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Research Article

Fabrication and Characterization of Aluminum (Al-6061) Matrix Composite Reinforced with Waste Glass for Engineering Applications

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Aluminum composites with various reinforcement materials are widely applicable in advanced engineering due to their better strength to weight ratio, better stiffness, and high thermal conductivity as well as excellent wear and corrosion properties. This stimulates curiosity to study aluminum metal matrix composite reinforced with waste glass to improve its mechanical and physical properties. The composite specimens were prepared using stir-casting rout by varying weight percentage of reinforcing waste glass powder from 0% to 30%. The fabricated composite samples were characterized using universal testing machine, FTIR, DSC, TGA, and optical microscope. The results revealed that as the waste glass particle content increased in the metal matrix, there was a significant enhancement of the mechanical properties like hardness and tensile strength as compared to the pristine sample. The microstructural properties analyzed using optical microscope show good bonding between the reinforcements and the pristine materials in the composite that indicates the glass particulates are uniformly distributed in the Al-6061 matrix. All in all, the effect of waste glass powder in aluminum metal matrix composite was clearly observed and it enhances the mechanical, physical, and thermal properties of the newly fabricated aluminum-based composite materials.

1. Introduction

Researchers are always searching new materials for different advanced engineering applications. In this aspect, a novel concept of combining dissimilar materials during manufacture led to the identification of composites as a new class [1, 2]. This concept of multiphase composites provides exciting opportunities for designing an exceedingly large variety of materials with property combinations that cannot be met by any of the monolithic conventional metal alloys, ceramics, and polymeric materials [3, 4]. The composites, especially metal matrix composites (MMCs), have received considerable attention in the field of materials research due to their lighter weight, higher strength, more wear resistance, and greater fatigue and dimensional stability than conventional composites [5–8]. MMCs are increasingly becoming a new class of material in device applications because their properties can be tailored through the addition of selected reinforcements [9, 10]. In particular, particulate-reinforced MMCs have recently found special interest because of their specific strength and specific stiffness at room and elevated temperatures [11, 12].

After more than a quarter of a century of active research, MMCs, particularly aluminum matrix composites (AMCs), are beginning to make a significant contribution to engineering application specifically in aerospace, automotive, and electronic industrial practice [13, 14]. Al-6061 has the advantages of low weight, high strength, ease of processing, low-temperature resistance, corrosion resistance, and low maintenance as a result it is widely used in machinery manufacturing, shipbuilding, aerospace, and chemical industries [15, 16]. Metals such as Al-6061, Al-7075, Al-6063, and Al-2024 and glasses like window glass, door glass, and bottle glass are the common waste materials that are discarded after primary uses so it is possible to fabricate different products, such as composite materials for different engineering applications from waste materials [16–19].

A composite consists of a matrix and a reinforcement phase meanwhile the reinforcing materials are strong with low densities and the matrix is usually ductile or tough materials. Reinforcements might exist in the form of particles, flakes, whiskers, short fibers, continuous fibers, or sheets [20, 21]. The strength of the composites depends primarily on the amount, arrangement, size or/and shape, and type of reinforcement in the matrix phase [22, 23]. For instance, glass particles are used as the reinforcement in MMCs; there are some challenges such as poor bonding between the glass particles and matrix [24–27]. The employment of a suitable fabrication method of MMCs reinforced with glass particulates can solve some of these challenges. Some of the traditional methods of fabricating waste glass particle-reinforced MMCs are stir casting, metal spraying, liquid metal infiltration, diffusion bonding, and powder metallurgy [28, 29]. Stir casting is one of the most established techniques for developing metal matrix composites [30, 31]. It is performed commercially due to its flexibility, simplicity, and applicability to large-quantity production. It is a liquid-state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) was mixed with a molten metal matrix by means of mechanical stirring [32, 33]. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional metal-forming technologies. Wetting is an important condition for the generation of a satisfactory bond between particle reinforcements and liquid aluminum metal matrix during casting composites, to allow transfer and distribution of load from the matrix to the reinforcements without failure [34, 35]. Excellent bonding is required at the interface for good wetting [36, 37]. These bonds may be formed by mutual dissolution or reaction of the particles and metal matrix [38, 39]. The reaction phenomena are very detrimental to the composite as they bring about a decrease of the mechanical properties. If the composite combines the strength of the reinforcement with the toughness of the matrix, it is possible to achieve a desirable property, which is not found in any monolithic conventional material [40, 41].

