mm) | Volume Zn (mm$^3$) |
|----|----------|---------------------------|---------------------|-------------------|-------------------|
| 1  | A1       | 1120                      | 0.2                 | 15                | 22                |
| 2  | A2       | 1120                      | 0.4                 | 15                | 45                |
| 3  | A3       | 1120                      | 0.6                 | 15                | 67                |
| 4  | A4       | 1120                      | 0.8                 | 15                | 90                |
| 5  | A5       | 1120                      | 0                   | 15                | 0                 |

2 Experimental Procedure

AA 1100 aluminium alloy plates, with dimensions of 70 mm × 40 mm × 4 mm, were used in the friction stir processing method. Holes, with a diameter of 12 mm and various depths of 0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm, were made on the surface of the workpiece to be filled with Zn particles at volumes of 22 mm$^3$ (A1), 45 mm$^3$ (A2), 67 mm$^3$ (A3), and 90 mm$^3$ (A4), respectively. FSP was carried out on the surface of the workpiece.

A pin-less tool made of HSS with a diameter of 15 mm was used to fabricate the specimen with the process parameters of the tool being a plunge depth of 1.2 mm, rotation speed of 1120 rpm and dwell time of 10 seconds. A schematic diagram of the friction stir processing is shown in Figure 1. The friction stir processing parameters are listed in Table 1. An FSP run with the same parameters was conducted, as a reference, on the specimen without the Zn particles. A Vickers micro hardness test was carried out using a Highwood HWMMT X7 with a load of 300 gr and dwell time of 10 s.

The microstructure of the friction stir-processed specimen was characterized using scanning electron microscopy and optical microscopy.

Figure 2 shows the measurement point for the Vickers hardness on a cross section of the friction stir-processed specimen with various volumes of Zn particles. The hardness testing was conducted on three rows to determine the effect of the FSP treatment on the hardness along the thickness of the workpiece.

3 Results and Discussion

Cross-sectional images of the FSP specimen with variations in the volume of Zn particles can be seen in Figure 3. The distribution of the Zn particles can be observed by the brighter colour compared to the surrounding area.

Most of the Zn particles moved to the outer diameter of the FSP tool. This could be explained by the fact that the rotating tool on the workpiece generated heat on the material beneath the tool [12], thereby softening both the aluminium and the Zn particles. The rotating action of the tool tended to draw the Zn particles to the edge of the FSP region [13]. The amount of Zn particles that accumulated
Figure 3: Cross sections of friction stir-processed AA1100 with various Zn particle volumes of (a) 22 mm$^3$, (b) 45 mm$^3$, (c) 67 mm$^3$, and (d) 90 mm$^3$.

Figure 4: Microstructure of friction stir-welded specimen under various Zn Particle volumes of (a) 22 mm$^3$, (b) 45 mm$^3$, (c) 67 mm$^3$, and (d) 90 mm$^3$. 
at the edge of the friction stir-processed zone varied. This was attributed to the differences in the volume of Zn particles used during the FSP process. Increasing the volume of Zn particles meant that there were more Zn particles. However, this had no significant effect on the distribution of Zn particles in the area beneath the tool.

The microstructure of the shoulder affected zone (SAZ) under various volumes of Zn particles is shown in Figure 4. The SAZ had a finer grain size compared to the other regions due to both the dynamic recrystallization and severe plastic deformation generated by the stirring action between the tool surface and workpiece [4]. It was observed that increasing the Zn particle volume resulted in finer grains in the SAZ. This was consistent with the results of a previous research, which stated that the addition of Zn particles led to the production of finer grains [11].

The distribution of various volumes of Zn particles on the cross section of the workpiece was tested using energy dispersive spectroscopy (EDS mapping), as shown in Figure 5. It could be discerned that the distribution of Zn particles across the processing zone was in line with the macrograph shown in Figure 3, where the Zn particles were concentrated at the edge of the processing zone, as indicated by the high concentration of purple dots. An increase in
Figure 6: Atomic percentage of Zn at the edge and centre of the friction stir processing zone

The volume of Zn caused the Zn particles to become more visible. It could be seen that the increased volume of Zn particles caused them to penetrate in the direction of thickness, making it more significant.

