Investigation on Tribological and mechanical behaviour of AA6082—Graphene based composites with Ti particles

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Abstract
In the recent years, high strength and low weight materials are being preferred in automobile sectors for fabricating high-speed rotating shafts and machineries. For satisfying dynamic requirements, Aluminium Metal Matrix Composites can be used. In this paper, an attempt has been made to fabricate AA 6082—graphene based Aluminium Matrix Composites reinforced with Titanium (Ti) particles. The effect of increase weight percentage of Graphene and Ti reinforcement on the mechanical characteristics was evaluated. Using tensile tests and surface micro hardness measurements, the fluctuations in mechanical aspects were measured. Tribological characteristics of the Aluminium Matrix Composites were found using pin on disc tribo wear meter, using Silver (Ag) nanoparticles incorporated Jatropha oil as bio-lubricant. Microstructural variations were evaluated by using FESEM which indicated surface tear offs, surface ploughing, demarcations, micro pits, grooves, demarcations, micro cuts and micro tears on the surfaces. The effect of Ag Nano particle addition on Jatropha oil was observed with the fluctuations in Coefficient of friction, specific wear rate and wear mass loss. On increase in reinforcement percentage of G and Ti, specific wear rate was found to decrease and coefficient of friction decreased till 3% by weight reinforcement and beyond 3%, it increased. The surface chemistry modifications were identified using XRD. It was observed that AA6082 Aluminium Matrix Composites reinforced with 3% G and 3% Ti exhibited better mechanical and tribological properties when used with 1% Ag Nanoparticles incorporated Jatropha oil as lubricant.

1. Introduction
Aluminium Matrix Composites are being used all over the world in fabrication, manufacturing, automobile and power sectors. Due to the ease of fabrication and better workability, it is being preferred. A lot of research is being done so as to enhance its mechanical characteristics of tribological aspects of aluminium, its alloys and its composites. Controlling friction and wear in dry abrasion is critical for homogeneous finishing surfaces. Lubricants play a significant character to reducing wear and friction between the two interfered surfaces.

Sivakumar et al (2019) prepared Aluminium Matrix Composites using ZrB2 as reinforcement medium & evaluated the effect of increase in weight percentage of ZrB2 on variations in structural and mechanical aspects. The fluctuations in compressive strength, surface micro-hardness, densification and coefficient of friction on ZrB2 as reinforcements were evaluated [1]. Ramkumar et al (2019) conducted tribological investigations on stir casted Aluminium Metal Matrix Composites with TiC reinforcements. The effect of increase in weight percentage of TiC reinforcements on ductility, flexural strength and surface micro hardness variations of the composites were evaluated [2]. Babu et al (2015) conducted tribological experiments on surface treated EN25 steels. The effects of Laser surface hardening treatment on surface wear characteristics were observed.
important tribo wear process parameters were optimized, for reducing surface wear [3]. Munagala et al (2019) conducted frictional wear experiments at elevated temperatures on Ti6Al4V and Ti6Al4V-TiC composite coated Titanium alloys. An attempt was made to enhance the wear resistance properties by fluctuating coatings thickness. The composite coating material was cold sprayed over the Titanium alloys and the effect of coating thickness on variations in wear resistance was studied [4].

Poria et al (2018) conducted tribo wear experiments on Aluminium Metal Matrix Composites reinforced by TiB2 Nano particles. Using stir casting process, Aluminium Metal Matrix Composites were prepared by increasing the weight percentage of TiB2 Nano particles and the corresponding fluctuations in wear resistance was evaluated. Using Taguchi optimization methodology, the vital process parameters were optimized so as to reduce surface wear [5]. Prakash et al (2018) conducted experiments using Ti-6Al-4V/B4C Metal Matrix Composites, prepared using powder metallurgy. The variations in density, surface hardness and mechanical properties and corrosion resistance aspects on increasing B4C reinforcement in the composites [6]. Pramod et al (2018) conducted experiments on Al 7075 Aluminium Metal Matrix Composites, reinforced with Al2O3 ceramic reinforcements. Using stir casting method, the Aluminium Matrix Composites were prepared and the casting process parameters were optimized by using Artificial Neural Network Algorithm thereby increasing the wear resistance [7]. Kumar et al (2019) investigated tribological aspects of Al6061 Aluminium Metal Matrix reinforced with ZrO2 Nano particles were used. A liquid metallurgy technique such as stir casting was adopted for preparation of Aluminium Metal Matrix Composites. The effect of increase in ZrO2 Nano particle reinforcement on fluctuating the wear resistance was studied [8]. Kanaya and Odoni 2016 attempted to enhance the wear resistance and mechanical aspects of Copper Matrix Composites by reinforcing it with steel machining chips. The fluctuations in corrosion aspects on increasing the reinforcement percentage of steel chips were observed [9].