The objective of this investigation is to characterize the effects of waste glass powder content on physical and mechanical properties such as hardness and tensile strength of aluminum alloy (Al-6061) for different engineering application. Microstructural analysis of waste glass particle reinforced aluminum composite samples was further examined by using optical microscopy.

2. Experimental Methods

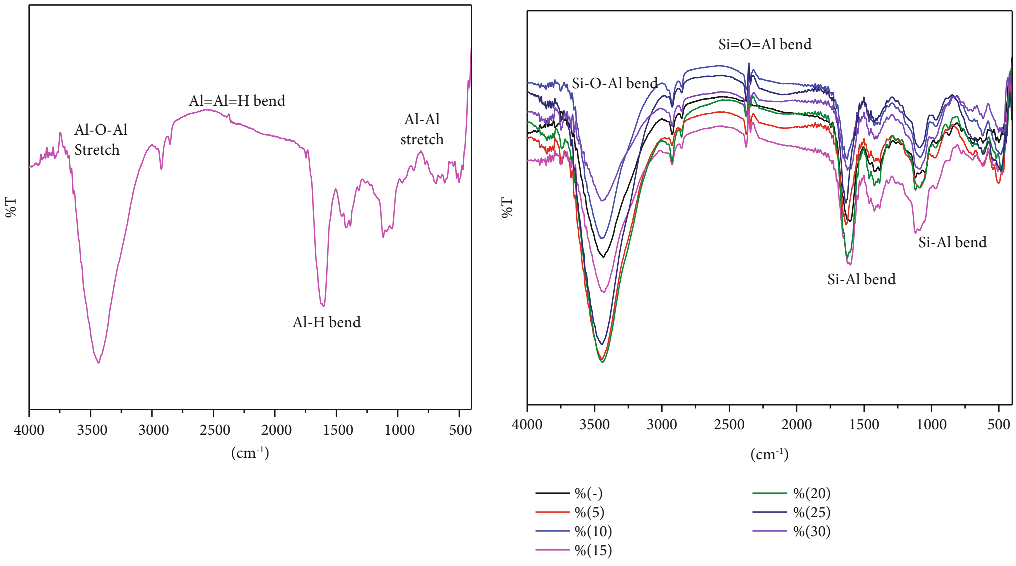
In this study, there are some core procedures which would be performed technically to realize the required output materials. The waste window glass and Al-6061 alloy are collected from the local place and are washed and filtered to remove dust and any undesirable waste. The washed waste window glasses and Al-6061 alloy were then sun dried for 6 hours. Dried and cleaned waste window glass was crushed using a roller mill and sieved in order to obtain a desirable particle size fraction in micro size of below 50 μm. The waste glass powder was then dried in the sun for 3 hours at room temperature to reduce moisture content. After that, the Al-6061 alloy was melted in crucible by heating in gas-fired furnace at 760°C for 3 hr per sample. Then, the required amount of the reinforcement waste glass powder was added and stirred 30minutes with controlled feed following stirring in order to form uniformly distributed reinforcement mass through the fabricated composite sample. At every stage, stirring was used at stirring speed of 500 rpm for 30 min. Then, the mixture was poured into the pattern mold. Finally, the required aluminum-based composites fabricated for characterization. Samples of appropriate dimension depend on the type of test is cut using a diamond cutter for physical and mechanical characterization.

We characterized the mechanical, thermal, and chemical properties using the tensile strength universal testing machine (ASTM D638) and hardness test by using brooks hardness testing (ASTM E384) machines. The microstructure analysis of different samples is measured by optical microscopy. Fourier transform infrared spectroscopy technique is being used extensively to perform reaction product analysis on the functional group's materials. FTIR-6061 type is a reliable technique to analyze the interaction between silicon and Al-6061 matrix composite materials. Fourier transform infrared spectroscopy (FTIR) is a standard method as a nondestructive testing tool. Differential scanning calorimetry (DSC) is used to measure the heat evolution from a sample under a controlled condition and studies the phase transformation, precipitation, and dissolution activities. We used DSC 3 - Differential Scanning Calorimeter instrument to analyze the thermal properties of the composites.

