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Investigation on Mechanical Properties of AA6061/TiB_2 Metal Matrix Composites Fabricated by Squeeze Casting Process

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Abstract

There is a requirement of lightweight structures in daily life. Metal matrix composites (MMCs) with aluminum as matrix material are predominantly used in industries like aerospace, sporting goods, automobiles, and military. Among the various methods for producing MMCs based on aluminum, the stir-casting route is predominantly used since it is a fast and affordable. The main problems with the stir casting method include porosity and an uneven distribution of reinforcing particles. Squeeze casting process is an effort to address these problems. In the current work, lightweight AA6061-TiB_2 composites were produced utilizing the squeeze casting method with varying reinforcement levels (0, 1.5, 3, and 4.5 wt.%) after process variables such melt temperature, stirring speed, and reinforcement percentage were optimized. The primary goals of this investigation are to examine the hardness, tensile strength and microstructure along with wear rate of MMCs. In contrast to the basic alloy, an increase of 33.27% in hardness and 26.12% increase in tensile strength were noted from the study. The findings of the wear test demonstrate that adding TiB_2 particles increased wear resistance.

Keywords

Squeeze casting, Microstructure, Hardness, Ultimate tensile strength, Wear rate

Introduction

Aluminum alloy-based composites are utilized to make parts for aircraft and automobiles due to the exceptional strength-to-weight ratio. It carries unique properties such as lower density, higher stiffness, and good thermal expansion with increased wear resistance [1]. In comparison to other lightweight materials like magnesium and titanium, aluminum alloys are inexpensive. It is well known that aluminum alloys have great mechanical qualities and high corrosion resistance, and these features can be varied to meet various requirements [2]. AMMCs consist of aluminum as the matrix, and various reinforcing components. Typically, the reinforcements are nonmetallic and made of common nano-ceramic particles like Al_2O_3, B_4C, SiC, C, B, TiB_2, BN, etc. [1]. The wear resistance and mechanical strength of the base material can be enhanced by these nanoparticles. MMCs with nanoparticle reinforcement, also known as metal matrix nanocomposites. Comparing titanium diboride (TiB_2) to other ceramic particles, it has many advantages. Al-TiB_2 composites can be made using both solid and liquid state processes because of thermodynamic stability of TiB_2 in molten aluminum [2]. As AMMCs are used in various structural, non-structural, and functional applications, one can alter their enforcement type and weight percent to check the behavior of AMMCs. To overcome the limitations imposed by the alloys now in use, novel materials with characteristics such as increased stiffness, lower density, and greater strength are required. This can be achieved by enhancing the specific strength or by making the composites lighter [1]. Al-TiB_2 nano composites are frequently used in high-tech structural and functional applications, such as those in the automotive industries, defence and aerospace because to the combination of TiB_2's exceptional characteristics. The most widespread applications of these materials are in cutting tools, crucibles, impact-resistant constructions, and wear-resistant coatings [2].

