

## MECHANICAL PROPERTIES AND PHASE EVOLUTIONS IN HEAT-TREATED CAST Al-SiC-TiO<sub>2</sub> METAL MATRIX COMPOSITES

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### ABSTRACT

The effect of heat treatment with an addition of titania on the phase development and mechanical properties of sand casted Al-SiC-TiO<sub>2</sub> metal matrix composite was investigated. The standard samples dimensions for tensile properties, wear and hardness were prepared. These samples were heat treated at different temperature of 180°C to 220°C without solution treatment. The samples were held at the heat treatment temperature for an hour after which they were allowed to cool in the air. Thereafter, samples were subjected to various mechanical and wear tests, respectively. The phases evolved due to heat treatment of the samples were examined using X-ray diffractometry. It was observed that the increase in heat treatment temperature of samples leads to the formation of precipitates within the aluminium matrix composite reinforced with SiC. The addition of 5 % titania inhibits the formation of aluminium silicon carbide phases in preference to SiO<sub>2</sub> and TiO<sub>2</sub>. The increase in heat treatment temperature leads to the formation of precipitates like TiSi<sub>2</sub>, Si<sub>11.4</sub>TiO<sub>24.4</sub>, TiC, Al<sub>2</sub>O<sub>3</sub>, and buckminsterfullerene C<sub>70</sub> within the aluminium matrix composite. The addition of 10 % titania leads to the development of precipitates like Al<sub>3</sub>Ti<sub>3</sub> and Ti-rich oxides with the aluminium matrix. At 220°C, alumina was formed within the metal aluminium matrix and no trace of SiC was found. All the samples have low wear loss but the heat treated at 180°C sample (A) has the lowest wear loss. The heat treatment of the sample without solution treatment has impact on the phase development in the samples. It gives rise to the development of precipitates in the samples which affects the hardness and other mechanical properties. The addition of SiC and TiO<sub>2</sub> to aluminium matrix makes the sample harden. Sample A heat treated at 200°C have the highest hardness.

*Keywords:* metal matrix composite, phases, buckminsterfullerene, hardenability, wear loss.

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### INTRODUCTION

The development of engineering materials with low density, high specific stiffness and dimensional stability have always attract great attention for applications in aerospace and automobile industries. Aluminium matrix composites, most especially those reinforced with ceramic particles, have been reported to be candidates for these applications due to their superior strength,

stiffness and wear resistance. Moreover, their excellent isotropic mechanical and physical properties both at ambient and elevated temperatures when compared with the conventional monolithic alloys give them further advantage [1 - 6].

Aluminium alloy matrix composites have been widely utilized in metal matrix composites (MMCs) for structural applications in various industries such as marine, aircraft and automobile [7 - 10]. In automobile

it is mainly used for piston rings, diesel engine pistons, cylinder liners, brake discs, drive shafts, connecting rods, due to its excellent properties and high specific strength [9, 11]. Composites comprising of ductile aluminium alloys and reinforcements such as ceramic oxides, nitrides, carbides, and graphite, exhibit substantially improved mechanical properties, which depend on particle sizes and volume fractions of the reinforcement phase [9, 12]. Das et al. reported that the strength of composites is determined by the fabrication process, grain size, microstructure, and composition [13].

Many researchers have carried out extensive studies on aluminium matrix composites (AMCs) with the intention of improving on their mechanical and tribological properties because of their potential in many applications. Different ceramic materials such as  $Al_2O_3$  [14], SiC [15 - 16], MgO [17], WC [6],  $B_4C$  [18],  $ZrB_2$  [19], SiC-TiC [18],  $ZrSiO_4$  [20],  $TiB_2$  [21], and  $TiO_2$  [22] as reinforcements within an aluminium matrix, are reported.

The aim of this work is to investigate the effect of heat treatment and addition of titania on the phase evolution and mechanical properties of aluminium-silicon carbide-titania metal matrix composite without solution treatment.

## EXPERIMENTAL

The material used in this research is aluminium ingot received from Aluminium Rolling Mills, Ota, Ogun State, Nigeria. The reinforcement phase was silicon carbide (SiC) particles size of 325 mesh and titanium oxide

( $TiO_2$ ) of 150 mesh. Both the SiC and  $TiO_2$  particles were produced by Alfa Aesar Company. Table 1 shows the chemical composition of the aluminium ingot used.

### Preparation of composites

The aluminium matrix composite samples (AM-MCs) were prepared by sand casting process. Aluminium was melted in a pit furnace inside a graphite crucible, when the temperature of the liquid metal reached at  $750^\circ C$ , preheated silicon carbide particles were and stirred with a stirrer continuously in the crucible until homogenous mixture is achieved. Then pre-calculated amount of titania was added to the homogenous mixture and continuously stirred. Sand moulds were prepared using a cylindrical rod pattern. The homogenous liquid metal was poured in preheated sand moulds at  $670^\circ C$ . The melt was allowed to solidify in the mould. The rods were prepared with standard sample dimensions for tensile, hardness, Scanning electron microscopy and XRD analyses. Table 2 shows the composition of the different sample produced.

