Strength and Wear Characteristics of Aluminum/Zircon/Graphite Composites

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Abstract: The need to have materials with stable structural integrity has prompted the study of the strength and wear characteristics of hybrid composites of aluminium/zircon/ graphite owing to the failure of monolithic alloys. In this study, varying amount (3, 7, and 12 wt. %) of zircon, graphite and the combination of the two (hybrid) particles were used as reinforcement in aluminium 6011 alloy. The cast samples were characterised for compressive strength, hardness, wear and morphological responses. For each reinforcement addition, composites’ compressive strength ranges from 57.3 – 205.8 MPa while the hardness ranges between 44 – 140 HV in this study. Aluminium reinforced with the hybrid of zircon and graphite particles demonstrated superior properties over others. The morphology showed fine crystals of AlFeSi with increase in the concentration precipitated Mg2Si phase in the aluminium matrix. Fluctuations in the wear characteristics of composites were observed except for Al/hybrid composite where wear volume rose steadily on application of 4.5, 8.9N and 13.35N for each filler content. All composites degrade at temperatures between 203-435oC, which implies that will maintain their properties in service within the temperature range. The composites will serve as potential materials for light automobile brake pads.

Keywords: Aluminum, Composite, Compressive strength, Graphite, Wear, Zircon

1. Introduction

Aluminum matrix composites (AlMCs) refer to the class of light weight high performance aluminum based material, usually 2xxx, 5xxx, 6xxx and 7xxx alloy series. These alloys are known for their effective fluidity, ease of casting, corrosion resistance and high strength-weight ratio (Singh et al., 2015). The properties of AlMCs can be tailored to the demands of different industrial applications via suitable combinations of matrix, reinforcement and processing route. These composites are being utilised in high-tech structural and functional applications in aerospace, defence, automotive, thermal management, sports and recreation due to their high strength to weight ratio (Surappa, 2003). Aluminum matrix can accommodate a variety of reinforcing agents including ceramics and organic wastes (in the form of fibres, whisker or particulates) with a maximum volume fraction of 70% (Surappa, 2003). Commonly used ceramic particles, which include silicon carbide (SiC), alumina (Al2O3) boron carbide (B4C), titanium carbide (TiC), graphite, quartz (SiO2) and zircon (ZrSiO4) have good hardness and wear characteristics, and these qualify them as potential reinforcing materials (Gopi et al., 2013; Raghavendra and Ramamurthy, 2014; Ramesh et al., 2009).

Zircon and graphite are chosen as reinforcement in this study because of their availability in the country. Graphite particle reinforced composites have applications in components requiring high wear resistance such as engine bearings, pistons, piston rings and cylinder liners (Barekar et al., 2008). Ramesh et al. (2009) observed that reinforcing Al6061 with graphite particles improves ductility, compressive strength and stiffness of the aluminum matrix but reduces its hardness. Macro and micro hardness of AA6082 Al alloy were found reduced on addition of graphite particles as reinforcement (Sharma et al., 2016). The density, ductility and tensile strength of the aluminum matrix with 0- 12wt. % graphite (in a step of 3) reduce. Mechanical properties such as yield, tensile and compressive strengths of AA6082 have been enhanced by addition of Yttrium oxide (Y2O3) and...
graphite as reinforcements (Kumar et al., 2020) processed by friction stir casting. Zircon on the other hand is a by-product of cassiterite (tin ore) beneficiation (Bamalli, et al., 2011) and has been used as reinforcement in light metals especially where wear resistance with improved mechanical and thermal properties are required. It essentially consists of zirconium silicate (ZrSiO₄) with hafnium, some rare-earth elements, titanium minerals and monazite, etc. It has also been used as ferro alloy and for facing of foundry moulds to increase the resistance against metal penetration (Rino et al., 2013).

