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Mechanical property performance of Fe-SnS hybrid reinforced aluminum composites

Maruf Yinka Kolawole*[a], Sefiu Adekunle Bello[b], Tolulope Peace Babatunde[c], and Kehinde Raheef Adebayo[d]

[a]Department of Mechanical Engineering, Kwara State University, Malete, Nigeria.
[b]Department of Materials Science and Engineering, Kwara State University, Malete, Nigeria.
[c]Department of Mechanical Engineering, Ekiti State University, Ado-ekiti, Nigeria.
[d]Department of Food and Agricultural Engineering, Kwara State University, Malete, Nigeria.

Abstract

In this paper, the mechanical properties of a hybrid iron filing (Fe)-snail shell (SnS)-reinforced discarded aluminum matrix were investigated. Prepared iron filling (20 µm) and snail shell (70 µm) particulates at a mix ratio of 1:3 constituting 2, 4, 6, and 8 wt% in hybrid weight fractions as the reinforcing phase in the aluminum matrix were investigated. Both the unreinforced aluminum matrix and the reinforced hybrid composites were produced via a double-stir die casting technique. Metallurgical optical examination, density, tensile, hardness, and impact testing were carried out to appraise the mechanical property performance of the developed composites relative to the unreinforced Al matrix. The results show that with increasing hybrid-Fe-SnS particulates in the reinforcing phase, the hardness and ultimate tensile strength (UTS) of the reinforced Al-matrix composite also increase. The maximum tensile strength (106.10 MPa) and hardness value (62.92 HRB) equivalent to 86.50% and 24.90% increments, respectively, were obtained at 8 w% of the hybrid reinforcement. Meanwhile, the hybrid reinforcement only increased the impact energy of the composite by 2.60% at 2 wt% Fe-SnS addition, beyond which the impact strength decreased. A marginal decrease in the weight of the composite with an increase in hybrid reinforcement was also observed. Hence, Fe-SnS hybrid particulates offered a favorable influence on the mechanical property performance of Al/Fe-SnS hybrid composites compared to that of the unreinforced Al matrix.

Keywords: Hybrid reinforcement; Aluminum matrix composite; Iron filling; Mechanical property; Stir casting

1. Introduction

The current global indiscriminate disposal rate of industrial and municipal wastes is becoming worrisome, with consequential effects on the environment and people therein at large. However, most of these wastes have low or no economic value and hence end up in open public spaces, land-fills, drainages, and rivers to constitute a societal nuisance, whereas these wastes possess an enormous latent potential as reinforcements in metal matrix composite development [1–3]. Discarded aluminum is one of the metals in greater use for various domestic, transportation, and industrial applications, constituting greater concerns by accumulating enormous metal scraps in society after their useful life [4]. For instance, the world's aluminum production and usage are now more than double due to increasing demand in automotive, aerospace, building, structural, and power transmission applications [4]. Unfortunately, the end-product of these aluminum-made devices and elements after their serviceable life is scrap with low economic value. Fortunately, recycling this metal scrap into a value-added product is not only faster but will also save approximately 95% of the energy needed with fewer environmental consequences compared to producing a similar ingot of aluminum from a primary source [4–6]. Today, metals such as aluminum and steel are commonly recycled [5]. However, the unique combination of properties of aluminum and its alloys makes it one of the most versatile, economical, and attractive metallic materials for a broad range of simple to the most demanding engineering applications. Meanwhile, the current structural improved property demands of aluminum in various critical engineering applications as opposed to its monolithic form, which is characterized by low strength, hardness, and stiffness, have attracted researchers' attention to aluminum composites [7]. Alloying and reinforcing the pure and/or alloyed form of aluminum into metal matrix composites using synthetic, industrial, or agro-wastes as reinforcement is a viable route for boosting the engineering properties of aluminum metal for enhanced performance in critical engineering applications. Consequently, several works [7–11] have been reported using the rarely available and expensive synthetic reinforcements (SiC, Al_2O_3, graphite) to the most available, cheap, and viable agro-wastes (eggshells, rice husk ash, snail shell, bean pod ash, maize stock ash) as reinforcement materials in an aluminum matrix. Interestingly, the use of agro-waste as a metal matrix reinforcement is now being considered for the sustainable development of composite materials due to the low cost of production, ease of accessibility, and environmentally friendly processing technique without compromising property enhancement for the synthesis and production of composite materials applicable in various engineering fields [2,12]. A snail shell is a hard brownish outer covering of a snail for protection from predators, dehydration, and physical damage. It has been used in different forms both in orthodox and scientific research for various applications. Locally, snail shells have been used in the manufacture of jewels, buttons, and collections for artworks [13]. Scientifically, it has been employed in the treatment of wastewater

