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Synergistic Effects on Enhancing Microstructures of Ash of Waste Bamboo Reinforced AA7075-T651 Hybrid Composites

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Abstract

This work investigates the use of waste bamboo ash (AWB), a renewable resource, as reinforcement in hybrid composites as a novel approach to sustainable material development. The purpose of this research involves improving AA7075-T651 alloy mechanical properties through the incorporation of AWB and B_4C reinforcement by stir casting techniques. The mechanical properties of Neat AA7075-T651 were compared to synthesized hybrid composite samples containing different reinforcement percentages of B_4C + AWB (3%, 6%, and 9%). The 6% and 9% B_4C composites display particle agglomeration through microstructural analysis results that leads to poor mechanical properties because stress distribution remains irregular. The 3 wt% and 6 wt% B_4C composites provide a good balance between mechanical properties and material integrity, while the 9% B_4C composite is more suitable for applications requiring extreme wear resistance, albeit with reduced ductility.

Keywords: *Sustainable, Waste, Microstructure, Hybrid composite.*

1. Introduction

The combination of aluminum matrix materials proves to be successful as industrial engineering materials. Aluminum matrix composites (AMCs) remain a limited engineering solution since they are more expensive than traditional aluminum materials. The objective of this research utilized bamboo leaf stem waste as reinforcement material for aluminum-based composites to break this cost limitation. Bannaravuri and Birru (2019) carried out a study on the mechanical properties of stir-cast Al-4.5%Cu alloy with specimens such as Al-4.5Cu/10SiC, Al-4.5Cu/10SiC/2BLA, and Al-4.5Cu/10SiC/4BLA. The researchers examined their produced composites through SEM and OM as well as tensile and hardness tests. The matrix and particle components show an obvious border region between each other. Additions of SiC in the material increased density whereas the inclusion of BLA yielded a reduced density value compared to the matrix alloy. Reinforcement particles elevated the tensile strength and hardness of Al-4.5Cu/10SiC/2BLA hybrid composites as well as single-reinforced Al-4.5Cu/10SiC composites. Kenneth et al. (2020) conducted research about how silicon carbide and bamboo leaf ash worked together to influence aluminum-based material properties under hot deformation conditions. A Gleeble 3500 thermomechanical simulator underwent isothermal compression tests on BLA-SIC hybrid aluminum composites throughout 300-400 °C deformation temperatures and 0.01^{-1} s^{-1} strain rates. The results revealed that flow stress showed strain rate-insensitive characteristics but it raised with temperature reductions that metal systems based on Al 6XXX typically exhibit.

A research by Haile et al. (2024) analyzed the effects that Bamboo Stem Ash Powder (BSAP) reinforced into pure aluminum. A typical natural fiber composite takes the form of BSAP. Scientists examined the mechanical and physical attributes of pure aluminum when BSAP was introduced as an additive. The study utilized the matrix with secondary reinforcements as well as testing different concentrations of BSAP varying from 0 to 2.5, 5, 7.5, and 10 wt%. Among various reinforced materials with BSAP, the combination of 7.5 wt% BSAP produced the peak hardness (239.66 HV) and compressive strength (308.32 MPa). Wang et al. (2022) managed to develop an environment-resistant bamboo composite that features a hierarchical SiO2 protective coating wrapped around a stress-resistant GO/bamboo structure. The GO/bamboo composite exceeds natural bamboo in all three measures of toughness (17.5 MJ/m3), flexural strength (428.4 MPa), and ultrahigh tensile strength (641.6 MPa). This strength delivery surpasses bamboo by approximately 480% and 250%, and 360%, respectively. The GO/bamboo composite reaches a specific tension strength level of 513.3 MPa·cm3/g at its low density of 1.25 g/cm^3, which surpasses both aluminum alloys and steel as well as titanium alloys. The research of Atuanya et al. (2018) investigated the utilization of cost-effective bamboo leaf stem waste as reinforcement in aluminum-based composites.