Xu et al (2019) used squeeze casting combined with additive manufacturing to prepare Fe alloy lattice reinforced with Copper Matrix Composite. The effect of Fe alloy reinforcement in enhancing the mechanical and metallurgical properties of Copper Matrix Composite was observed [10]. Somani et al (2018) conducted tribo wear experiments on SiC Reinforced Copper Matrix Composites. A significant reduction in wear was observed on increasing SiC reinforcement in Copper Matrix Composites [11]. Mistey et al (2019) attempted to enhance the wear resistance of Si3N4 incorporated AA 7075 Aluminium Matrix Composites by using heat treatment [12]. Satyanatayana et al (2019) conducted wear experiments Metal Matrix Hybrid Composites reinforced with graphite and granite particles. The fluctuation in friction coefficient on increasing granite and graphite particulates have been studied [13]. Wang et al (2020) studies the tribo wear behaviour of TiC/Al-Cu13.7-Mg1.4 by increasing the reinforcement percentage of TiC nano particles combined with nacre like structures. A protective layer was formed which was responsible for increasing the wear resistance of the nano composites [14]. Bhowmik et al (2020) evaluated the tribological properties of Aluminium-Titanium Diboride (Al7075-TiB2) Metal Matrix Composites. The effect of interaction between the wear surface and the prepared composite material was observed using microscopic evaluation and the chemical variations in the wear surface was studied using x-ray Diffraction Spectroscopy [15].

Dhar et al (2020) conducted tribo wear experiments on Aluminium Matrix Composites reinforced with micro-sized iron fillers. The variation in harness and electrical conductivity was observed upon increasing the reinforcement percentage [16]. Roseline and Paramasivam (2019) evaluated the corrosion aspects of Aluminium Metal Matrix Composites reinforced with Fused Zirconia Alumina. The corroded surfaces were evaluated using X-Ray Diffraction Spectroscopy for identifying the chemical variations in the corroded surface [17]. Radhika et al (2020) evaluated the frictional wear aspects of Aluminium Metal Matrix Composites reinforced with B4C. a significant reduction in surface wear was observed on increasing B4C reinforcement [18]. Venkatesan and Xavior (2020) used stir and squeeze casting process to prepare Graphene reinforced AA7050 Aluminium Metal Matrix Composites. The fluctuations in wear aspects on increasing Graphene reinforcements were observed [19]. Aswinprasad et al (2020) evaluated the wear aspects of Graphite and Molybdenum di-sulfide reinforced Aluminium 6063 hybrid Metal Matrix Composites [20].

A lot of researches have been conducted in identifying different lubricants and additives to enhance lubrication. Xu et al (2019) used Pentaerythritol rosin ester incorporated vegetable oil as lubricant and conducted tribo wear experiments. The effect of increase in Pentaerythritol rosin ester on enhancing the lubricating aspect of vegetable oils [21]. Noorawzi et al (2015) conducted tribo wear experiments by using double fractionated palm oil as bio lubricant. The effect of reduction in wear rate on using bio lubricant was evaluated [22]. Thakre et al (2016) evaluated the boundary lubrication properties of lubricants, on addition of Aluminium Oxide Nano particles. The fluctuations in the lubrication aspects on increasing the concentration of Aluminium Oxide Nano particles were studied [23]. Kumar et al (2019) used molybdenum di sulphide (MoS2) and graphite (Gr) reinforced Aluminium Matrix Composites and conducted wear experiments by using tyre oil as lubricant. A significant reduction in wear rate was observed on using tyre oil as lubricant [24]. Singh et al (2020) used Multi Wall Carbon Nano tube incorporated SPAN 80 oil as lubricant for evaluating the wear behaviour of Aluminium
Matrix Composites using tribo wear experiments. The wear mechanism was evaluated by studying the worn-out surfaces [25]. Zhou et al (2018) conducted tribo wear experiments on hybrid multi-walled CNTs and nano-SiC particulate reinforced nanocomposites under oil lubrication. The variations in wear mechanisms on using lubrication oil were observed [26].

From study of previous literatures, it was evident that no previous investigations were reported on tribological investigations of Ti & G reinforced AA 6082 Hybrid Metal Matrix Composite materials. Thus, in this investigation, mechanical and tribological characterization was conducted on AA 6082 Metal Matrix Composite reinforced with Ti & G additives, possessing low coefficient of friction and high wear resistance properties suitable for aerospace and automobile applications.

2. Materials and methods

In this investigation, AA 6082 was chosen to be the matrix material for preparation of the Aluminium Matrix Composite. The base material was procured in rolled plates.

2.1. Chemical evaluation of the base material

The chemical composition of the base material AA 6082 was evaluated by using spark spectrometer. Cleaned AA 6082 specimens were placed in spark spectrometer. By igniting sparks at different places in the specimen, the spectrum evolved was evaluated for identifying the percentage of different elements present in the base material sample. The chemical composition of the base AA 6082 material in weight percentage has been indicated in table 1.

| Alloy | Fe | Cu | Mn | Mg | Zn | Si | Cr | Ti | Al |
|-------|----|----|----|----|----|----|----|----|----|
| Al6082| 0.47 | 0.18 | 0.87 | 1.24 | 0.08 | 0.24 | 0.21 | 0.37 | Bal. |

Table 1. Chemical composition of base material (in weight %).

2.2. Mechanical property test

Tensile strength of the base material was evaluated by using ASTM E 08 standards. The schematic representation of standard tensile test specimen have been indicated in figure 1. Tensile tests were conducted in INSTRON 115 Make (60 KN Capacity) universal Testing Equipment. Using electro pneumatic control, an incremental load of 1.5 KN min⁻¹ was given to the test specimens till fracture. The tensile strength and elongation percentage of the base material was found and the values have been indicated in table 2.

| Alloy | Melting point (°C) | Density (g cm⁻³) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Elongation (%) | Hardness (HV) |
|-------|-------------------|-----------------|--------------------------------|---------------------|----------------|-------------|
| Al6082| 591               | 2.79            | 306                            | 233                 | 14.5           | 79         |

Table 2. Important mechanical characteristics of Al 6082.
2.3. Microstructural characterisation of Ti, G additives, Jatropha Oil and Ag nanoparticles

In this research, Titanium and Graphene additives were used as reinforcement materials. The average size of the Graphene particles used in this investigation were 5 to 15 μm. The purpose of adding Titanium was to attain excellent mechanical and metallurgical properties (Liu et al 2019)[27]. Using FE-SEM (SIGMA Model), the Ti particles were observed at 20 kx magnification. The FE-SEM micrograph of Ti additive has been indicated in figure 2.