James et al. [3] investigated the mechanical characteristics of hybrid AMMCs by considering reinforcements as SiC and TiB_2. They asserted that reinforcement addition enhanced the wear resistance, hardness and strength of the composite materials.AA6061 and TiB_2composites were created using stir casting route while studying the corrosion behavior, wear and friction of forged components along with casted components [4]. The study found that *in-situ* composites had increased corrosion resistance. Al-TiB_2 nanocomposites have become a viable alternative to AMMCs in recent years because of the TiB_2 nanoparticles' high melting point, low specific gravity, excellent thermal and electrical conductivity, high hardness, and high Young's modulus [5]. Prasad et al. [6] highlighted the effects of SiC, TiB_2 nanoparticles on AMMC's mechanical characteristics, microstructure and wear characteristics, and highlighted that resistance to wear improved with surge in stress. The properties of composite materials with aluminium as matrix and TiB_2 as reinforcement were examined by stir casting route [2]. The study revealed significant improvement in mechanical characteristics. Multiple studies have highlighted the advantages of manufacturing of Al-TiB_2 composites via *in-situ* route. In case of *in-situ* approaches, the grain boundary is separated as the TiB_2% exceeds a particular value due to an accumulation of reinforcement particles. Additionally, a higher weight % of TiB_2 results in agglomeration, which has a detrimental effect on characteristics [5]. The reinforcing phases are typically in powder form and are dispersed throughout the molten aluminum during the stir casting process. But stir casted aluminum castings include a number of flaws, including porosities, segregations. Casting flaws can be eliminated via squeeze casting, a developing technique capable of creating castings without any flaws [7]. By managing the stirring process, maintaining TiB_2 particle size at a lower level, preheating the particles, and using moulding techniques, non-uniformity in the distribution of particles and porosity may be easily addressed [5]. Microstructural characteristics and mechanical behavior of aluminum nanocomposite was studied after fabrication by squeeze casting method [8]. The study demonstrated enhancement in the homogenous dispersion of reinforcements. Squeeze casting was used to create composites with TiB_2 as reinforcements in varying weight proportion and magnesium as matrix material [9]. The analysis showed that the ceramic reinforcing particles had uniform distribution throughout the magnesium matrix. During the stir casting, response surface methodology was used to optimize process parameters [10]. Deshmukh et al. [11] fabricated AA6061-TiB_2 MMCs using stir casting route to check mechanical properties. The study revealed enrichment in the hardness as well as tensile strength of composite materials. The synthesis of TiB_2 nano particles by *in-situ* way through a chemical interaction between TiO_2, Al, and B_2O_3 was studied to demonstrate improvement in the ultimate tensile stresses of the manufactured composite [12]. Most researchers created Al-TiB_2 composites using the *in-situ* process, but very little literature is known on *ex-situ* techniques. Considering all these aspects nanocomposites were created by taking matrix material as AA6061 and TiB_2 as reinforcing nanoparticles with varying percentages utilising the squeeze casting route. These reinforcing levels were selected after optimization of the parameters [10]. The primary goal of this research is to examine the mechanical characteristics and to perform microstructural analysis on the MMCs manufactured by squeeze casting technique.

Experimentation

Materials

In this study AA6061 alloy is used as matrix material, while TiB_2 nano particles are utilized as the reinforcements having average mesh size of 5.5 µm. AA6061 exhibits good strength, weldability, formability, and corrosion resistance. The reinforcement particle plays important role in fabrication of composites because its size affects its wettability and dispersion. TiB_2 nanoparticles exhibit remarkable hardness, strong electrical and thermal conductivity, and characteristics that outperform B_4C and TiC [13]. Table 1 and table 2 highlight the chemical composition of matrix material AA6061 and reinforcement material TiB_2, respectively.

Squeeze casting process

It is challenging to produce MMCs through straight forward liquid mixing route because of difficulties in wetting of reinforcements inside matrix in liquid form. The main problems with the stir casting method include porosity and an uneven distribution of reinforcing particles. Squeeze casting technique is an effort to address these problems and to prepare the composites. Combining stir casting and hydraulic forging is known as squeeze casting [14]. During the process, the furnace was filled with AA6061 ingots by keeping preheating temperature of furnace at 850 ºC. Using a two bade stirrer, the molten metal was continuously rotated to create vortex. Argon gas was used to create inert atmosphere within the furnace chamber. Impurities were manually removed from the top surface of the melt using a scoop, and oxides were removed from

Table 2: TiB_2 reinforcement (99% purity) chemical analysis.

Element	% value
Iron	0.04
Carbon	0.08
Oxygen	0.7

Table 1: Chemical composition of AA6061.

Element	Al	Si	Mg	Fe	Cu	Mn	Ti	Zn	Cr
Weight %	97.59	0.69	0.89	0.23	0.20	0.13	0.03	0.02	0.012

the melt using a bottom pouring system. The preheating of reinforcement (at 400 °C for 30 min) was carried out simultaneously to remove moistures and allow the creation of an oxide layer around the reinforcing particles. Magnesium (Mg) (1 weight %) was progressively added as a wetting agent inside the melt alloy, and stirring for five minutes at constant speed of 700 rpm. The TiB_2 nanoparticles were preheated and added into the liquid and continuous stirring of the slurry was carried out at 700 rpm for 10 more minutes while maintaining the upside down motion of stirrer to confirm that the AA6061 ingots, TiB_2 reinforcements and Mg were mixed properly. Simultaneously, the mold was heated at 300 ºC for 30 min. To move molten material from the furnace to the preheated die, a runway was attached between the mold and bottom pouring mechanism. In the squeeze casting process, the molten material is put into the preheated die and hydraulic press is used for instantaneous forging under intense pressure. After the melt had time to cool and solidify inside the mold, a composite sample was extracted. The samples were properly cut according to different testing requirements using wire EDM process. Squeeze casting furnace (SWAMEQIP, DIAT, Pune) used in this research for the fabrication of composites is shown in figure 1, cast composites are shown in figure 2, and process parameters are depicted in table 3.

