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# Investigation of wear performance of friction stir processed aluminium metal matrix composites

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ABSTRACT

In this work the reference materials used were AA6061 Al alloy. Hence, the wear performance was to be improved by introducing friction stir processing (FSP) aluminium alloy AA6061. Furthermore, FSPed AA6061 was reinforced by rice husk ash (RHA) of 6% volume fraction. The FSP fabrication parameters used were rotation speeds at 1000 rpm, 1400 rpm and 1600 rpm with a constant traversed speed of 25 mm/min. Pin-on-disc tribometer was used to investigate the wear properties. The mass loss and specimen materials' wear rate were the final outcomes. It was found that wear properties had improved for FSPed AA6061/6 vol% RHA compared to FSPed AA6061 followed by AA6061. The best result was achieved by FSPed AA6061/6 vol% RHA fabricated at 1600 rpm and 25 mm/min, the mass loss was 0.02 g and the rate of wear is $0.97 \times 10^{-3}$ $mm^3/Nm$.

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## 1. Introduction

For years, the upper surface's properties of metallic materials were suggested to be altered by using friction stir processing (FSP) [1]. FSP promotes a high-strain-rate processing which initially has been introduced on aluminium as well as on magnesium alloys [2]. FSP can be used for both processes to refine grains structure and produce a surface layer of composite to boost the material's mechanical properties [3,4]. Studies have shown the potential of FSP in synthesizing particulate reinforced aluminium composites as it is a simple, fast and cost-effective method [5,6].

FSP is a promising surfacing technique that can overcome fusion problems coming from the fusion process [7], as well as other casting techniques. FSP has been used in grain refinement [8] as well as to fabricate surface composite. In the production of surface composite, there are two ways of introducing the reinforced material on the base material or subtracting it before performing the FSP. For the first method, the reinforcement is mixed into volatile solvent example methanol and mixing them. The solution then will be implemented onto the substrate's surface to form a thin layer of the reinforcement and next will be subjected to FSP. Unfortunately, this method produces an uneven thickness of the coating. An alternative method is to prepare a hole or to cut a groove along the direction of FSP which filled by the reinforcement. The FSP will travel along the groove to create a thick layer of surface composite [9].

Furthermore, the surface composite produced from FSP are denser and has higher strength. FSP improves the distribution of the reinforced particles and promotes a strong interfacial bonding between matrices and reinforced particles. This leads to a thermodynamically stable and more homogeneous metallurgical properties [10]. Therefore, to perform the fabrication of metal matrix composites (MMC), FSP will be utilised in this research.

Aluminium alloy is a lightweight material for industrial application. It has high strength to weight ratio, hardness, good at resisting thermal shock, modulus and fatigue strength [11]. Aluminium is classified based on their chemical composition. In the heat-treatable 6000 series, silicon and magnesium are the main alloying elements [12]. In this research, AA6061 aluminium alloy was considered as a matrix material. AA6061 contains Al–Mg–Si alloy that was utilized in engineering and industrial sector as it can be accepted widely in the fabrication of lightweight structures that required a high strength-to-weight ratio and good at resisting corrosion [13,14]. Due to these properties and potential to be recycled, AA6061 is widely used in the aircraft, automobiles, defence and marine areas [15]. Unfortunately, AA6061 demonstrates low

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tribological properties. It has a poor wear resistance which limits its application [16].

In this study Al AA6061 alloy will be reinforced with risk husk ash (RHA), ceramic material rich with hard silicon carbide. RHA is a by-product of rice husk, an abundant-waste material from rice processing plant. RHA is a lightweight material with higher silica contents (about 87 to 97 wt% SiO2), RHA shows a potential reinforcement to MMC and ceramic matrix composite (CMC) due to high silicon content. Therefore, a mixture of Al alloy and RHA will produced an aluminium metal matrix composite. The main purpose of this study is to improve AA6061 aluminium alloy tribological properties, specifically the wear performance.

## 2. Experimental procedure

The H13 steel material was used as the FSP tool. The steel was obtained from PH Hardware, Malaysia. Table 1 shows the FSP tool's chemical composition.

The main dimensions of the tool were as follows: 16 mm shoulder diameter (D), 5 mm probe length (L), and 6.5 mm probe diameter (d). Fig. 1 presents a detailed graphic of the FSP tool used in this research.

