Mechanical and wear behavior of AA7075 aluminum matrix composites reinforced by Al₂O₃ nanoparticles

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ABSTRACT
An attempt was made to synthesize aluminum alloy (AA) 7075 matrix reinforced with 0, 1, 3, 5 wt% Al₂O₃ particulates by using stir casting technique. Mechanical properties and wear behavior were examined. The hardness and tensile properties were obtained before and after addition of Al₂O₃ particulates to reveal the extent improvement. Wear behavior was examined by using a pin-on-disc device to validate the improvement of the wear resistance. The results showed that adding of Al₂O₃ reinforcement were significantly enhanced the mechanical properties. The ultimate tensile strength (UTS) and yield tensile strength (YTS) were observed 133 MPa, 35 MPa for the unfilled aluminum matrix, whereas 152 MPa and 47 MPa were achieved at 5 wt% Al₂O₃ nanocomposites which resulted in 14.3 and 34.3% improvement, respectively. The hardness was observed 57 BHN and 72 BHN at 0 wt% and 5 wt% Al₂O₃ respectively, resulting in an improvement of 26.3%.

1. Introduction
It is well known that aluminium matrix composites (AMC) are defined as the materials that are normally reinforced by hard particles such as carbides (Al₄C₃, SiC, TiC), oxides (Al₂O₃) or nitrides (TiN, AlN) into the matrix [1]. The metal matrix that is synthesized by nanoparticles exhibits a unique physical and mechanical properties which are variant from those of the matrix. Hence, reinforcing aluminum matrix with smaller particles either submicron or even nano-sized range, is one of the essential factors for fabricating high-performance composites.

AA 7075 matrix has been widely used as structural materials in the aeronautic industry, due to their attractive properties [2]. It has been used in several applications such as aircraft fittings, shafts, gears and defense applications. It exhibits lower tribological properties, since it is relatively hard to create a fully homogenized microstructure for Al alloys and Al matrix composites [2, 3]. The adhesive wear normally occurs when the material transfers from a surface to another during their relative movement. This occurs when the surfaces slide and a load between asperities in contact is enough to promote local plastic deformation [2]. The phase separation can lead to variations in the microstructure because the potential energies of the individual phases exhibit different rates of dealloying [4]. The composite of the aluminum metal matrix is a mixture of two or more components, matrix and reinforcements. Usually these reinforcements are processed by powder metallurgy, fluid cast metal technology or through the use of unique production processes. The powder metallurgy process has its own limitation such as processing cost and size of the components. Therefore, only the stir casting technique should be regarded as the best way to process aluminum composite materials [5].

This technique involves melting the matrix alloy followed by stirring in the particulate reinforcement to create the nanocomposite. Meanwhile, the stir parameters such as casting temperature, stirring velocity, reinforcement content and stirring time should be optimized, in order to attain a lower of porosity, particles agglomeration, oxide inclusions and interfacial reactions during stir casting [5–7]. Accordingly, processing parameters must be critically selected in the melt stir technique to achieve a high degree of microstructural reliability.

Tribological behavior and mechanical properties of AA 7075 composites reinforced with nanoparticles have examined by several studies. Baradeswaran and Elaya Perumal [8] examined the mechanical properties and wear behavior of AA 7075 reinforced by Al₂O₃ and graphite hybrid composites. Ceramic particles were synthesized with aluminum alloy matrix to achieve an enhancement in...
the wear resistance and coefficient of friction. It was found that the wear properties of the hybrid composites containing graphite exhibited the superior wear resistance properties. Pradeep et al. [9] studied the mechanical properties of AA 7075 reinforced with silicon carbide nanoparticles. It was found that the combination of a matrix material reinforced by nanoparticles improved ultimate tensile strength, compressive strength, hardness and yield strength.

Suresha et al. [10] inspected the dry sliding friction of hybrid AMC aluminum matrix composite synthesized by SiC and graphite particles. It was confirmed that the load was the essential factor for affecting on the friction coefficient of the hybrid composite followed by sliding speed factor. Additionally, it was observed that the coefficient of friction increased with an increase in the load and sliding distance. Shipway et al. [11], on the other hand, observed the effect of the load and TiC content on the dry sliding wear of Al-4Cu/TiC, Al (A356)/TiC, and Al (pure)/TiC composite. It was found that there was a noticeable reduction in the wear rates of composite reinforced by TiC particles in comparison with pure alloy. Tee et al. [12] inspected the dry sliding wear of Al-Tib and Al-4.5% Cu-Tib2 composites which were fabricated by stir casting technique. It was found that there was a noticeable reduction in the wear losses for both composite alloys as the concentration of Tib2 increased.