The samples were heat treated in an electric furnace at temperatures of  $180^\circ C$ ,  $200^\circ C$  and  $220^\circ C$ . The samples were heated to the heat treatment temperature from room temperature at  $3^\circ C/min$ . When the temperature is reached, they were heat treated for an hour. Then the samples were allowed to cool in the air. Each heat treated sample was then subjected to experimental testing. The hardness of the composite samples were determined with the aid of Rockwell hardness tester (Indentec, 2007 model). It measures the samples' resistance to penetration by

Table 1. The chemical composition of the aluminium ingot.

| Element         | Si   | Fe   | Zn    | Ga    | Cu    | Mg    | Al    |
|-----------------|------|------|-------|-------|-------|-------|-------|
| Composition (%) | 0.07 | 0.18 | 0.018 | 0.012 | 0.005 | 0.015 | 99.70 |

Table 2. Composition of the samples.

| Sample | Aluminium (wt. %) | Silicon carbide (wt. %) | Titania (wt. %) |
|--------|-------------------|-------------------------|-----------------|
| A      | 70                | 30                      | 0               |
| B      | 70                | 25                      | 5               |
| C      | 70                | 20                      | 10              |

measuring the depth of impression and the hardness is indicated directly on the scale attached to the machine. Tensile strength tests were performed on INSTRON 1195 at a fixed crosshead speed of 10 mm min<sup>-1</sup>. Samples were prepared according to ASTM [23]. Tensile strength, modulus of elasticity and absorbed energy of the samples were then calculated from the data generated. The samples were prepared for XRD analysis using a back loading preparation method. The samples were analysed using a PANalytical X'Pert Pro powder diffractometer with X'Celerator detector and variable divergence and receiving slits with Fe filtered Co-K $\alpha$  radiation. The phases obtained were identified using X'Pert Highscore plus software. For graphical representations of the qualitative results was used Origin-Pro software. The wear test was conducted in compliance with ASTM standard [24]. The abrasion resistance test was carried out with Taber abraser, Model ISE AO16. Each specimen was a flat and round disc of approximately 100 mm diameter and a standard thickness of approximately 6.35 mm. It was affixed to the turntable platform and rotated at 1000 rpm for 5 h. Abrasion resistance was measured using the weight difference before and after abrasion (weight loss technique). Care was taken to remove loose particles adhering to specimens during testing, especially prior to weighing. This procedure was carried out for all the various samples to determine the effect of abrasion on the material using equation (1).

$$L = A - B \quad (1)$$

where: L - weight loss; A - weight of test sample before abrasion, g, and B - weight of test sample after abrasion, g.

## RESULTS AND DISCUSSION

Figs. 1(a), 1(b) and 1(c) show the XRD patterns of samples A, B and C, respectively, after heat treatment at different temperatures. Figs. 2 - 7 show the effects of heat treatment temperature on the tensile strength, tensile strain, Young's modulus of elasticity, absorbed energy, hardness and wear load of the samples, respectively.

### Effects of heat treatment temperatures of the phases present in the various sample

The XRD patterns of the samples heat treated at various temperature is shown in Figs. 1(a), 1(b) and

1(c). From the figures the various phases present in the samples are clearly seen.

Fig. 1(a) shows the phases observed in the sample A (0 % titania) after heat treatment. From the figure it is observed that at 180°C the sample contains carbon (C), aluminium silicon carbides (Al<sub>4</sub>SiC<sub>4</sub> and Al<sub>8</sub>SiC<sub>7</sub>), silicon carbide (SiC), aluminium (Al), carbon 60 (Buckminsterfullerene, C<sub>60</sub>), silica (SiO<sub>2</sub>) and silicon (Si). This could be explained that carbon (C) carbon 60 (Buckminsterfullerene, C<sub>60</sub>) and silicon (Si) are originated from the dissociation of some of the reinforcing phase of silicon carbide (SiC) within the aluminium matrix to silicon (Si) and carbon (C). Some of the carbon (C) in the product of dissociation then crystallized to buckminsterfullerene, C<sub>60</sub>. The silica (SiO<sub>2</sub>) could be an inclusion from the sand mould in which the samples were produced as there is no other justification for the presence of the oxide in the sample. The presence of the various phases of aluminium silicon carbides (Al<sub>4</sub>SiC<sub>4</sub> and Al<sub>8</sub>SiC<sub>7</sub>) could be attributed to the reactions between the aluminium matrix and the reinforcing phase (SiC) at the heat treatment temperature. When the heat treatment temperature of the sample was increased to 200°C, the phases observed in the sample are carbons 70 and 60 (Buckminsterfullerene; C<sub>70</sub> and C<sub>60</sub>), aluminium silicon carbides (Al<sub>4</sub>SiC<sub>4</sub> and Al<sub>8</sub>SiC<sub>7</sub>), silicon carbide (SiC), aluminium (Al), and silica (SiO<sub>2</sub>). No silicon (Si) is observed in the sample heat treated at 200°C, but carbons 70 is observed in addition to the presence of carbon 60. The same explanation given above on the origin of the various phases is applicable to this case too. Furthermore, when the heat treatment temperature of the sample was increased to 220°C, the phases observed in the sample, are carbons 8, 70 and 60 (C<sub>8</sub>, C<sub>70</sub> and C<sub>60</sub>), aluminium silicon carbide (Al<sub>4</sub>SiC<sub>4</sub>), silicon carbide (SiC) and aluminium (Al). It is observed that the phase Al<sub>8</sub>SiC<sub>7</sub> has been dissolved. It can be inferred that increase in heat treatment temperature of sample A leads to the formation of precipitates C<sub>8</sub>, C<sub>60</sub>, C<sub>70</sub>, Al<sub>4</sub>SiC<sub>4</sub>, Al<sub>8</sub>SiC<sub>7</sub> within the aluminium matrix composite reinforced with SiC.