From figure 2, the shape of the Ti particles could be observed. The globular shape with abrupt ends of the Ti particles could be seen. The shape was mostly irregular except for small additive particles, which was intended to be evenly spread in the Aluminium Matrix for effective reinforcement. For enhancing the surface wear resistance, G additives were also used as reinforcements. The properties of AA6082 along with G and Ti particles have been indicated in table 3. Using FE-SEM, the G particles were evaluated. The FE-SEM image of G particles at 30 kx magnification has been indicated in figure 3.

From figure 3, very fine particle structure of Graphene could be observed. Very fine tears and ridges on the particle edges were observed. These abrupt edges help in interlocking the matrix material such as Aluminium very strongly, thereby enhancing the strength of the Metal Matrix Composites.

For reducing the frictional wear of AA6082 Graphene based Composites with Ti, Jatropha oil was used. Singh et al (2019) used Jatropha oil as lubricant in tribo wear experiments for reducing Coefficient of friction, wear rate, mean wear scar diameter and improved the worn surface morphology [28]. As per ASTM D1217, ASTM D445 and ASTM D664 standards, the specific gravity, kinematic viscosity and acid number of Jatropha oil was evaluated. The important properties of Jatropha oil have been indicated in table 4.

In this investigation Ag nano particles were used for enhancing the lubrication properties of Jatropha oil. The microstructure of the Ag powder was evaluated by using High Resolution Scanning Electron Microscopy.

The HR-SEM image of Ag Nano particles have been indicated in figure 4. The average diameter of the Ag Nanoparticles was found to be between 70 nm to 130 nm. Mostly the Ag nano particles were spherical in shape. This shape of the Ag particles was found to enhance the lubricating aspects of the vegetable oil (Basha and Anand 2010) [29]. Using Ultrasonication process, the Ag particles were suspended in Jatropha oil. For a time duration of 20 min, at 35 kHz frequency, the Ag incorporated Jatropha oil suspension was prepared.

### Table 3. Properties of AA6082, Graphene and Titanium.

| Material   | Strength (GPa) | Thermal conductivity (W mk⁻¹) | Electrical conductivity (S m⁻¹) | Colour | Purity | Surface area (m² g⁻¹) | Average Thickness (μm) |
|------------|----------------|-------------------------------|--------------------------------|--------|--------|-----------------------|------------------------|
| AA6082     | 185            | 180                           | 2.5 × 10⁶                      | Silvery| 45     | 5 mm                  |
| Graphene   | 130            | 5000                          | 10 × 10⁷                      | Black  | 180    | 5–15 μm               |
| Titanium   | 240            | 17                            | 2.3 × 10⁷                      | Silvery| 168    | 25–40 μm              |

![Figure 2. FE-SEM image of Ti powder.](image-url)
2.4. Preparation of composites by stir casting process

AA6082—graphene-based composites with Ti particles, were prepared by using stir casting process. Based on literature studies and trial and error experiments, the percentage of reinforcement of Graphene was identified in-between 1% to 5%. Up to 1% by weight addition of Graphene, no significant increase in the desirable properties of AMCs were observed. At 1% by weight substitution of Graphene and above, in the casting process of AMCs, strain hardening and dislocation generation occurred, which resulted in hardness enhancement (Choi and Awaji 2005) [30]. On increasing the reinforcement percentage of Graphene beyond 5% by weight, enormous Graphene agglomeration resulted in reduction in tensile strength of the AMCs (Tiwart et al 2016)

Table 4. Properties of Jatropha oil.

| Property                                | Value  |
|-----------------------------------------|--------|
| Specific gravity (20 °C)                | 0.865  |
| Kinematic viscosity (CST at 40 °C)      | 44.19 CST |
| Kinematic viscosity (CST at 100 °C)     | 4.63 CST |
| Acid Number                             | 0.398  |

Figure 3. FE-SEM image of Graphene particles.

Figure 4. HR-SEM image of Ag Nano particles.
Graphene reinforced composites are used to manufacture structural load bearing components and rotary machine parts (Bajor et al 2010) [32].

For enhancement of the rigidity and strength of Graphene reinforced AA6082 AMCs, Ti powder was added as reinforcements. Ti reinforced AMCs were found to be better in terms of strength, rigidity and workability (Kim et al 2020) [33]. On adding Ti in Graphene based AMCs, with less than 1% by weight, no significant improvement in mechanical or tribological characteristics were observed. From 1% to 5% by weight addition of Ti in G based AMCs, a measurable increase in the durability and strength was observed. Also, a reduction in dislocation density was observed (Dinaharan et al 2016) [34]. On increasing the reinforcement of Ti beyond 5% by weight, surface roughness and hardness was increased beyond desirable limits and the brittleness increased. Thus, in this investigation, AMCs were prepared with 1% to 5% by weight addition of Graphene and Ti.