Hardness study

Using an ASTM standard (E384-22) and a hardness tester having diamond indenter, testing for micro indentation hardness was done on highly polished composite samples. A load of 500 gf is applied to the samples for a dwell time of 10 s. The specimen surface's diagonal indentations were measured in length, and the micro indentation hardness value was determined using an optical microscope. Each sample underwent a total of twenty-five indentations at separate positions to prevent the indenter's potential of settling on the hard TiB_2 particles. These twenty-five readings were averaged to establish the samples' hardness.

Tensile strength testing

The samples for the tensile test were cut using wire EDM. Tensile samples were developed using ASTM E8/E8M-2021 standard in the shape of big bones. To check the ultimate tensile strength (UTS) values of theAA6061 based composites, universal testing machine is utilized (INSTRON BISS, DIAT, Pune). The testing was conducted with constant rate of deformation (0.5 mm/min). Three samples from each composite casting were tested, and the average tensile strength value was calculated. Figure 3a shows ASTM E8/E8M-2021 standard tensile testing specimen and figure 3b shows and the prepared tensile specimens with different weight % of TiB_2.

Figure 1: Squeeze casting unit.

Figure 2: Squeeze casted composites.

Table 3: The parameters used in squeeze casting.

Parameter	Values
Melt temperature	750 °C
Stirring speed	700 rpm
Squeeze pressure	120 MPa
Stirring time	5 to 10 min
Squeeze time	25 s
Heating temperature of mold	300 °C
Mold dimension	Outside diameter 50 mm and length 300 mm
Heating temperature of TiB_2	400 °C for 30 min

Wear measurement

From literature it was found that the sliding wear characteristics under dry conditions of *in-situ* Al-TiB_2 nanocomposites have been widely documented. To the best of the authors' knowledge, Al-TiB_2 *ex-situ* (squeeze-cast) composites wear behavior has not previously been described. As illustrated in figure 4a and 4b, pins with diameter of 10 mm and length of 25 mm were cut from composite to test the wear on pin-on-disk wear and friction test rig (MAGNUM). The disc (diameter of 165 mm) made of EN-31 steel, hardened 58 - 60 HRC and a roughness of 0.274 μm is utilized in this study. Three different composites and base alloy variations are examined in comparison to EN-31 steel. Testing was carried out at load of 10 N, 20 N, 30 N, and 40 N with track radius of 40 mm with sliding velocity 1 m/s and sliding distance of 942.5 m. This test was carried out as per ASTM G99-05 guidelines. Throughout

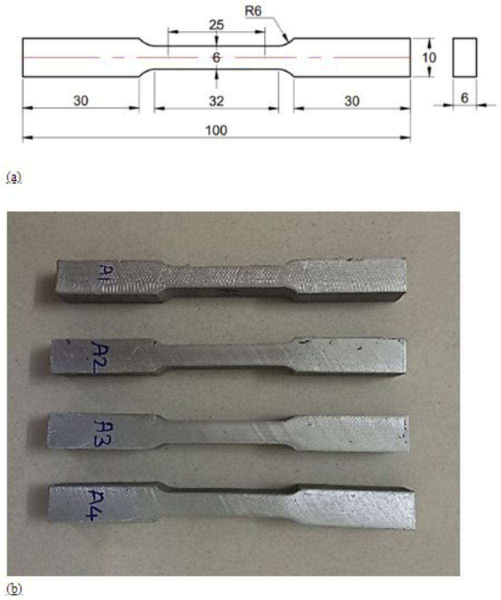

Figure 3: **(a)** ASTM E8M standard tensile strength specimen and **(b)** AA6061-TiB$_2$ tensile specimens.