The spectra in Fig. 1(b) show the phases observed in sample B (5 % titania) after heat treatment. It is observed that at 180°C the sample contains carbon 70 (Buckminsterfullerene, C<sub>70</sub>), silicon carbide (SiC) aluminium (Al), silica (SiO<sub>2</sub>) and titanium oxide (TiO). The origin of the carbon 70 (C<sub>70</sub>) has been discussed above, the source

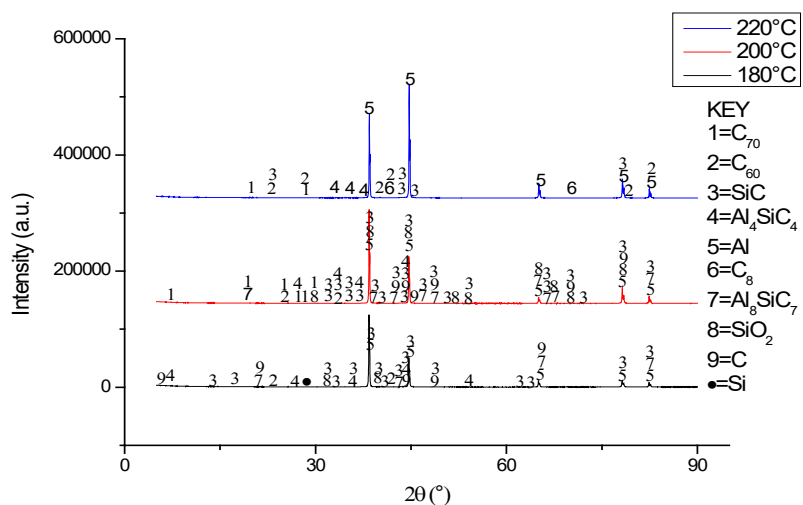


Fig. 1(a). XRD patterns of sample A heat treated at 180°C, 200°C and 220°C.

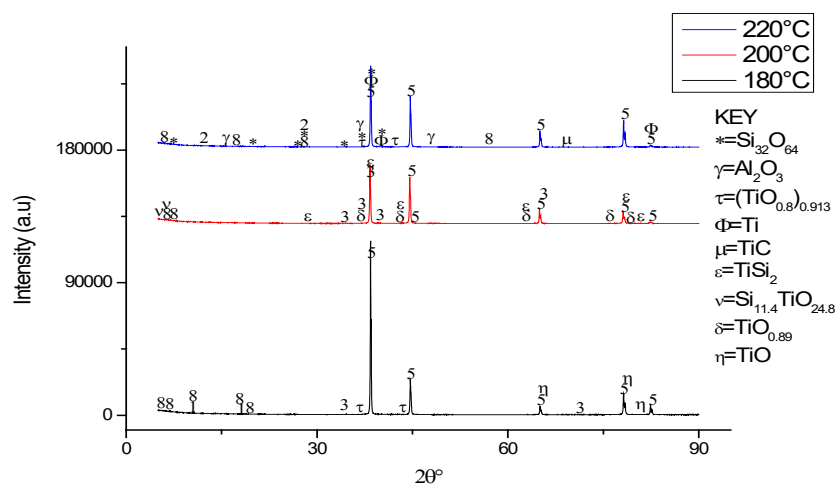


Fig. 1(b). XRD patterns of sample B heat treated at 180°C, 200°C and 220°C.

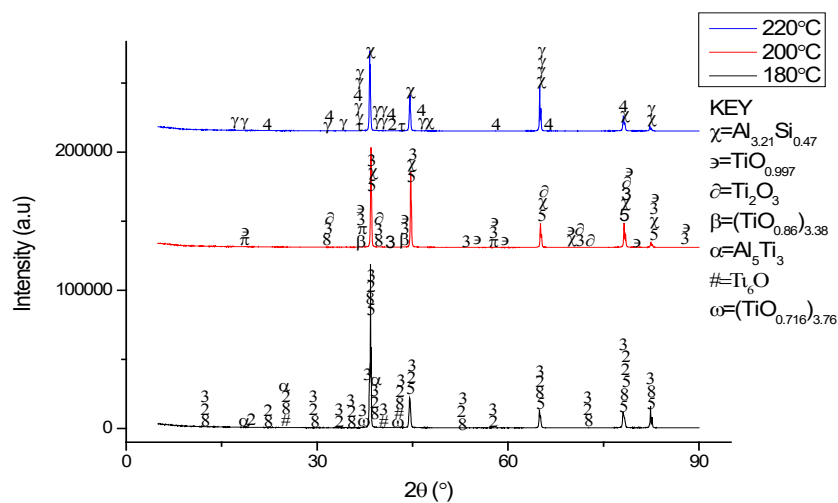


Fig. 1(c). XRD patterns of sample C heat treated at 180°C, 200°C and 220°C.

