Influence of Wood Fly Ash Reinforcement on the Wear Behaviour of Friction Stir Processed Aluminium-Based Surface Matrix Composite

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Abstract

In order to achieve low cost and cleaner production of metal matrix composites (MMC) has propelled younger researchers into using various forms of agrowastes powders as promising and potential alternative to metallic powder for reinforcement during the development and production of MMC. In recent past, industrial coal fly ash has been used extensively for reinforcement both in stir casting and friction stir processing and this material are basically found in big cities of some countries and as such not easily accessible to everyone. In this study, domestic wood fly ash has been developed, characterized and utilized as reinforcement during friction stir processing of aluminium alloy 7075-T651 due to its accessibility and availability to everyone, even people in the villages. The friction and wear behaviours such as wear resistance, wear rate, wear volume, and coefficient of friction of the processed samples were studied. Ball on flat disk tests were performed using Rtec Universal tribometer MTF 5000 with varying loads of 20 and 50 N under influence of dry friction. It was noted that at higher load of 50 N addition of wood fly ash greatly reduced wear rate, volume loss and coefficient of friction and also increased wear resistance. It was also obvious that abrasive wear was conspicuous at lower load of 20 N than at higher load and as such more debris were noted at lower load.

Keywords: aluminium matrix composite, friction stir processing, wear, wood fly ash.

1. Introduction

High strength, aluminium-based surface matrix composite (ABSMC) especially AA7075 series has found huge demand in aerospace, ballistic, electrical, aviation, tribological, space and air vehicle, automotive, thermal, structure, defense industries, military, transportation, engineering, agrochemical, manufacturing, mineral processing and allied industries because of their remarkable and unbeatable combination of surface matrix composites mechanical, physical and electrochemical properties like high strength-to-weight ratio, superior damping capacities, oxidation and wear resistance, creep and good corrosion resistance, high thermal and electrical conductivity, high fatigue and plastic flow strength, high specific stiffness and strength and low coefficient thermal expansion (Cerit, Karamiş, Fehmi, & Kemal, 2008; N.Sun and Apelian, 2011).

In recent past, several metallic reinforcements particles have been deployed to develop metal matrix composites (AMC) such powders as graphite(Baradeswaran & Perumal, 2014), stainless steel powder of various types, copper powder(Sarmadi, Kokabi, & Reihani, 2013), titanium alloy powders of different kind, graphene, silicon carbide, nitrides and oxides, to mention but a few. Nowadays, researchers have developed interest in utilizing agrowastes powders as reinforcements in both frictions stir processing as well as stir casting techniques of developing AMC that can serve as potential and promising replacement to metallic powders due to its availability and accessibility with low cost of production. In recent time, some great works had been carried out using rice husk ash (Dinaharan, Kalaiselvan, Akinlabi, & Davim, 2017; Zuhailawati, Halmy, Almanar, Seman, & Dhindaw, 2016), palm kernel shell ash (Ikumapayi & Akinlabi, 2018), bamboo powder, coconut shell ash, fly ash especially coal fly ash and wood fly ash (An, Zhu, Li, Lu, & Liu, 2019; Dinaharan, Nelson, Vijay, & Akinlabi, 2016; Ikumapayi & Akinlabi, 2019a; Sharma, Singh, & Chaudhary, 2017).

Wear behaviours of AA7075 at different tapered conditions have been studied extensively in the past under the influence of different reinforcement particles. Wear behaviour of aluminium matrix surface composite (AMSC) of AA7075 using multiwall carbon nanotubes (MWCNT) as reinforcement and ANOVA software was employed in validating wear experimental results received from friction stir processing. In this study the rotational speed was varying between 900 – 1200 rpm while traverse speed was between 42 – 50 mm/min. It was observed that at a rotational speed of 1120 rpm and travel speed of 40 mm/min, there exist the minimum wear rate of 7.0 mm^3/m at deployment of three passes (Pasha, P, & P, 2017). Wear parametric behaviour on the armour grade AA7075 under the influence of solid lubricant MoS2 fabricated by friction stir processing was investigated. Different sizes of B_4C was used while at 30 µm with addition of solid lubricant MoS2 gave the lowest COF, highest hardness with the best ballistic properties(I. Sudhakar, Madhu, Madhusudhan Reddy, & Srinivasa Rao, 2015). Similar wear behaviour of AA7075 with the use of 2 wt%ZrB2 nanocomposites (NC) as reinforcement particle. There was an improvement in the hardness properties of the processed zone and there exists reduction in the abrasion as the number of passes increases as a result increases the delamination (Prasad, Tewari, & Singh, 2019).