The AA6061 block was obtained from PHH Steel Hardware, Malaysia. The AA6061 block was later cut into rectangular shape with (125 mm × 30 mm × 10 mm) as the dimension using electrical discharge machine (EDM) wire cut to form eleven specimens. AA6061 alloy's chemical composition was presented in Table 2.

One block was kept as a reference material while five blocks were used for FSPed AA606 and the other five blocks were used for FSPed AA6061 reinforced with 6% volume fraction of RHA. The subsequent block for the composite was drilled to occupy the RHA as in Fig. 2. For the composite specimens, set of holes with 3 mm diameter and in depth of 5 mm were drilled on the surface of the blocks.

Initially, RHA was prepared from rice husk (RH). The RH was obtained from the rice mill of Padiberas National Berhad (BERNAS), Malaysia and mainly comprises of cellulose and lignin with a density 0.55 g/cm$^3$ [17]. The RHA preparation comprises of several of cleaning and heating process at maximum of 600 °C for 12 h.

### 2.1. Friction stir processing using a milling machine

The process experiments of friction stir were performed using a vertical milling machine, (MAKINO, Model KE 55) that was shown in Fig. 3. The process involved a fixed travel speed of 25 mm/min and varies by several rotation speeds for both AA6061 and FSPed AA6061/6 vol% RHA. Fig. 4 presents the schematic diagram of the friction stir processing.

The specimens then were prepared for microscopic observation. This would examine the effect of FSP and adding RHA as reinforcement to the AA6061 matrix. The microstructural analysis were performed by using an optical microscope (OLYMPUS, Model BX51M) for etched specimens including, AA6061, FSPed AA6061 and FSPed AA6061/6 vol% RHA at the magnification of 20x.

**Table 1**
Chemical composition for FSP tool.

| Constituent | % |
|---|---|
| Carbon | 0.32–0.45 |
| Chromium | 4.75–5.5 |
| Manganese | 0.2–0.5 |
| Molybdenum | 1.1–1.75 |
| Vanadium | 0.8–1.2 |
| Silicon | 0.8–1.2 |
| Sulphur | 0.03 max |
| Phosphorus | 0.03 max |

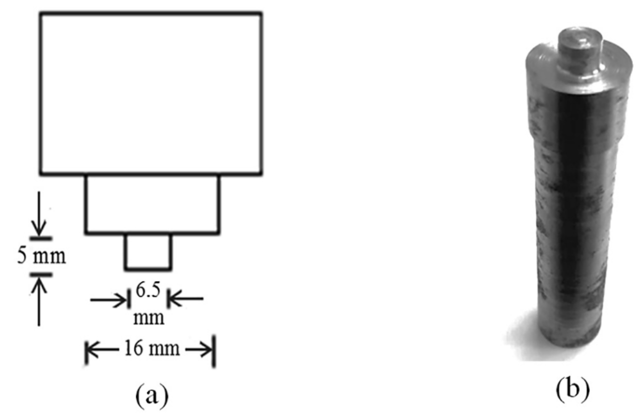


**Fig. 1.** FSP tool for this research (a) schematic diagram and (b) actual tool.

**Table 2**
Chemical composition of AA6061.

| Constituent | % |
|---|---|
| Aluminium | Remaining |
| Silicon | 0.4–0.8 |
| Magnesium | 0.8–1.2 |
| Ferrum | 0.7 |
| Copper | 0.15–0.40 |
| Manganese | 0.15 |
| Chromium | 0.04–0.35 |
| Zinc | 0.25 |
| Titanium | 0.15 |
| Vanadium | 0.01 |

Dry sliding wear experiment then subject for the specimens. A pin-on-disc tribometer machine (CSEM Instruments) was used to carry out the work. This machine function as an instrument for frictional force and wear measurement. Two types of specimens were needed in the pin-on-disc wear test, which are one cylindrical pin and one flat counter disc. The cylindrical pin will be positioned perpendicular to the counter disc. Pin specimen was pressed against the disc at a specified load which also rotates at several speeds. This was by means of a lever that attached to some weights. By weighing pin specimens before and after the experiment, the value of wear can be determined. In this case, the specimens was the counter disc. The test followed standard procedure in ASTM G99, to evaluate wear properties of AA6061, FSPed AA6061 and FSPed AA6061/6 vol% RHA. The test was conducted in a dry condition with a parameter load of 10 N, linear speed 10 cm/s, radius 10 mm with constant sliding distance of 800 m.