of the silica in this could be both inclusion and reaction between silicon (product of dissociation of some of the SiC) and oxygen from titania. When the heat treatment temperature of the sample was increased to 200°C, the phases observed in the sample are SiC, Al, silica, silicon titanium oxide ( $\text{Si}_{11.4}\text{TiO}_{24.8}$ ), titanium oxide ( $\text{TiO}_{0.89}$ ) and titanium silicide ( $\text{TiSi}_2$ ). It is observed that the frequency of the silica in sample B at 200°C is reduced when compared with its frequency in sample at 180°C. Moreover, dissociation of some of the SiC and titania occurred and the products of their dissociations reacted together to form titanium silicide ( $\text{TiSi}_2$ ) and silicon titanium oxide ( $\text{Si}_{11.4}\text{TiO}_{24.8}$ ). It is also noted that, there is no trace of carbon 70 ( $\text{C}_{70}$ ) in the sample at 200°C. Moreover, when the heat treatment temperature of the sample was increased to 220°C, the phases observed in the sample are carbon 60 ( $\text{C}_{60}$ ), Al, silica phases ( $\text{SiO}_2$  and  $\text{Si}_{32}\text{O}_{64}$ ), alumina ( $\text{Al}_2\text{O}_3$ ), titanium oxide ( $\text{TiO}_{0.8}^{0.913}$ ), titanium (Ti) and titanium carbide (TiC). It is observed that no trace of SiC is seen in the sample treated at 220°C. This could be explained that the silicon carbide dissociated and reacted with some of the titania to form Ti and TiC. It can also be observed that the oxygen concentration in the titanium oxide ( $\text{TiO}_{0.8}^{0.913}$ ) phase present in the sample is far less than in the added titania ( $\text{TiO}_2$ ). This is because this oxygen was consumed in the reaction with Si from the SiC to form  $\text{Si}_{32}\text{O}_{64}$  and with Al to form alumina. The formation of alumina has been reported by some researchers in the heat treated  $\text{TiO}_2$  ( $\text{Rb}_2\text{O}$ )/Al MMC [25 - 27]. It is inferred that the addition of 5 % titania inhibits the formation of aluminium silicon carbide phases in preference to  $\text{SiO}_2$  and TiO. Increase in heat treatment temperature leads to the formation of precipitates like  $\text{TiSi}_2$ ,  $\text{Si}_{11.4}\text{TiO}_{24.4}$ , TiC,  $\text{Al}_2\text{O}_3$  and Buckminsterfullerene  $\text{C}_{70}$  within the aluminium matrix composite.

Fig. 1(c) depicts the phases observed in sample C (10 % titania). It is observed that at 180°C the sample contains carbon 60 (Buckminsterfullerene,  $\text{C}_{60}$ ), silicon carbide (SiC) aluminium (Al), silica ( $\text{SiO}_2$ ), aluminium titanium ( $\text{Al}_5\text{Ti}_3$ ), and different titanium rich oxide phases ( $\text{Ti}_6\text{O}$  and  $(\text{TiO}_{0.716})_{3.76}$ ). The source of the carbon 60 has been earlier discussed. The origin of silica was also attributed to both the inclusion from the sand mould and the reaction between the Si (which dissociated from some of the SiC) and the oxygen (from some of the titania). This corroborates why the oxygen concentration in the different phases of titanium oxide present in the sample is observed to be less than that in the original titania

added. The phase  $\text{Al}_5\text{Ti}_3$  can be attributed to the inter-metallic reaction between the aluminium matrix and the titanium from the titania [25]. However, when the heat treatment temperature of the sample was increased to 200°C, the phases observed are SiC, Al, silica, different phases of titanium oxide ( $\text{TiO}_{0.997}$ ,  $\text{Ti}_2\text{O}_3$  and  $(\text{TiO}_{0.86})_{3.38}$ ), aluminium silicide ( $\text{Al}_{3.21}\text{Si}_{0.47}$ ) and aluminium titanium ( $\text{Al}_2\text{Ti}$ ) [25]. The sources of  $\text{Al}_{3.21}\text{Si}_{0.47}$  and  $\text{Al}_2\text{Ti}$  could be linked to the reaction between the SiC and the titania used in developing the composite. Furthermore, when the heat treatment temperature was raised to 220°C, the phases observed in the sample are  $\text{Al}_4\text{SiC}_4$ ,  $\text{Al}_2\text{O}_3$ ,  $(\text{TiO}_{0.8}^{0.913})$  and  $\text{Al}_{3.21}\text{Si}_{0.47}$ . It is inferred that addition of 10 % titania lead to the development of precipitates like  $\text{Al}_5\text{Ti}_3$  and Ti-rich oxides with the aluminium matrix. At 220°C, alumina was formed within the metal aluminium matrix and no trace of SiC is found.

### Effect of heat treatment temperatures on the mechanical properties of the samples

Table 3 and Fig. 2 show the effect of the heat treatment temperature on the tensile strength of the MMC samples. It is observed that the tensile strength of sample A (0 %  $\text{TiO}_2$ ) initially reduced its highest value of about 93.55 MPa when it was heat treated at 180°C to about 71.1 MPa at the heat treatment temperature of 200°C. Further increase in the heat treatment temperature to 220°C resulted in the tensile strength being increased to about 85.7 MPa. Moreover, it is observed that the tensile strength of sample B (5 %  $\text{TiO}_2$ ) initially increased from its lowest value of about 38.5 MPa when it was heat treated at 180°C to a tensile strength of about 59.3 MPa when it was heat treated at 200°C. Further increase in the heat treatment temperature to 220°C resulted in its tensile strength being reduced to about 52 MPa. Furthermore, for sample C heat treated at 180°C, its tensile strength is observed to be about 78.6 MPa. Its tensile strength reduced to about 72.2 MPa when it was heat treated at 200°C. It further reduced to about 60.5 MPa when it was heat treated at 220°C. The tensile strengths fall within the range reported by earlier researchers who worked with similar materials [28 - 30].

