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Mechanical and wear performance of Al/SiC surface composite prepared through friction stir processing

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Abstract

In the present research work, AA7075 composite reinforced with silicon carbide particles has been fabricated using Friction stir processing (FSP). The silicon carbide particles having a size of 40 μm were placed in grooves of length 160 mm, width 2 mm, depth 3.5 mm, that were generated on the AA7075 plate. The square pin tool is utilized for fabricating the composite at two different rotational speed i.e. 700 and 1000 rpm. Effect of processing, particle addition and tool rotational speed is analyzed on mechanical and wear properties of the material. On friction stir processing the microhardness value and elongation of the material increased. Reinforcement addition contributed to decrease in ductility and tensile strength while on the contrary microhardness and wear resistance of the material improved. Tool rotational speed showed a direct relation with the tested mechanical and wear properties. Adhesive wear was the prominent wear mechanism and Fe layer formation was analyzed on the worn surface, contributing to increased wear resistance. These fabricated composites can find vast application in industries like automotive, defence and aerospace.

1. Introduction

Composites can be defined as a mixture of two or more different materials having different physical and chemical properties [1, 2]. The fabricated composite shows different properties than its constituent materials [3]. Materials like aluminium, copper require enhanced mechanical and wear properties to widen the scope of their application. In industries, aluminium and its alloys find vast application due to their high strength to weight ratio [4, 5]. The composite materials are fabricated in order to attain better properties than their parent material. Metal matrices are reinforced with a variety of reinforcements like TiC, SiC, Al₂O₃, and B₄C in order to improve performance [6, 7]. Nowadays aluminium metal matrix composites (AMMC) find wide application in aerospace, marine industries and they are also used as cylinder liners, brake rotors, pistons [8, 9]. AMMCs are acquiring great interest of researchers also, and various aluminium composites have been fabricated and analysed by researchers. Zawawi et al [10] analysed the dry sliding wear behaviour of Al6061 reinforced with SiC with graphite particulates. Liquid metallurgy route was used for fabricating the composite, taking graphite content up to 4 wt% and taking constant silicon carbide content of 7 wt%. Due to the low density of Gr, it is not possible to reinforce composite with more than 4 wt% of SiC. Wear resistance increased on addition of SiC and it further increased with increasing content of Gr till 4 wt%. Heat treatment had an intense effect on wear properties; of all processes, ice quenching showed the best improvement in wear resistance for all samples.

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Caliman [12] analysed the wear properties of aluminium composite having short carbon fibre as reinforcement. It was observed that due to the development of lubrication film, CoF and wear rate decreased with time and reached a static value. Raghavendra et al [13], by electro-deposition, fabricated a Ni-Al2O3 coating on an aluminium substrate. They produced a design of experiment using central composite design, taking process variables like coating density, particles loading and bath temperature as varying parameters. For all developed composites, they observed the surface roughness before and after the coating. They found that with the presence of Al2O3, wear resistance increased and better wear resistance was achieved. Shankar et al [14] fabricated AA8011 + Gr composite by two-step stir casting process at varying weight% of reinforcement and analysed the fabricated composites for its wear properties. They found that with increasing load, the wear of material increased. With the incorporation of reinforcement, wear resistance increased, and it further increased on increasing the graphite content in the composite. Razzaq et al [15] reinforced AA6063 with varying wt% of fly ash particulate with compo-casting technique. They investigated the effect of applied load and fly content on tribological properties of the fabricated composites. They found that on increasing the applied load, the wear increased and it decreased with the increasing content of particulate. Nagaral et al [16] studied the dry sliding behaviour of Al6061 hybrid metal matrix composite reinforced with silicon carbide and graphite, fabricated using vortex method. It was observed that with increasing load wear loss increased. With the introduction of reinforcement, wear decreased as most of the load on the matrix was beared by hard ceramic particles. Wear loss increased with the increasing sliding speed, though the increase was not constant. The microstructures revealed that the distribution of reinforcement throughout the matrix was uniform. Mittal et al [17] analysed the abrasive wear of aluminium composite reinforced with SiC, red mud and Al2O3. Stir casting process was used for fabricating the composite. It was observed that wear resistance was improved with the addition of reinforcement of Al2O3, red mid and silicon carbide. With increasing concentration of SiC, Al2O3 an increase in wear resistance was observed whereas for red mud wear resistance increased till 7.5 wt% and on further addition, it decreased.