## 3. Result and discussions

The metallurgical observation shows that FSP had altered the structure of the AA6061 as it decreased the grain size of AA6061 by 62–98% (Fig. 5). This finding is supported by a study from Alidokht [18] which found that FSP results in a smoother, recrystallised grains in aluminium alloy matrix. It is also in line with the finding reported in Eskandari and Taheri [19] which stated high input heat produced showed higher friction between the probe and the tool's shoulder during FSP. By referring to Fig. 5(b), recrystallisation had been occurred and refined the grain in the aluminium matrix.

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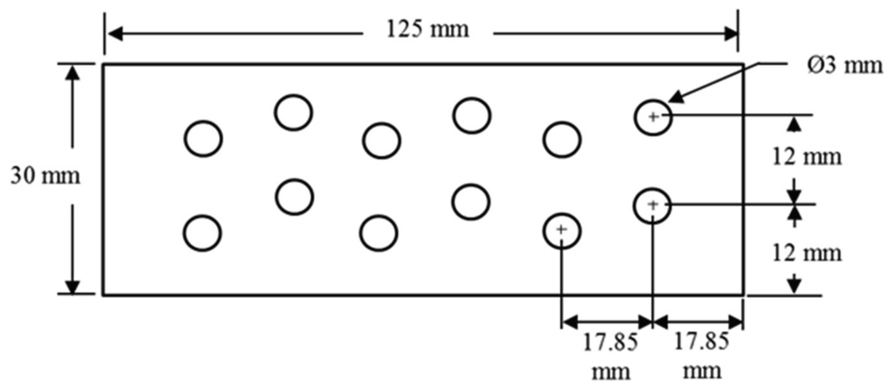


**Fig. 2.** A set of holes on AA6061.


**Fig. 3.** Vertical milling machine for FSP.

There was a homogenous dispersion of RHA within the AA6061 with no voids. This shows that aluminium matrix and RHA particles had a good bonding towards each other. Among stirred zone, RHA particles were uniformly scattered within the aluminium matrix. There was no segregation or aggregation of RHA particles to be found. RHA particles represented as sites for grain nucleation and also refined the grain of the aluminium matrix as shown in Fig. 5(c).

Wear resistance is associated with the material removal of a solid surface. The process of removing this material may involve physical separation or chemical dissolution. In this light, plastic deformation of the material controlled wear in most metallic alloys [20–21]. During the solid surfaces relative motion, friction and wear are the two important tribological phenomenas. Usually both tend to deteriorate materials and scatter energy [22].

In this work, wear characteristics was determined by loss of weight and rate of wear. As given, by using the weight loss of the specimens presented in Fig. 6, the wear rate of the specimens can be determined.

The mass loss of AA6061 is 0.06 g. By employing FSP, the mass loss during wear test was reduced to 0.03 g for 1000 rpm, 0.04 g for 1400 rpm and 0.05 g for 1600 rpm. As for FSPed AA6061/6 vol% RHA, mass loss during wear test was minimal at 0.02 g for FSP at 1000 rpm 0.03 g and 0.04 g for FSP at 1400 and 1600 rpm, respectively.

The wear rate can be expressed as the mass loss from the specimen divided by the sliding distance. Wear rate can be calculated using Eq. (1) as in [23].

$$\text{Wear rate, } mm^3/\text{N.m} = \frac{\text{Volume loss, } mm^3}{\text{Sliding distance, m x 1000 N}} \quad (1)$$

The conversion mass loss to volume loss can be obtained by using Eq. (2) as in [24].

$$Volume\ loss, mm^3 = \frac{Mass\ loss, g}{Density, g/cm^3} \times 1000 \quad (2)$$