### Tensile strain

Table 3 and Fig. 3 show the effect of the heat treatment temperature on the tensile strain of the MMC samples. It is observed that the tensile strain of sample

Table 3. Mechanical properties of the samples.

| Sample                       | Aging Temperature | Tensile Strength (MPa) | Tensile Strain | Young's Modulus E (MPa) | Absorbed Energy (J) | Hardness (Hv) | Wear Loss (g) |
|------------------------------|-------------------|------------------------|----------------|-------------------------|---------------------|---------------|---------------|
| A<br>(0% TiO <sub>2</sub> )  | 180               | 93.55127               | 0.12109        | 5357.12318              | 4.01442             | 46.3          | 0.0233        |
|                              | 200               | 71.07082               | 0.07422        | 4604.47350              | 1.72169             | 95.2          | 0.0249        |
|                              | 220               | 85.69847               | 0.09319        | 6727.44446              | 2.54769             | 89.95         | 0.07018       |
| B<br>(5% TiO <sub>2</sub> )  | 180               | 38.52513               | 0.03375        | 7947.67227              | 0.23371             | 52.55         | 0.0402        |
|                              | 200               | 59.30995               | 0.14648        | 6418.56842              | 2.95564             | 92.25         | 0.0309        |
|                              | 220               | 51.98335               | 0.07840        | 4580.11665              | 1.24888             | 95.1          | 0.0395        |
| C<br>(10% TiO <sub>2</sub> ) | 180               | 78.62863               | 0.15540        | 6426.39847              | 4.17271             | 94.35         | 0.0316        |
|                              | 200               | 72.24259               | 0.11440        | 5026.89171              | 2.66224             | 51.85         | 0.0709        |
|                              | 220               | 60.51261               | 0.09236        | 6877.02789              | 1.73196             | 94.5          | 0.0867        |

A (0 % TiO<sub>2</sub>) heat treated at 180°C was initially about 0.121, and when the sample was heat treated at 200°C its tensile strain reduced to about 0.074. Further increase in the heat treatment temperature of the sample to 220°C leads to an increase in its tensile strain to about 0.093.

This should be expected since tensile strain is a measure of ductility of the sample. The overall reduction in the ductility of the sample means that the sample is hardened with the increase of heat treatment temperature. This can be corroborated by looking at the hardness of the samples in Table 3. It will be observed that the hardness followed a trend opposite to

the tensile strength and strain followed for the same sample. However, for sample B (5 % TiO<sub>2</sub>) heat treated at 180°C, the tensile strain was about 0.034. Its tensile strain initially increased sharply to about 0.146 when it was heat treated at 200°C. Further increase in the heat treatment temperature of the sample to 220°C resulted in its tensile strain reduction to about 0.078. Moreover, it is observed that the tensile strain of sample C (10 % TiO<sub>2</sub>) followed almost the same trend as that of sample A. For sample C heat treated at 180°C, its tensile strain was about 0.155, it reduced progressively with increased heat treatment temperature through 200°C to 220°C.

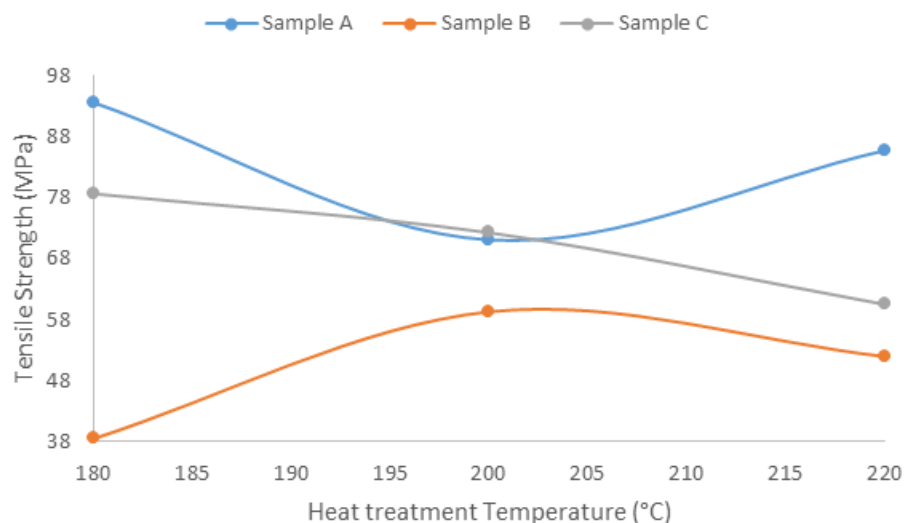


Fig. 2. Effect of heat treatment temperature on the tensile strength of the samples.



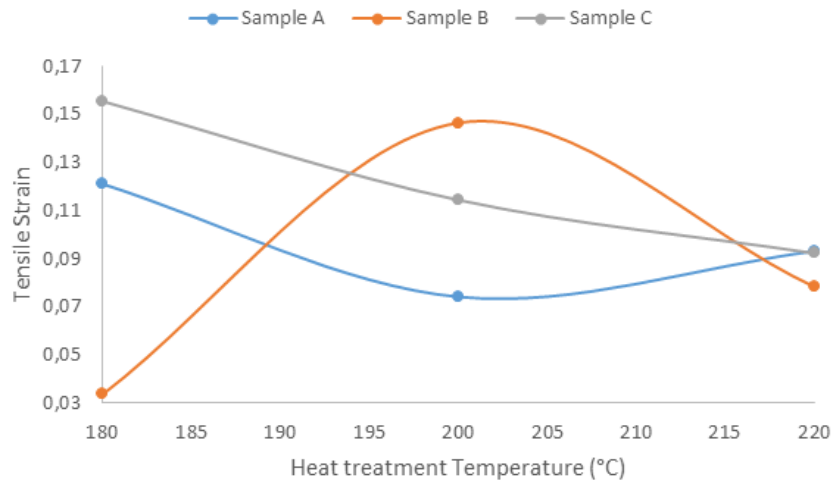


Fig. 3. Effect of the heat treatment temperature on the tensile strain of the samples.