A schematic representation of the stir casting setup has been indicated in figure 5(a) and the actual stir casting setup used in this investigation has been indicated in figure 5(b). The important stir casting process parameters used for preparation of AA6082—graphene-based composites with Ti particles have been indicated in table 5.

Initially, the temperature of the stir casting setup was increased beyond 800 °C. The purpose of increasing the temperature to such high range was to completely melt the matrix material. The cut pieces of AA6082 material were put in the furnace and it was melted. The completely molten material was cooled to a little above solidus temperature of around 525 °C. At this temperature, the density of the matrix material was higher, which was suitable to retain the additives in the suspended state. The purpose of reducing the temperature of the matrix material (AA6082) is to enable proper mix of the reinforcements and keep them suspended in the matrix till the castings are cooled.

### Table 5. Stir casting process parameters.

| S No | Process Parameters                  | Value   |
|------|-------------------------------------|---------|
| 1    | Stirring Temperature                | 850 °C  |
| 2    | Stirring Time                       | 20 (minutes) |
| 3    | Stirring Speed                      | 240 (rpm) |
| 4    | Preheat Temperature of Permanent Mould | 220 °C |
| 5    | Preheat Temperature of Reinforcement Particles | 400 °C |

[31]. Graphene reinforced composites are used to manufacture structural load bearing components and rotary machine parts (Bajor et al 2010) [32].
Graphene particles with an average size of 5–15 μm and Ti powder with an average size of 25–40 μm were preheated to 400 °C and were added into the molten matrix. From 1 to 5 wt.% G and Ti were reinforced to form Aluminium Metal Matrix Composites. After adding the reinforcements, by creating a vortex, the entire mixture was stirred, to evenly distribute it in all the regions. The stirring was done so as to ensure proper fluidity and wettability in-between the matrix material and the reinforcement particles. After distribution of the additives, the temperature was reduced to cool the casting, thereby forming AA6082—graphene-based composites with Ti particles. Five combinations of AA6082 Graphene based composites with Ti particles were prepared, i.e., from 1% by weight of G and Ti each till 5% by weight of G and Ti each, as rods. The photograph of as cast AA6082 Graphene based composites with Ti particles, have been indicated in figure 6.

The prepared AA6082—graphene-based composites with Ti particles were subjected to mechanical testing using universal Testing Machine and the variations in the surface micro hardness were identified by using Vickers Micro hardness testing equipment.

2.5. Pin on disc tribo wear test
Tribological studies on the prepared AA 6082 + Ti+G Aluminium Matrix Composites were conducted by using Pin on Disc Tribo wear testing equipment. The schematic representation of the pin on disc tribo wear equipment has been indicated in figure 7(a) and the actual equipment used for the experiments have been indicated in figure 7(b).

Pin on Disc tribo wear experiments were conducted by using the prepared AA 6082 + Ti+G Aluminium Matrix Composites as pin material. The pin samples were prepared with a pin diameter of 10 mm and 25 mm length they have been shown in figure 7(c).

Pin on disc tribo wear tests were conducted by using Ag incorporated Jatropha oil as lubricant. By using trial and error experiments and studying previous literatures, the quantity Ag nano particle addition in Jatropha oil was ascertained. Increase in weight % of Ag in Jatropha oil was found to fluctuate the viscosity of the lubricant (Zhou et al 2000) [35]. Jatropha oil with Ag nano particles lesser than 1% by weight did not increase the lubricating properties. On conducting tribo wear experiments with Jatropha oil incorporated with 1% by weight of Ag nanoparticles, a significant reduction in surface wear and coefficient of friction was observed (Ghaednia et al 2013) [36]. Excessive addition of Ag nano particles greater than 1.5% by weight in Jatropha oil resulted in enhanced viscosity resulting in undesirable friction and wear [37]. Thus, the experiments in this present investigation was conducted with Jatropha oil incorporated with Ag nano particles at 1% by weight. The tribo wear testing parameters have been indicated in table 6.

The tribo wear parameters for conducting pin on disc tribo wear experiments were fixed using trial and error experiments. During experiments, when pin load was lesser than 20 N, the disc rotation caused the pins to jump causing defects in the pin surface. On using pin loads greater than 80 N, during experiments, excessive vibrational distortions occurred. When the disc speed was fixed lesser than 800 rpm, during experiments, sticking of pin surface with disc occurred, thereby resulting in surface wear offs. On conducting tribo wear experiments with disc speed greater than 1200 rpm, excessive frictional wear and tear occurred. Thus, in this research, tribo wear experiments were conducted win pin load between 20 N to 80 N and disc rotation speed of 1000 rpm. The sliding distance was 1000 m and the experiments were conducted by heating the pin materials (AA 6082 Graphene based composites with Ti reinforcements) to 100 °C. AA6082 G based Ti reinforced AMCs were subjected to tribo wear tests and the variations in specific wear rate and coefficient of friction was evaluated.
3. Results and discussion

3.1. Microstructure examination

Using FESEM analysis to evaluate the variations in grain structure upon increasing the addition of Ti and G in AA6082 Aluminium Matrix Composites were studied. The FESEM images of AA6082 G based Ti reinforced

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**Figure 7.** (a) Schematic representation of pin on disc tribo wear experiments (b) Photograph of pin on disc tribo meter (c) Pin samples prepared from AA6082 Graphene based composites with Ti.