Fig. 7 depicts the wear rate for AA6061 and FSPed specimens machined at rotational speed of 1000, 1400 and 1600 rpm. Wear rate for AA6061 was estimated to be $2.82 \times 10^{-3}$ $mm^3$/Nm. The wear rate of FSPed AA6061 was calculated at $1.29 \times 10^{-3}$ $mm^3$/Nm at 1000 rpm, $1.83 \times 10^{-3}$ $mm^3$/Nm at 1400 rpm and $2.32 \times 10^{-3}$ $mm^3$/Nm at 1600 rpm. From FSPed of AA6061, enhancement upto 54% of wear rate compared to AA6061. Wear rate of FSPed AA6061/6 vol% RHA calculated at $0.97 \times 10^{-3}$ $mm^3$/Nm at 1000 rpm, $1.48 \times 10^{-3}$ $mm^3$/Nm at 1400 rpm and $2.09 \times 10^{-3}$ $mm^3$/Nm at 1600 rpm. The composite surface of FSPed AA6061/6 vol% RHA shows an further improvement in wear profile upto 24.8% compared to FSPed AA6061. It was found that the wear rate performance for both FSPed specimens with and without reinforcement had decreased with respect to increasing the rotational speed. Compared to both FSPed specimens, reinforced RHA in aluminium has a significantly improved wear performance of AA6061.

The results were supported by Martín et al. [21] which advocated the Archard's classic model which states that worn volume and material hardness is inversely proportional to each other. Additionally, Singh et al. [25] mentioned that rate of wear and weight loss is proportional to each other. These results agreed with the findings of other studies. Alidokht et al. [26] found that the improvement in wear resistance was credited to size modification, morphology, and homogeneous distribution, grain refinement, and hardness improvement. Hence, it can be concluded that to increase in hardness value and homogenous dispersion of fine grain size.

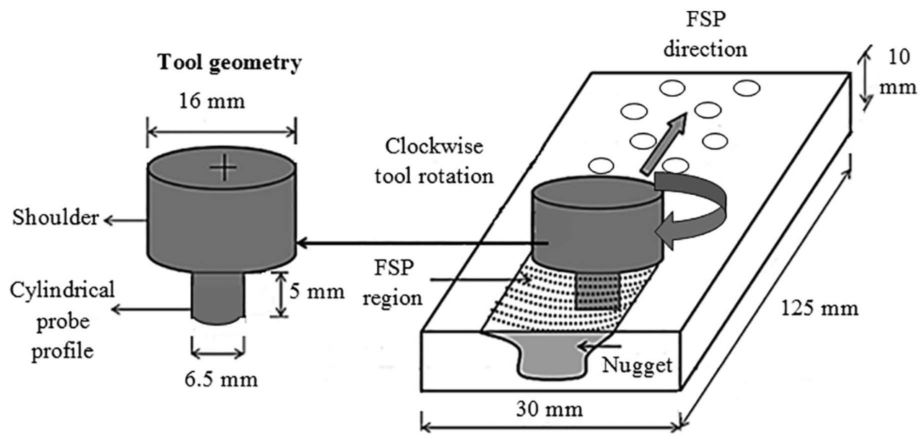


**Fig. 4.** Schematic diagram of friction stir processing.

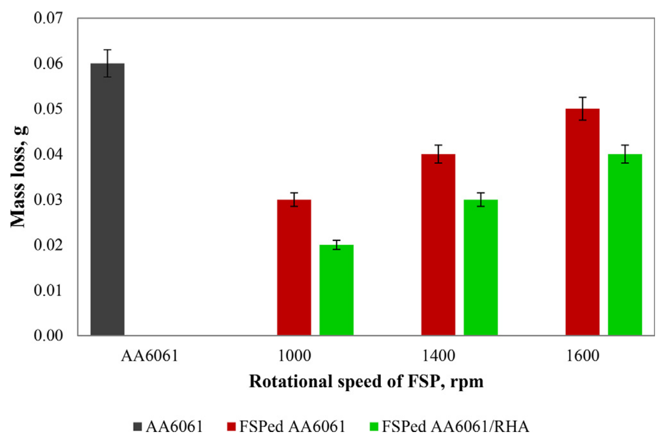


**Fig. 5.** Microstructure of specimens (a) AA6061 as-received (b) FSPed AA6061 1000 rpm (c) FSPed AA6061/6 vol% RHA 1000 rpm.

The hardness and the size of grain in the FSPed A356 specimens can influence the wear resistance. Furthermore, a research by Mahmoud [27] on A390 alloy supported that FSPed specimens improved in wear resistance compared to the as-received A390 alloy. The rates of wear were decreasing when reducing the rotational speed of the FSP tool. FSP eliminates the cavities, refines the grain structure. By reducing the tool rotational speed, the hardness of the FSPed area was found out to be increased.