2. Materials and Methods

2.1 Materials:

Commercially rolled alumionium alloy 7075-T651 metal plates which was procured from Bharat Aerospace Metals, Mumbai, India and supply in a dimension 500 x 600 x 6 mm^3 and later sectioned to a usable dimension of 300 x 125 x 6 mm^3 were used as base metal during friction stir processing experiment. The spark spectrometric analysis of as received base metal was carried out and the result is presented in Table 1 and the mechanical properties in as received form are Shear Modulus (26 GPa), Brinell Hardness (150), Fatigue strength (160Mpa), shear strength (330 MPa), Elastic Modulus (70 GPa), Poisson's Ratio (0.32), Yield Strength (500 MPa) and Ultimate tensile strength (UTS) (570 MPa) (Ikumapayi & Akinlabi, 2019c). The base material was reinforced with nanoparticle of wood fly ash (WFA-NPs).

Table 1: Chemical composition AA7075-T651 aluminium alloy

Elements	Mg	Fe	Ti	Si	Mn	Zn	Cu	Cr	Al
Wt.% Composition	2.8	0.15	0.02	0.05	0.01	5.92	1.93	0.193	**Bal**

2.2 Wood Fly Ash Characterizations

Bunch of fire-wood was fired and after complete combustion, a by-product was obtained which is wood fly ash. The ash was then collected, sieved with 75 µm and washed with deionized water to remove every trace of impurity present therein and then drained to dryness. It was further dried in an electric oven of temperature 80° C for 2 days. This was then milled for one hour using vibratory disc milling machine. The structural and morphological behaviour of the powder were studied using scanning electron microscope (SEM), Energy Dispersive X-ray Spectrometer (EDXS), X-Ray Fluorescence (XRF) as well as X-ray Diffraction. The SEM Images and their corresponding EDXS are presented in Figure 1. The XRF analysis revealed the chemical compositions contained in the WFA as Al_2O_3 (10.7%), SiO_2 (46.31%), MgO (0.36%), TiO_2 (0.933%), Fe_2O_3 (17.28%), CaO (3.002%), MnO_2 (0.0471 %), Na_2O (2.48%), P_2O_5 (0.113%), K_2O (2.53%), SO_3 (3.423 %) and LOI (8.00%). The XRD analysis revealed the following crystal phases that are present in WFA as hexagonal, tetragonal, cubic and rhombohedral and the following minerals are said to be present in WFA: Lime (CaO), calcite ($CaC0_3$), Sylvite (KCl), nitratetine ($Na(NO_3)$), quartz (SiO_2), maghemite-Q (Ɣ-Fe_2O_3), and magnetite (Fe_3O_4).

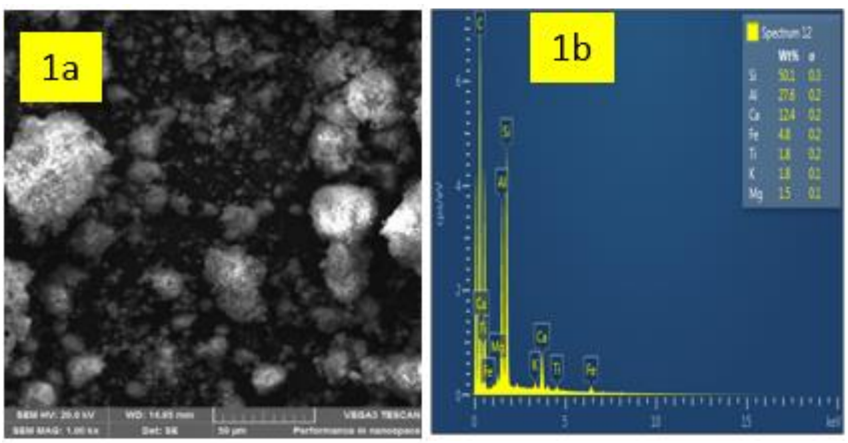
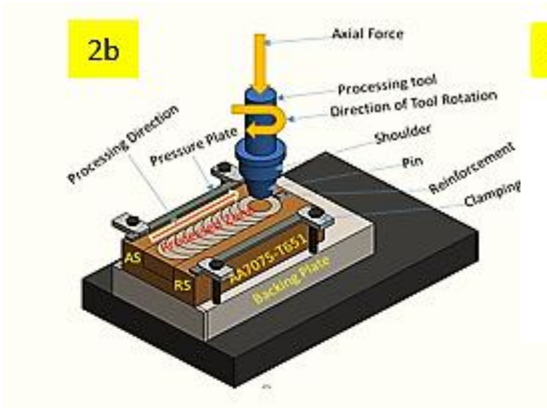


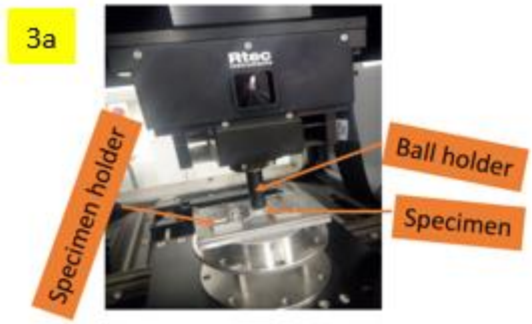
Figure 1: (a) Morphology of WFA (b) WFA EDS