Aluminum A356/ZrSiO₄ MMC has been processed by Kumar et al. (2018) via stir casting. The reinforcement improves the wear characteristics of the composite and as a result, suitable for components such as cylinder sheets and cylinder blocks in automobiles. Zircon sand is a Neso silicate tetragonal crystal structured material with specific gravity between 4.60-4.71. Works on Al/zircon composite are enjoying increasing patronage as reinforcement in aluminium composites due to its unique properties (Kumar et al., 2015) such as its high refractoriness and resistance to sudden volume changes at elevated temperatures, resistance to abrasion, impact and chemical attack. The high hardness of Zircon (Moh’s hardness scale of 7.5) has made it a sought after potential replacement for more commonly used ceramic reinforcement for aluminum (Kumar et al., 2015; Sujitharan et al., 2013). The impact of the combination of these two components on the morphology and mechanical properties of aluminum matrix needs to be appraised. This research is aimed at evaluating the mechanical and wear characteristics of aluminium 6011 alloy reinforced with zircon, graphite and the hybrid of these reinforcements.

2. Materials and Methods

2.1. Materials

The aluminium ingot (6011) was obtained from Tower Aluminum Rolling Mills, Ota, Ogun state, Nigeria. Ingot was cut with the use of a powered hack saw and further sheared into smaller pieces with the use of shear cutter. Graphite, zircon and magnesia, obtained from Peters Ventures, Lagos, Nigeria were milled to 150µm at Federal Institute of Industrial Research Oshodi (FIIRO), Lagos, Nigeria using a planetary ball Mill Machine (model 28A20 92). An electric furnace designed for the casting was built by assembling low density refractory bricks (light bricks) and electric resistant wire (Nichrome 80) as source of heat energy. The refractory bricks were obtained from Peters Ventures, Lagos, Nigeria while nichrome was obtained from Lightning Vapes, United States of America. The light bricks were 23cm x 7cm x 12cm in dimension, with a density of 0.763g/cm³. The Nichrome wire has a diameter of AWG 18 (0.102 cm), maximum operating temperature of 1180°C and resistance of 20 Ω.

2.2. Composite Production

The composites were produced by adding 3, 7 and 12wt. % of the filler (zircon and graphite) to aluminium matrix. To obtain the composition by weight for the hybrid (combination of zircon and graphite) reinforcement, the density ratio for each particle was used. Aluminum ingot was charged into the furnace while the reinforcement, wetting agent (magnesium) and mould were preheated to 300 °C. The reinforcement and the wetting agent were added to the molten aluminum at 750°C. The mix was stirred with a mild steel flat bar for 30 seconds and then poured into a mild steel metal mould of height of 135mm and diameter 15mm.

After pouring, the mould (and its contents) was allowed to cool to ambient temperature before removing the cast. The cast samples were solution heat treated at 530 °C for 3 hours in an electric resistant furnace and subsequently quenched in water. After quenching the samples, the samples were returned into the electric resistant furnace for artificial ageing at 180 °C for 5 hours.

2.3. Characterisations

2.3.1. Compression Test

The compression test was carried out on test samples using compression test equipment at the Centre for Energy Research and Development, Obafemi Awolowo University Ile-Ife. The samples were subjected to compression loads of 50 KN at 2 mms⁻¹. Compressive and fracture strengths were obtained from the test.

2.3.2. Hardness Test

The hardness test was conducted using a SIOMM Vickers hardness tester with model HVD – 10001S situated in the Metallurgical and Materials Department Laboratory, University of Lagos Nigeria. The samples were prepared by grinding them with emery paper of grit sizes 60, 150, 220, 320 and 400 in successive order to allow for proper microstructural view of the micro hardness tester indentation. The samples were indented for a dwell time of 10s and indentation was taken at three different points and the average results taken.