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*Corresponding author. Email: maruf.kolawole@kwasu.edu.ng and purification of aqueous solutions [13–17]. It has also been used in the production of biomaterials and drugs in medicine [18–20]. Furthermore, the snail shell has extensively been used as a matrix-reinforcing phase in the production of composite materials with promising findings [21–25]. For instance, Pruncu et al. explored the influence of Physella Acuta Snail Shell particles in aluminum metal–matrix composites. Atuanya et al. and Kolawole et al. [21, 24] investigated the influence of snail shells in aluminum matrix composites and empirical models for estimating the mechanical and morphological properties of recycled low-density polyethylene/snail shell bio-composites. Their reports indicated an improved mechanical property of the resulting aluminum composites using snail shells as reinforcement. In addition, iron filing is one of the industrial wastes recycled and used in engineering fields as filler in construction materials [26]. Iron filings are very small pieces of iron in a fine particulate form. They are usually byproducts of filling, shaping, grinding, or cutting operations as obtained during the parts fabrication and/or machining or secondary operation processes. The most common uses of iron fillings are electromagnetism experiments, chemistry experiments, artworks, powder metallurgy, fireworks, (sparklers), sandblasting, and concrete additives [27, 28]. Most of these metal wastes pose significant environmental hazards if not carefully managed, whereas they possess latent advantages when properly treated and processed into value-added products such as composites. However, despite the potential of these wastes as reinforcements in the aluminum matrix, to the best of the author's knowledge, no work has explored the hybrid characteristics of iron-filling (Fe) and snail shell (SnS) powder in aluminum matrix composites. Hence, this research presents the mechanical performance characteristics of snail/shell-iron filling reinforced aluminum scrap composites for engineering applications.

2. Experimental

2.1. Materials and equipment

The major materials used in this research work include aluminum scrap from window and door frames, iron fillings, and snail shells (particles). Equipment used in the execution of the project work includes a carbolite electric furnace (KSL 1500X) with a maximum operating temperature of 12000C, die casting mold, universal testing machine (UTM), sieving machine, and digital electronic balance. X-ray fluorescence (XRF-Pananalytical, minipal 4).

2.2. Preparation of reinforcement materials

The snail shells (Fig. 1) used in this work were sourced from a local market in Laoso community located in Ondo west local government area of Ondo State, Nigeria. The snail shells were thoroughly washed with clean water and detergent to remove the adhered contaminants and thereafter sun-dried for three days. The dried snail shells were crushed with a hammer mill, ground, pulverized with a disc mill, and thereafter sieved to 100 μm particle sizes (Fig. 1) using an electrical standard sieving machine. The iron filings (Fig. 1) were collected from a local machine shop in Kainji, Niger State, Nigeria. It was sieved to 63 μm particle sizes (Fig. 1) by arranging the sieve sizes in descending order and left to vibrate for 15 minutes following Hassan and Aigbodion, [29].

2.3. Processing of aluminum scrap

Aluminum scraps (Fig. 1) were obtained from a local aluminum door and window fabricator in Ilorin, Kwara State of Nigeria. Aluminum weighing approximately 18 kilograms was beaten into small pieces to fit into the melting crucible and melted in a 24 kg-capacity pit furnace. Before the pouring of molten Al onto a flat steel plate of 850 mm x 920 mm, treatments such as fluxing, degassing, and skimming were carried out to clean off the impurities in the melt. After cooling (Fig. 1), the ingots were removed from the surface of the flat steel plate and crushed into smaller pieces, which were used as matrix material in this work. The elemental compositional analysis of the recycled aluminum is represented in Table 1. In addition, the XRF chemical compositions of the iron fillings and snail shell powders using XRF-Pananalytical, minipal, 4 as conducted at the National Geosciences Research Laboratories (NGRL) Kaduna, Nigeria are displayed in Tables 2 and 3.