Fig. 2a NC-controlled FSW machine

2.3 Friction Stir Processing Experimental Procedures

Friction stir processing (FSP) experiment was conducted on the two (2) Ton linear numerically controlled (NC) friction stir welding machine as shown in figure 2a which was manufactured by ETA Bangalore, India Ltd. A groove made up of 2 mm width and 3.5 mm depth was made on 300 x 125 x 6 mm^3 AA7075-T651 to accommodate WFA particles. Two passes were employed using two different processing tools (The Pinless tool and tapered cylindrical tool), both are made from AISI H13 tool steel. The pinless was first adopted to close up the groove after the compartment of WFA in the groove, this was operated at rotational speed of 1000 rpm and travel speed of 100 mm/min while the second tool configurations are 18 mm shoulder diameter, 5 mm pin length and 5 mm pin diameter, this was used to stir and mix the reinforcement with the substrate to ensure homogeneity of the Aluminium metal composite (AMC). This second tool operated at 1500 rpm rotational speed, and 20 mm/min travel speed while the machine was tilted at 3 °, and the 0.3 mm plunge depth was maintained (Ikumapayi & Akinlabi, 2019b). The schematic illustration of friction stir processing is as shown in Figure 2b.





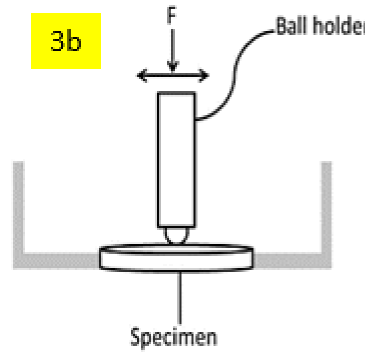


Fig. 2b. Schematic of Friction Stir Processing **Fig. 3a.** Tribometer experimental set-up
Fig. 3b. Illustration of Tribometer set-up

2.4 Wear Mechanism

Wear behaviours of the fabricated aluminium metal matrix composite (AMMC) using wood fly ash as reinforcement was experiemnted alongside with the friction stir processed base metal – FSPed AA7075-T651 and unprocessed base metal – AA7075-T651 to serve as control experiments. Dry sliding wear test was carried out on the dimensions 24 mm x 10 mm x 6 mm using Rtec Universal tribometer MTF 5000 which has integrated 3D in-line profilometer for Imaging and is capable of performing the test on nano, micro, and macro load. It has a force sensor, temperature, and humidity controller, environmental isolation panel to reduce acoustic interference as well as data acquisition and motion controller. In this study, a Cyclic, ball on flat disc wear test mode was used with E52100 alloy steel ball of grade 25 and the ball diameter of 6.35 mm and the tests were conducted in accordance with ASTM G133-05 standards (Erinosho et al., 2017). Two different types of loads were applied on the surface of each sample which is 20 N and 50 N with sliding distance 3 mm and 5 mm respectively while both have a sliding speed of 3 mm/s. The wear tracks were captured with an attached microscope on the tribometer. The data were acquired from MFT17 software installed on the computer that was linked to Rtec Universal tribometer for analysis. The coefficient of friction (COF), wear volume, friction force for all the tested samples and other parameters were acquired from MTF17 software. The experiments were conducted at an ambient temperature of 25 ° C.

3. RESULTS AND DISCUSSION

3.1 Friction and Wear Results for Aluminium –Based Surface Matrix Composite

The efficacy of wood fly ash (WFA) on the wear behaviour under the influence of varying loads during friction stir processing were experimented in this study. In order to evaluate the influence of WFA on wear characteristics some parameters were considered, measured, computed and recorded in the course of the experiments and after the completion of the experiments. Such parameters are, wear resistance, coefficient of friction, wear volu me (volume loss), wear rate, wear depth as well as friction force (Ikumapayi, OM, Akinlabi, Esther T and Majumdar, 2019).

Volume loss from each tested sample was extracted from the profiler generated by the machine after the experiment and recorded, and this can be computed using the following mathematical equations in Equations (i) and ii (Deuis, Subramanian, & Yellup, 1997) (D. Sudhakar, Jeyasimman, & Duraiselvam, 2015).

$$V_w = \frac{C_w dL}{3h} \quad \text{(i)}$$

Where V_w = Wear Volume, Cw = Wear Coefficient, d = Sliding distance, L = Load applied and h = Substrate bulk hardness

$$Volume\ loss\ (mm^3) = \left(\frac{Weight\ loss\ (g)}{Density\ (\frac{g}{mm^3})}\right) x\ 1000 \qquad \text{(ii)}$$

Wear rate was computed using equation (iii) and wear resistance at different loading was also estimated using equation (iv) (Baruwa, Oladijo, Maledi, & Akinlabi, 2018; Kumar & Wani, 2017; D. Sudhakar et al., 2015) while the average coefficient of friction was obtained from the data extracted from the machine and this can be calculated theoretically using equation (v) (Jeyaprakash, Yang, Duraiselvam, & Prabu, 2019).