2.3.3. Scanning Electron Microscopy

The Scanning electron microscopy (SEM) test was carried out using a High-Performance Scanning Electron Microscope (VEGA 3 TESCAN) at accelerated voltage of 20KV to observe the microstructure of the samples, lines, pores and cracks at Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa. The samples were prepared by grinding with emery papers with grit size 60, 150, 220, 320, 400, 600, 800 and 1200, in successive order. The samples to be observed under the SEM were mounted on a conductive carbon imprint left by the adhesive tape prepared by placing the samples on the circular holder and coated for 5 minutes to enable it conduct electricity.
2.2.4. X-Ray Diffraction
The X-ray diffraction (XRD) of the samples was conducted using PW1710 Philips X-ray diffractometer. Analysis was done with the use of PANalytical X’Pert High Score software for phase search-match in the Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa. Samples were exposed to a monochromatic Cu Ka radiation (k = 1.5406 Å), operating at 40KV and 40mA. The samples were registered in a zero-background sample holder to avoid external background interferences. The diffractograms were registered in the range of 5° to 90° (2θ) in a step scan mode of 0.0170 at a scan step time of 1.00 second.

2.2.5. Wear Test
Wear rate measurements were performed using friction and wear testing equipment. To evaluate the durability of the materials in sliding contact with another surface under different conditions (load, distance, time and weight fraction) in this study, prepared samples were tested under dry sliding wear conditions. Dry sliding wear was carried out using a pin on disc equipment. Cylindrical specimens (both alloy and composites) of 15 mm diameter and 25 mm height were used as test samples. The specimen end surfaces were polished metallographically. Wear studies were conducted under varying conditions of load and sliding velocities. Measurement of wear loss of the pin was used to evaluate the volumetric loss (VL) during the wear test. Load was varied from 4.5, 8.9 and 13.35N was used to evaluate the volumetric loss (VL) during the sliding velocities. Measurement of wear loss of the pin were conducted using a pin on disc equipment. Cylindrical specimens (both alloy and composites) of 15 mm diameter and 25 mm height were used as test samples. The specimen end surfaces were polished metallographically. Wear studies were conducted under varying conditions of load and sliding velocities. Measurement of wear loss of the pin was used to evaluate the volumetric loss (VL) during the wear test. Load was varied from 4.5, 8.9 and 13.35N while the disc speed was fixed at 123 rpm and time duration of 30s per wear session. A track radius of 7mm and varying sliding distance of 27, 54, 81 and 108 m were used for all the experiments. All the tests were conducted in air at room temperature. The weight loss method was used to calculate the wear rates. The wear rates of all the specimens were obtained. Furthermore, specific wear rate of the samples was calculated using the weight loss method given in Equation 1. The determination of the specific wear rate was based on derivations of Wear rate, Wear volume, Sliding distance and Weight loss. Formulas used are given in Equations (1)-(5).

\[ \text{Weight loss} = w_2 - w_1 \]  
\[ \text{Sliding Distance (m)} = 2 \pi NDt \]  
\[ \text{Wear Volume (m}^3) = \frac{\text{Weight loss (g)}}{\text{Density (g/cm}^3)} \times 1000 \]  
\[ \text{Wear rate (mm}^3/m) = \frac{\text{Wear Volume}}{\text{Sliding Distance}} \]  
\[ \text{Specific wear rate (mm}^3/Nm) = \frac{\text{Wear rate}}{\text{Load}} \]  

2.2.6 Thermal Analysis
Thermal degradation of aluminium alloy and processed composites were determined with the use of Perkin Elmer thermogravimetric analyser (model TGA 17011909). Samples weighing 40mg were charged at 20 mL/min from 45°C to a final temperature of 850°C at a heating rate of 5°C/min. The heating was initiated with a residence time of 1min at 45°C before increasing the temperature. Temperature at the onset of degradation was recorded for each sample as a measure of composites, resistance to thermal degradation (thermal stability). This analysis was carried out at the Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa.