The production of these composites occurred through the stir-casting method. The tensile strength and hardness values experienced a 16.93% increase, while the 12.15% increase took place when the experiment utilized 15wt%BLSAp. When the composition reached 15wt%BLSAp, both density values decreased by 14.91% while impact energy levels declined by 18.64%. Scientists have shown that bamboo leaf stems, which are discarded, can make A356 alloy characteristics more advanced. Kumar and Birru (2017) employed 2%, 4%, and 6% of bamboo leaf ash (BLA) as reinforcement in the Al-4.5%Cu alloy matrix. Up to 4% of BLA could be added to the composite to increase its hardness and tensile strength; beyond that, the hardness and tensile strength declined. As the mass fraction of BLA particles increased, the density decreased and the porosity increased as well.

Using a double stir casting process, Alaneme et al. (2014) synthesized Alumina samples added with 2, 3, and 4 wt% bamboo leaf ash (BLA) were used to prepare 10 wt% of the reinforcing phase with Al-Mg-Si alloy as a matrix. Among the composite samples produced, the hybrid composite containing 4 wt% BLA was found to have the highest coefficient of friction and, as a result, the highest wear rate. The wear rates of the hybrid composites with 2 and 3 wt% BLA and the single alumina-reinforced composites were similar, with the hybrids exhibiting marginally better wear resistance. In their 2013 study, Alaneme et al. created low-cost, high-performance Al matrix hybrid composites by combining silicon carbide and bamboo leaf ash as complementary reinforcements. Using a two-step stir casting process, silicon carbide (SiC) particles were added with 0, 2, 3, and 4 wt% bamboo leaf ash (BLA) to prepare 10 wt% of the reinforcing phase with Al-Mg-Si alloy. Nonetheless, the hybrid composites' fracture toughness was higher than that of the Al 10 wt% SiC composite, which was reinforced only once. The only hybrid composite with a specific strength value comparable to the single-reinforced composite was the 2 wt% BLA-containing 1 wt%. The 2 and 3 wt% BLA-containing hybrid composites were found to have higher corrosion resistance in a 5 wt% NaCl solution when compared to the single-reinforced Al 10 wt% SiC composite. However, the opposite trend was seen in a 0.3 wt% H2SO4 solution, where the single-reinforced composite had superior corrosion resistance.

In order to create composites, Bannaravuri and Birru (2018) used a stir casting method to add 0, 2, 4, and 6 wt% of bamboo leaf ash to an Al-4.5%Cu matrix. When, compared to an Al-4.5%Cu matrix alloy, the wear rate of the composites was reduced with the addition of BLA particles, and the composites with the highest anti-wear properties were those that contained 4 wt% of BLA. The strengthening of the composites may be due to an increase in dislocation density with a increase in BLA wt%. By using the stir casting technique, the base A356.2 aluminum alloy is reinforced with bamboo leaf ash particulates, with the reinforcement percentages being adjusted to 2, 4, and 6 wt%. Using a standard watt's bath, nickel is electrodeposited onto the created Al-BLA composites. Polarization tests are used to thoroughly examine the corrosion behavior of the test samples in an aerated 3.5% NaCl environment. It was observed that as the percentage of reinforcement increased, the nickel-deposited Al-BLA composites demonstrated improved mechanical behavior and increased corrosion resistance (Ebenezer et al., 2021). The study fills in a significant research gap in the creation of high-performing, sustainable materials. Although natural fibers and waste materials have been extensively studied for their potential as reinforcements in polymer and metal matrix composites, there hasn't been much research done specifically on the ash of waste bamboo (AWB) in combination with advanced aluminum alloys such as AA7075-T651. By assessing AWB's potential as a reinforcing material, this study seeks to close the gap and pave the way for more affordable and ecologically friendly composite material substitutes.