Baradesawaran et al [18] used stir casting method to fabricate Al7075 composite reinforced with B4C particles. They analysed the fabricated composites for mechanical and tribological properties. Increased hardness was observed in the fabricated composites due to the presence of hard ceramic particles. They found that due to the formation of mechanical mixed layers, wear loss and CoF decreased as metal-to-metal contact was avoided. With the introduction of reinforcement, CoF and wear loss decreased and it further decreased with the increasing B4C content and achieved its minimum value at 10 vol% B4C. Rahman et al [19] analysed the aluminium composite reinforced with SiC for its mechanical and wear properties. Stir casting process was used for fabricating the composite with varying concentration of silicon carbide i.e. 0, 5, 10, 20 wt%. It was found that hardness, tensile strength and wear resistance were maximum for the composite with 20 wt% of SiC. With the increasing content of SiC, increased porosity was observed. Non-homogeneous and clustering distribution on reinforcement was observed in the generated microstructures. Pradhan et al [20] reinforced 5 wt% silicon carbide with LM6 base by stir casting process and under corrosion observed its wear behaviour. Wear test was carried out on different normal load and sliding speed, for a fixed time period under different environments i.e. deionised, dilute acid and dry. Due to acidic environment being most corrosive of all, maximum wear loss occurred here; wear loss increased with increasing load in all three conditions. Through SEM, adhesive and abrasive wear traces are observed on the wear surface. Thirth et al [21] developed aluminium hybrid aluminium matrix composite via stir casting and reported the effect of reinforcement and ageing on the wear behaviour of the material. He concluded that with the increasing sliding distance wear loss increases, wear rate increases with the load and decreases with the addition of reinforcement. Also, aging contributed to decrease in wear rate and volume loss in unreinforced alloy. Bansal et al [22] observed the mechanical and tribological properties of Al 359 matrix reinforced with silicon carbide and silicon carbide/graphite particles. The composites are fabricated using stir casting process. It was found that hardness of composite reinforced with SiC/Gr was more than that of composite reinforced with SiC. With the introduction of reinforcement wear resistance of the alloy increased and composite with SiC/Gr reinforcement showed the superior wear resistance of all.

Friction stir processing (FSP) is used for surface modification and manufacturing of composite, by localised plastic deformation [23]. Enhanced tribological, mechanical and corrosion properties of material can be achieved by using this technique [24]. This process is the succedent of Friction stir welding (FSW). Yuvaraj et al [25] fabricated AA5083 composites reinforced with boron carbide, titanium carbide and with a combination of both by friction stir processing. On evaluating for mechanical and wear properties, they found that the composite reinforced with boron carbide showed the highest tensile strength and microhardness, whereas superior wear properties were shown by the hybrid composite. They utilised SEM for analysing the worn out surfaces. Dhayalan et al [26] fabricated AA6063 composites reinforced silicon carbide, graphite and a hybrid of both via friction stir processing. FSP was carried out using a circular pin profile tool made of high carbon high chromium. On analysing its hardness it was found that on the incorporation of reinforcements, the hardness was enhanced and it showed a maximum value for the composite reinforced with silicon carbide. Microstructural changes were governed by scanning electron microscopy (SEM). Dolatkhah et al [27] reinforced...
silicon carbide with aluminium 5052 sheets via friction stir processing at different process parameters. They studied the influence of particle size, tool rotation direction between passed, number of passes, tool rotational and traverse speed on wear properties and microhardness. It was found that for proper dispersion of reinforcement, optimum values of tool rotational and traverse speed should be achieved. Saadatmand et al [28], using friction stir processing, fabricated Al6061/SiC composite. They studied the effect of mass function SiC distribution on wear and mechanical properties of the fabricated composites. Hardness increased and elongation decreased on increasing the mass fraction of SiC. The optimum functional graded composite obtained for better wear resistance and tensile strength was the composite having 10 wt% of SiC. Due to clustering, the tensile strength and wear resistance decreased on further addition of SiC. Butola et al [29] by FSP, along with self-assembled monolayer (SAM), fabricated AA7075-T6 + B4C composite. They found that wear and frictional resistance behaviour enhanced with the addition of reinforcement particulate. Butola et al [30] in their study analysed the effect of different process parameters i.e. tool rotational speed, tool pin profile and reinforcement type, using the ANOVA for better microhardness value.