3.0. Results and Discussion
3.1. Compression test
Figure 1 shows the compressive strength (CST) of aluminum reinforced with varying contents of particles (zircon, graphite and the hybrid). Composites’ CSTs are of higher magnitude than the unreinforced aluminum (0 wt. %) whose CST is 68.7 MPa, owing to improved strengthening effects of reinforcements on matrix. Aluminum reinforced with 3 and 7wt. % graphite was exceptions with strengthening effect of 57.3 and 29.9 MPa, respectively. Thus, the use of hybrid reinforcement will enhance the CST of aluminum as it displayed superlative results compared to other singly/monolithic used reinforcements. Aluminum’s CST increased from 68.7 MPa to 114.4 and 305.8 MPa with the use of 3 and 7wt. % hybrid reinforcements respectively. The results here are superior to that obtained with the use of dolomite and calcium carbonate as separate fillers in reinforcing phenolic resin mixed with graphite and alumina to design brake pads carried out by Ruzaidi et al. (2013), where CST of approximately 80 and 90MPa for calcium carbonate and dolomite fillers respectively was observed. Trends of samples’ CST are similar to their fracture strengths with approximately same magnitudes as shown in Figure 2. This implies that most of the samples fracture at their maximum compressive stress values; hence, material with the highest magnitude of CST will be of importance during selection. Incorporation of 3, 7 and 12 wt. % zircon equally improve aluminum’s fracture strength.

Results in this study have shown that the fracture strength of aluminium is improved at any composition of the zircon/graphite hybrid filler with 7wt. % hybrid filler having a superlative resistance to fracture under compression as it fractures at 206.8MPa. At the same filler content, Al/3wt.% zircon possesses fracture strength of 106.4MPa, which is the best achieved for Al/zircon composite while Al/graphite composite exhibits a maximum fracture stress of 99.5MPa at 12wt. % graphite addition. Comparing samples with similar particle content, Figure 2 shows that hybrid of zircon/graphite impacts the best fracture stress.
When compared with the control sample (0 wt. % filler content with 95HV), it is observed that reinforcing 6011 aluminum yields improved hardness at some filler contents. Addition of 3, 7 and 12 wt. % zircon to aluminum yields 108, 103 and 66 HV, respectively. The least hardness value of 45 HV, which is ≈53% lower than the control specimen (95 HV), is attained at 3 wt. % graphite while 58 and 135 HV are obtained in composite with 7 and 12 wt. % graphite, respectively. Reinforcement with 12 wt. % hybrid produces the highest magnitude of 140 HV.

3.3. Morphology

The morphologies of unreinforced aluminum and its composites as captured by SEM are discussed in Figures 4-12. The morphology of as-cast 6011 aluminum (see Figure 4a) shows the presence of dark black crystals of Mg2Si phase in the alloy distributed over the α – aluminum matrix. The Mg2Si intermetallic has been confirmed to provide strength and hardness when finely dispersed in the alloy (Velasco et al., 1995).

According to Qin et al. (2007), an intermetallic compound of Mg2Si contributes to good mechanical properties of alloy by providing high hardness, reasonably
high elastic modulus and low thermal expansion. The morphology also reveals the existence of Fe-rich intermetallic compound, which has been identified as AlFeSi. In the as-cast sample shown in Figure 4a, this phase occurs as tiny crystals scattered over the surface of the matrix. This fine Fe-rich intermetallic phase was discovered by Shouxun et al. (2013) to maintain a chemical structure of "α" Al8Fe2Si. This compound is regarded as the most undesired because it causes brittleness (Mohammad et al., 2016). Salleh et al. (2015) agree that the effect of iron in aluminium alloys can lead to reduced tensile strength and ductility. The phases present in this material are comparable to that observed in as-cast aluminium processed by Adeosun et al. (2016a and b). The XRD pattern of the unreinforced aluminium alloy in Figure 4b shows the presence of intermetallic phases of AlFeSi and Mg2Si. Aluminum matrix exists on 2θ = 37.4, 44, 64.4 and 78° (Kumar et al., 2018). Diffractions on 2θ = 46 and 58.9° represent the presence of AlFeSi and Mg2Si respectively (Farshidi et al., 2018; Kumar et al., 2012; Wunderlich et al., 2014; Kumar et al., 2016a).