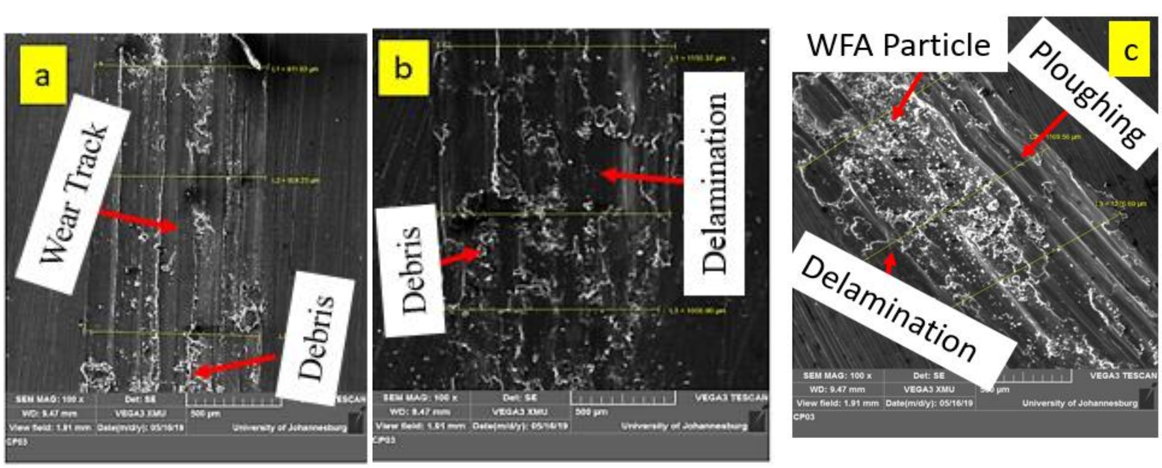
$$\text{Wear rate (mm}^3\text{/m)} = \left(\frac{Volume\ loss\ (mm^3)}{Sliding\ distance\ (m)}\right) x\ 1000 \qquad \text{(iii)}$$

$$\text{Wear resistance (m/mm}^3\text{)} = \left(\frac{Sliding\ distance\ (m)}{Volume\ loss\ (mm^3)}\right) x\ 1000 \qquad \text{(iv)}$$

$$\text{Coefficient of friction } (\mu) = \frac{Friction\ Force\ (F_f)}{Applied\ Load\ (L)} \qquad \text{(v)}$$

Figure 4 (a-c) represents the SEM micrographs when 20 N load was applied on the unprocessed base metal -AA7075-T651, processed base metal – FSPed AA7075-T761 and the fabricated aluminium metal matrix composite reinfoced with wood fly ash - AA7075-T651/WFA. The abrasive and delamination are the predominant when 20 N load was applied. In Fig. 4a, there are clear and continuous (longitudinal) abrasive marks along the direction of the steel ball, with the deepest marks/scratches at the mid of the wear track. At the end of the wear track large wear debris can be observed; with obvious free bright (small) particles (debris) fully delaminated from the tested sample (unprocessed base metal – AA7075-T651). These small particles are dominant at the edges of the wear grooves. In Fig. 4(b), the scratch marks along the direction of the reciprocating steel ball are discontinuous, with large (partially bright) particles randomly distributed throughout the wear track. The discontinuous scratches are indicators of some form of wear resistance by the large particles distributed on the wear tracks (Baradeswaran & Perumal, 2014). In Fig. 4(c), the wear debris are also distributed randomly but appear dense and fully broken, particles of WFA were seen, there was delamination of the AA7075-T651/WFA. In these samples, the free broken particles get attached or pushed by the steel ball onto the substrate, thereby enhancing grooving and contribute to 3 body wear mechanism as also reported in the of Prasad et al. (Prasad et al., 2019).

Fig. 4(ai) - (ci): In these samples, the wear is predominated by delamination and adhesion. Due to higher loads (50N), there is generation of heat, which degrades the mechanical properties of the samples and therefore enhancing softening and plastic deformation of material along the wear paths. Softening and plastic deformation of the material along the wear path ensures that the material being removed gets 'smeared' onto the walls of the wear track or onto the steel ball and as such, it is not obvious to see the wear debris as it was conspicuous in the case when 20 N was applied.