Table 1: Elemental composition of processed aluminum scrap

Elements	Al	Mg	Zn	Fe	Sb	Sn
Content (wt%)	95.008	2.617	1.313	0.481	0.341	0.241

Table 2: Elemental composition of Iron-fillings particulates

Elements	Fe	Co	Al	Si	S	Ca	Cr	Mn
Content (wt%)	93.46	3.20	0.28	0.66	0.56	1.10	0.30	0.44

2.4. Fabrication of Fe/SnS hybrid reinforced aluminum composite

The casting process adopted in this work was the double stir casting technique. A certain quantity of processed aluminum ingots was weighed and packed into a crucible and placed in the carbolite furnace with a temperature set to 780 °C for enhanced fluidity [30] at a 13 °C/min heating rate. The molten aluminum without reinforcement (control sample) was poured at a constant rate into the steel mold (ϕ15 mm by 250 mm long) preheated at 250 °C for 30 minutes. Thereafter, a weighed quantity of processed aluminum scrap was heated to 780 °C and brought to a molten state. This was mixed with 2 wt% hybrid mixtures of iron (63 μm) and snail shell (100 μm) particulates (Fe/SnS) as reinforcement in a ratio of 1:3 preheated at 300 °C. The added reinforcement was manually stirred until the molten composite slurry turned semisolid and was difficult to stir. Before stirring, 1% magnesium foil was added to improve the wettability between the matrix and the reinforcement bonding interface, as reported in earlier work [21]. It was returned to the furnace and reheated to 780 °C and allowed to dwell for 10 minutes to enhance flowability. Slags and other oxide impurities were ladled off, stirred for 60s before it was poured into the preheated steel mold and allowed to solidify, as shown in Fig. 1. A similar procedure was adopted in the production of composites having 4, 6, and 8 wt% Fe/SnS reinforcement additions at a constant 1:3 Fe/SnS hybrid-mixture fraction in each of the compositions.

2.5. Physical and mechanical property determination

The density was used to determine the physical properties of the developed composites. Archimedes' principle as described and reported by Usman et al. [31] was used to evaluate the density of the Al-xFe/SnS hybrid composite and the control samples. The weight of the Al-xFe/SnS hybrid composite was initially weighed in air as

Table 3: Elemental composition of snail shells

Elements	Ca	Sn	Al	Si	P	S	Fe	Mo	Si
Content (wt%)	97.27	0.45	0.33	0.35	0.37	0.65	0.14	0.17	0.27