A crucial knowledge void exists regarding high-performing sustainable materials thus, the study plays an important role in filling this gap. Research regarding the combination of ash of waste bamboo (AWB) with advanced aluminum alloy AA7075-T651 as well as natural fibers and waste materials for composite reinforcement, remains minimally studied. This study evaluates AWB's reinforcing attributes to create sustainable material options that are both cost-effective and environmentally friendly.

This investigation introduces pioneering research integrating waste bamboo ash into hybrid composite materials using its sustainable natural origin. Natural resources serve both purposes of creating advanced materials and solving waste management issues. This investigation defines how the mechanical and microstructural characteristics of AA7075-T651 hybrid composite transform when AWB is used as a reinforcement material. The analysis demonstrates that these materials will achieve performance advancements in strength and hardness and durability, which makes them suitable for high-performance industry uses such as automotive and aerospace sectors. The study demonstrates that composite production techniques present a possible solution to cut down or eliminate dependence on non-renewable materials and synthetic fibers for manufacturing. AWB serves multiple advantages by minimizing environmental harm while providing economic value to refuse that was otherwise unneeded. This study's findings can possibly trigger the development of advanced hybrid composites featuring superior characteristics, which temperature the potential for utilization across industrial applications demanding lightweight, robust, and environmentally responsible materials.

2. Materials and Methods

The AA7075-T651 base metal alloy was acquired from an ingot form. Spectrochemical analysis was used to check the mix of chemical substances present in the sample. For reinforcement, 50 µm-sized average boron carbide particles served as the chosen material.

Figure 1. Synthesis of composites

Ash production required the gathering of bamboo chips, followed by furnace heating at 700°C for three hours. When ash reached below a 75 µm size range, it underwent sieving. Figure 1 shows the preparation of the composite in the stir casting method. An electric resistance furnace heated 2 kg of AA7075-T651 alloy in a graphite holding container. A 30-minute maintenance time at 750°C inside the furnace served to achieve uniform melting conditions. The molten AA7075 alloy required solid hexachloroethane (C_2Cl_6) to degas it from trapped gases. The preheating of B_4C particles and bamboo ash in the muffle furnace at 450°C for one hour served to remove moisture before wettability enhancement with the molten aluminum alloy.

A mechanical stirrer equipped with a zirconia-coated impeller produced the vortex in the molten alloy. The stirring speed remained at 500 rpm for ten minutes to ensure uniform distribution. B_4C particles received stepwise addition into the vortex during the stirring operation before bamboo ash was introduced. The reinforcement particles, including 3% B_4C together with 2% weight of bamboo ash, were introduced to the mixture for two initial minutes of stirring in order to stop agglomeration.

Figure 2 The Prepared Samples

A 150mm×150mm×10mm mild steel mould was heated to 250°C before pouring the molten composite material. The molten material reacted with the mold because its surface received a graphite coating. The molten composite needed to maintain 730°C as its pouring temperature. Following the pouring process, the mould remained at room temperature for two hours to ensure composite solidification. When the casting was extracted from the mould and it was cooled with additional cooling time until reaching room temperature. After solidification, the material went through a T6 treatment for mechanical property enhancement. The cast composite received solution treatment by immersing it in water after maintaining heat at 480°C for two hours in a muffle furnace. Following water quenching, the composite went through a heating phase at 120°C, which lasted for one complete day until natural cooling occurred. Tests on the heat-treated material required the machining of the composite to eliminate surface defects.

The prepared composite samples are shown in Figure 2. A maximum of 100 images with magnification were acquired by using Keller's Reagent according to the following steps: The abrasive cutter first prepared small sections, which were suitable for metallographic analysis.

