Mechanical behaviour of stir cast TiO$_2$/Redmud/Al6061 metal matrix composites

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Abstract
The present work deals with mechanical characterization of titanium oxide (TiO$_2$)/Redmud/Aluminium alloy 6061 (Al6061) hybrid metal matrix composites (HMMC’s) processed using stir casting method. The weight fractions of TiO$_2$ are varied (2%, 4% and 6%) and amount of redmud is kept constant (2%) in Al6061. The optimised parameters for stir casting are employed for fabrication the samples of all the configurations and cut according to ASTM standards. The presence of the elements of the constituents is confirmed by XRD and EDS. Effect of TiO$_2$ and redmud content on Tensile, Compression and Hardness are studied in detail. The results reveal that the tensile, compressive and hardness of the prepared composites enhance with TiO$_2$ content. The yield and ultimate strength increase in the range of 29.77%–72.36% and 29.96%–63.90% respectively than the Al6061. The compressive strength enhanced in the range of 9.28%–33.20% than the Al6061. Enhancement of hardness in the range of 9.41%–41.17% is observed as compared to Al6061. The fractography studies confirm uniform mixing of the constituents and load transfer mechanism.

Nomenclature

| Symbol  | Description            |
|---------|------------------------|
| Al$_2$O$_3$ | Aluminium Oxide       |
| SiC     | Silicon Carbide        |
| SiO$_2$ | Silicon Dioxide        |
| TiC     | Titanium Carbide       |
| TiO$_2$ | Titanium Dioxide       |
| MMC’s   | Metal matrix composites|
| HMMC’s  | Hybrid metal matrix composites |
| Al7075  | Aluminium 7075 alloy   |
| Al6061  | Aluminium 6061 alloy   |
| Fe$_2$O$_3$ | Ferric Oxide         |
| ZrO$_2$ | Zircon Dioxide         |

1. Introduction

Aluminium based composites are developed and used in response to the ever-increasing need for lightweight materials with high specific strength suitable for aerospace and automotive applications [1]. Metal matrix composites (MMC’s) are replacing aluminium alloys in aerospace and automobile structural applications due to their superior strength, low density and energy-saving potential. The reinforcements in these composites are in
the form of continuous, discontinuous, short, whiskers, etc, which have enhanced chemical, electrical and mechanical properties [2, 3]. Aluminium composites, particularly those based on aluminium 6061 alloy (Al 6061) and aluminium 7075 alloy (Al 7075), have found applications in a variety of engineering applications, particularly in the automotive industry and their characteristics are of great interest to researchers all over the world [1–11]. The corrosion-resistant and lightweight Al 6061 alloy is suited for use in the manufacturing of engine casings, brake liners and bicycle frames [12–14]. Magnesium (Mg) and silicon (Si) are the two main alloying constituents of the Al6061 alloy and can be cast, extruded, rolled, and machined easily and has good mechanical qualities. Al6061 is employed in the construction, automotive, and marine industries because it has more corrosion resistance than other aluminium alloys. Applications in vehicles, particularly engine components and brakes, led scientists to enhance the characteristics of aluminium alloys hence in the present work Al6061 is used. Several approaches for fabricating aluminium metal matrix composites with diverse reinforcements have been developed in recent years [15–20]. Stir casting is a low-cost, straight forward technology that is employed in liquid state fabrication of the aluminium based components. The stir cast processing route has benefits over other processing routes, including ease of use, adaptability to a variety of materials, affordability, and a high production rate for large-scale composite manufacturing and is employed in present work [21, 22].

Reinforcements play a pivotal role in defining the properties of the composites, especially when novel reinforcements such as fly ash, red mud, TiO2, TiC, Al2O3, B4C, SiC are added to the aluminium matrix [4, 5, 21, 23–26]. Proper bonding between the constituents play an important parameter, that ensures efficient load transmission [23, 27]. Hybrid metal matrix composites (HMMC’s) are next-generation composite materials that use two or more types of reinforcements to alter the characteristics. When compared to single-reinforced composites, HMMC’s have better properties because they incorporate the benefits of their constituent reinforcements [24]. The residue of bauxite ore during extraction of alumina, red mud is produced abundantly, can be utilised in MMC’s [28]. Massive amounts of red mud (industrial waste) becoming the cause of increased pollution and increase landfill burden [25, 29, 30]. Keeping this in the note Kar and Surekha [31] utilised the red mud as reinforcements in the Al7075 matrix and compared it with Al/TiC Composites. The hardness of red mud reinforced composites was observed 62% improvement than the Al/TiC Composite. The studies revealed red mud can be mixed homogenously in the aluminium matrix by the stir casting process and further found that the tensile strength and hardness increased with the increase in volume fraction of red mud [32–34]. However, literature articles on HMMC’s of red mud and TiO2 are scarce and hence the present investigates the mechanical behaviour of these composites.