Micrograph of aluminium reinforced with 3 wt.% of zircon at low (x200) and high (x600) magnifications is shown in Figure 5a and b. The image shows a uniform distribution of reinforcement (white spots) in the aluminium matrix at higher magnifications (see Figure 5b). At a lower magnification (see Figure 5a), the Mg2Si intermetallic phases have significantly reduced geometry while the AlFeSi phase is of a lower concentration with few clusters of its crystals. Observing the microstructure at a higher magnification, zircon particles are shown to be strongly bonded to the matrix as both Mg2Si and AlFeSi precipitates are embedded in the microstructure. Combined influence of well bonded zircon particles with existence of Mg2Si could be responsible for the composite's improved resistance to compression and indentation when its hardness and compression values are compared with that of the unreinforced sample.

The existence of zircon in the alloy is generally affirmed to increase the tensile strength of aluminium but increase in its content as reinforcement will evidently enhance brittleness thereby lowering its elongation (Ramnath et al., 2018). Zircon in the composite is evidenced by the diffraction on 2θ = 27 and 36° (Figure 5c). These are some of the diffractions of zircon observed by kumar et al., (2018) where A356 aluminium was reinforced with zircon. X-Ray diffraction of zircon particles characterised by Genoveva et al., (2007) shows peaks at 2θ = 27.08 and 35.69° Figure 6a is the micrograph of aluminum reinforced with 7 wt. % zircon at x200, which shows denser Mg2Si phase (compared to 3 wt. % zircon). This phase is found to elongate along the deformation direction with few crystals precipitating on the slip lines as shown at higher magnifications of x200 and x600 (Figure 6a and b). These tend to impede dislocations, thereby creating improved deformation resistance of sample. The AlFeSi phase shows reduced concentration in the matrix while the zircon and Mg2Si particles are uniformly distributed on the aluminium matrix.

Increasing the volume of reinforcement to 12wt. % (see Figure 7), poor bonding of Al/zircon is revealed in the microstructure at higher magnification with evidence of visible cracks distributed over the grey aluminium matrix. This is accompanied with reduced Mg2Si volume fraction with increase in AlFeSi phase, which is responsible for the reduction in compressive strength and fracture stress.
Reinforcing aluminium with graphite of a similar content (3 wt. %), there exists clusters of the reinforcement (see Figure 8), which appears to form on the surface making the Mg$_2$Si phase look invisible compared to Al/zircon composite shown in Figures 5-7. There are very few Mg$_2$Si crystals on the surface of the composite with Fe-rich intermetallic crystals, which clustered at a point as in Figure 7b (higher magnification). This is responsible for the cause of decrease in composite’s, compressive strength, fracture strength and hardness (see Figures 2 and 3) compared to Al/zircon of the same filler content. The morphology of the Al/graphite composite also gives reasons for the diminished mechanical properties compared to unreinforced aluminum (see Figure 4a), which reveals volume fraction of Mg$_2$Si phases.

The graphite particle in the composite is diffracted at $2\theta = 26.3^\circ$ (see Figure 8c) and this is comparable to the findings of Peng et al., (2013) and Sayah et al., (2018) where graphite’s XRD analysis shows diffraction at $2\theta = 26.5^\circ$.

The morphological effect of reinforcing aluminum with 7wt. % is shown in Figure 9. Few particles of AlFeSi, are observed to be fairly dispersed in the microstructure with Mg$_2$Si intermetallic crystals clustered at certain regions. The morphology of the $\alpha$-Al matrix appears rough with few cracks caused by the presence of un-bonded graphite. The lack of proper bonding between graphite and matrix may be the reason for the least compressive and fracture strengths observed in Figures 1 and 2.