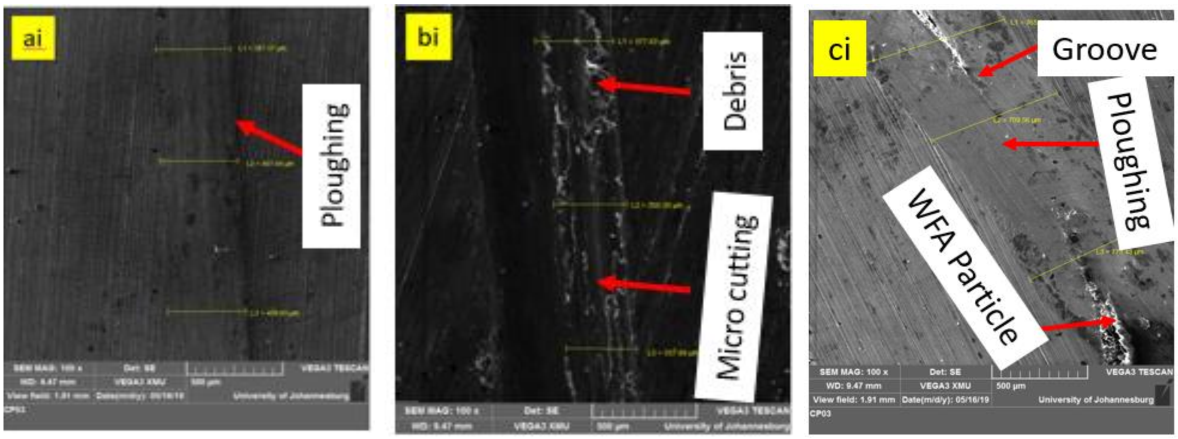


Fig. 4. SEM Images for Wear track showing wear width of 20 N Load (a) AA7075-T651 (b) FSPed AA7075-T651 (c) AA7075-T651/WFA; SEM Images for Wear track showing wear width of 50 N Load (ai) AA7075-T651 (bi) FSPed AA7075-T651 (ci) AA7075-T651/WFA

3.2 Effects of Varying Load on the Wear Properties

The parametric behaviours when 20 N applied load, sliding distance and speed of 3 mm each, and cyclic time of 5 min conducted at an ambient temperature of 25 ° C is shown in Table 2 while the data obtained when 50 N applied load, at sliding distance and sliding time of 5 mm each with sliding speed of 3 mm is equally displayed in Table 3.

It was evidentially clear that lots of debris were seen on the morphological examination when 20 N applied load was engaged while very few of debris were seen on the morphological surface when 50 N applied load was used and this may be as a result of intense heat generated during the reciprocating sliding movement of the steel ball on the workpiece and as such leads to degeneration of mechanical properties by causing plastic deformation and softening the wear paths (Baradeswaran & Perumal, 2014), thereby removing the deposited wear debris along the wear track. It was also seen from the morphology examination that average wear widths taken on the SEM Image in Figure 4 were noticed to have been larger at an applied load of 20 N and lower at an applied load of 50 N. Delamination was also noticed in each wear tracks when 20 N load wear applied at different tested samples than when 50 N load was applied. Figures 5 and 6 show the wear tracks when 20 N force and 50 N force was respectively applied on the unprocessed base metal – AA7075-T651, processed base metal – FSPed AA7075-T651 and the reinforced metal matrix composite - AA7075-T651/WFA. The wear profiling at different testing stages, i.e. AA7075-T651, FSPed AA7075-T651, and FSPed AA7075-T651/WFA AMC were also presented and 3D geometry of 50 N load for AA7075-T651, FSPed AA7075-T651 and FSPed AA7075-T651/WFA AMC were also presented.