### Young's Modulus of Elasticity

The modulus of elasticity of a sample is a measure of its rigidity. Fig. 4 and Table 3 show the effects of heat treatment temperatures on the Young's modulus of the samples.

From the figure it is observed that the modulus for sample A (0 % TiO<sub>2</sub>) heat treated at 180°C was about 5357 MPa. It initially reduced to about 4604 MPa when the sample was heat treated at 200°C. The heat treatment of the sample at 220°C leads to an increase in the modulus of the sample to about 6727 MPa. Furthermore, sample C (10 % TiO<sub>2</sub>) followed with sample A. This means that both samples have the lowest rigidity at the heat treatment temperature of 200°C and they are more rigid at 220°C. Moreover, it is observed that the modulus

of sample B (5 % TiO<sub>2</sub>) reduced with increase in the heat treatment temperature. This implies that its rigidity reduces with increasing the heat treatment temperature.

### Absorbed Energy

The absorbed energy of a sample is a measure of its resistance to plastic deformation. Fig. 5 and Table 3 show the effect of the temperature on the absorbed energy of the samples. It is observed that the absorbed energy of sample A followed the same trend followed by its tensile strength with heat treatment temperatures. It is observed that sample A heat treated at 180°C had a value of about 4 J for its absorbed energy. Its value reduced sharply to about 1.7 J when the sample was heat treated at 200°C. Further increase in the heat treatment

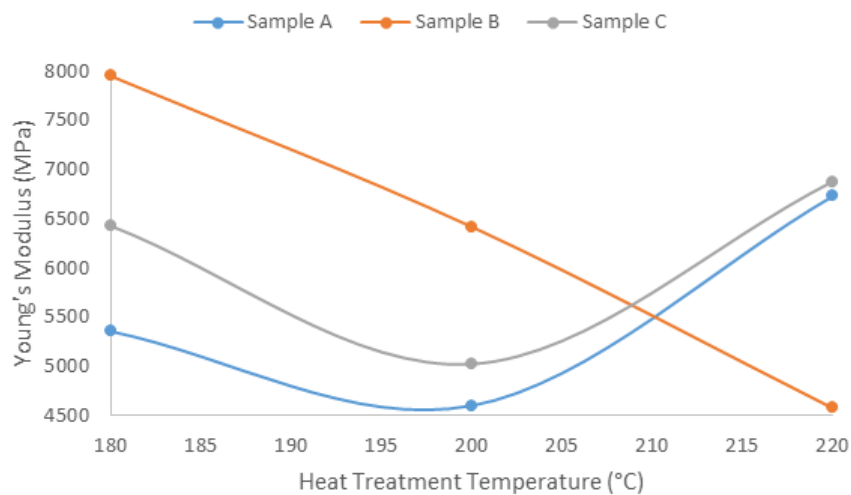


Fig. 4. Effect of the heat treatment temperature on the Young's modulus of elasticity of the samples.

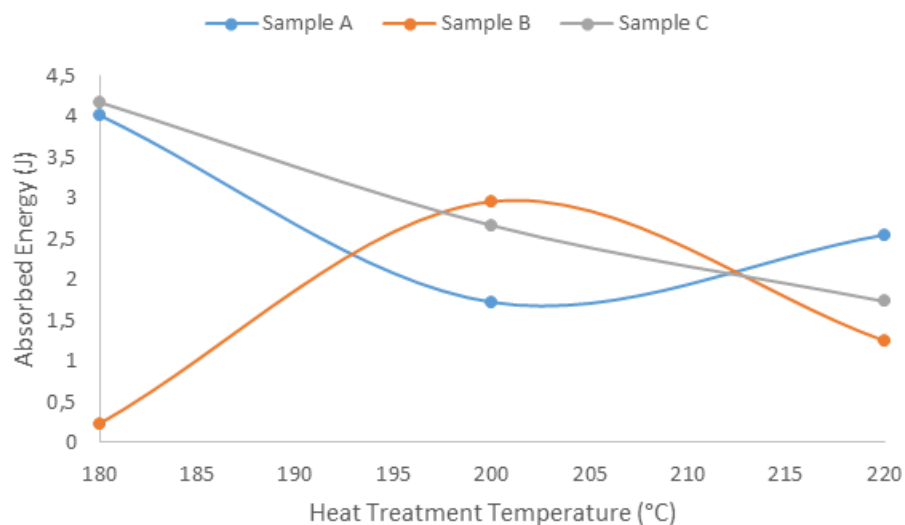


Fig. 5. Effect of the heat treatment temperature on the absorbed energy of the samples.

temperature leads to the value of its absorbed energy being increased to about 2.55 J. However, for sample B heat treated at 180°C it is observed that its absorbed energy is about 0.23 J, this value increased to its maximum of about 2.96 J when the sample was heat treated at 200°C. Further increase in the heat treatment temperature to 220°C leads to reduction in the absorbed energy of the sample to about 1.25 J.

Also for sample C, it is observed that the absorbed energy of the sample decreases progressively with increased heat treatment temperature. It can be inferred that the sample C heat treated at 180°C is tougher than all the samples.