3. Results and Discussions

Figure 1 shows the FTIR spectrum of the fabricated composites which enables to identify the properties of the specimen. The indicated peaks in the figure play an important role to measure the functional group of the prepared composite and its bond interface interaction. It should be noted that the peaks of glass powder appeared from 3200 to 2900 cm^{-1} which corresponds to Si-Ai-O stretching. The peak appeared at 2400-2300 cm^{-1} which corresponds to Si-Al-H stretching. The peak appeared at 1273 cm^{-1} which corresponds to 1700-1600 cm^{-1} Si-Al stretching whereas a small peak at 650 cm^{-1} indicated Al-O cm^{-1} stretching. Some of the groups have been removed from the Al-6061 matrix materials that indicates the brittleness of the glass powder as compared to the Al-6061 matrix materials due to oxidation, reduction, and thermal degradation.

Figure 2 presents thermogravimetric analysis (TGA) curve of reinforced Al-6061 with waste glass particles. Comparing the TGA curves of the different samples, it can be seen that in almost all cases, these curves follow a similar course. The Al-6061 matrix degradation starts at 220°C. The weight loss of different samples is monotonously increased as the temperature elevated from low to high level. This happened due to diffusion movement on the Aluminum (Al-6061) matrix in



(a)

(b)

Figure 1: The FTIR spectrum of waste glass reinforced Al-6061 matrix composite: (a) unreinforced Al-6061 matrix, (b) samples with varying weight percentage of reinforcing waste glass powder.

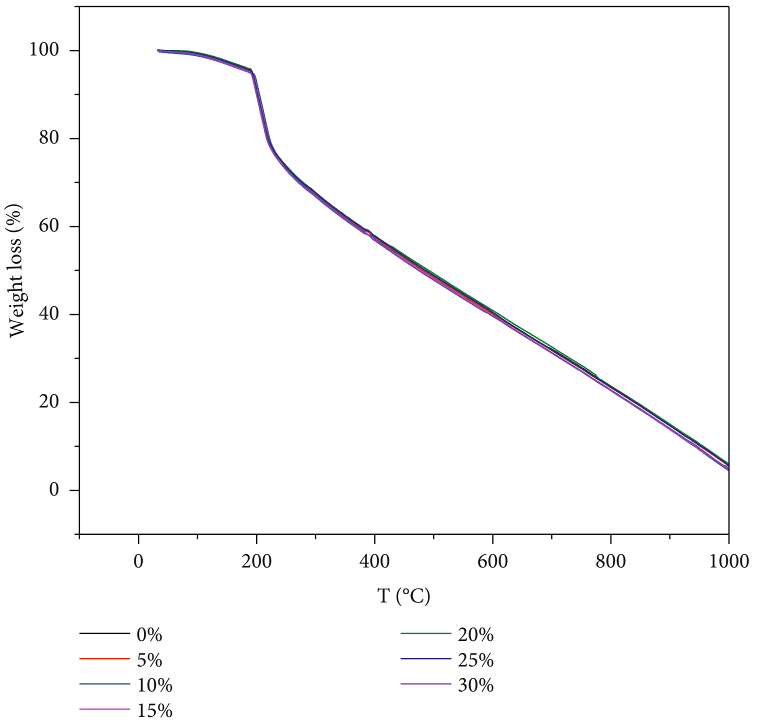


Figure 2: TGA curve for reinforced Aluminum (Al-6061) matrix with different amount of waste glass powder content that varies from 0 to 30 wt %.

the case of using annealed or heating process. Which lead strong interaction bond will have between aluminum (Al-6061) and glass powder. The first weight loss, which was observed at ~220°C, is related to the removal of less stable impurities in the composites and due to removal of surface absorbed water. This means that reinforced Al-6061 samples are thermally stable up to certain temperature.