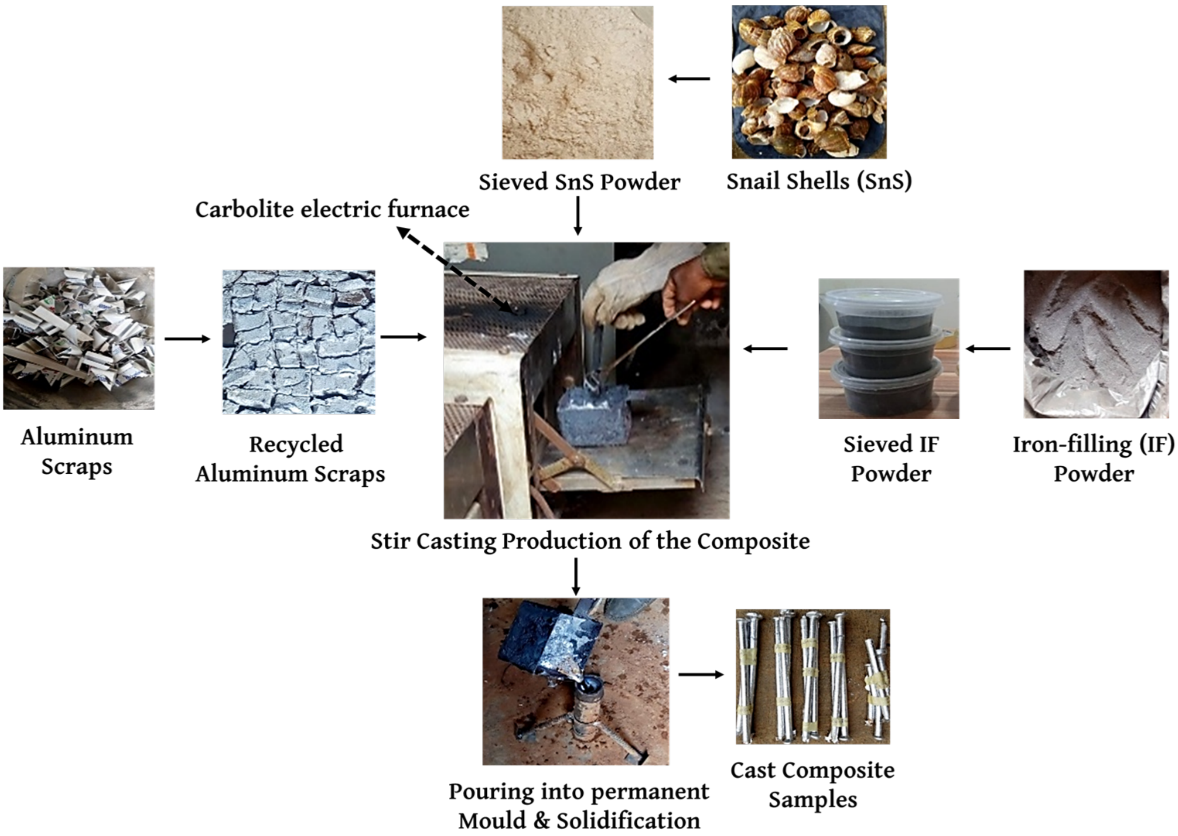


Figure 1: Preparation and production of Al-Fe/SnS hybrid composites

(a) In Air **(b)** In Water

Figure 2: Determination of Al-xFe/SnS hybrid composite density

(w_a) on a digital electronic weighing balance (Fig. 2a) and then immersed in a graduated measuring cylinder containing water (Fig. 2b) to obtain the corresponding weight in water (w_l) equivalent to a rise in volume. The weight in water was recorded to obtain the density of the developed composite using Eq. 1.

$$\rho = \frac{w_a}{w_a - w_l} \tag{1}$$

where ρ = density (g/cm^3), w_a = weight in air and w_l= weight in water.

The tensile strength and strain, impact strength, and hardness properties were used to investigate the mechanical properties of the developed iron-filling/snail shell hybrid composites. The tensile test of both control and Al-xFe/SnS hybrid composite specimens (Fig. 3a) was performed on a universal testing machine (UTM-0500-10080) at the Materials Testing Laboratory of the National Centre for Agricultural Mechanization, (NCAM) Idofia, Kwara State. The specimens were prepared as per the ASTM E-8 standard strain rate [32–34]. After proper clamping, the specimens were subjected to a gradually applied tensile force at a strain rate of 10-3 s-1 until fracture occurred to obtain the corresponding tensile strength and strain.

The impact energy determination of the developed composites was carried out at the Strength of Materials Laboratory, Department of Mechanical Engineering, University of Ilorin, following the ASTM E23 standard on the Avery Dension Universal Izod Impact – Testing machine, model number 6705U/33122 [35]. Prepared specimens (75 X ϕ 10) mm (Fig. 3b) for both unreinforced and reinforced aluminum alloy samples were conducted on notched specimens at a depth of 2 mm in the middle with a notch tip radius of 0.25 mm at an angle of 45°. The testing was performed by raising the striking to the maximum height and releasing freely to fall with gravity on the already clamped specimen. The corresponding readings of the energy absorbed to fracture by each specimen were taken and recorded.