Siddhesha et al [35] investigated the effect of TiO2 particles in Al2024 matrix medium fabricated using the stir casting process. Results revealed that the tensile strength, hardness, and impact strength increased due to the homogeneous distribution of TiO2 particles and strong bonding with the aluminium matrix. Yoganandam et al [36] studied the effect of varying weight percentage (3%,6% and 9%) of TiO2 particles in Al6082 matrix. It was found that ultimate tensile strength and hardness enhanced with increase in weight percentage of TiO2. The aluminium-based HMMC’s with varying SiO2 and TiO2 weight percentages are manufactured using stir casting by Singh et al [37]. The testing results reveal that the increase in tensile strength, hardness, and wear resistance for higher reinforcements. Nagendra et al [38] fabricated aluminium based HMMC’s by adding varying weight percentage of SiC and TiO2 as reinforcement by the stir casting process. The result showed the increase in tensile strength and hardness of composites compared to Al6061 alloy. Ravichandran and Dinesh Kumar [39] investigated the tensile and hardness of 5% TiO2/Aluminium composite fabricated using the liquid metallurgy route. The result showed that the addition of TiO2 improves the tensile strength and hardness properties of the MMC. And the observations of Shirvanimoghadam et al [40] showed addition of red mud reduced elongation in Al matrix composites. Hence the present study aims to observe the effect of adding both TiO2 (98% Purity) and red mud as reinforcements in an aluminium matrix which may lead to better mechanical properties. The goal is to create composites using inexpensive, light-weight reinforcements. Graphite, fly ash, red mud, and other readily accessible low-cost materials have the potential to be employed as reinforcement in MMCs. As a by-product of the extraction of aluminium from bauxite, red mud is produced in vast quantities and is the least expensive of these components. Al2O3 and Fe2O3 are two of the main components of red mud. One of the most often used ceramic fillers is TiO2, which has a high hardness and modulus, is chemically inert, and has exceptional corrosion resistance. As a result, the TiO2/red mud reinforced composite will be less expensive and suitable for automotive applications.

Present work deals with the mechanical characterization of stir cast TiO2/Red mud/Al 6061 metal matrix composites. The weight fraction of red mud (2%) is kept constant and the weight fraction of TiO2 is varied (2%,4% and 6%) in Al 6061 alloy. The stir casting is carried out using optimised parameters to get uniform mixing of the constituents. The cast samples are trimmed as per ASTM standards and tested for their tensile, compression and hardness properties. The purpose of this study is to gain understanding of the influence of TiO2 and red mud weight fraction in Al6061 on the mechanical properties and identify the key failure mechanisms and elucidate the reasons for the observed behaviours. These properties will help in better designing of components such as Cams, Gears, Bearings, Engine casing and Bicycle frames.
2. Materials and methods

2.1. Constituent materials
Al6061 in the form of plates are procured from Omshree Alloys, Mumbai, India and used as matrix material. The composition of Al 6061 is represented in Table 1. Titanium oxide (TiO₂) in powdered form (Figure 1(a)) is purchased from Mincometals, Bangalore, India. The SEM image (Figure 1(a)) depicts the size of the particles.
range from 1–10 μm. Redmud in powdered form (figure 1(b)) supplied by Nangal Enterprise, Jamnagar, Gujarat, India. TiO₂ and redmud are used reinforcements to form hybrid Al6061 matrix composites. Three different compositions as depicted in table 2 are fabricated using stir casting. The Quantity of redmud is maintained constant (2% weight fraction) and TiO₂ content is varied in the step of 2% weight fraction up to 6% (table 2).