Figure 3 shows the measurement result of the differential scanning calorimetric (DSC) analysis, which has four distinct phase changes represented by A, B, C, and D. Region A indicates melting phase of the composite and both B and C regions indicate glass transition, while region (D) indicates crystallization phase of the composite. At curve (A), the composite specimens start to melt at a temperature range

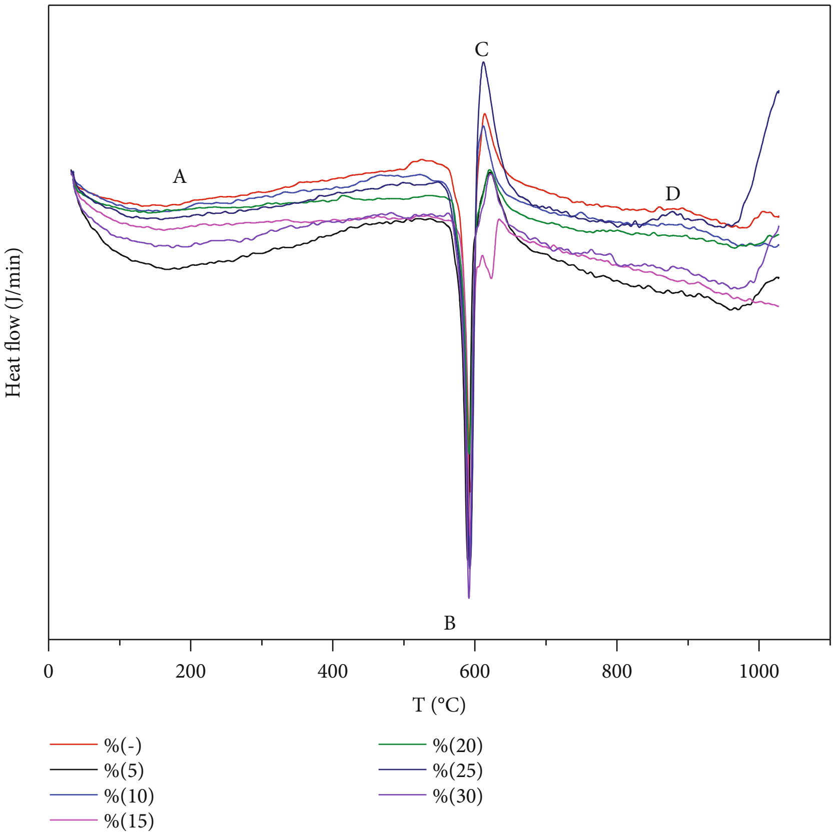
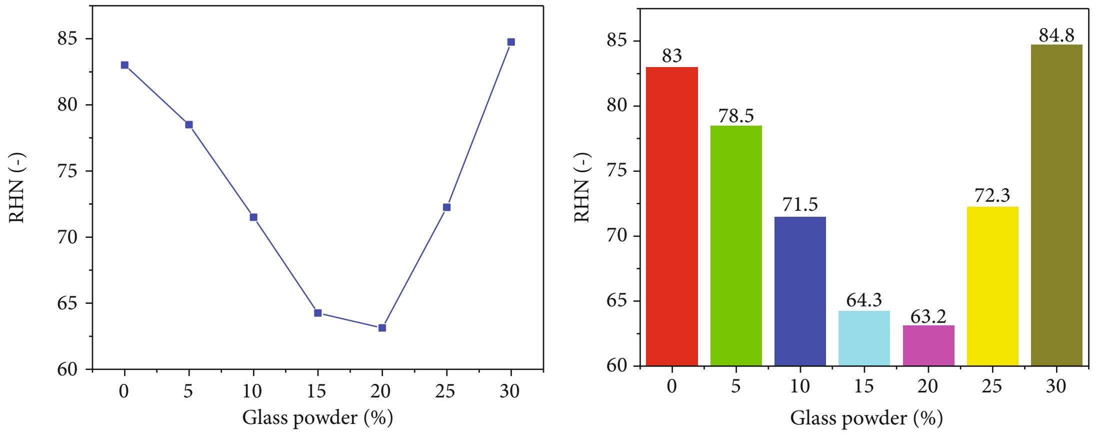


Figure 3: DSC curves for waste glass particle reinforced Al-6061 metal matrix samples.

from 564°C, which is the composite high endothermic reaction and high heat absorbed phase process due to diffusion movement and effect of temperature, whereas at point (C), it can be seen that fabricated composite has a melting temperature between 500 and 650°C while for Al-6061, matrix in the range of 580 to 650°C. The glass transition temperature estimates the maximum operating temperature of the composite, which is about 620°C. In the effect of glass powder on Al-6061 matrix at a temperature of 625°C, which has a high peak value and the bonding of glass powder on Al-6061 matrix composite is higher, the process is exothermic reaction. It reveals that the composite material is released heat and its phase is glass transition phase. On the other hand, region (D) in the temperature range of 630°C-1000°C, the composite materials have endothermic reaction and heat is absorbed with the composite.