The hardness test was performed on a Rockwell hardness tester situated at the Department of Materials Science and Engineering Laboratory, Kwara State University, Malete. The specimens (Fig. 3c) were ground up to 1200 grit size at 400, 800, and 1200 grit sizes for surface flatness and smoothness following a standard procedure. Five readings were taken, and the average was recorded as the hardness of the composite samples. The metallurgical optical examination of the samples after ground up to 1200 μm under constantly running water were viewed using Olympus BX 41M optical microscope at Material Science and Engineering Laboratory, Obafemi Awolowo University Ile-Ife, Nigeria.

(a) Tensile Specimen

(b) Impact Specimen

(c) Hardness Specimen

Figure 3: Prepared samples for mechanical property testing

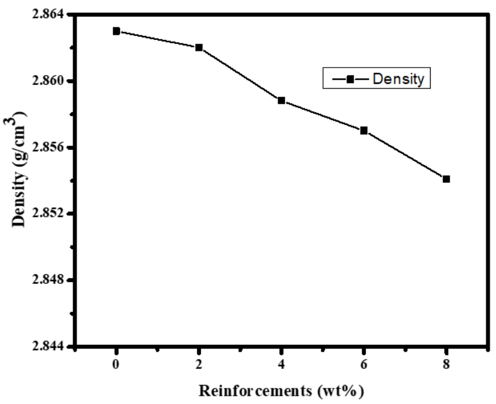
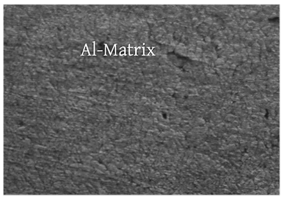


Figure 4: Density determination of Fe-SnS hybrid reinforced Al-scrap

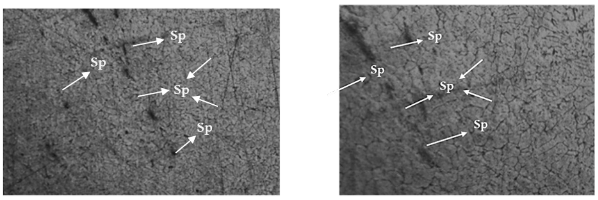
3. Result and discussion

3.1. Density characteristics of Fe-SnS particulate-reinforced aluminum scrap

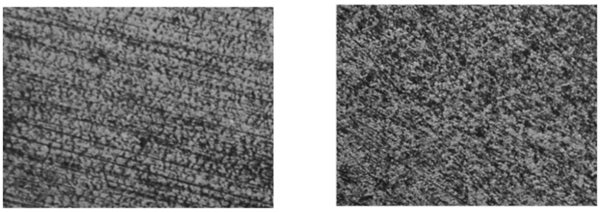
Fig. 4 shows the experimental density values for the recycled aluminum scrap composites reinforced with the hybrid mixture of iron filings and snail shell powders. It is obvious from Fig. 4 that the reinforcement only had a slight reduction in the density of the reinforced matrix with increasing wt% fraction of the hybrid Fe-SnS reinforcement in the matrix metal. Quantitatively, the density of the unreinforced recycled aluminum scrap decreased from 2.863 g/cm^3 to 2.862 g/cm^3 when 2 wt% of Fe-SnS powder was incorporated into the matrix. This characteristic behavior in density reduction of the composite with increasing addition of reinforcement continued in that manner until it dropped to 2.854 g/cm^3, equivalent to a 0.31% reduction in density at 8 wt% Fe-SnS reinforcement addition in the base aluminum matrix. The less significant drop in the density of the composite can be attributed to the addition of a lesser percentage of high-density iron fillings (7.87 g/cm^3) and a large percentage of less dense Snail shell powder (1.63 g/cm^3) as reinforcement in the composite compared to the matrix metal during the production process [21, 36]. This implies that the addition of Fe-SnS hybrid particulates as reinforcement in the aluminum matrix has a minimal effect on the reduction in the density of the developed Al composite. These results are in line with earlier research [31] and the discoveries of Deshpande et al. [37], where carbon fibers were used to reinforce aluminum AA7075 as the matrix. In their work, it was reported that the measured density for composites reinforced with carbon fiber was less than that of the aluminum matrix due to the lower density of the carbon fiber relative to the aluminum base metal.