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**Table 6.** Pin on Disc tribo wear testing parameters.

| S. No | Process Parameters                  | Value       |
|-------|-------------------------------------|-------------|
| 1     | Tribo disc rotation speed           | 1000 rpm    |
| 2     | Pin Load                            | 20, 40, 60, 80 N |
| 3     | Sliding Distance                    | 1000 m      |
| 4     | Preheat Temperature of Pins         | 100 °C      |
| 5     | Ag Nano particle weight addition in Jatropha oil | 1% by wt. |

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Figure 8. FESEM images of AA6082-G based Ti reinforced AMCs.
AMCs have been indicated in figure 8. In figure 8(a), FESEM image of AA6082 material without G or Ti reinforcement with fine grained structure can be observed.

In figure 8(b), FESEM image of AA6082 AMC with 1% G reinforcement indicates very sparsely distributed G particle in the fine-grained Aluminium matrix. In figure 8(c), FESEM image of AA6082 with 1% Ti reinforcement indicates the presence of sparsely distributed Ti particles in the Aluminium matrix. In figure 8(d), FESEM image of AA6082 AMC with 1% Gr + 1% Ti indicates evenly distributed Ti and G particles over the Al surface. In figure 8(e), FESEM image of AA6082 AMC with 2% G + 2% Ti indicates a rough Al surface with Ti and G particles on the surface. In figure 8(f), FESEM image of AA6082 AMC with 3% G + 3% Ti indicates coarse surface with distinct G fused region and distinct Ti regions. In figure 8(g), FESEM image of AA6082 AMC with 4% G + 4% Ti indicates uneven mix of G and Ti over Al surface. Denser regions indicate reinforcement agglomeration. In figure 8(h), FESEM image of AA6082 with 5%G + 5% Ti indicates rough patches on the surface and more blow holes due to improper fusion at certain regions. Due to excessive increase in reinforcements, cracks at certain regions were observed.

3.2. Hardness

The surface microhardness of the AA 6082 G based Ti reinforced composites was evaluated by using Vickers microhardness tester. As per ASTM E 92 standards, the micro hardness testing was done. The surface of the test specimens was placed in the testing equipment and for a dwell period of 15 s 5 kgf load was given on the indenter. By evaluating the indentation dimensions, the hardness values were found. The variations in surface microhardness of the AA 6082 G based Ti reinforced composites has been indicated in figure 9.

From figure 9, a significant increase in surface micro hardness was observed on increasing the weight percentage of Ti and G in AA6082 Aluminium Matrix Composites. The density of AA 6082 was 2.63 g cm$^{-3}$, the hardness was found to be 79 HV. Due to grain refinement during stir casting and due to reinforcements, fluctuations in surface hardness was observed.

For AA6082 AMC with 1%, 2% and 3% reinforcement of G and Ti, the density was 2.67 g cm$^{-3}$, 2.72 g cm$^{-3}$, 2.86 g cm$^{-3}$ and the surface micro hardness values were 86 HV, 89 HV and 91 HV. From 1 to 3 percent increase in reinforcements, Ti to G interaction was found to increase the density of the AMCs. Even distribution of G and Ti particles in the surface region resulted in fluctuating the surface hardness (Tiwart et al 2016) [31](Dinaharan et al 2016) [34]. On increasing the reinforcement percentage to 4% and 5% by weight, the density was increased to 2.91 g cm$^{-3}$, and 2.96 g cm$^{-3}$ surface hardness was 103 HV and 107 HV. For 5% reinforcement. Due to hinderance in movement of dislocation, at high concentration of reinforcements, the surface hardness was found to increase.

3.3. Mass loss evaluation

Pin on disc tribo wear experiments were conducted for all the prepared Aluminium Matrix Composite specimens. Experiments were conducted by increasing the load from 20 N to 80 N. The experiments were
conducted by using Ag Nano particle incorporated (1% wt.) Jatropha oil as lubricant. The experiments were conducted as per ASTM G99 17 standards. For a wear length of 1000 m, wear experiments were conducted. The mass of the wear specimens was measured before and after conducting tribo wear experiments. The pin load was increased from 20 N to 80 N and the variations in wear mass loss was evaluated. On increasing the weight percentage of the G and Ti additive addition in AA6082 Aluminium Matrix Composites, reduction in surface wear occurred. From 1% to 3% increase in Ti % and G %, the wear resistance was found to increase, for all the four loaded conditions. On increasing the reinforcement percentage beyond 3%, due to excessive presence of reinforcements, brittleness was increased owing to increased mass loss.

3.4. Specific wear rate
The variations in specific wear rate of the different pin samples under lubricated conditions, on increasing the loads have been indicated in figure 10. For all the samples, it was found that the specific wear rate was high, at low loads. On increasing the loads, the specific wear rate was found to reduce gradually. A significant reduction in specific wear rate was observed on increasing the reinforcement weight percentage of G and Ti additive for 1% to 3%. The contact area and the percentage of reinforcement were found to fluctuate the specific wear rate, during tribological interaction under lubrication (Mistry et al 2019) [12]. The increase in hardness of the reinforced AA6082 Aluminium Matrix Composites due to increase in reinforcement concentration was primarily responsible for reducing the specific wear rate at all loading conditions. On increasing the reinforcement concentration beyond 3%, undesirable increase in surface porosity of the reinforced aluminium matrix composites occurred, which was responsible for reducing the specific wear rate.