The morphology of aluminum reinforced with 7wt. % graphite (see Figure 10a) shows the presence of few Mg$_2$Si scattered on the surface of the composite. The presence of graphite and Fe-rich intermetallic (AlFeSi) is also seen on the matrix surface. Figure 10b shows a higher magnification. The microstructure indicates good interfacial bonding between graphite and $\alpha$-aluminum matrix. The maximum increase in hardness of this composite (see Figure 3) is attributed to good interfacial bonding between matrix and reinforcement and the presence of the hard Fe-rich crystals. The AlFeSi intermetallic crystals are formed along the visible stress direction (which could have occurred during solidification) while the Mg$_2$Si phases are not formed on these sites. At maximum graphite content of (12wt. %) the flow of Mg$_2$Si crystals along solidification direction could be prevented. Existence of more AlFeSi crystals compared to that of Mg$_2$Si may be responsible for this occurrence.

Very fine AlFeSi crystals are produced in 3wt. % hybrid composite shown in Figure 11 and a decline in volume fraction is observed in the matrix than those observed in previous morphologies. The microstructure shows considerable amount of Mg$_2$Si sparsely dispersed in the aluminum matrix with few clustering sites. A higher magnification of the microstructure (see Figure 11b) shows clearly the clusters of Mg$_2$Si with clusters of both Mg$_2$Si and graphite phases, resulting into a thick layer on the surface coupled with the existence of fine crystals of zircon. It is observed that the compressive and fracture
strengths of this composite are superior to both aluminium/graphite and aluminium/zircon composites for each content of reinforcement addition. This implies that these clusters have strong interface with the matrix. Addition of 12wt. % graphite/zircon (see Figure 12) enhances more precipitations of MgSi phases with formation of thicker MgSi/graphite/zircon layer. X-Ray Diffraction of Al/Hybrid composite in Figure 12c shows the presence of graphite and zircon coupled with the intermetallic phases.

![Figure 11. SEM of hybrid (3wt. %) composites (a) x200 (b) x600](image)

![Figure 12. SEM (a) x200 (b) x600 of hybrid (12wt. %) composites (c) XRD of hybrid (3wt. %) composites](image)

3.4. Wear Test

3.4.1. Wear volume

Wear volume describes the amount of worn debris occurring during dry sliding wear and is fundamental to explaining the tribological behaviour of materials. Figure 13a shows the wear volume in mm³ of Al/Zircon composites at loads of 4.45N, 8.9N and 13.35N. There is a general reduction of wear volume compared to 3wt. % Al/Zircon composites except at 7wt. % where wear volume increases for 13.85N. The reduction is attributed to increased hardness (as there is an increase in volume fraction of zircon particles in the matrix) but does not vary significantly with increasing weight fractions between 7 and 12 wt. %. It can also be observed that for 7 and 12wt. %, wear volume increases with increase in loads except for composites at 3wt. %. The exemption might be due to clogs of debris preventing contact between the disk and pin during wear as increase in load is expected to lead to increased wear volume.

![Figure 13. Wear volume of composites (a) Al/zircon (b) Al/Graphite (c) Al/hybrid](image)
wear volume. Wear volume reaches peak for each of the loads at 7wt. % graphite. The initial increase in wear can be attributed to reduced fracture toughness of graphite. However, as the graphite increases in weight fraction, presence or formation of thick solid lubricant film, which overrides the effect of fracture toughness, is responsible for the reduced wear volume (Ted and Chi, 2000). It can also be observed that the range of wear volume of Al/Graphite is less than in Al/zircon composites due to the resistance to wear shown by graphite via forming lubricating films on the surface during wear. The wear volume of hybrid composites at 4.5, 8.9 and 13.45N are shown in Figure 13c. It is observed that increase in load leads to increase in wear volume at all weight fractions. Wear volume with similar pattern as Al /graphite composites, increases up to 7wt. % before declining. This suggests that presence of graphite plays a significant role in the volume of wear than zircon particles.