a. Unreinforced Al-Scrap x50x



b. 2wt%-reinforced Al-Scrap x50x c. 4wt%-reinforced Al-Scrap x50x



d. 6wt%-reinforced Al-Scrap x50x e. 8wt%-reinforced Al-Scrap x50x

Figure 5: Optical metallography micrograph of Fe-SnS-reinforced Al-scrap

3.2. Optical metallurgical examination of reinforced aluminum scrap

The optical metallurgical micrographs of unreinforced and reinforced alloy samples are shown in Fig. 5. The Fig. reveals a clear difference between the morphology of the unreinforced and reinforced aluminum matrix. For the unreinforced matrix, the surface was characterized by a resemblance of the eutectoid phase of the aluminum alloy matrix with no identification of the secondary phase of the reinforcement materials. With the addition of 2 wt% hybrid Fe-SnS particulates, a notice of secondary phase (Sp) crescent emergence was observed in the composite morphology (Fig. 5b). When the volume fraction of Fe-SnS hybrid particulates was increased to 4, 6, and 8 wt%, it gradually unveiled the evolution of the secondary phase (Sp) in the matrix composites (Fig. 5c-e). The micrographs of the composite in Fig. 5 depict a uniform and homogenous distribution of hybrid Fe-SnS reinforcement particles in the matrix alloy, with neither voids nor discontinuities or agglomeration within the alloy matrix. This, therefore, signaled the existence of good interfacial bonding between the hybrid reinforcing particles and the aluminum matrix alloy. Consequently, this characteristic interaction between the reinforcement and the matrix, as discernible in Fig. 5, is a good indicator of the improved mechanical properties of the newly developed aluminum composite, as revealed in Fig. 6 and 8.

3.3. Tensile strength characteristics of the Fe-SnS reinforced Al matrix

The characteristic performance of Fe-SnS-reinforced and unreinforced Al-matrix composites at the yield point when subjected to tensile loading application is represented in Fig. 6. It was revealed that the incorporation of Fe-SnS hybrid reinforcement influences the tensile strength and strain of the samples. The tensile yield strength increases with the increased volume fraction of the hybrid reinforcement, while the strain decreases. At no addition of the reinforcement, the yield tensile strength and strain of the matrix were 56.89 MPa and 13.83%, respectively. When 2 wt% of the reinforcement was incorporated, the tensile strength increased to

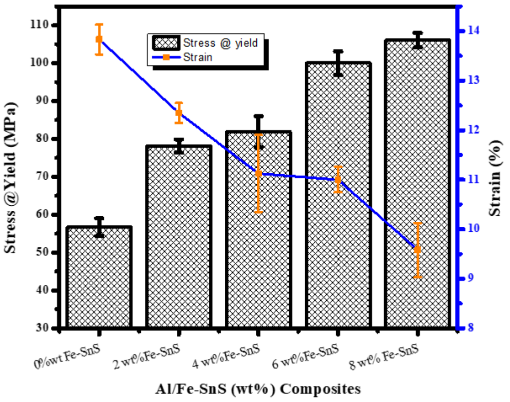


Figure 6: Tensile strength and strain characteristics of the Fe-SnS hybrid reinforced Al-scrap