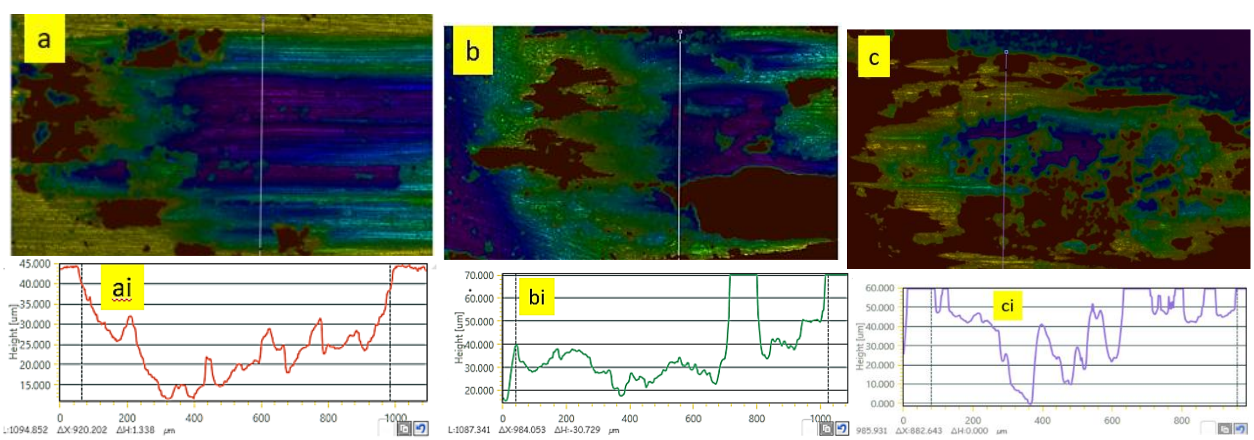


Fig. 5. Wear track for Load of 20 N (a) AA7075-T651 (b) FSPed AA7075-T651 (c) AA7075-T651/WFA; and Profiler (ai) AA7075-T651 (bi) FSPed AA7075-T651 (ci) AA7075-T651/WFA

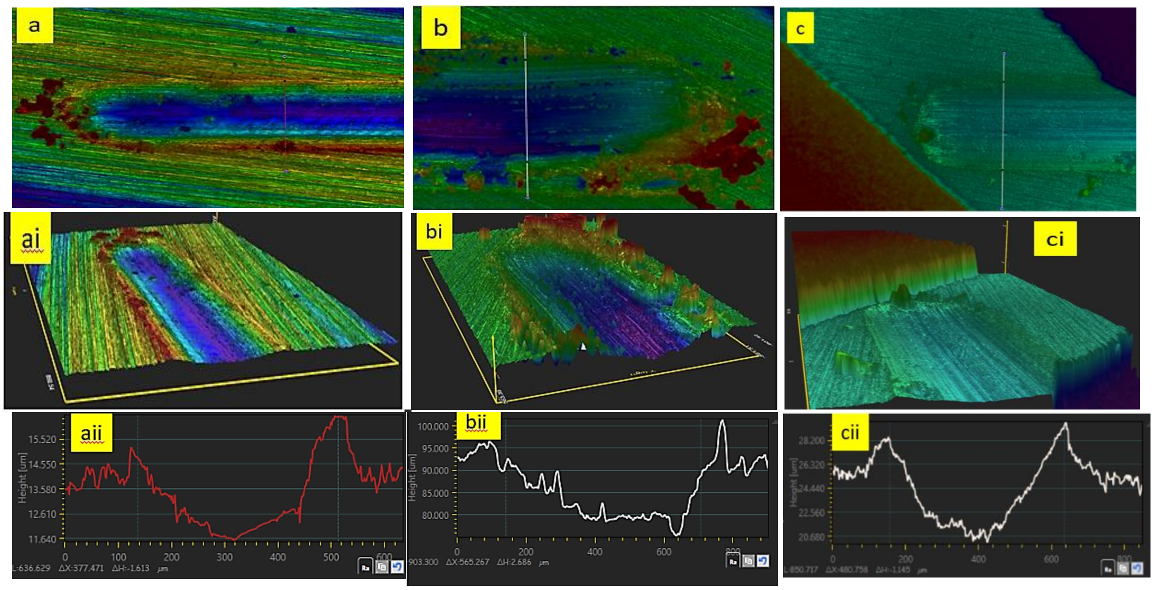


Fig. 6. 2D View of Wear track for Load of 50 N (a) AA7075-T651 (b) FSPed AA7075-T651 (c) AA7075-T651/WFA; 3D View (ai) AA7075-T651 (bi) FSPed AA7075-T651 (ci) AA7075-T651/WFA; Profiler (aii) AA7075-T651 (bii) FSPed AA7075-T651 (cii) AA7075-T651/WFA

Figure 7 presents different plots that explicitly explain the effects of varying load on the wear parametric properties such as wear volume, wear rate, wear resistance and coefficient of friction while other parameters are presented in Tables 2 and 3 for the base metal – AA7075-T651, FSPed AA7075-T651 and AA7075-T651/WFA AMC.

Table 2. Wear Results conducted at ambient temperature for Load of 20 N

Parameters	20 N,	5 mins,	3 mm and	3 mm/s			
Sample	Wear Depth (mm)	COF	Wear Volume (mm^3)	Wear Rate (mm^3/m)	Wear Resistance (m/mm^3)	Wear width (µm)	Friction Force (N)
AA7075-T651	0.0213	0.4680	0.049940	16.647	60072.09	920.22	9.360
FSPed AA7075-T651	0.0201	0.4568	0.042313	14.104	70900.19	1099.76	9.136
AA7075-T651/WFA	0.1543	0.4181	0.038761	12.920	77397.38	1163.85	8.362