In this research work, a Rockwell hardness number (RHN) tester (1/16-inch, ball indenter) was used to determine the hardness of the hybrid composite specimens. A load of 100 KN was applied for 15 seconds on each specimen. As illustrated in Figures 4(a) and 4(b), Rockwell hardness number (RHN) of the samples increase with increasing the glass powder concentration in the new fabricated composite. A combination of 20 wt % glass powder and 80 wt % Al-6061 metal matrix composite exhibited a minimum deformation approximately 63.2 ± 0.756 value of RHN is found for the reinforced composite. The newly fabricated aluminum-based composite is enhanced by 23.94% as compared to the parent materials. This is an indication that a good interfacial bonding is obtained and that the critical size of the reinforcement for load transfer is reached. On the other hand, the hardness strength of Al-6061 matrix and glass powder composites decreases due to (i) weak bonding interaction of the composite, (ii) the density difference on Al-6061 matrix and glass powder, a further increase in glass powder leads to increase of the RHN value which indicates that there is no good chemical reaction in the composite materials, agglomeration, grain found for the reinforced composite and as a result, the composite should have the properties of the nonreinforced metal matrix, (iii) less hardness properties of glass powder and Al-6061 matrix materials, (iv) glass powder to glass powder entanglements and due to these easily pull-out the glass powder from Al-6061 matrix materials, (v) the minimum weight percentage of glass powder is used, and (vi) it may be poor interfacial interaction of the composite. In general, the more the weight percentage of glass powder associated with the harder property of the composite materials, and the higher the hardness numbers, the smaller the strength of the materials will have. It is clearly seen that the hardness of Al-6061 is found to reinforcements thereby improving the tribological characteristics of the composite. Also, the addition of glass powder enables the elimination of voids in the composite, thereby increasing the bonding and strength of the matrix and reinforcement materials.

Figure 5 shows the stress-strain curve of the fabricated composites. Specimens were prepared for tensile test with a dimension of length, width, and thickness of 150 mm,



(a)

(b)

FIGURE 4: Rockwell hardness number versus glass powder content measurements of reinforced Al-6061 composite.