Baradeswaran and Elaya Perumal [13] examined AA 7075 composites reinforced with B4C particles by stir casting technique. It was found that the wear resistance increased by increasing the volume fraction of reinforcement B4C particles. The effect of Al2O3 particles on the microstructure, corrosion properties and fracture toughness of AA7075 and AA5083 were examined by Saeidi et al. [14]. It was confirmed that the presence of Al2O3 particles leads to an increase in the corrosion resistance of the joint when compared to that without reinforcements. From the literature, it was found that there are a few studies examined the wear resistance of AA 7075 reinforced with Al2O3 nanoparticles.

Therefore, the goal of this study is to obtain the optimum combination of the nanoreinforcements (Al2O3) in the matrix aluminum composite (AA7075) with the best tribological and mechanical properties of fabricated AMC (AA7075) which were synthesized at different wt% of Al2O3 nanoparticles.

2. Experimental procedures

AA7075 was selected as the matrix and Al2O3 (APS 20-30 nm) as a reinforcement. In order to achieve a uniform dispersion of the reinforcing particles, the stir casting technique was adopted to manufacture the AA7075/Al2O3 composites by using the nanocomposites manifesting device. The steps of manufacturing are described as follows:-

1. Cutting AA 7075 into cubes with size (1–2) cm³, and washed with alcohol and distilled water several times.
2. Dry AA 7075 cubes by a hot air to the temperature of 100 °C.
3. Heating AA 7075 cubes to 200 °C by an electric heater.
4. The oven lid lifted and loaded parts resulting from the heating process from the top and closes the lid tightly. The air is withdrawn from the oven by vacuum.
5. Al argon gas is pumped into the oven and heat the oven to 850 °C.
6. Addition of reinforced nanoparticles to the molten aluminum alloy with a gas pump.

2.1. Process parameters

- Stirring speed was 450 rpm
- Stirring temperature 850 °C
- Reinforcement preheats temperature 200 °C
- Stirring time (10–12) min
- Preheated temperature of metal die casting mold to (300–400) °C
- To improve the mechanical and wear properties of cast composites and to remove the entrapped gases from the mold powder feed rate was (1 g/kg min) [15].

It should be noted that AA 7075 in this process, was heated exceeding its melting temperature. When the matrix was in liquid condition, stir casting involved mixing the base materials with nanoparticles for 4 min with gradual increasing speed ranged from 0 to 450 rpm with the help of a speed controller.

2.2. Mechanical properties

Mechanical properties such as ultimate tensile strength, yield tensile strength, hardness tests and wear resistance for AA 7075 reinforced with Al2O3 particles were examined using cast samples.

2.2.1. Tensile tests

Tensile tests were carried out to assess the mechanical behavior of cast AA7075 and fabricated nanocomposites. Figure 1 shows the tensile test specimen according to ASTM (E8/E8-09) [16]. The tensile specimens were prepared from the cast AMC.
tensile tests were conducted on the round tensile specimens with diameter 9 mm and 36 mm gage length by using a universal testing machine WDW/200E of 200KN capacity. The dimensions of the specimens are shown in Figure 1. Tensile properties and elongation percentage as well as the ultimate tensile strength were calculated. The results were based on the average of three samples.

2.2.2. Hardness tests

It is well known that the hardness test depends on the depth of the penetration under external uniform load. The hardness of AA 7075 reinforced with 1, 3 and 5 wt.% of Al₂O₃ nanoparticles was carried out using a Brinell Hardness Tester having a steel ball indenter with a load of 1.96 N.

2.2.3. Wear tests

Wear tests were also examined with a total sliding distance of approximately 660 m. The pin samples were designed as 30 mm in length and 12 mm diameter. The surfaces of the pin samples were sanded by utilizing emery paper (80 grit size) prior to the test in order to attain the effective contact surface with the steel disc shown in Figure 2. The wear rate was determined in terms of the wear volume loss per unit sliding distance.

3. Results and discussion

3.1. Tensile tests results

Tensile tests were used for the evaluating the ultimate tensile strength, yield tensile strength and other properties. The experimental testing established the stress–strain curves for pure AA 7075 and AA 7075 reinforced with 1, 3 and 5 wt% Al₂O₃ nanoparticles, as shown in Figure 3.

The mechanical properties results of pure AA 7075 and its composites of different amounts of Al₂O₃ which were determined from Figure 3 are shown in Table 1.

The variations in ultimate tensile strength and yield tensile strength with different amount of Al₂O₃ are shown in Figure 4. The ultimate tensile strength and yield tensile strength of composites were significantly improved, since the ultimate tensile strength and yield tensile strength, increased with increasing amount of Al₂O₃ reinforcement. The ultimate tensile strength and yield tensile strength with 5 wt% Al₂O₃ were improved by 14.3% and 34.3%, respectively. This increase in ultimate tensile strength was attributed to the presence of hard particles of Al₂O₃ in the matrix AA7075, which leads to an increase in the strength of AA7075. Strength values (tensile and yield) increased with an increase in the amount of Al₂O₃ which is attributed to the low degree of porosity and uniform distribution of nanoparticles Al₂O₃ [17]. It is believed that the introduction of nanoparticles Al₂O₃ into the matrix provides some heterogeneous nucleation sites during solidification resulting to the refined grains. Accordingly, the enhancement of the tensile properties can be attributed to the grain size [18].