3.5. Coefficient of friction
The variation in coefficient of friction upon varying the loads, on the different AA 6082 AMC reinforced with G and Ti particles have been indicated in figure 11. The coefficient of friction decreased on increasing the reinforcement percentage of G and Ti from 1% by weight to 5% by weight. On increasing pin load, for all reinforcement percentages, the coefficient of friction was found to increase. The surface degradation in the form of surface tear offs has been identified due to interaction between disc material and AA6082 surface.

3.6. Worn surface analysis for pin materials
When AA6082 G based Ti reinforced AMC s are subjected to wear tests, the worn surfaces would depend upon the sliding direction, degree of wear and adhesion between the pin surface and abrasive disc surface. All wear tests were conducted by using 1% by weight Ag nano particle incorporated Jatropha oil as lubricant.

Figure 12(a)–(h) indicates the SEM images of the Aluminium Matrix Composites after tribo wear tests. Figure 12(a) indicates the SEM image of tribo wear tested AA6082 material. Surface tear offs have been identified due to interaction between disc material and AA6082 surface.
Figure 12(b) indicates the SEM image of tribo wear tested AA6082 reinforced with 1% by weight of Graphene. The variations in surface morphology on subjecting to the G rich surface to wear with Ag nanoparticles incorporated lubrication has been indicated in the form of erratic surface tear off, similar to (Zhou et al 2000) [35]. Figure 12(c) indicates the SEM image of tribo wear tested AA6082 with 1% Ti. On subjecting the Ti incorporated surface to tribo wear, the difference in Al and Ti wear was evident in the form of demarcations. Demarcations were formed due to the fluctuations in tribolayer induced unsteadiness formation of The demarcations in Ti rich region were found to be less pronounced and Al rich region were found to be more pronounced. Ti protrusions were observed at certain regions (Narayanasamy et al 2015) [41]. Figure 12(d) indicates the SEM image of tribio wear tested AA6082 AMC with 1% G + 1% Ti. A reduction in surface wear was evident due to surface wear resistance created by combination of both the reinforcements. Except for surface ploughing in certain regions the surface was smooth due to the presence of Ag incorporated Jatropa oil lubricant in the interacting surfaces (Venkatesan et al 2020) [19]. Figure 12(e) indicates the SEM image of tribo wear tested AA6082 AMC with 2% G + 2% Ti. On increasing the reinforcements in the surface, reduction surface wear was evident. At certain regions perpendicular to the direction of wear eruptions were identified. The eruptions occurred due to inter granular fracture and particle dislocations with dimples similar to (Jabinth et al 2019) [42]. Figure 12(f) indicates SEM image of tribo wear tested AA6082 AMC with 3% Gr + 3% Ti. At this combination of reinforcements, a significant reduction in surface wear was evident. A more or less crack free surface was observed, with micro pits at certain regions. Figure 12(g) indicates SEM image of tribo wear tested AA6082 AMC with 4% G + 4% Ti. On increasing the reinforcement concentration, agglomeration of Ti and G contributed to surface wear. Cracks and micro cuts were found. A definite combination of dimples and quasi cleavage in Ti concentrated region was observed. (Narayanasamy and Selvakumar 2016) [43]. Figure 12(h) indicates SEM image of tribo wear tested AA6082 AMC with 5% G + 5% Ti. Excessive reinforcements in the surface induced eruptions and severe ploughing. The eroded particles created micro cracks and surface pits. On subjecting AA6082 G based Ti reinforced AMCs to tribo wear tests using Ag incorporated Jatropha oil, surface tear offs, surface ploughing, demarcations, micro pits, grooves, demarcations, micro cuts and micro tears on the surfaces were observed.

3.7. XRD evaluation
The surface chemistry of the wear surfaces was investigated by using x ray Diffraction Spectroscopy. The variations in the XRD intensity peaks were compared with JCPDS data and the elements were identified. Due to interaction between Aluminium, Graphene, Titanium and Ag, different intermetallic compounds were formed in-between the pin surface and tribo wear disc. The XRD evaluation of tribo wear tested AA 6082 G based Ti reinforced AMCs has been indicated in figure 13.

XRD result of AA6082 indicated the presence of Al, Mg & Ag. XRD result of AA6082 with 1% G indicated the presence of G, Ag, Al₂O₃, Al & Mg. XRD result of AA6082 with 1% Ti indicated the presence of Ti, Mg, Al, Al₂O₃, GO and Ag. XRD result of AA6082 AMC with 1% G + 1% Ti indicated G, Al, Ti, Mg, GO, Ag and TiO₂. XRD result of AA6082 AMC with 2% G + 2% Ti indicated Ti, TiAl, G, Mg, Ag, TiAl₂, TiO₂, & Al. XRD result of AA6082 AMC with 3% G + 3% Ti indicated G, GO, Ti, TiAl₂, Ag, Mg & TiO₂. XRD result of AA6082 AMC with 4% G + 4% Ti indicated G, GO, Ti, TiAl, Ag, Mg & TiO₂. XRD result of AA6082 AMC with 5% G + 5% Ti indicated Ti, TiAl, Al, Mg, GO, Ag and G. As high temperatures were met during stir casting of the AA6082
Figure 12. (a)–(h) SEM images of tribo wear tested AA6082 G based Ti reinforced AMCs.
Graphene based composites with Ti particles, TiO₂, AlO₂ and GO were formed in the AMCs. Due to interaction between Aluminium and Titanium, TiAl and TiAl₃ were formed.