The primary objective of the present research work is to create a layer of SiC particles mixed with a viscous liquid, Di-ethyl ether and fabricate aluminium composite via friction stir processing technique. This is done to analyse the effect of the processing, tool rotational speed and addition of reinforcement, on the mechanical and wear properties of the material.

2. Experimental procedure

2.1. Materials

7075-T6 aluminium alloy is taken as matrix material because of its excellent strength to weight ratio. Plates having dimensions 200 mm × 80 mm × 6 mm are taken and groove of length 160 mm width 2 mm, depth 3.5 mm are generated on the plates using a milling cutter. This alloy of aluminium has good resistance, high strength and toughness, and improved mechanical properties. It is mostly utilized in the aerospace industry for structural parts. Figure 1 shows EDS of the base alloy. Silicon Carbide (SiC) powder having a particle size of 40 μm is used as a reinforcement for the study. SiC is taken as reinforcement material because it exhibits enhanced mechanical properties and good wear resistance [31]. SiC find wide application in semiconductors, turbines, pumping equipment, ball valve parts etc. Prior to FSP, SiC particles are mixed with Di-ethyl ether and a viscous paste is generated. Then this paste is filled in the grooves that have been made on the aluminium plates.

2.2. Fabrication of surface composite

FSP is used for fabricating the surface composite in this work. FSP is carried out on a semi-automatic machine setup. Clamping of workpiece, vertical and traverse motion of tool are all governed by a hydraulic system. Before processing the composite, capping pass is done with a pinless tool. This is done to protect the viscous solution from escaping during the actual processing. Then FSP is carried out with a non-consumable square pin tool made of H13 tool steel. The tool has a total length of 117 mm, pin length 3.5 mm and the tool is made to have a flat shoulder profile with a shoulder diameter of 19.95 mm. The tilt angle is 2°, kept constant for all fabricated
composites. Figure 2 shows the FSP set up used for fabricating. Tool rotational speed i.e. 700, 1000 rpm, is selected based on the literature review \[30\]. The tool is rotated at selected rpm and inserted in the clamped workpiece gently. For some time, it is made to rotate to produce heat and plastic deformation and then it is made to travel in the traverse direction. Table 1 shows all processed composites. Three different composites are fabricated i.e. sample 1, sample 2 and sample 3. Sample 1 is FSPed of base metal without reinforcement, sample 2 is AA7075 + SiC (2 wt%) FSPed at 700 rpm and sample 3 is AA7075 + SiC (2 wt%) FSPed at 1000 rpm. For this work, the projection of tool pin is mentioned in equation (1), area of groove in equation (2) and Fraction volume of reinforcement in equation (3) respectively.

\[
\text{Projection of tool pin} = \text{pin length} \times \text{square base diagonal}
\]

(1)

\[
\text{Groove area} = \text{Depth} \times \text{Width of groove}
\]

(2)

\[
\text{Volume fraction of particle} = \frac{\text{Area of groove}}{\text{Projection of tool pin}}
\]

(3)

### 2.3. Microhardness

Fisherscope HM2000S is utilised to generate Vickers microhardness value of the prepared samples. In this process, an intender is made to press on the surface with predefined force, for a limited period of time. Diagonals of the produced indentation are measured and quantified giving the microhardness of the sample. Four readings
are taken for each sample and average of the four is considered as the microhardness value of the sample. The indenter is in dwell for 20 s with a force of 0.3 N.