The hard particulates Al₂O₃ impart their strength to the AA 7075 matrix by load transfer from the matrix to the reinforcing nanoparticles. Raghavendra et al. [19] examined the mechanical
properties of AA 7075 reinforced by silicon carbide using stir casting method and reported a 15.07% and 46.7% improvement in ultimate tensile strength and yield tensile strength, respectively. The increase in ultimate tensile strength and yield tensile strength is mainly due to Al₂O₃ particles acting as barriers to dislocations. The improvement of strength is coming from the matrix strengthening following a reduction in AA7075/Al₂O₃ grain size. The generation of high dislocation density in AA 7075 matrix is a result of the difference in the thermal expansion between Al₂O₃ and AMC. Saikeerthi [20] concluded that the properties of hard ceramic particles control the mechanical properties of the composite. Also, the strong interface bonding load from the matrix is transferred to the reinforced material exhibiting enhanced strength of composites.

Al-Jafaari [21] studied the AA 7075/Al₂O₃ nanocomposites for various amounts of Al₂O₃ using stir casting method. It was found that the ultimate tensile strength and yield tensile strength were significantly improved by 8% and 7.14% at 0.3 wt% Al₂O₃ for ultimate tensile strength and yield tensile strength, respectively. Higher tensile and yield stress of nanocomposite could be attributed to the fact that Al₂O₃ particles act as obstacles to the movement of the dislocations.

3.2. Hardness test results

The measured Brinell hardness numbers (BHN) are illustrated in Figure 5, on the other hand, it displays the effect of the amount of Al₂O₃ filler on Brinell hardness. A notable rise in the hardness of AA 7075 matrix can be seen with the addition of Al₂O₃ particles. It is clearly shown that the hardness of composites was higher than that of the pure alloy, since the hardness increases with the increase of Al₂O₃ particles.

The improvement in Brinell hardness was attributed to the uniform dispersion of reinforcement throughout the AMC. Furthermore, the presence of hard Al₂O₃ material in the soft AA7075 matrix enhances the overall hardness of the matrix material. Dinesh and Ravindran [22] reported an enhancement of 16.12% in RHN of AA7075 reinforced by 4%Cr and 1%Cu.

It is clearly evident that hardness increases with the increasing amount of Al₂O₃ particles. The best results were obtained for the cast AA7075/Al₂O₃ composite which contains 5 wt% of Al₂O₃ particles. This composite exhibited higher hardness values than the other composites as well as the pure matrix material in the present investigation. An improvement in BHN 26.3% was observed. It is believed that Al₂O₃ particles are harder than AA 7075, the inherent property of hardness is rendered to the soft matrix. Halverson et al. [23] reported that the main reason for improvement the hardness is the presence of B₄C particles in AA 7075 matrix. Whenever a hard reinforcement is incorporated into a soft, ductile matrix, the hardness of the matrix is improved.

The high hardness may be coming from the high hardness of nanoparticles itself, which is attributed positively to the hardness of composites. Mazhary et al. [17] revealed that there is 38.8% improvement in the hardness at 5 wt% of Al₂O₃ for Al–Si alloy reinforced with Al₂O₃.

3.3. Wear rest results

Tribological experiments were performed to understand the wear behavior of AA7075/Al₂O₃ composite using a pin-on-disk machine. Wear tests were conducted using a ‘pin-on-disc wear tester’ for 1, 3, and 5 wt% Al₂O₃. The experimental wear results obtained from testing 16 specimens are shown in Table 2.

3.4. Effect of nanoreinforcements

The variation of the wear rate of the nano AMC at different loads is shown in Figure 6. It is clearly shown that the maximum wear rate was observed for composites containing 1 wt% of Al₂O₃ and loads of 10 N to 50 N.

It seems that the wear rate of composites decreases with the addition of Al₂O₃ reinforcement. Marigoudar and Sadashivappa [24] confirmed that
the wear rate was strongly dependent on the contents of reinforcement. Previous study [25] examined the wear and friction of aluminum metal matrix composites containing 10, 20 and 30 wt% Al2O3. It was found that the increase in Al2O3 decreases the wear rate. The wear rate under the loads 30 N, 40 N and 50 N indicated an increasing tendency of the wear rate with an increase of wt% of Al2O3. Mahajan et al. [26] found that the wear rate decreases up to a certain amount and then remain unaffected because of various factors like wettability and the bonding between the base metal and the nano reinforcement. These reasons could lead to a decrease in wear resistance of nanocomposite.