4. Conclusions

Thus, in this paper, Ti and G incorporated AA 6082 Aluminium Matrix Composites were prepared and subjected to tribo wear analysis, and the following conclusions were drawn.

(i) On evaluation of mechanical properties, increase in reinforcements caused an increase in tensile strength and micro hardness till a certain extent and on increasing the reinforcement of Ti and G beyond a certain limit (3%), mechanical aspects was found to decrease.

(ii) Surface modifications of the Ti and G incorporated AA 6082 Aluminium Matrix Composites before and after conducting tribo wear tests were evaluated. The effect of increase in reinforcements on grain modifications and the effect of tribo wear on surface degradation were identified. Microscopic evaluation indicated surface tear offs, surface ploughing, demarcations, micro pits, grooves, demarcations, micro cuts and micro tears on the surfaces.

(iii) In Pin on disc tribometer tests, the Coefficient of friction was found to reduce till increasing the reinforcement percentage of G and Ti till 3% by weight and beyond that, it started to increase. Specific wear rate was found to reduce on increasing the reinforcement percentage of G and Ti, from 1 to 5 percent by weight.

(iv) The surface chemistry modifications in the tribo wear tested Ti and G incorporated AA 6082 Aluminium Matrix Composites were identified. Presence of Titanium Aluminate and Graphene Oxide was found.

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References

[1] Sivakumar S, Golla B R and Rajulapati K V 2019 Influence of ZrB₂ hard ceramic reinforcement on mechanical and wear properties of aluminium Ceram. Int. 45 7055–70
[2] Ramkumar K R, Sivasankaran S, Mufadi F A A, Siddharth S and Raghu R 2019 Investigations on microstructure, mechanical, and tribological behaviour of AA 7075–x wt.% TiC composites for aerospace applications. Archives of Civil & Mechanical Engineering 19 428–38

[3] Babu P D, Buvaneshkaran G and Balasubramanian K R 2015 The elevated temperature wear analysis of laser surface hardened EN25 steel using response surface methodology Tribol. Trans. 58 602–15

[4] Munagala V N, Torgerson T S, Schair T W and Chromik R R 2019 High temperature friction and wear behavior of cold-sprayed Ti6Al4V and Ti6Al4V–TiC composites Wear 426 357–69

[5] Poria S, Sahoo P and Sutrakar D G 2018 Design of experiments analysis of wear behavior of stir cast Al–TiB2 composite in lubricated condition Materials Today: Proceedings 5 5223–8

[6] Prakash S, Gopal P M, Anbusroo D and Kavimani V 2018 Mechanical, corrosion and wear characteristics of powder metallurgy processed Ti 6Al–4V/B4C metal matrix composites Am Shams Engineering Journal 9 1489–96

[7] Pramod R, Kumar G B V, Gouda P S and Mathew A T 2018 A study on the Al6061 reinforced Al7075 metal matrix composites wear behavior using artificial neural networks Materials Today Proceedings 5 11376–85

[8] Kumar G B V, Pramod R, Sekhar C G, Kumar G P and Bhanumurthy T 2019 Investigation of physical, mechanical and tribological properties of Al6061–ZrO2 nano–composites Heliyon 5 e02858

[9] Kanaya A K and Odomi B U 2016 Mechanical properties, wear and corrosion behaviour of copper matrix composites reinforced with steel machining chips Engineering Science and Technology 19 1593–9

[10] Xu H, Li Z, Teng B, Ren B and Li X 2019 Preparation and properties of copper matrix composite reinforced with SLM Fe alloy lattice Mater. Res. Express 6 1–6

[11] Somani N, Tyagi Y K, Kumar P and Srivastava V 2018 Enhancedtribological behaviour of reinforced copper metal matrix composites Mater. Res. Express 6 1–23

[12] Mistry J M and Gehlot P P 2019 Experimental investigations on wear and friction behaviour of Si3N4 reinforced heat-treated aluminium matrix composites produced using electromagnetic stir casting process Composites Part B: Engineering 161 190–204

[13] Satyanarayana T, Rao P S and Krishna M G 2019 Influence of wear parameters on friction performance of A356 aluminum—graphite/ granite particles reinforced metal matrix hybrid composites Heliyon 5 1–10

[14] Wang L, Dong B, Qiu F, Geng R and Jiang Q 2020 Dry sliding friction and wear characterization of in situ TiC/Al–Cu47.3–Mg7.3 nanocomposites with nacre-like structures Journal of Materials Research and Technology 9 641–53

[15] Bhowmik A, Dey D and Biswas A 2020 Tribological behaviour of aluminium-titanium diboride (Al7075–TiB2) metal matrix composites prepared by stir casting process Materials Today Proceedings 26 2000–4

[16] Dhar S, Jena A, Patnaik S C, Sahoo S K and Tripathy O 2020 A study on microstructure and mechanical properties of aluminium matrix composites with micro-sized iron fillers produced by powder metallurgy route Materials Today: Proceedings (Accepted) (https://doi. org/10.1016/j.matpr.2020.03.733)

[17] Roseline S and Paramasivam V 2019 Corrosion behaviour of heat treated aluminium metal matrix composites reinforced with fused zirconia alumina 40 J. Alloys Compd. 799 205–20

[18] Radhika N, Sasikumar J, Syelle J L and Kishore R 2020 Dry reciprocating wear and frictional behaviour of B4C reinforced functionally graded and homogenous aluminium matrix composites Journal of Materials Research and Technology 9 1578–92