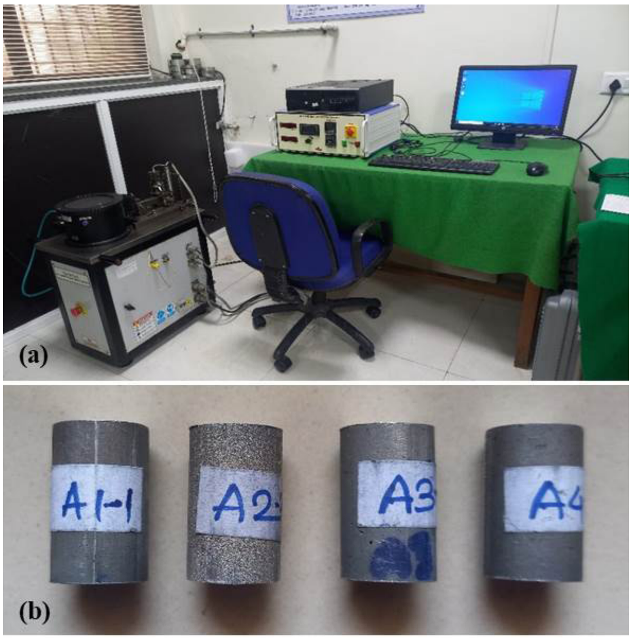

Figure 4: (a) Pin-on-disc wear and friction test rig and **(b)** AA6061-TiB$_2$ wear test specimens.

the wear testing, the frictional force is continuously measured in order to determine the coefficient of friction.

Results and Discussion

Particle distribution

Figure 5 depicts SEM (Scanning electron microscope) micrographs of AA6061-alloy based composites with changing percentages of reinforcement nanoparticles. The SEM images reveal that the TiB$_2$ reinforcement distribution is relatively homogeneous inside the matrix. Figure 5a illustrates a SEM image of pure AA6061 alloy with varied sizes of grains. Figure 5b depicts the dispersion of magnesium di-silicate particles and eutectic Al-Mg-Si in the matrix. Figure 5c and 5d illustrate the presence of TiB$_2$ particles with a shiny appearance. The distribution of various alloying substances and patterns of the inter dendrites can be easily observed in the microstructure of pure AA6061 casting. TiB$_2$ reinforcements with different percentages are added inside the melt resulting in homogenization of the composites, preservation of homogeneity, and reduction in dendrites. The TiB$_2$ nanoparticles weight percentage in the AA6061 matrix is restricted to 4.5% as increasing the TiB$_2$ weight percentage induces formation of clusters along with porosities, as depicted in figure 5d. Figure 6 depicts the EDX (Energy X-ray dispersive spectroscopy) of composite with AA6061 and 4.5% TiB$_2$ reinforcement highlighting elements such as Ti, Fe, B, Cu, and Mg.

Hardness

For evaluating material hardness properties, micro indentation hardness tests have been proven to be highly helpful. These tests are used for evaluating and quantifying

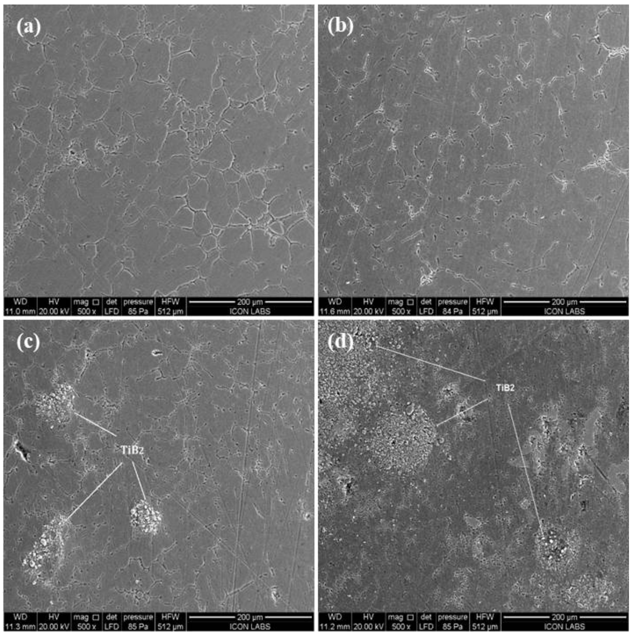

Figure 5: SEM images of composites **(a)** pure AA6061 casting, **(b)** AA6061 with 1.5% TiB$_2$, **(c)** AA6061 with 3% TiB$_2$, and **(d)** AA6061with 4.5 % TiB$_2$.