### Hardness

Table 3 and Fig. 6 show the effects of heat treatment temperatures on the hardness of the aluminium matrix composite samples. From the figure it is observed that for sample A heat treated at 180°C, the hardness value was initially about 46.3 Hv. When the sample was heat treated at 200°C, its hardness increased sharply to about 95.2 Hv, further increase in the heat treatment temperature to 220°C resulted in its hardness value's slight reduction to about 89.95 Hv. It can be broadly stated that the hardness of the sample increased with increase in heat treatment temperature.

This relationship is not unconnected with the phases developed during the heat treatment of the samples. Looking at Fig. 1(a) it is observed that silicon (Si) phase was detected by the XRD in sample A heat treated at

180°C; which is not in the samples heat treated at the other temperatures. It can also be observed that carbon 70 (C<sub>70</sub>) was detected in the samples heat treated at the other temperatures but not in the sample heat treated at 180°C. It can be inferred that both the presence of Si and the absence of C<sub>70</sub> in sample A heat treated at 180°C collectively contributed to its low hardness. Moreover, it is observed that sample A heat treated at 200°C contains both C<sub>70</sub> and C<sub>8</sub> while when it was heat treated at 220°C, C<sub>8</sub> is conspicuously missing. This could be said to contribute to the lower hardness observed for sample A heat treated at 220°C when compared with that of the sample heat treated at 200°C.

Furthermore, the hardness of sample B followed almost the same trend followed by that of sample A. It is observed that sample B heat treated at 180°C has the hardness value of about 52.55 Hv; its hardness increased sharply to about 92.25 Hv when it was heat treated at 200°C. Further increase in the heat treatment temperature to 220°C resulted into its hardness being increased to about 95.1 Hv. Considering the phases present in the sample heat treated at different temperature, it is observed that sample B heat treated at 180°C contains C<sub>70</sub> and TiO phases which are not observable in the samples heat treated at the other temperatures. The presence of the phase TiO could be inferred to be responsible for the lower hardness of the sample heat treated at 180°C. It is also observed that the sample that was heat treated at 200°C contains TiSi, TiO<sub>0.89</sub> and Si<sub>11.4</sub>TiO<sub>24.8</sub> phases which are not observed in the sample when heat treated



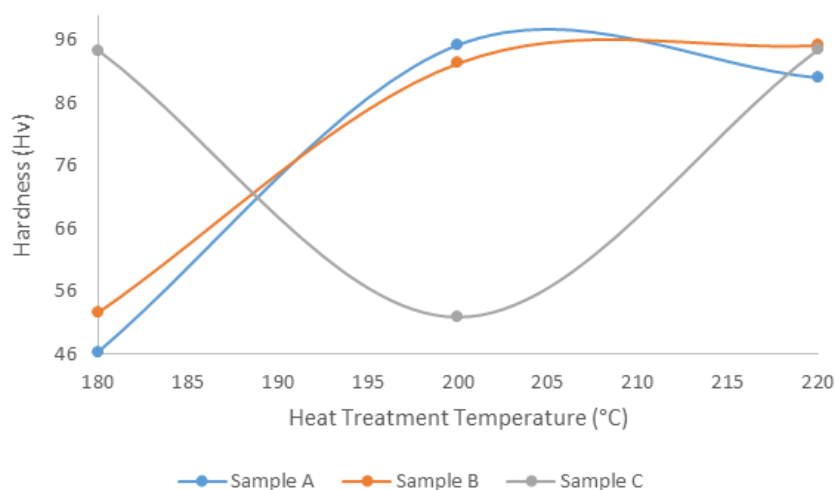


Fig. 6. Effect of the heat treatment temperature on the hardness of the sample.

at 180°C. It can be inferred that these phases are responsible for the sharp increase in the hardness of the sample when it was heat treated at 200°C compared to that of 180°C. Moreover, when the sample was heat treated at 220°C the phases present in it exclusively are  $\text{Al}_2\text{O}_3$ ,  $\text{Si}_{32}\text{O}_{64}$ , Ti, TiC and  $\text{C}_{60}$ . These phases most especially the TiC could be said to account for the high hardness of the sample. Moreover, it is observed that the hardness of sample C heat treated at 180°C is about 94.35 Hv. When it was heat treated at 200°C, its hardness dropped to about 51.85 Hv, further increase in the heat treatment temperature resulted in the hardness of the sample being increased to about 94.5 Hv. Relating to the observed phases in the samples heat treated at different temperatures, it is noted that in the sample heat treated at 180°C the following phases were observed:  $\text{C}_{60}$  (also in sample C heat treated at 220°C),  $\text{Al}_5\text{Ti}_3$ ,  $\text{Ti}_6\text{O}$  and  $(\text{TiO}_{0.716})_{3.76}$ , (i.e. Ti rich oxides). The carbon 60, intermetallic and the titanium rich oxides are considered to be responsible for the high hardness of the sample heat treated at 180°C. Most especially the intermetallic  $\text{Al}_5\text{Ti}_3$  has been reported by some researchers as being able to improve on the hardness of materials [31 - 33]. Some researchers have also reported that in the vicinity of 65 at. % of Al the formation of the equilibrium  $\text{r-Al}_2\text{Ti}$  often does not follow the phase diagram however, firstly the metastable phases  $\text{Al}_5\text{Ti}_3$  and the orthorhombic  $\text{Al}_2\text{Ti}$  nucleate, grow and dissolve in the quenched alloys [34, 35]. Furthermore, the phases observed in the sample heat

treated at 200°C include:  $\text{Al}_2\text{Ti}$ ,  $\text{Ti}_2\text{O}_3$ ,  $(\text{TiO}_{0.86})_{3.38}$  and  $\text{TiO}_{0.997}$ . The predominant phases in the sample are different phase titanium oxides, most of which are rich in oxygen; this accounts for the low hardness of the sample. However, the predominant phases in the sample heat treated at 220°C include:  $\text{C}_{60}$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Al}_4\text{SiC}_4$  and  $(\text{TiO}_{0.8})_{0.913}$ . The alumina, carbon 60 and the aluminium silicon carbide are considered responsible for the high hardness of the sample.