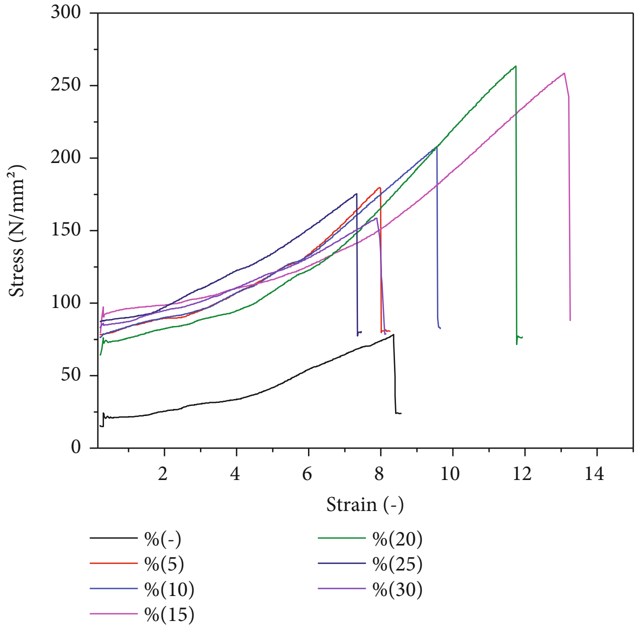
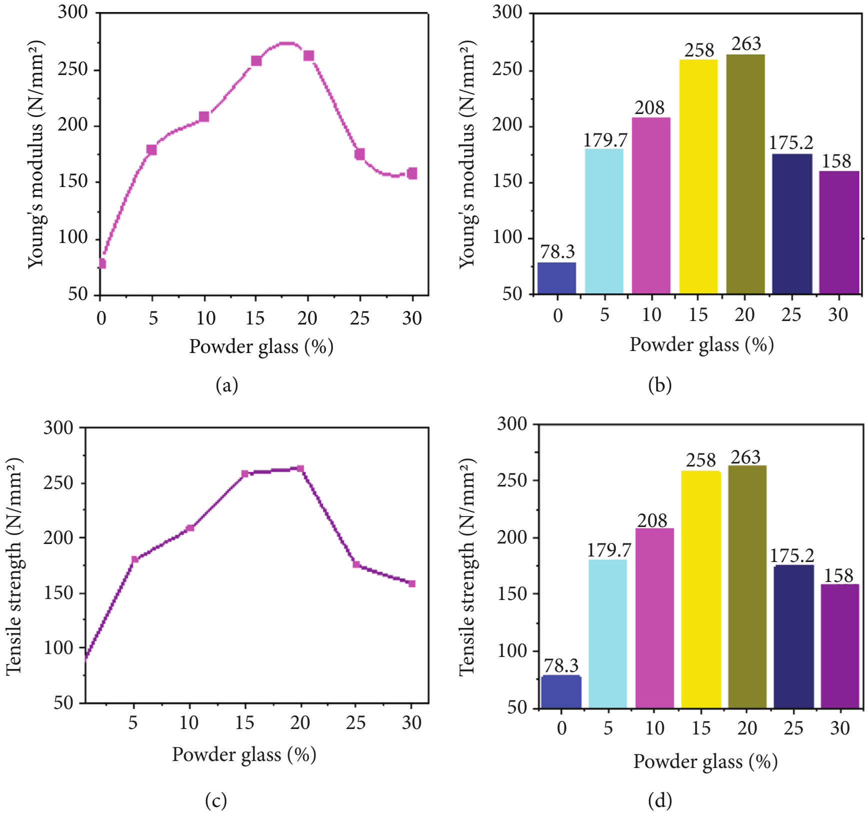


FIGURE 5: The stress–strain curve of the fabricated specimens that result in tensile strength of different percentage composition glass powder composites.

20 mm, and 3.5 mm, respectively. The ultimate tensile strength (UTS) value of unreinforced Al-6061 matrix materials is recorded at 78.3 N/mm^2. Among several glass powder added specimens, a composite material with 20 wt % of glass powder and 80 wt % of Al-6061 matrix reaches a maximum ultimate tensile strength value of 263 ± 0.546 N/mm^2, showing an approximately 56.6% enhancement over the parent material. The highest tensile strength improvement achieved for specimen 20 wt % of glass powder might be attributed to the reason of a sufficient adhesive bond between the glass powder particles and the Al-6061 matrix compared to that of the other specimens. The glass powder served as reinforcement because the major share of load was taken up by the glass powder.

On the other hand, tensile strength of the composite is decreased with increasing the weight percentage of matrix (Al-6061) (70-75 wt %). It can be deduced that the initial linear portion of the graph shows the elastic properties of the composite specimen, which is consistent as observed in the linear increments from 0 to 20 wt % of glass powder loading and from 80 to 100% of matrix loading. This linear increment indicates that there is a better interfacial distribution between glass powder and Al-6061 matrix and the composite becoming stiff and could withstand higher stress at the same strain portion. According to Hooks' law, Young's modulus of the composite is increased and the tensile stress–strain curve can be separated into three regions. Initially, the tensile strength deformation is linear until a maximum stress (the yield stress) is reached. The tensile strength is increased up to 20 wt % glass powder due to molecular orientation, high bonding formation, and absence of defect between the glass powder and aluminum matrix that gives uniform distribution to the composites. The tensile modulus shows a linear increase with glass powder content in the composites. Figures 6(a) and 6(b) and 6(c) and 6(d) generally show Young's modulus and tensile strength versus the glass powder content, respectively. These curves depicted the maximum value at 20 wt % of glass powder which shows an approximate 56.6% enhancement compared to the unreinforced Al-6061 matrix materials.