2.2. Fabrication procedure

The Hybrid Al6061 matrix composites in the present study are produced using stir casting setup having tilt table electric resistance melting furnace which operates at 220 V and 50 Hz with a stirrer supplied by Tecnovia Engineering, Ahmedabad, India. Stirrer has a speed range from 200 r min⁻¹ to 450 r min⁻¹. The step-by-step procedure is represented in figure 2. 2 kg of Al6061 is melted at 750 °C (figure 2(a)) and stirred by an electric motor is driven ceramic coated mechanical stirrer which forms the vortex. Crucible is made of graphite and cylindrical die (250 mm length and 25 mm diameter) is made of high chrome high carbon steel. Once the molten pool attains the uniform temperature of 750 °C the degassing agent Hexachloroethane (0.3% by weight) is added (figure 2(b)) [39–42]. Magnesium chips (1% by weight) (figure 2(c)) is added to enhance the wettability of the reinforcements [43]. The Redmud and TiO₂ particles of known proportions are weighed and preheated to a temperature of 200 °C for 30 min in an electric muffle furnace (figure 2(d)) and then added in the molten Al6061. The molten Al6061 is further agitated with both the reinforcements in 10 min with the constant stirrer speed of 200 rpm (figure 2(e)). Later the mixture of all the constituents is poured into a preheated cast iron mould and left for solidification (figure 2(f)). The solidified HMMC’s as shown in figure 2(g) are machined according to ASTM Standard and tested. Samples of Al6061 are also produced in the same manner for comparison purpose. The stir casting process parameters for the present work are selected according to the initial pilot experimental trials and literature survey carried out. Further, the stir casting process parameters were optimized to obtain the homogeneous distribution of the reinforcements in the matrix phase.

3. Experimentation

3.1. Tensile testing

Tensile behaviour of the stir casted TiO₂/Redmud/Al6061 metal matrix composites are studied using a computer-controlled universal testing machine (Make: MCS Testing Machines, Model UTE FLG-20) with the load cell capacity of 20 kN. The six specimens of each configuration as per ASTM E8M-16a are prepared as shown in figure 3(a) and tested, average values with standard deviations are reported. The strain rate of 2 mm min⁻¹ is maintained for testing.

3.2. Compression testing

The compressive behaviour of stir casted TiO₂/Redmud/Al6061 metal matrix composites is studied using the same machine which is used to study tensile properties. The six specimens of each configuration having 25 ± 1.0 mm length and 13 ± 0.2 mm are prepared according to ASTM E9–09 (figure 4).
3.3. Hardness test

A Brinell hardness test (BATLI BOI Ltd) carried out using a 5 mm ball indenter with a load application of 250 kgf and a dwell time of 30 seconds for each sample at different locations. The hardness test is performed according to ASTM E10–18.

Figure 4. Compression Test Specimen.

Figure 5. SEM micrographs of specimen before testing. (a) AL6061 (b) AL6061 + 2% Redmud +2% TiO$_2$. (b) AL6061 + 2% Redmud +4% TiO$_2$. (c) AL6061 + 2% Redmud +6% TiO$_2$. 

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3.4. Morphological analysis using scanning electron microscope (SEM)

In the current work, the SEM images are taken on a VEGA 3 TESCAN machine for different magnifications on a fractured surface.

4. Results and discussion

After the fabrication of samples, SEM analysis is carried out to understand the uniform mixing of the constituents as represented in figure 5. From the SEM images, it is evident that the TiO\textsubscript{2} and Redmud are being distributed uniformly. Which states the process parameters employed for stir casting have resulted in better distribution. Further, it is also noted that the good adhesion between the constituents is evident from the SEM images. Agglomeration of the TiO\textsubscript{2} and Redmud particulates is not observed in the micrographs (figure 5). As the weight fraction of TiO\textsubscript{2} is increased the greater number of particles are witnessed in the SEM images (figure 5) and the same amount of Redmud particles are observed in all the images.

The x-ray diffractograms (XRD) of the fabricated configurations, Al6061 (figure 6(a)), Al6061 + 2% Redmud +2% TiO\textsubscript{2} (figure 6(b)), Al6061 + 2% Redmud +4% TiO\textsubscript{2} (figure 6(c)) and Al6061 + 2% Redmud +6% TiO\textsubscript{2} composites (figure 6(d)) are represented. The XRD is performed by a h–2 h diffractometer.
Panalytical using Cu-Kα radiation, voltage of 35 kV and current of 50 mA is applied. Figure 6(a) shows the peaks observed at 38.850, 45.060, 65.360 and 78.460 approximately showing the presence of alloying elements for the Al6061 alloy. Figure 6(b) represents the peaks at 38.790, 38.990, 45.050, 45.210, 65.50, 78.460 and 78.740 indicating the elements of redmud and TiO₂ for 2%wt redmud and 2%wt TiO₂ reinforced composite. Figure 6(c) depicts the 2%wt redmud and 4%wt TiO₂ reinforced Al6061 composite, where the peaks are observed at 38.830, 45.040, 65.380, 78.470 and 82.670 representing the elements of redmud and TiO₂ along with the Al6061. The peaks are observed at 38.740, 44.960, 65.300 and 78.410 for 2%wt redmud and 6%wt TiO₂ reinforced in Al6061, indicating the elements of the constituent materials. The x-ray diffractograms confirms the presence of redmud and TiO₂ in Al6061 composites.