Then the sample was placed into a bakelite mounting to enable better sample handling during the polishing process. The mirror-like surface finish was achieved when the mounted specimen received silicon carbide paper treatment from 240 grit up to 1200 grit in sequential order. The procedure continued with alumina suspension for finishing. The mixture of distilled water, 5 mL Nitric acid (HNO_3), 3 mL Hydrochloric acid (HCl), with 2 mL Hydrofluoric acid (HF) produced Keller's Reagent. The polished sample required a ten to thirty-second dip in a prepared etchant in order to observe both microstructural characteristics and grain structure. The sample received distilled water rinsing immediately after etching to stop the process before finishing it with a hot-air-drying process. A 10x objective lens and 10x eyepiece were combined on an optical microscope for the 100x magnification needs. The microscope stage held the etched sample, and focus adjustments enabled proper observation of grain boundaries and other microstructural components. The optical microscope contained a camera that captured images of the microstructure at 100x magnification. The images acquired with Keller's Reagent revealed both grain boundaries and second-phase particles after the etching.

3. Results and Discussions

3.1 Microstructural Analysis

The microstructure of Neat AA7075-T651, shown in photo 1 of Figure 3, features a uniformly distributed grain structure. Which is typical of heat-treated aluminum alloys. No additional reinforcement elements exist along with a lack of second-phase particles, as the grains maintain defined borders. The homogenous arrangement of grains in this alloy indicates its strong base characteristics, including high strength and toughness, but excludes the strengthening effect of ceramic particles. The main characteristics of this material include fine equiaxed grains and typical AA7075 composition, together with a complete absence of visible secondary phase and particulate matter. The main purpose of AA7075 lies in its capability to deliver exceptional strength while minimizing weight.

Two percent AWB ash, along with three percent B_4C ash, results in significant microstructural changes (review Photo 2 of Figure 3). These materials have both bamboo ash powder dispersed throughout the matrix along with tiny B_4C particles. The B_4C reinforcement contributes to grain refinement as well as dispersing fine second-phase particles inside grains, which is helped by the bamboo ash. Grain refinement in the alloy occurred to a limited extent because of the B_4C particles establishing a pinning effect that surpasses the results from the pure metal. The mechanical properties improve through B_4C particle dispersion because it provides better wear resistance and higher hardness values. The distribution of bamboo ash is even, but its single contribution to mechanical characteristics seems weaker than that of B_4C.