At 20 N applied load in Table 2, the wear volume for unprocessed base metal – AA7075-T651 was 0.049940 mm^3 which was higher than when 50 N load is applied in Table 3 which gave wear volume of 0.028358 mm^3 for the same unprocessed base metal. By implication, for unprocessed base metal - AA7075-T651, the wear rate is lower when 50 N load is applied than when 20 N load is applied which gave 5.672 mm^3/m in 50 N load and 16.647 mm^3/m in 20 N load. This also dictates that there was greater wear resistance in 50 N applied load for unprocessed base metal – AA7075-T651 than 20 N which was found to be 176317.09 m/mm^3 as against 60072.09 m/mm^3 in 20 applied loads. The COF was noticed to be lower in 50 N applied Load for unprocessed base metal which is 0.1969 than in 2 0 N for the same AA7075-T651 which gave 0.4680 as also evidence in Figure 7, and the same trend was noticed in friction

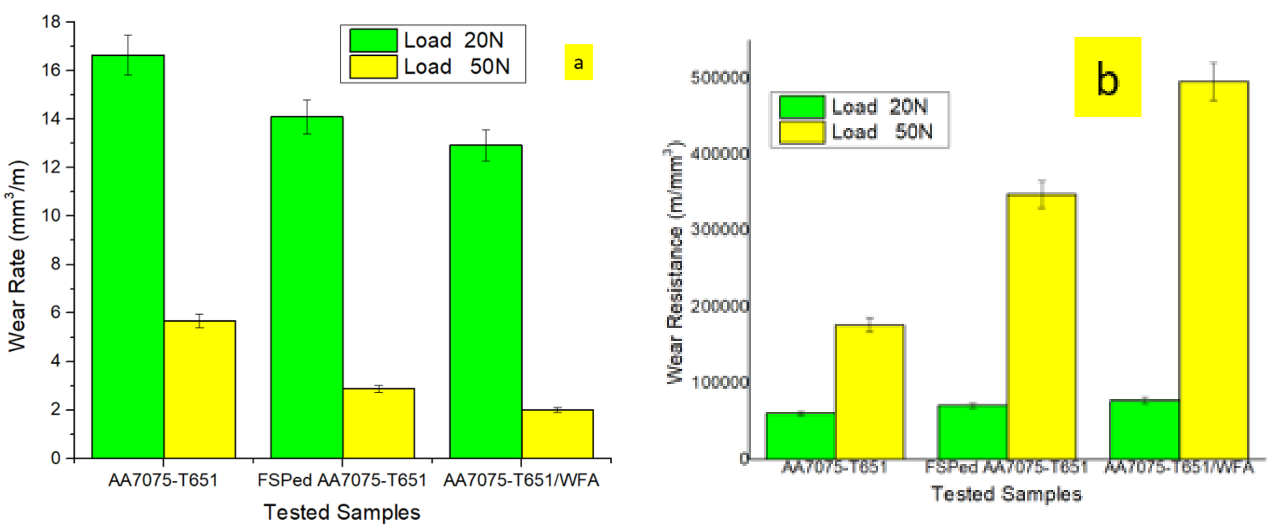
force results for AA7075-T651 but it was noticed that the wear depth for unprocessed base metal – AA7075-T651 when 20 N load was applied is lower than when 50 N is applied which was 0.0213 mm as against 0.0288 mm.

On examining FSPed AA7075-T651 at different varying load it was observed that the wear volume was more in 20 N load than in 50 N load which resulted to 0.042313 mm^3 as against 0.014390 mm^3 in 50 N. The results in Tables 2 and 3 further show that FSPed AA7075-T651 has lower wear rate when 50 N load is applied than when 20 N load is applied, i.e. the wear rate for 50 N load was 2.878 mm^3/m which that of 20 N was 14.04 mm^3/m while the wear resistance is higher in 50 N than in 20 N applied load. The wear resistance was 347463.51 m/mm^3 in 50 N load and 70900.19 m/mm^3 in 20 N for processed base metal – AA7075-T651p. Wear depth was 0.1135 mm in 50 N which was higher than in 20 N of 0.0714 mm for FSPed AA7075-T651. The average COF was lower in 50 N which was 0.1320 than in 20 N load which was 0.4568 for AA7075-T651.

Aluminium matrix composite reinforced with WFA also followed the same trend as above. It was noticed that 50 N, its wear volume was 0.010087 mm^3 while that of 20 N load was 0.038761 mm^3, this performs better than either FSPed AA7075-T651 and AA7075-T651. The wear rate was 2.0174 mm^3/m in 50 N load while it was 12.920 mm^3/m in 20 N load; the wear resistance was 495687.51 m/mm^3 in 50 N load and that of 20 N load was 77397.38 m/mm^3. The average COF was lower in 50 N which was 0.1119 and that of 20 N was 0.4181. Overall, it was observed that AA7075-T651/WFA AMC performed better than FSPed AA7075-T651 and AA7075-T651 in terms of wear rate as well as wear resistance, the results corroborated with the work of Irfan et al. (El-Aziz, Saber, & Sallam, 2015).