2.4. Tensile testing
The tensile test of the base alloy and FSPed samples was analysed using a computer-controlled universal testing machine (Tinius Olsen H50KS) at a constant crosshead speed of 1 mm/min at room temperature. Dog bone-shaped samples prepared according to ASTM: E8/E8M-011 standard with a length and thickness of 80 mm and 3.5 mm respectively, were used for tensile testing. The samples are clamped from both sides and applied with a force till the breaking of the sample is achieved. The samples i.e. Base, sample 1, sample 2, sample 3, were recorded for their ultimate tensile strength (UTS) and elongation in order to analyse the effect of processing, tool rotational speed and reinforcement on the material.

2.5. Wear testing
Pin on disc wear tests is performed on all three fabricated composites i.e. sample 1, sample 2, sample 3 and also on the base metal. Wear testing is performed using DUCOM manufactured High Temperature Rotary Tribometer shown in figure 3. In order to carry out the experiment cylindrical shaped samples of length 6 mm and diameter 10 mm are carved out from processed region, shown in figure 4. Electric discharge machining (EDM) process is used for carving out the cylindrical samples. A total of 12 pins are used for wear test and all pins were weighed before the wear test. 3 from each sample 1, sample 2, sample 3 and base metal. Pins are slid along the disc made of EN24 steel having a hardness of 56 HRC. Wear is tested at different applied loads of 20 N, 30 N, 40 N at corresponding track diameter of 30 mm, 40 mm, 50 mm. Pins are slid for a distance of 950 m in a time period of 16 min. After the completion of test, pins are weighed again and the difference in weights before and after the test is then analysed.
3. Results and discussion

3.1. Microhardness
Figure 5 shows the recorded microhardness for all samples. It can be seen that minimum microhardness recorded was for base metal, having a value of 102 Hv. Recorded microhardness for sample 1 is 132 Hv, this enhancement in microhardness might be because of grain refinement due to processing. Yuvaraj et al [25] reported similar type of results in their study. Microhardness of sample 2 is 145 Hv, which is more than that of sample 1; this increase can be attributed to well-dispersed SiC particles in the matrix [32]. Sample 3 showed a microhardness value of 152 Hv. On comparing the microhardness value of sample 2 and sample 3 it can be concluded that on increasing the tool rpm the hardness of the material is enhanced. This increase in hardness might be attributed to the grain boundary refinement because at higher rpm finer grains are produced [33]. Decrease in wear rate of sample can be attributed to the increase in hardness of samples i.e. the harder the sample, less it will wear out during the process.

3.2. Tensile testing
The effect of reinforcement and processing on ultimate tensile strength (UTS) can be observed in figure 6. All FSPed samples showed decreased UTS value when compared to that of base metal. There are a variety of microstructural properties on which tensile properties depends i.e. dislocation density, grain size and interaction reinforcement and the base metal. This decrease in UTS might be due to softening of the matrix due to FSP [34]. The reinforced specimen displayed less UTS value compared to that of FSPed material without reinforcement. Similar type of results was reported by Yuvaraj et al [35] and Butola et al [29] in their studies on aluminium composites. The UTS of material processed at 1000 rpm is more than that of the material produced at 700 rpm. This might be attributed to the finer grains produced at high tool rpm [36]. It is well observed from figure 6, that on processing the material without reinforcement, the elongation increases. The grain refinement due to processing increases the plastic deformation of the material, adding to elongation of the material [34]. Due to the hindrance in the mobility of dislocation with the addition of SiC, the elongation percentage decreases and the recorded elongation was little more for the material processed at 1000 rpm than the sample processed at 700 rpm, because of smaller grains produced at higher rpm.