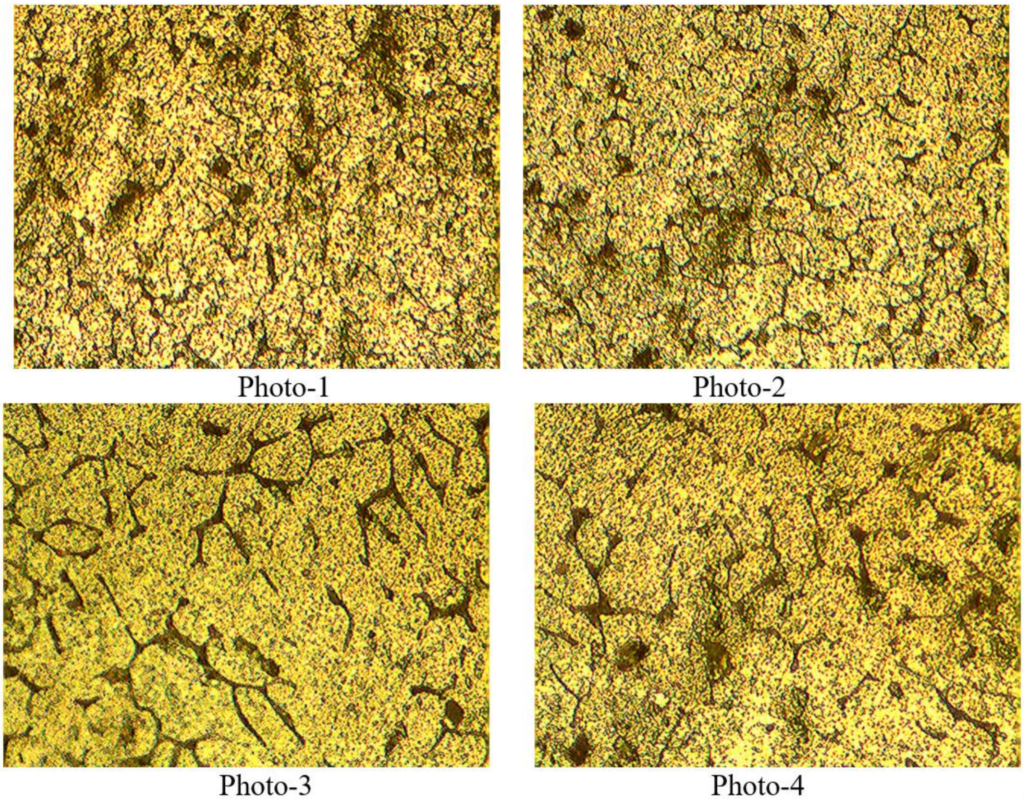

Figure 3. Micro structure images of Alloy and Composites

The images comprise Neat AA7075-T651 microstructure followed by AA7075-T651 + 3% B_4C + 2% AWB, AA7075-T651 +6% B_4C + 2% AWB, then AA7075-T651 + 9% B_4C + 2% AWB microstructure. Photo 3 of Figure 3 shows a high density of B4C second-phase particles that occurs due to the 6% B_4C reinforcement. Photo 2 displays finer grains, which demonstrate that increased B_4C amount enhances grain boundary pinning while promoting grain refinement. The introduction of higher concentration levels allows noticeable agglomeration and clustering effects that could slightly affect uniform dispersion. Some structural integrity of the grains remains present thanks to the bamboo ash content. The primary outcome from extra B_4C content is enhanced grain refinement that leads to improved material hardness, along with wear resistance. The localized stress accumulation may result from B_4C aggregation points, but the 3% B_4C composite exhibits superior mechanical properties in terms of strength and hardness.

The microstructure illustrates (Photo 4 of Figure 3) greater B_4C particle distribution across the volume of the material at 9% B_4C. The examined particles demonstrate increased density and show signs of clustering as well as segregation patterns in specific sections. In the refinement stage of the grains, the particles demonstrate stronger aggregation behaviors that might cause inconsistent mechanical properties in specific areas. The non-ductility of ceramic materials like B_4C increases material brittleness when too many reinforcement additives are added. Maximum refinement occurs because the research shows substantial grain size reduction compared to the base alloy material. B4C content raises material hardness and strength levels, although it causes ductility to decrease. Under high mechanical force applications, stress risers develop and eventually lead to cracking because of clustering and agglomeration effects. B_4C particles dispersed in the matrix create reinforcement while bamboo ash contributes to a minor extent in crystal structure refinement compared to B4C particles.

The B_4C composites at 6% and 9% show visible particle agglomeration that might reduce mechanical properties because internal stress produces an uneven stress distribution. The pure form of AA7075-T651 shows high durability and strength, yet lacks resistance to enhanced hardness requirements or material wear. The combination of 3% B_4C + 2% AWB produces a suitable ratio of ductility alongside hardness and strength. along with minimum observations of particle accumulation. The combination of 6% B_4C with 2% AWB reinforcement provides better wear resistance and improved hardness, however the solution contains a minimal risk of localized particle clustering effects on material ductility. The combination of 9% B_4C + 2% AWB gives the best results regarding strength and hardness, yet poses challenges to ductility along with possible stress concentration points due to particle clustering. Measuring mechanical characteristics proved the reliability of the data obtained from the tests.

4. Conclusions

The reinforcement level of B_4C directly affects both the grain structure refinement and improves the mechanical properties by strengthening and enhancing hardness. The ductility levels decrease while the tendency for particle agglomeration increases when the B_4C content surpasses 6%.

The mechanical reinforcement effectiveness of B_4C exceeds that of bamboo ash, which serves primarily as a microstructure refining agent. The combination of 9% B_4C provides superior wear resistance yet compromises ductility, while the 3% B_4C and 6% B_4C composites maintain a suitable balance between these attributes. Among all the composites tested, the material with 2% AWB / 9% B_4C / 90% AA7075-T651 exhibited superior results.

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