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Research Article

Enhancing Mechanical Properties of Aluminium-Based Biocomposites through the Addition of Hybrid Reinforcing Particulates

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Abstract

This study looks into the improvement of mechanical properties in Al-7Mg-2Si-0.1Nb-based biocomposites by incorporating hybrid additions of Irvingia Wombolu Shell Particulates (IWSP) and Mangifera indica shell particulates (MISP). The biocomposites were created using the stir-casting technique. Tensile, hardness, and impact strength were used to determine the mechanical properties of the developed biocomposites. The study shows that the additions of IWSP and MISp have a significant impact on the biocomposites' properties. The addition of hybrid 2wt% IWSP and 10wt% MISP resulted in a higher percentage elongation compared to the base alloy. The ultimate tensile strength of the biocomposites increased significantly with the addition of both IWSP and MISP, peaking at 6wt% IWSP and 6 wt% MISP. The hybrids of IWSP and MISP consistently demonstrated higher tensile strength, reaching a maximum ultimate tensile strength of 132 MPa. The hardness properties of the biocomposites improved with the addition of IWSP and MISP, with the highest values observed in hybrid combinations of 6 wt% IWSP and 6 wt% MISP. Specifically, the addition of 6wt% IWSP and 6wt% MISP resulted in a remarkable 34.9% increase in hardness. The study found that adding IWSP and MISP significantly improved the impact strength of the Al-7wt%Mg-2wt%Si-0.1wt%Nb alloy matrix, with a maximum value of 45 J at a hybrid 6 wt% IWSP and 6 wt% MISP. These findings demonstrate the ability of hybrid additions to improve the mechanical properties of Al-7Mg-2Si-0.1Nb-based biocomposites, making them a promising candidate for a variety of engineering applications.

Introduction

Aluminum has grown in popularity in recent decades due to its high technological value and numerous industrial applications, particularly in the production of structural components for the building, automotive, and aerospace industries [1,2]. This is primarily due to their superior properties, which include high strength, good formability, low weight, and high corrosion resistance. The primary issue in high-temperature lightweight engineering is microstructure alteration, which results in a sharp decline in stiffness and strength. It is reasonable to expect that using metal matrix composites with the appropriate reinforcement structure will prevent this effect [3,4]. Aluminium alloy-based particle-reinforced composites are becoming increasingly popular for a variety of engineering applications. Among the many useful aluminum 6061 alloys are distinguished by properties such as castability, corrosion resistance, fluidity, and a high strength-to-weight ratio. This alloy has long been used as a base metal for metal matrix composites reinforced with various fibers, particles, and whiskers [5-8].

Bio-Composites have shown promise as a competitive substitute for glass fiber-reinforced composites in building and automotive applications [9-12]. Natural fibers' strength, lightweight, affordability, and ability to be recycled have all contributed to a significant increase in interest in using them as reinforcement in composites development [13-15]. The development of materials, products, and processes for the future generation is primarily guided by four principles: sustainability, eco-efficiency, industrial ecology, and green chemistry [16-18]. According to Khan, et al. [19], using natural fibers as reinforcement in composite materials reduced pollution, greenhouse gas emissions, and reliance on non-renewable energy and material sources.

Mangifera Indica (MI) is a mango species from the

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Anacardiaceae family that grows in tropical and subtropical areas [20,21]. Its parts are frequently used in folk medicine for a wide range of treatments. Various plant parts are used as a laxative, antiseptic, stomachic, astringent, dentrifrice, vermifuge, tonic, diaphoretic, and diuretic. *Irvingiawombolu* (IW) is a plant commonly referred to as Ogbono in Nigeria. Every year, the plant bears fruit, and human soup can be made from the endocarp. Because they can be used to treat yellow fever, hernias, diabetes, toothaches, diarrhea, scabby skin, and poisoning, the leaves are believed to have medicinal properties. (Mbah, et al. 2020). Irvingia species are abundant in Nigeria and can be used as animal feed (Mbah, et al. 2020).