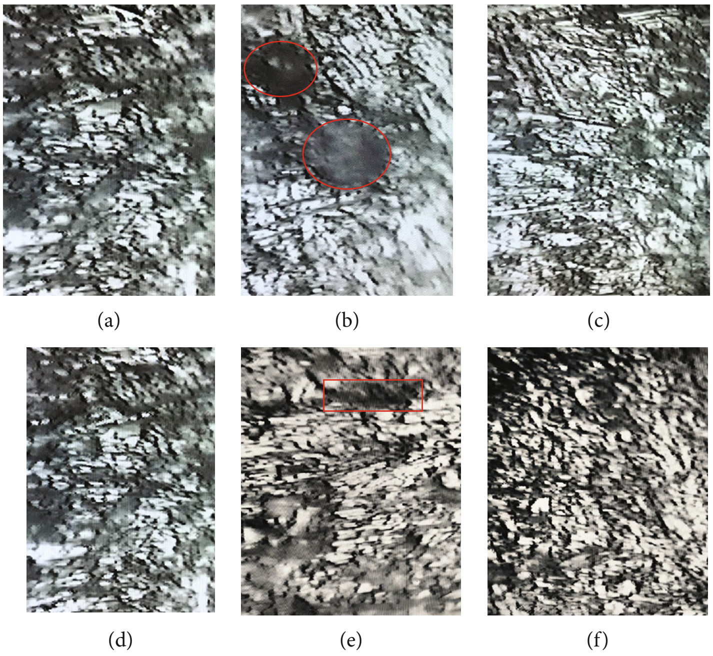
Figure 7 shows the microstructure of the fabricated aluminum-glass particle composite samples at a filler content of 5-30 wt % at 60x magnification. The optical micrographs depicted in Figure 7 show the homogeneous distribution of glass powder with some debris observed in some parts of the composites as it exceeds beyond the limit of solubility that is 20 wt % of waste glass particulates. At all contents of aluminum considered, homogeneous filler particle's distribution and dispersion were found for all concentrations, with a particle density proportional to the glass particle filler content. It is also observed that the addition of glass powder indicates a minimum grain size, defect, agglomeration with proper stirring speed, and uniform distribution of the composite due to good bonding interaction



(a) (b)

(c) (d)

Figure 6: Young's modulus curve of the composite material in (N/mm^2) (a, b) and tensile strength (N/mm^2) (c, d).



(a) (b) (c)

(d) (e) (f)

Figure 7: Optical microscope images of Al6061 alloy with reinforced particles: (a) Al6061+5 wt % waste glass particles; (b) Al6061+10 wt %; (c) Al6061+15 wt %; (d) Al6061+20 wt %; (e) Al6061+25 wt %; (f) Al6061+30 wt % composites.

and fair proportion of the composite. We observed agglomeration because of clustering effect and nonuniform distribution of particles specially in Figures 7(b) and 7(e), the interfacial bonding and the matrix hardening.

4. Conclusions

This experimental study aimed at preparing an Al-6061 metal matrix composite reinforced with glass powder using the stir-casting technique. The effect of the glass particles on the bonding properties of Al-6061 was investigated because of its impact on the mechanical properties of the composites. The microstructural and mechanical properties of the composite sample were also examined. The fabricated composite with composition of 80 wt % Al-6061 and 20 wt % glass powder enhanced its tensile strength by 56.6% compared to the pristine. This enhancement is due to a sufficient adhesive bond between the glass powder and the Al-6061. The presence of 20 wt % glass powder in the parent material has increased its hardness by 23.94% due to strong harmonic bonding interaction and fair proportion of density difference. The specimen with this combination is found to have a minimum hardness number value of 63.2 ± 0.756 RH. In comparison with the unreinforced metal Al-6061, the proposed composite exhibits a good improvement in hardness and tensile strength. The microstructural analysis using optical microscope shows good bonding of the reinforcement with the matrix material. It is evident that waste glass powder is a low-cost material that can be used as reinforcement in metal matrix of aluminum with improved mechanical properties. Generally, we conclude that aluminum alloy with reinforcement of powder glass improves properties of the base alloy especially mechanical properties with their excellent quality of hardness and tensile strength of the composite.

Data Availability

All relevant data to the manuscript have been included.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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