4.1. Tensile test
Six specimens of each configuration are tested and average values with standard deviations for tensile strength and Yield strength are reported. The representative stress-strain curves obtained from the test are represented in figure 7(a) and table 3. It is observed that the stress-strain behaviour is similar to studies presented in references [1, 4, 5, 12]. The typical stress-strain behaviour is linear elastic till the upper yield point, post yielding strain hardening is observed and strain hardening effect is increased with increasing content of TiO₂. The tensile strength of the composite specimens varies from 127 MPa to 160 MPa as compared to 98 MPa of Al6061. The
composite with 2 weight percentage of redmud and 6 weight percentage of TiO$_2$ exhibits the maximum tensile strength due to strong coherent bonding between the matrix and reinforcement phase in the composites developed. The interfacial bonding strength is further accelerated by the addition of magnesium, which predominantly helps in enhancing the wettability of TiO$_2$ and Redmud with the aluminium 6061 matrix phase. Strong interfacial bonding between the constituents is built up due the addition of the reinforcements. And due to additions of TiO$_2$ and Redmud particles the pores in the microstructure are occupied leading to enhancement of tensile strength. Addition of both these reinforcements and the formation of precipitates are limiting the mobility of the dislocations, leading to increased yield and ultimate tensile strength [44]. The mobility of the dislocations is limited due the better bonding the constituents [45, 46]. Similar effect is observed when the TiO$_2$ is added into Al matrix composites [22, 34, 37]. Further, addition of Redmud in MMC have shown increase in tensile strength [28–30, 47]. The processing temperature and uniform mixing of the constituents in the matrix medium might have led to unstable exothermic reactions at the interface of the constituents and helped in increasing the strength of the composites [48, 49].

The ultimate tensile strength of the HMMC’s increased with an increase in the weight percentage of redmud and TiO$_2$ mainly due to the higher strength of TiO$_2$ and better bonding between the constituents with the aluminium matrix as depicted in figure 7(b) and table 3. However, the addition of TiO$_2$ beyond the 6 weight percentage leads to severe embrittlement that reduces the tensile strength [12]. It is seen from figure 7(c) and table 3 the tensile strength of TiO$_2$ (2%)/Redmud (2%)/Al6061 composites shows enhancement of 29.96% and TiO$_2$ (6%)/Redmud (2%)/Al6061 shows 63.90% this is attributed to strain hardening effect of the composites added and properties rendered due to the addition of constituents. The failure is predominantly due to elongation in the matrix phase than the debonding between the constituents.

Figure 7. (a) Stress-strain behaviour, (b) Yield strength, (c) Ultimate tensile strength of stir casted TiO$_2$/Redmud/Al6061 metal matrix composites and (d) Young’s Modulus.
Table 3. Tensile properties of prepared HMMC’s.

| Sample type                  | Young’s modulus (GPa) | Young’s modulus | Yield strength (N mm\(^{-2}\)) | Ultimate tensile strength (N mm\(^{-2}\)) | Percentage enhancement compared to Al6061 |
|------------------------------|-----------------------|-----------------|----------------------------------|--------------------------------------------|----------------------------------------|
| Al6061                       | 68.43 ± 1.71          | 68.93 ± 1.72    | 85.68 ± 1.77                     | 97.98 ± 2.05                               | —                                      |
| Al6061 + 2% Redmud + 2% TiO2| 73.31 ± 1.83          | 67.64 ± 1.69    | 111.19 ± 3.54                    | 127.34 ± 4.07                              | 29.96                                  |
| Al6061 + 2% Redmud + 4% TiO2| 74.52 ± 1.86          | 65.43 ± 1.64    | 115.56 ± 3.87                    | 138.30 ± 4.60                              | 40.32                                  |
| Al6061 + 2% Redmud + 6% TiO2| 79.83 ± 1.99          | 63.85 ± 1.59    | 147.68 ± 4.97                    | 160.59 ± 5.49                              | 63.90                                  |
4.2. Compression test