To investigate the economic potential of MI and IW given their availability in Nigeria, this study is innovatively designed to investigate the reinforcing potential of IW/MI shells particulates hybrids on the mechanical properties of Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposites. By incorporating these natural waste materials into the composite, this study hopes to contribute to the development of more sustainable and environmentally friendly materials, in line with the growing global emphasis on eco-friendly solutions in material science.

Materials and methods

Materials sourcing

Aluminum wire purchased from Cutix Cable Plc Nnewi, Anambra State, Nigeria, was used in the experimental investigation. The niobium nanopowder, magnesium powder, and silicon powder were supplied by Sigma-Aldrich. The MI and IW shells that were used were from Obolo Afor in the Udenu Local Government Area of Enugu State, Nigeria.

Fiber extraction and composites production

The shells of *Irvingia wombolu* and *Mangifera indica* were extracted, washed with distilled water, and sun-dried. After drying, the shells were ground and sieved to obtain particulates with a particle size of 50 µm, which were then stored.

The double-layer feeding stir casting method was used to create the metal matrix composites used in this investigation. The Al-7wt%Mg-2wt% alloy matrixSi-0.1wt%Nb (control sample) was prepared without any reinforcement, and composites containing 2, 4, 6, 8, and 10wt% (IWSP/MISP) were prepared while maintaining constant magnesium and niobium contents. Table 1 displays the composite formulations. About 1 kg of aluminum was charged into a preheated steel crucible pot (at 200 °C) for the base alloy (Al-7wt%Mg-2wt%Si-0.1wt%Nb). The temperature of the steel crucible pot was then gradually raised until the aluminum melted at 660 °C. To make the aluminum melt more fluidly, it was heated to 800 °C. To prevent agglomeration and element loss, the necessary amounts of silicon, niobium, and magnesium nanopowder were added to the aluminum melt while it was covered in aluminum foil. For 2 minutes, the mixture was kept at that temperature and vigorously stirred to ensure total homogeneity. An internal steel mold measuring 250 mm in length and 16 mm in diameter was filled with the melted material, which was heated to 200 °C. The steel mold was then allowed to cool gradually until it reached room temperature. For every composite formulation, the Al-7wt%Mg-2wt%Si-0.1wt%Nb alloy melt was covered with aluminum foil, mixed, left for 2 minutes, and then cast with the necessary amounts of IWSP and MISP added.

Table 1: Composite formulations.

Specifications	Composite composition
A (Control)	Al-7wt%Mg-2wt%Si-0.1wt%Nb
B.	Al-7wt%Mg-2wt%Si-0.1wt%Nb-2wt%IWSP-10wt%MISP
C.	Al-7wt%Mg-2wt%Si-0.1wt%Nb-4wt%IWSP-8wt%MISP
D.	Al-7wt%Mg-2wt%Si-0.1wt%Nb-6wt%IWSP-6wt%MISP
E.	Al-7wt%Mg-2wt%Si-0.1wt%Nb-8wt%IWSP-4wt%MISP
F.	Al-7wt%Mg-2wt%Si-0.1wt%Nb-10wt%IWSP-2wt%MISP

Mechanical testing

Tensile testing on a specimen measuring 50 mm gauge length, 120 mm length, and 10 mm diameter was carried out by ASTM D638 standards using a JPL tensile strength tester (Model 130812). To prepare for the hardness test, samples 20 mm long and 10 mm in diameter were polished and ground to a smooth surface. The hardness was measured using a Phase II 900-355 digital motorized Brinell hardness tester equipped with a 20X optical microscope. During this procedure, a 2.5 mm diamond ball was used to indent the polished surface of the samples while under a load of 183.9 kg and dwelling for 5 seconds. The diameters of the 4 indentations per sample were measured and averaged using an optical microscope at 20X. The impact strength was measured using a pendulum impact testing machine (Model: U1820) following the ASTM D256 standard. A 2 mm deep V-notch specimen with dimensions of 55 x 10 x 10 mm3 was placed horizontally between anvils 55 mm apart, and a striking hammer was released at a 270-degree angle from the specimen to strike the specimen on the face opposite the notch. The reading in joules was obtained from the machine's scale and recorded immediately.