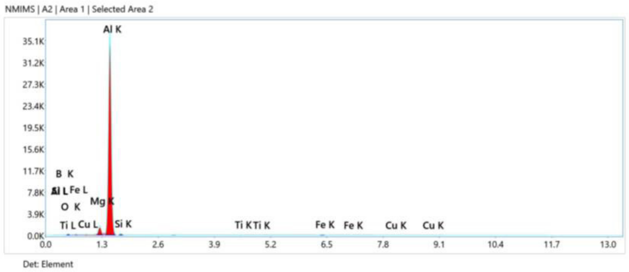

Figure 6: EDX of AA6061-4.5% TiB$_2$.

hardness differences that take place within smaller distances. MMCs exceptional hardness is due to strong interfacial contacts and precisely controlled microstructure grain. Figure 7 depicts the results of hardness testing on AA6061 with varied quantities of TiB$_2$. When compared with pure AA6061 cast sample, composites with TiB$_2$ nanoparticles addition exhibit a significant improvement in hardness. The hardness value of the composite was greater than that of the pure AA6061 casting because of the homogeneous distribution of alloying components after homogenization. For composite of AA6061 with 4.5% TiB$_2$ reinforcement, the maximum hardness value was 90.87 HV as compared to 68.18 HV for AA6061 alloy without any reinforcements.

Tensile strength

Figure 8a shows effect of increasing percent of TiB$_2$ reinforcements affecting the UTS of composites. The UTS of composites increases as the reinforcement percentage increases. The best results were seen in a sample with 3% TiB$_2$ reinforcement with an UTS of 257.73 MPa. The UTS for the sample with 4.5% reinforcement was 212 MPa, while the UTS for the as cast AA6061 was 204.34 MPa. It was found that adhesion between matrix and reinforcement influences tensile characteristics of the composite materials; the aforementioned decline in UTS could be caused by of improper adhesion between matrix and reinforcement particles. The tensile stress-strain curve of AA6061-TiB$_2$ composites is shown in figure 8b.The elongation of the composites of AA6061 and TiB$_2$ exceeded than that of base alloy suggests that adding reinforcements into the matrix material enhanced ductility of the composite. It was found that, adding reinforcement particles increases the composite materials' ability to carry a load, and as a result, improvement in the yield strength. It was found that grain refinement plays crucial role in improving tensile strength of the composites. The variation of coefficient of thermal expansion among theTiB$_2$ nanoparticles and the AA6061 material at room temperature also helps in improving the tensile strength.

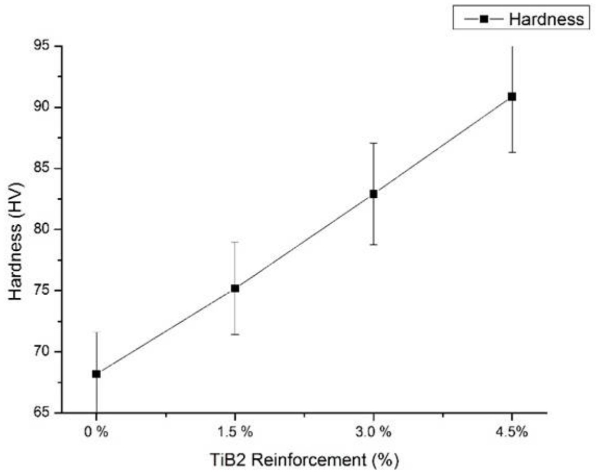

Figure 7: Hardness for composites with addition of TiB$_2$ reinforcements.

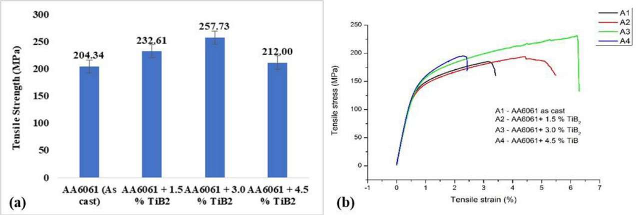

Figure 8: **(a)** Tensile strength with % increase in TiB$_2$ and **(b)** Stress-strain curve for composites with % increase in TiB$_2$.

Fractography

Figure 9a displays the outcomes of a SEM examination of damaged surfaces after a tensile test. It can be said that the main causes of fracture were voids and matrix tearing. In figure 9b, a crack is developing on the fractured surface. This is explained by the resistance due to the TiB$_2$ nanoparticles spread throughout the AA6061 matrix. Tiny dimples can be seen on fractured surface as depicted in figure 9c and 9d. These dimples demonstrate ductile fracture in the composite.

Wear

Figure 10 shows the wear rate of AA6061-TiB$_2$ composites under various loading conditions at a sliding distance as 942.5 m and speed of 250 rpm. It was found that with the increase in load from 10 to 40 N the wear rate also increases. Base alloy as well as composites suffers higher wear loss at increased loading condition. As the load on the pin increases, both the base alloy and the AA6061-TiB$_2$ composites experience rise in wear loss. As the weight percentage of TiB$_2$ reinforcements varies, the amount of wear loss of the nanocomposite decreases. The increased resistance to wear is due to the high hardness of TiB$_2$ nanoparticles, which acts as a barrier for material loss.