### 3.5. Effect of load

The applied load during wear testing plays a major role in wear resistance. Twenty specimens were tested to observe the effect of the load on the wear rate of AA 7075. Figure 7 shows the wear rate against varying loads of 10 N, 20 N, 30 N, 40 N and 50 N at room temperature. It was observed that the wear rate increases with load. The hard Al2O3 particles reduce the wear rate, resulting in an increasing in wear resistance for a given amount of Al2O3. At 20 N was not obvious like 30, 40, 50 N.

The increase of normal load leads to a significant improvement in wear rate. Salahuddin et al. [27] concluded that the AA7025 reinforced with 3 wt% and 6 wt% of B4C composites exhibited better wear properties compared to the pure AA 7025.

### 3.6. Effect of sliding distance

The experimental wear results were obtained for different sliding distances. Figure 8 shows the variation of wear rate of the nano AMC for different sliding distances.

It is clearly shown from Figure 8 that there is a proportional relationship between the sliding distance and wear rate. By increasing the sliding distance, there was a steady increase in the wear rate up to a plateau was reached at around 1000–1500 m. The reason for that was attributed to the presence of hard Al2O3 particles which act as sharp asperities on the surface of the composites. Initially for small distances, Al2O3 particles protrude from the composite surface and reduce the area of contact between disk and test specimen resulting in an increased rate of wear.

With the increase in distance, abrasion these asperities take place between sliding surfaces causing them to become blunt and leading an increase in the contact area between these sliding surfaces, which might be the cause for the increased wear behavior of the composite at large distance. It was observed from Figure 8 that the wear rate increased with increasing in sliding distance for all the Al2O3 composite materials. As the sliding distance increases, subsurface plastic deformation causes disintegration of the tribo layer. Tsuya [28] considered the surface plastic deformation

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**Table 2.** Experimental wear test results under 660 m sliding distance.

| Load N | Al2O3 wt% | Weight Loss g | V = m/ρ mm³ | WR x 10⁻³ mm³/Nm |
|--------|------------|----------------|-------------|------------------|
| 10     | 0.017      | 6.05           | 0.917       |                  |
| 20     | 0.0088     | 3.132          | 0.474       |                  |
| 30     | 0.0028     | 0.996          | 0.151       |                  |
| 40     | 0.018      | 6.406          | 0.485       |                  |
| 50     | 0.0172     | 6.121          | 0.464       |                  |
| 60     | 0.018      | 6.406          | 0.485       |                  |
| 70     | 0.021      | 7.473          | 0.377       |                  |
| 80     | 0.013      | 4.626          | 0.234       |                  |
| 90     | 0.01      | 3.559          | 0.18        |                  |
| 100    | 0.051      | 18.149         | 0.687       |                  |
| 110    | 0.025      | 8.897          | 0.337       |                  |
| 120    | 0.02      | 7.117          | 0.27        |                  |
| 130    | 0.102     | 36.299         | 1.1         |                  |
| 140    | 0.071     | 25.267         | 0.767       |                  |
| 150    | 0.052     | 18.505         | 0.561       |                  |

**Figure 6.** Wear rate as a function of Al2O3 content.

**Figure 7.** The effect of the load on the wear rate.

**Figure 8.** Wear rate as a function of sliding distance for different Al2O3 content.
to be significant phenomena which influences the wear rate and friction force.

3.7. Worn surface morphology

Scanning electron microscopy was conducted on the pure AA 7075 and AA 7075/Al2O3 5 wt% composite samples. The surface morphology after wear testing are shown in Figure 9.

It indicates that the addition of hard Al2O3 particles improved the wear resistance of composites. The wear track is observed in the pure alloy AA 7075 which indicates that the abrasive wear mechanism, due to the high temperature and friction, only oxide wear has been placed. These results revealed that the AA 7075 reinforced with Al2O3 particles has better wear resistance property compared with pure AA 7075.

4. Conclusions

AA 7075 reinforced with Al2O3 nanoparticles (APS2 0-30 nm) was manufactured by stir casting technique. Ultimate tensile strength, yield tensile strength, hardness and wear rate behavior were experimentally examined. The following conclusions can be drawn:

1. Wear resistance and mechanical properties (ultimate tensile strength, yield tensile strength and hardness) of the AA7075 composites were significantly enhanced by adding Al2O3 nanoparticles.

2. All the above properties were considerably improved as the wt% increased from 1% to 5%. An improvement of 14.3%, 34.3% and 26.3% was reported for ultimate tensile strength, yield tensile strength and hardness, respectively.

3. The increase in the load and sliding distance lead to an increase in the wear rate, AA7075 composite containing 5 wt% Al2O3 showed a lower wear rate compared to that of 1 wt% Al2O3 composites.

Disclosure statement

No potential conflict of interest was reported by the authors.

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