The results of the EDS test, as shown in Figure 6, proved that a Zn particle content of 0.2% was obtained at the centre of the friction processing zone, whereas the content was 4.2% at the edge. Increasing the Zn particle volume from 22 mm$^3$ to 45 mm$^3$ caused the Zn content to rise at both the centre and edge of the friction stir processing zone by 0.5% and 7.8%, respectively. The largest Zn particle content at the centre of the friction stir processing zone was 1.7%, while a Zn particle content of 11.4% was obtained at the edge of the friction processing zone at a Zn particle volume of 95 mm$^3$.

The Vickers hardness values of the friction stir-processed AA1100 under various Zn particle volumes at the uppermost surface are shown in Figure 7. The mechanical behaviour of the specimens produced by friction stir processing under various volumes of Zn particles showed that an increase in the Zn particle volume led to an increase in the hardness. The shoulder affected zone (SAZ) experienced an increase in hardness when the Zn particle volume was increased. An increase in Zn particle volume to 22 mm$^3$ (A1), 45 mm$^3$ (A2), 67 mm$^3$ (A3), and 90 mm$^3$ (A4) showed an increase in the Vickers hardness numbers to 35.5 HV, 36.1 HV, 40.7 HV, and 46.1 HV, respectively at the centre of the friction stir processing zone, and an increase to 65.6 HV, 74.6 HV, 80.4 HV, and 87.1 HV, respectively at the edge of the zone.

A gradual increase in hardness could be observed from the centre to the edge of the friction stir processing zone. When the Zn particle volume was 90 mm$^3$ (A4), the
Figure 8: Vickers micro hardness values at middle thickness of friction stir-processed specimen under various Zn particle volumes of 22 mm$^3$ (A1), 45 mm$^3$ (A2), 67 mm$^3$ (A3), 90 mm$^3$ (A4) and 0 mm$^3$.

The hardness value was 46.1 HV at the centre of the friction stir processing zone, and it gradually increased to 87.1 HV at the edge of the friction stir processing zone.

The variation in hardness along the cross section of the specimen was due to the uneven distribution of Zn particles along the cross section. When the stirring process occurred, the heat energy that was generated softened the Al and the rotational motion of the tool blended it with the Zn particles. The higher hardness was the result of the refined grain size and the presence of a solid solution of Zn particles. This was due to the rotating tool, which rubbed the surface of the workpiece, thereby generating the heat that led to the recrystallization of the grains. The severe plastic deformation caused by the stirring action of the tool resulted in dynamic recrystallization, which led to the production of very fine grains [8, 15].

Figure 8 shows the Vickers micro hardness value at the middle thickness of the specimen. Generally, the hardness at the middle thickness will be lower than that of the uppermost surface. This is because the Zn particle distribution along the thickness will gradually decrease, as seen in Figure 5.

### 4 Conclusions

Surface hardening by the friction stir process method on AA 1100 aluminium under various Zn particle volumes was investigated, and the following conclusions were drawn:

1. In the microstructure of the shoulder affected zone (SAZ), the grains were finer than the base metal due to recrystallization and severe plastic deformation. The SAZ region contained more Zn particles when the volume of Zn particles was increased. The existence of Zn in the AA1100 aluminium caused the AA1100 material to be stronger.

2. Increasing the volume of Zn particles caused the AA1100 friction stir-processed specimen to have a higher hardness. The highest hardness of 87.5 HV was found at the edge of the friction stir-processed specimen with the highest Zn particle volume of 90 mm$^3$. The highest hardness of 46.1 HV was found at the centre of the friction stir-processed specimen with the highest Zn particle volume of 90 mm$^3$, while the lowest hardness of 35.5 HV was found at the lowest Zn particle volume of 22 mm$^3$. The increasing volume of Zn particles was effective in increasing the hardness of the material.

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