3.3. Microstructural analysis
Microstructure images shown in figure 7 are generated using Olympus GX41 inverted metallurgical optical microscope at 50 μm. The conversion scale of 2 pixels per microns is used for the measurement of the microstructures. Microstructure holds great importance when analysing the processing effect of techniques like FSP. On evaluating figures 7(a) and (b), it can be concluded that there is extreme plastic deformation and grain refinement in base metal when processed using FSP i.e. sample 1. This confirms that improved properties are because of grain refinement. It can be observed that grains in figure 7(d) are finer compared to the grains in figure 7(c), this confirms that on processing the material at higher tool rpm more fine grains are produced.
3.4. Weight loss
Weight loss of all tested samples at different applied load is shown in figure 8. For all loads it can be observed that maximum weight loss is shown by the base metal followed by FSPed base metal, then by AA7075 + SiC composite fabricated at 700 tool rpm and minimum weight loss is shown by the AA7075 + SiC composite fabricated at 1000 tool rpm. From observing weight loss for base and sample 1 it is evident that on processing the weight loss decreases. This might be because of the grain refinement due to FSP [26]. Sample 1 shows less weight loss than sample 2 for all applied load. This shows that on incorporating the matrix with reinforcement wear resistance increases. This is because the load from aluminium alloy is transferred to the hard-ceramic particles introduced in the matrix [37]. Sample 3 shows less weight loss than sample 2, which shows that on fabricating composite at higher tool rotational speed, weight loss decreases. This is because less cavities and defects are generated at higher tool rotational speed and proper reinforcement distribution is there at high tool rpm [38].
3.5. Effect of load
Coefficient of friction variation with load can be observed in figure 9 (a), at lower load it is more marked. It can be observed that CoF increases with increasing load, though the increase in non-reinforced samples is more
compared to the reinforced samples. Coefficient of friction is reduced in reinforced samples because of the formation of the mechanical matrix layer which performs as a lubricant. Similar type of results was reported by Tyagi \textit{et al} in their study \cite{32}. Variation of wear rate with load can be observed in figure 7 (b). It can be seen that wear rate increases with increasing load and it is more pronounced at larger loads. As at higher loads, more pressure is between the mating surfaces, so more wear rate is observed; at low loads, less pressure is there, less wear loss is observed \cite{39}. Wear rate decreased on processing the samples, it decreased with the introduction of reinforcement in the matrix and it further decreased on fabricating the reinforced samples at higher tool rpm.

3.6. Wear morphology

SEM image of the worn surface of all tested samples at 40 N load is illustrated in figure 10. Wear tracks can be attributed to the sliding of the sample against the disc, and white particles in the SEM images illustrate the presence of the carbide particles. The SEM images indicate that adhesive wear is the primary wear mechanism. In adhesive wear, a part of the surface ploughs and sticks to a different section of the surface. The part sticks to the surface because of the large heat generated due to friction. Presence of different elements i.e. Fe, C, Si, Zn, Mg and Al can be seen in the sample, figure 11. The EDS indicates the high content of Fe-this might be because of the element transfer that takes place between the pin and the disc, during early phase of wear test. This also indicates the Fe layer formation, as it acts as a solid lubricant so it might be responsible for the decreased value of wear and coefficient of friction. Alam \textit{et al} \cite{40} reported similar kind of result in their study.

4. Conclusions

AA7075 matrix composites reinforced with silicon carbide having a particle size of 40 μm is successfully developed using friction stir processing (FSP). Effect of reinforcement, processing and tool rotational speed are analyzed on wear performance of the material. Major conclusions of the study are –

- Weight loss decreases on processing the alloy due to refinement of the grains.
- On addition of reinforcement, weight loss decreases because load from the alloy matrix is transferred to the hard-distributed silicon carbide particles.
At high tool rotational speed, fabricated defects-free surface composite and uniform distribution of reinforcement is there, which contribute to increased wear resistance.

Presence of C, Fe, Mg, Zn, Al, Si is confirmed in the worn out sample tested by EDS and it indicates the formation of Fe layer.

SEM images of the worn out samples illustrates that adhesive wear is the prominent wear mechanism.

Microhardness of the composite fabricated at 1000 tool rpm was 49% more than that of the base alloy.

Elongation % of the FSPed without reinforcement particles increased on processing due to grain refinement as compare to the FSPed with reinforcement; it decreases the FSPed sample with the addition of reinforcement due to hardness increases.

Microstructure confirms that on processing, the grains refined and grains were even finer on processing the material at higher tool rpm, which justified the increased hardness of the material produced at higher tool rpm.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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