Results and discussion

The percentage elongation (%E), impact strength, hardness (BHN), and ultimate tensile strength (UTS) of Al-7wt%Mg-2wt%Si-0.1wt%Nb reinforced with hybrid additions of IW and MI shell particles are presented in Figures 1,2. The impact of hybrid additions of IW and MI shell particulates on the ultimate tensile strength and percentage elongation of Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposites is depicted in Figure 1. The alloy Al-7Mg-2Si-0.1Nb, used as the control sample, showed a percentage elongation of 37.5%. Upon adding 2 wt% IWSP and 10 wt% MISP, Figure 1 showed a decrease in percentage elongation of approximately 25.9%. As the concentration of the reinforcing particulates increased, the developed biocomposites' percentage elongation trended downward. In contrast, Figure 1 shows that at 2 wt% IWSP and 10 wt% MISP concentration, the hybrid addition of IWSP and MISP recorded a higher percentage elongation, and similar results were reported by Aigbodion & Ezema, 2020 [22] and Chukwuneke, et al. 2024 [12]. This result depicted that the based alloy is a more ductile material than the biocomposite material with a lower percentage elongation which is more brittle.

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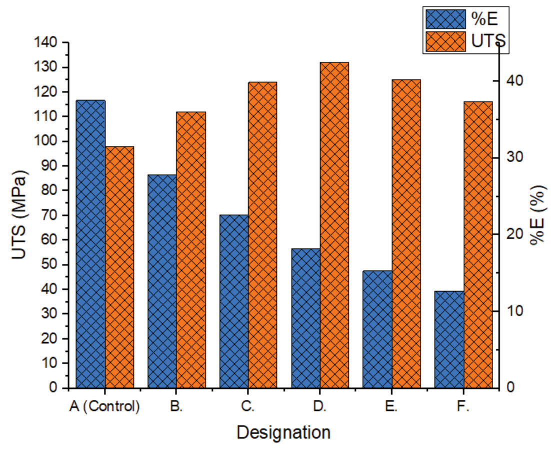

Figure 1: Percentage Elongation and Tensile Strength of Al-7wt%Mg-2wt%Si-0.1wt%Nb/IWSP/MISP Biocomposites.

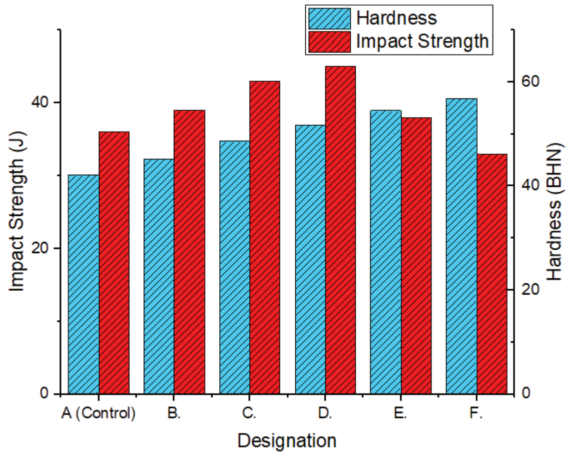

Figure 2: Hardness and Impact Strength of Al-7wt%Mg-2wt%Si-0.1wt%Nb/IWSP/MISP Biocomposites.

Figure 1 depicts variations in the ultimate tensile strength of Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposite reinforced with hybrid concentrations of IW and MI shell particulates. Figure 1 shows that adding IW and MI shell particulates to the control sample significantly increases its ultimate tensile strength. The ultimate tensile strength of the Al-7wt%Mg-2wt%Si-0.1wt%Nb/IWSP/MISP biocomposite increased from 98 MPa to 112 MPa after being reinforced with 2 wt% IWSP and 10 wt% MISP. The ultimate tensile strength of the developed composites increased with increasing concentrations of both IWSP and MISP, reaching maximum values at 6 wt% IWSP and 6 wt% MISP. The improved ultimate tensile strength of the developed biocomposites can be attributed to the increased dispersion of reinforcing particulates in the alloy matrix. The higher the tensile strength of a material, the greater its ability to endure tensile forces without failure [23]. Additions of IWSP and MISP exceeding 6 wt% IWSP and less than 6 wt% MISP reduced the biocomposite's ultimate tensile strength. The biocomposite with the following composition achieved the maximum ultimate tensile strength of 132 MPa: Al-7wt%Mg-2wt%Si-0.1wt%Nb-6wt%MISP-6wt%IWSP. This result is similar to the results reported by Nwigbo, et al. 2016 [24] and Ononiwu, et al. 2021 [25].