Furthermore the result of increased wear performance of AA6061/6 vol% RHA was supported by finding in Dinaharan et al. [28]. They explained that Archard's law establishes a relationship between hardness and rate of wear for metallic materials of AA6061 reinforced fly ash (FA) particles. During sliding wear, the loss in volume for material is inversely proportional to the hardness. Hence, higher hardness will indicate lower wear rate. The hardness increment of the composite lead to improvement in resisting sliding wear. Morever, particles are usually easily worn away from the matrix during sliding. Thus, FA particles bear the applied normal load and lead to reduction of the effective contact area between AA6061/FA specimen and the counter disc. Detachment of FA particles from the aluminium matrix will be resisted during sliding when there is better bonding between the aluminium matrix and the FA particles. Consequently, excellent interfacial bonding will result in an enhancement in the properties.

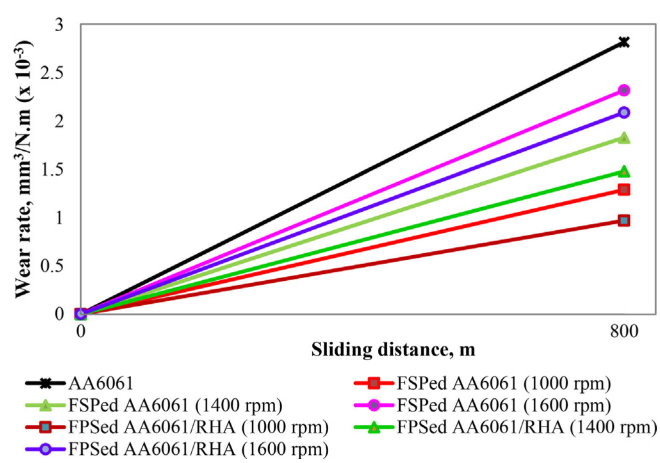


**Fig. 7.** Variation of wear rate of specimens versus sliding distance.

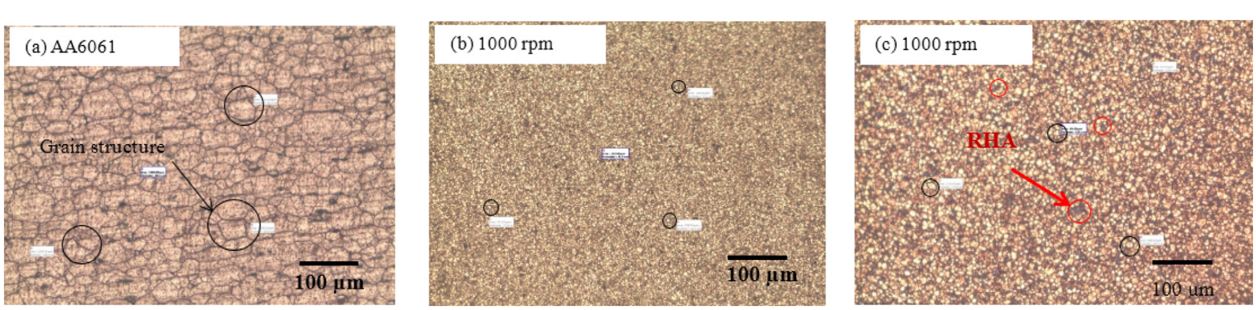


**Fig. 6.** Weight loss of the wear specimens.

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## 4. Conclusion

From the result, it can be concluded that the wear performance of the AA6061 had increased because of the FSP and incorporation of RHA particles. The relationship between hardness and the wear rate is inversely proportional when referring to Archard's wear law. The wear rate decreases as the hardness of the material increases. Hence, increment in hardness of the composite leads to a decrement in material loss during sliding. The reduction of wear rate happened because of the presence of hard reinforced particles. The rubbing probe and the rotating disc contact surface is reduced because of the presence of RHA particles. Moreover, the wear performance of AA6061 was further improved due to the good bonding between the aluminium matrix and RHA particles.

## CRediT authorship contribution statement

**CD. Marini:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing - review & editing. **Nanang Fatchurrohman:** Funding acquisition, Resources, Supervision, Writing - original draft. **Zuhairah Zulkfli:** Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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