It could be inferred that the heat treatment of the sample without solution treatment has impact on the phase development in the samples. It gives rise to the development of precipitates in the samples which affects its hardness and other mechanical properties. Addition of SiC and  $\text{TiO}_2$  to aluminium matrix makes the sample hardenable. Sample A heat treated at 200°C have the highest hardness.

#### Weight loss due to wear

Fig. 7 and Table 3 show the effects of heat treatment temperatures on the weight loss due to wear of the samples. From the figure it is observed that weight loss due to wear of samples A and C increases with increased heat treatment temperature. It is observed that for sample A heat treated at 180°C, its weight loss due to wear is about 0.0233 g. It slightly increases to 0.0249 g when the heat treatment temperature was raised to 200°C. Further increase in the heat treatment temperature to 220°C leads to more increase in the wear loss of the sample to 0.07018 g.

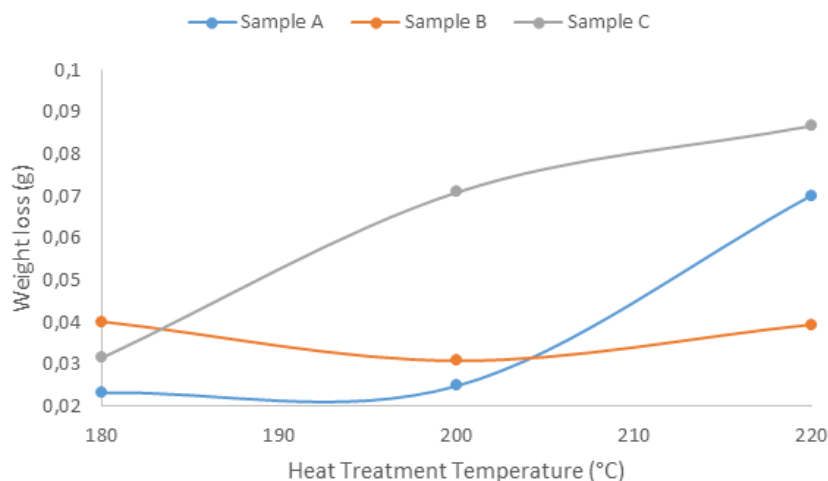


Fig. 7. Effect of the heat treatment temperature on the wear loss of the samples.

This implies that the sample heat treated at lower temperature is more resistant to wear than those at higher temperature. Moreover, it is observed that the weight loss of sample B heat treated at 180°C was 0.0402 g, it however reduced to 0.0309 g when the heat treatment temperature was raised to 200°C. Further increase in the temperature to 220°C leads to increase in the wear loss of the sample to 0.0395 g. It can be inferred that sample A heat treated at 180°C and 200°C is more resistant to wear than sample B heat treated at the same temperatures. Furthermore, it is observed that the wear loss of sample C heat treated at 180°C was 0.0316 g, it increased to 0.0709 g when the heat treatment temperature was raised to 200°C. Further increase in the heat treatment temperature to 220°C leads to further increase in the wear loss of the sample to 0.0867 g. This followed the same trend with sample A whose wear loss increased with increase of the heat treatment temperature. It is observed that all the samples have low wear loss but sample A heat treated at 180°C has the lowest wear loss. It is inferred that the sample A heat treated at 180°C is more resistant to wear.

## CONCLUSIONS

From the data discussed above it is concluded that:

- The increase in heat treatment temperature of sample A leads to the formation of precipitates  $C_8$ ,  $C_{60}$ ,  $C_{70}$ ,  $Al_4SiC_4$ ,  $Al_8SiC_7$  within the aluminium matrix composite reinforced with SiC;
- The addition of 5 % titania inhibits the formation of

aluminium silicon carbide phases in preference to  $SiO_2$  and TiO. Increase in heat treatment temperature leads to the formation of precipitates like  $TiSi_2$ ,  $Si_{11.4}TiO_{24.4}$ , TiC,  $Al_2O_3$  and Buckminsterfullerene  $C_{70}$  within the aluminium matrix composite;

- The addition of 10 % titania leads to the development of precipitates like  $Al_5Ti_3$  and Ti-rich oxides with the aluminium matrix. At 220°C alumina was formed within the metal aluminium matrix and no trace of SiC is found;
- The sample C heat treated at 180°C is tougher than all the samples;
- The heat treatment of the sample without solution treatment has impact on the phase development in the samples. It gives rise to the development of precipitates in the samples which affects its hardness and other mechanical properties. Addition of SiC and  $TiO_2$  to aluminium matrix makes the sample hardenable. Sample A heat treated at 200°C have the highest hardness;
- All the samples have low wear loss but sample A heat treated at 180°C has the lowest wear loss. It is inferred that the sample A heat treated at 180°C is more resistant to wear.

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