Figure 2 shows how reinforcement concentration affects the hardness of reinforced Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposite. Figure 2 clearly shows that the addition of IWSP and MISP increased the hardness of the biocomposites under study. It was discovered that increasing IWSP concentrations from 2wt% to 10 wt% and decreasing MISP concentrations from 10wt% to 2 wt% resulted in a further increase in the hardness of the developed composites. The addition of 10% IWSP and 2% MISP increased the hardness of the control sample by 34.9%. Figure 2 shows that hybrids of 6 wt% IWSP and 6 wt% MISP achieved the highest hardness value. The biocomposite Al-7wt%Mg-2wt%Si-0.1wt%Nb-6wt%MISP-6wt%IWSP achieved a maximum hardness of 56.8 BHN. As the concentrations of IWSP and MISP increased, so did the volume of hard particles, increasing the biocomposite's hardness. Similar results were reported by Ononiwu, et al. 2021 [25] and Chukwuneke, et al. 2024 [12]. As hardness increases, ductility and toughness decrease and the material becomes more brittle. Although the material will be able to withstand higher applied loads, it will be much less flexible in its response to the applied load. Harder surfaces are subjected to greater internal stresses and tend to increase in brittleness. Increasing hardness can hinder the movement of dislocations or grain boundaries, leading to an increase in strength [26,27]. Figure 2 depicts the effect of IW and MI shell particulate concentration on the impact strength of a reinforced Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposite. Figure 2 clearly shows that the addition of IW and MI particulates significantly increased the impact strength of the parent alloy (control sample), reaching maximum values of 45 J at 6 wt% IWSP and 6 wt% MISP. The impact strength of the studied biocomposite increased with IWSP and MISP up to 6 wt%. Furthermore, an increase in IW concentrations and a decrease in MI shell particulates reduced the biocomposite's impact strength. This behavior could be attributed to increased concentrations of hard reinforcement particles in the alloy matrix. The hybrid concentrations of IWSP and MISP achieved a maximum impact strength of 45 J.

Conclusion

The impact of hybrid IWSp and MISp additions on the mechanical properties of Al-7Mg-2Si-0.1Nb biocomposites was examined in this study. The Al-7Mg-2Si-0.1Nb alloy had a higher percentage elongation value than the biocomposite. Hybrid combinations of IWSp and MISP resulted in lower percentage elongation which is more brittle than the based alloys which is more ductile. The biocomposites' ultimate tensile strength increased significantly after the addition of both IWSP and MISP. The highest tensile strength was obtained with 6wt% IWSP and 6 wt% MISP of these additives. Hybrid combinations of IWSP and MISP demonstrated higher tensile strength, reaching a maximum of 132 MPa. The hardness of the biocomposites increased with the addition of 2wt% IWSp, and this trend continued as concentrations increased while wt% MISP decreased. The hybrid combinations had the highest hardness values, with the Al-7Mg-2Si-0.1Nb-6MISp-6IWSP biocomposite reaching a peak of 56.8 BHN. The addition of IW and MI shell particulates significantly increased the impact

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strength of the parent alloy (control sample), reaching a maximum impact strength of 45 J at 6 wt% IWSP and 6 wt% MISP. The hybrid of 6 wt% IWSP and 6 wt% MISP reinforced material with Al-7Mg-2Si-0.1Nb based alloy gives a better biocomposite because of its improved mechanical properties. Thus, this study found that the addition of hybridized 6 wt% IWSP and 6 wt% MISP had a significant impact on the mechanical properties of Al-7Mg-2Si-0.1Nb biocomposites, with hybrid combinations resulting in the best results (Al-7Mg-2Si-0.1Nb-6IWSP-6MISP). Further study should be carried out to establish the influence of particulate sizes and pretreatment of IWSP and MISP on the mechanical properties of Al-7wt%Mg-2wt%Si-0.1wt%Nb biocomposites.

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