3.4.2. Specific Wear Rate

Figure 14a-c shows the specific wear rate of aluminum composites at 4.45N. For Al/zircon composites, specific wear rate reduces after 3wt. % compared to others at higher weight fractions. The increase in specific wear rate can be attributed to increase in hardness of the composites as hard zircon particles are expected to heighten the hardness of the composites. Al/Graphite and Hybrid composites show the highest specific wear at 7wt. % before subsequently declining. The behaviour of Hybrid composites is attributed to the contributions of the reinforcements to the resistance of wear. The hard reinforcement (zircon) is expected to protect the matrix from wearing off while the soft reinforcement (graphite) is expected to form a tribo layer to resist wear. Thus, there is expected to be improved wear reduction. However, the Figure shows higher specific wear at 7wt. % compared to Al/Graphite and Al/Zircon composites. Figure 14b shows the specific wear of aluminum composites at 8.9N. Al/Zircon composites show similar pattern in behaviour to what is observed in Figure 5a. The specific wear rates of Al/Graphite and hybrid composites increase up to 7wt. % before declining.

Figure 14. Specific wear rates of aluminium composites (a) 4.5N (b) 8.9N (c) 13.35N

Figure 14c shows the specific wear of aluminum composites at 13.35N. Al/Zircon composites show reduction in specific wear rate with increasing weight fractions.

3.5. Morphology of worn samples

The SEM images of worn surfaces of unreinforced aluminum and its composites in Figure 15. Surface debris, groves and cracks are observed on samples after wear indicating delamination and abrasion (Idusuyi and Olayinka, 2019; Kumar et al., 2016b; Kumar et al., 2018; Kumar et al., 2020). Shallow groves and minor cracks with direction of metal flow are observed on the worn surface of unreinforced aluminum (see Figure 15a) while severe cracks with deep groves are observed on Al/Zircon worn surface (see Figure 15b). This form of crack, according to Rajesh et al., (2018) grows and culminates in long thin wear sheets after shearing to the metal surface. More pits are formed on the worn surface of Al/Graphite (see Figure 15c) compared to worn surfaces of unreinforced Al and Al/Zircon. The pits elongate along the direction of deformation which makes them look parallel along metal flow orientation. Ghosh et al. (2012) attribute this to micro cutting tendency which further explains abrasion/abrasive wear. There exist groves, pits
and cracks with some thick debris on the worn surface of Al/Hybrid composite (see Figure 15d).

3.6. Thermal Stability

Determination of thermal stability of composites is highly required in wear applications. This is due to the heat generated during friction, which can distort the properties of materials being used. Figure 16 shows the onset of degradation temperatures of unreinforced aluminum and its composites via reinforcement with zircon, graphite and the hybrid.

Degradation temperature of Al/Zircon composites increases with filler contents from 203-280°C. Graphite-reinforced aluminum samples show no significant change in thermal degradation profile as a constant temperature of 400°C is maintained for 5, 7 and 12 wt. % reinforcements. The maximum temperature that can be attained before the hybrid composites start deteriorating in properties is observed at 435°C 7wt. % additions while the least temperature it can withstand is 304°C at 5wt. %. All composites will display good performance between 203-435°C, which is greater than that observed for unreinforced aluminum which starts deteriorating at 197°C.

4. Conclusion

This study investigated the wear and mechanical characteristics of Al/Graphite, Al/Zircon and A/l/Zircon/Graphite (Al/Hybrid) composites. For each category of filler addition, hardness, compressive and fracture strengths are of the highest magnitudes when the hybrid of zircon and graphite reinforcements is used above 3wt. %.

Beyond this filler content, precipitation of Mg2Si is much pronounced within the Al matrix. Wear volume of Al/Hybrid composites increases with increasing load compared to Al/Graphite and Al/Zircon composites. There are fluctuations in the wear characteristics of composites except for Al/hybrid where wear volume rose steadily on application of 4.5, 8.9N and 13.35N for each filler content. The composites will serve as potential materials for light automobile brake pads.

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