[19] Venkatesan S and Xavier M A 2020 Wear property evaluation of aluminum alloy (AA7050) metal matrix composite reinforced with grapheme fabricated by stir and squeeze cast processes Materials Today: Proceedings 22 3330–9

[20] Aswini Prasad V, Srirahith V S, Venkatesh C, Meda A H and Kamalakannan N 2020 Experimental investigation of wear characteristics of aluminium 6063 hybrid composite reinforced with graphite and molybdenum disulfide (MoS2) Materials Today Proceedings 22 3190–6

[21] Xu Z, Lou W, Zhao G, Zhang M, Hao I and Wang X 2019 Pentaerythritol resin ester as an environmentally friendly multifunctional additive in vegetable oil-based lubricant Tribol. Int. 135 213–8

[22] Noorawzi N and Saimon S 2015 Tribological effects of vegetable oil as alternative lubricant: a pin-on-disk tribometer and wear study Tribol. Trans. 58 1–9

[23] Thakre A A, Shinde A and Mundhe G 2016 Improvement in boundary lubrication characteristics of SAE20W40 oil using aluminium oxide nanoparticles J. Tribol. 138 1–4035401

[24] Kumar I R, Saravanakumar A, Bhuvaneswari V, Gokul G and Karunan M P 2019 Optimization of wear behaviour for AA2219–Mo2C metal matrix composites in dry and lubricated conditions Materials Today: Proceedings 23 26 2645–9

[25] Singh H and Bhowmik A 2021 Lubrication characteristics and wear mechanism of Al matrix metal matrix composite sliding under surfactant functionalized MWCNT-oil Tribol. Int. 145 Article10612

[26] Zhou X, Li L, Wen D, Liu X and Wu C W 2018 Effect of hybrid ratio on friction and wear behavior of AZ91D matrix nanocomposites under oil lubricated conditions Transactions of Nonferrous Metals Society of China 28 440–50

[27] Liu Y, Zheng Z, Cao G, Zhu D, Yang C and Luo M 2019 Interface structure and mechanical properties of 7075 Al hybrid composite reinforced with micron Ti metal particles using pressure infiltration Metals 9 763–74

[28] Singh Y, Garg R and Kumar S 2019 Friction and wear characterization of modified jatropha oil (Jatropha Curcas) using pin on disc tribometer Energy Sources Part A 1–12

[29] Bashia J S and Anand B R 2010 Effects of alumina nanoparticles blended jatropha biodiesel fuel on working characteristics of a diesel engine International Journal of Industrial Engineering and Technology 2 53–62

[30] Choi S M and Awaii H 2005 Nanocomposites—a new material design concept Sci. Technol. Adv. Mater. 6 2–10

[31] Tiwari J K, Mandal A, Sathish N, Venkat A N C and Srivastava A K 2016 Graphene platelets reinforced aluminium matrix composite with enhanced strength by hot accumulative roll bonding Appl. Phys. 1 187 1–807.01998

[32] Bajor T, Muskałski Z and Suliga M 2010 Research on the drawing process with a large total deformation wire of AZ31 alloy J. Phys. Conf. Ser. 240 12107

[33] Kim I, Song M Y and Kim J H 2020 Effects of Ti–B and Si additions on microstructure and mechanical properties of Al–Cu–Mg based aluminium matrix composites J. Alloys Compd. 83215 154827

[34] Dinaharan I, Murugan N and Thangarasu A 2016 Development of empirical relationships for prediction of mechanical and wear properties of AA6082 aluminium matrix composites produced using friction stir processing Engineering Science and Technology, an International Journal 19 1132–44

[35] Zhou J, Wu Z, Zhang Z, Liu W and Xue Q 2000 Tribological behavior and lubricating mechanism of Cu nanoparticles in oil Tribol. Lett. 8 213–8

[36] Ghadimia H, Jackson R I and Khodadadi J M 2013 Experimental analysis of stable CuO nanoparticle enhanced lubricants J. Exp. Nanosci. 10 1–18

15
[37] Ghaednia H, Hossain M S and Jackson R I. 2016 Tribological performance of silver nanoparticle–enhanced polyethylene glycol lubricants Tribol. Trans. 59 585–92

[38] Feng Z X, Lin Z X, Hua W A and Wen H Z 2009 Microstructure and properties of HVOF sprayed Ni-based submicron WS2/ CaF2 self-lubricating composite coating Transactions of Nonferrous Metals Society of China 9 85–92

[39] Ravindran P, Manisekar K, Rathika P and Narayanasamy P 2013 Tribological properties of powder metallurgy–processed aluminium self-lubricating hybrid composites with SiC additions Mater. Des. 45 561–70

[40] Wang L, Gong P, Li W, Luo T and Cao B 2020 Mono-dispersed Ag/Graphene nanocomposite as lubricant additive to reduce friction and wear Tribol. Int. 146 106228

[41] Narayanasamy P, Selvakumar N and Balasundar P 2015 Effect of hybridizing MoS2 on the tribological behaviour of Mg–TiC Composites, Transactions of Indian Institute of Metals 68 911–25

[42] Jabinth J and Selvakumar N 2019 Effect of vanadium on enhancing the mechanical and wear behaviour of copper by using stir casting technique Mater. Res. Express 6 096531

[43] Narayanasamy P and Selvakumar N 2017 Tensile, compressive and wear behaviour of self-lubricating sintered magnesium-based composites Trans. Nonferrous Met. Soc. China 27 312–23