Table 3. Wear Results conducted at ambient temperature for Load of 50 N

Parameters	50 N,	5 mins,	5 mm and	3 mm/s			
Sample	Wear Depth (mm)	COF	Wear Volume (mm^3)	Wear Rate (mm^3/m)	Wear Resistance (m/mm^3)	Wear width (µm)	Friction Force (N)
AA7075-T651	0.0288	0.1969	0.028358	5.672	176317.09	401.65	9.845
FSPed AA7075	0.1135	0.1320	0.014390	2.878	347463.51	355.27	6.600
AA7075-T651/WFA	0.0165	0.1119	0.010087	2.0174	495687.51	749.41	5.595



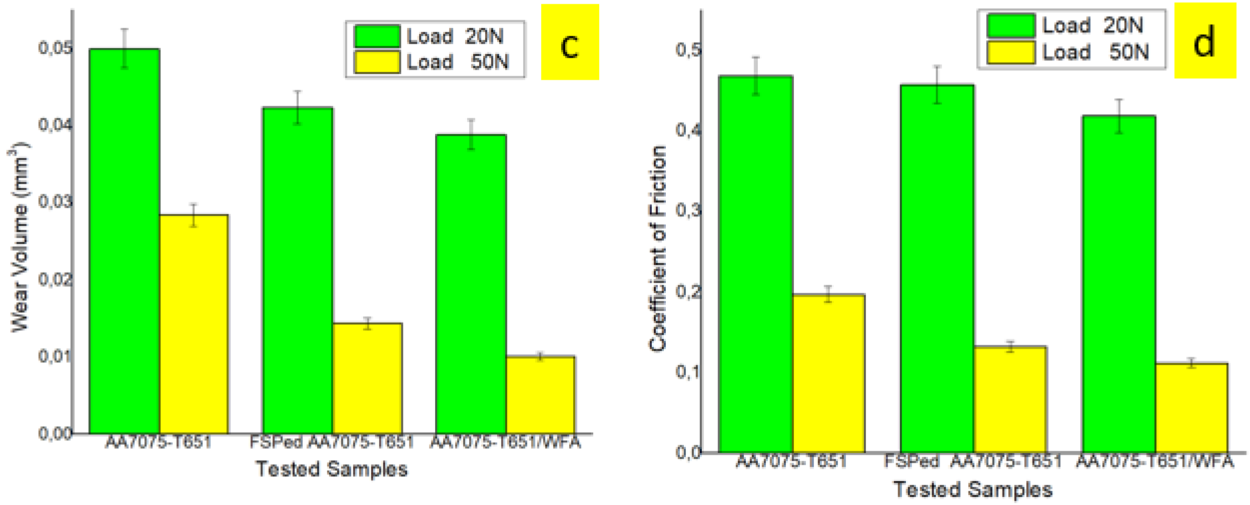


Fig. 7 (a) Wear Rate (b) Wear Resistance (c) Wear Volume (d) Average COF for AA7075-T651, FSPed AA7075-T651 and FSPed AA7075-T651/WFA AMC at load 20N and 50 N

Figure 7 (a-d) represent the plots of wear volume, wear resistance, wear rate and COF for the unprocessed base metal – AA7075-T651, unreinforced but processed base metal – FSPed AA7075-T651 as well as fabricated aluminium matrix composite – AA7075-T651/WFA at different loading conditions of 20 N and 50 N. In Figure 7a, wear rate was lower when 50 N applied load was engaged, at different tested samples, wear rate at higher load is lower. Wear resistance is higher at higher load as seen in Figure 7b. The higher the load, the higher the wear resistance but the lower the wear rate, wear volume and the coefficient of friction as seen in Figure 7. It is essential to mention that Wear rate and wear volume are directly proportional and they inversely proportional to wear resistance as noticed in Figure 7 (a-d). Increase in wear volume, increases the wear rate and decreases the wear resistance, while the lower the COF the better as shown in Fig. 7d (Irfan, Haq, & Anand, 2018; D. Sudhakar et al., 2015).

Conclusion

The influence of wood fly ash (WFA) on wear properties at varying loads has been experimentally studied. Characterizations of WFA such as elemental and chemical compositions, minerals and phases present were presented. Morphology of worn surfaces, and wear tracks were also presented. It was noted that addition of WFA greatly enhanced the wear integrities on friction stir processed AA7075-T651. From the results and the discussions, it can be concluded that higher load improved wear properties. It was noted that at 50 N, the wear rate, volume loss and average COF were reduced while wear resistance was higher at all instances. It was further observed that AA7075-T651/WFA AMC performed far better than FSPed AA7075-T651.

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