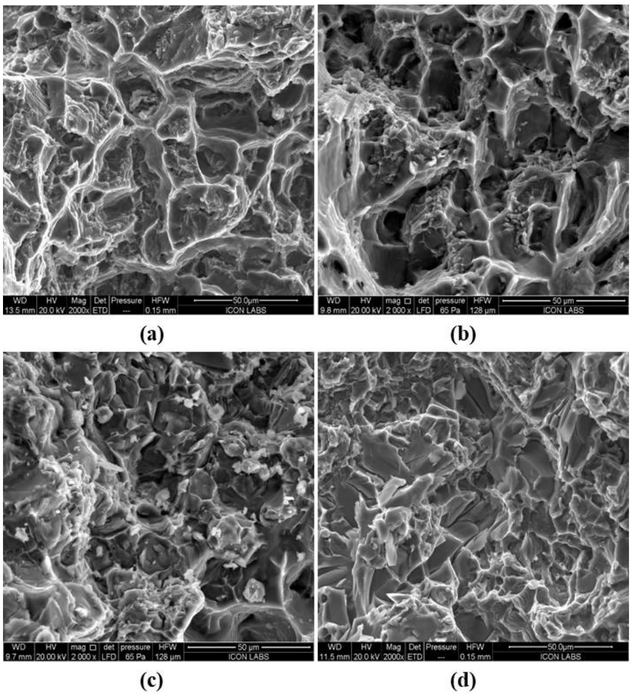

Figure 9: Fractography images of composites **(a)** pure AA6061 casting, **(b)** AA6061 with 1.5% TiB$_2$, **(c)** AA6061 with 3% TiB$_2$, and **(d)** AA6061 with 4.5% TiB$_2$.

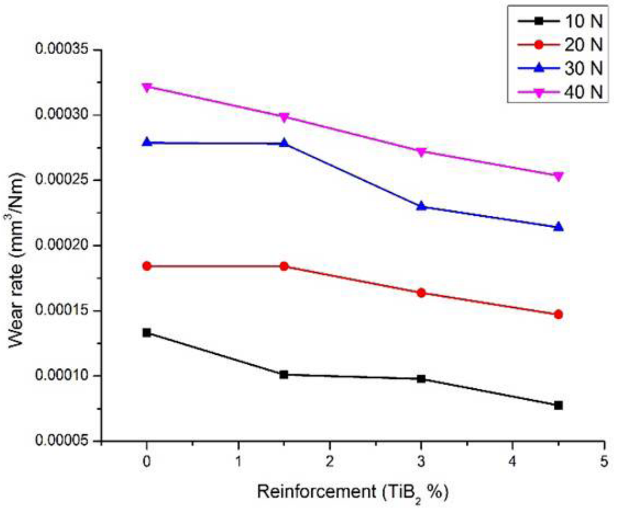

Figure 10: Wear rate of AA6061 matrix and TiB_2 composites at varying loads and 250 rpm constant speed.

Conclusions

In the present study, squeeze casting technique was utilized to create composites with AA6061 as matrix material and TiB_2 as reinforcing nanoparticles, with different proportions. The following conclusions were drawn after examination of the mechanical properties along with the microstructural analysis of the fabricated composites:

- SEM images revealed uniform dispersion of TiB_2 nanoparticles in the composites when squeeze casting process was used.
- With the increase in weight proportion of TiB_2 nanoparticles, the hardness of the composites was increased significantly. The maximum hardness value for composite with AA6061 and 4.5% TiB_2 was 90.87 HV as compared to 68.18 HV for pure AA6061 casting.
- The addition of TiB_2 nanoparticles increased the strength of the resulting composites without noticeable reduction in elongation. For composite with AA6061 and 3% TiB_2 reinforcement, tensile strength increased to 257.73 MPa. The tensile strength for as cast AA6061 was 204.34 MPa.
- In comparison to base alloy, the wear resistance of composite with AA6061 and TiB_2 reinforcement is significantly higher.
- It was found that grain refinement plays vital role in improving mechanical characteristics of the composites because of addition of reinforcing nanoparticles when compared with base alloy.

Acknowledgements

None.

Conflict of Interest

None.

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