Six specimens of each configuration are tested under axial compression at the strain rate of 1 mm min\(^{-1}\). The fractured samples are as shown in figure 8, all the samples have undergone enormous deformation in axial directions and finally fractured indicating the shear planes. The deformations in axial directions replicate the ductility of material is retained prior to fracture. Figure and table 4 represents the compressive strength of the tested HMMC’s. The compressive strength is enhanced with increase in TiO\(_2\) weight fraction. TiO\(_2\)/Redmud/Al6061 composites with 2% of TiO\(_2\) indicated the compressive strength of 647.87 MPa and 9.28% higher that neat Al6061. HMMC’s with 6% of TiO\(_2\) represented the strength to the tune of 863 MPa which is 33.20% greater than the Al6061 (figure 9). This enhance in the compressive strength is attributed to addition of redmud and TiO\(_2\) and mainly due to the higher strength of the reinforcing TiO\(_2\). Further, leading to better bonding between the reinforcements of TiO\(_2\) and Redmud with the aluminium matrix phase. Where the pores from the aluminium matrix phase are replaced by the reinforcements and have reduce the ductility of the composites. The increase in the volume fraction of TiO\(_2\) and Redmud have exhibited the cracks and debonding in the fractured composites resulting in the brittle fracture [12].

| Sample type                          | Compressive Strength (N/mm\(^2\)) | Percentage Enhancement compared to Al6061 |
|--------------------------------------|-----------------------------------|------------------------------------------|
| Al6061                               | 647.87 ± 13.15                    | —                                        |
| Al6061 + 2% Redmud + 2% TiO\(_2\)    | 708.00 ± 21.80                    | 9.28                                     |
| Al6061 + 2% Redmud + 4% TiO\(_2\)    | 749.76 ± 24.06                    | 15.72                                    |
| Al6061 + 2% Redmud + 6% TiO\(_2\)    | 863.00 ± 28.73                    | 33.20                                    |

Figure 8. Fractured Specimen after compression test.
4.3. Hardness test

The prepared HMMC’s are tested to measure the resistance to indentation (Brinell hardness) by determining the depth of indentation as per ASTM E10 (figure 11). The indentations are made six different locations as shown in figure 10 and average values are reported in figure 1. It is observed from the bar graph (figure 1) that adding Redmud and TiO₂ particles to an aluminium alloy increases its hardness to the tune of 85 BHN to 120 BHN. Previous articles have shown additions of TiO₂ [34] and Redmud [29, 30, 47] individually have enhanced the hardness. This enhancement may be due to reduction in porosity that has led into reduced plastic deformations of the composites. Further the hardness has been in increased due to the change in microstructure due to
processing temperature of the composites. Apart from the strong interfacial bonding between the constituents, the Hall-Pitch strengthening \[34, 50, 51\] mechanism may also be contributed for enhancement of the hardness in the fabricated composites.
4.4. Morphological analysis using scanning electron microscope (SEM)

SEM fractographs presented in figure 12 shows ductile fracture and dimple formation in various samples. It can be observed from the images that the distribution of the TiO$_2$ and Redmud particles in the aluminium matrix is noticeably uniform. With the increase in percentage reinforcement, the number of particles visible in the images are greater, which indicates good wettability between matrix and reinforcement.

Energy dispersive spectroscopy (EDS) of fabricated samples confirms the presence of redmud and TiO$_2$ in prepared aluminium 6061 composites. The spectrums of EDS are shown in figure 3. EDS analysis reveals the
The results reveal that the tensile, compressive and hardness of the prepared composites enhance with TiO$_2$ and Red-mud based composites have been successfully fabricated using the stir casting method. In this work, three different samples are fabricated and the following inferences are made.

5. Conclusions

In this work, three different samples are fabricated and the following inferences are made.

- TiO$_2$ and Red-mud based composites have been successfully fabricated using the stir casting method.
- The presence of the elements in prepared composites are confirmed using XRD analysis.
- The results reveal that the tensile, compressive and hardness of the prepared composites enhance with TiO$_2$ content.
- The yield and ultimate strength increase in the range of 29.77%–72.36% and 29.96%–63.90% respectively than the Al6061.
- The compressive strength enhanced in the range of 9.28%–33.20% than the Al6061.
- Enhancement of hardness in the range of 9.41%–41.17% is observed as compared to Al6061,
- SEM images show that a fairly uniform distribution of TiO$_2$ and red-mud particles have been obtained in the aluminium 6061 matrix. The EDS of the fabricated casting reveals the presence of Calcium (Ca), Oxygen (O), Iron (Fe), Sodium (Na), Zinc (Zn), silicon (Si), Titanium (Ti), and potassium (K) inside the material.
- The property map is prepared in comparison with studies available, indicated the prepared composites are inline with the other studies and probably can be future replacements.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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