78.108 MPa, and the strain drops to 12.35%. This increment in strength and decrease in strain are equivalent to 37% and 10.7%, respectively. This trend continued with a further increase in the amount of reinforcement up to 8 wt% in the matrix. At this zenith of reinforcement weight fraction, the tensile yield strength and strain were 106.10 MPa and 9.58%, equivalent to an 86% strength increment and a 30.7% strain reduction of the composites. This implies that the incorporation of hybrid reinforcement enhances the tensile strength of the composite developed at the expense of its ductility. The improvement in the tensile strength of the composite is attributed to good interfacial bonding between the matrix and the reinforcing phase, as depicted in Fig. 5, which raises the dislocation density at the grain boundary interface, hence requiring a higher force for deformation. In addition, the uniform dispersion of reinforcement, absence of voids, and other forms of stress raisers have relieved the composite from being free of the high-stress concentration, hence increasing the tensile strength of the sample produced. However, the decrease in percentage strain with an increase in hybrid reinforcement is traceable to the formation of harder and brittle intermetallic phases, as envisaged with the reinforcement-richer phase at higher additions of the reinforcement in the matrix. These results are in good agreement with previous researchers [38–40]. In their work, enhancement in the mechanical properties of the composites produced was attributed to good interfacial bonding between the reinforcing coconut shell microparticles and the presence of a hard phase in the Al matrix.

3.4. Impact energy of Fe-SnS reinforced Al-composites

Fig. 7 shows the impact energy of Fe-SnS reinforced Al-composites against the increasing weight addition of reinforcements. A skewed parabolic relationship between the impact energies and the increasing addition of reinforcement is displayed in Fig. 7. When no reinforcement was added, the impact energy was 109.8 J. This value increased to 112.65 J on the addition of 2 wt% reinforcement of Fe-SnS particulates equivalent to 2.6% in cement. Above 2 wt% addition of this reinforcement, there was a corresponding reduction in the impact energy of the composites. The minimum impact energy was obtained at 8 wt% addition of the reinforcement in the Al-matrix, which is equivalent to an 11.68% reduction. The initial increase in impact energy is a result of the homogeneous dispersion of reinforcement and strong bonding force with the low formation of brittle intermetallic phases in the matrix. However, more addition of reinforcement beyond 2 wt% led to the emergence of more formation of a hard brittle phase that led to the loss of ductility of the composite, as discernible in Fig. 6, hence the corresponding decrease in impact energy of the resulting composites. These results corroborated previous work, as found in the literature [35,38,41]. They attributed the drop in the impact energy to the extreme hardness of the new phases, which imparts brittleness to the Al matrix.

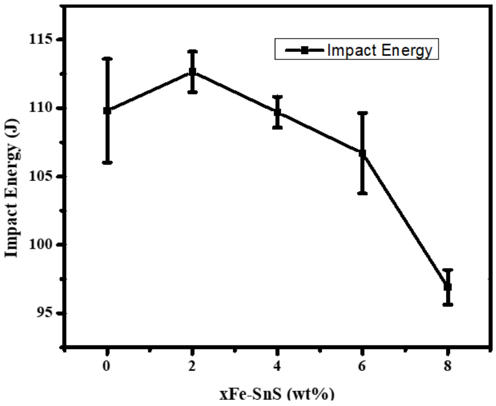


Figure 7: Impact strength of Fe-SnS hybrid reinforced Al-scrap

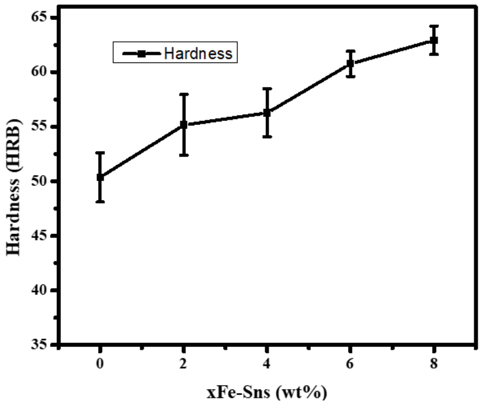


Figure 8: Effect of Fe-SnS hybrid reinforcement on the hardness of Al-scrap

3.5. Hardness variation of the Al/Fe-SnS-matrix composites

The hardness distribution of Al/Fe-SnS matrix composites versus wt% variation of hybrid reinforcements in the matrix alloy is shown in Fig. 8. The hardness of the composites increased with the increasing addition of Fe-SnS particulates. The hardness of the unreinforced Al-matrix was 50.36 HRB, and it increased to 55.17 HRB when 2 wt% of reinforcements were added. This increment is equivalent to 9.6% relative to the unreinforced parent-based metal. The increasing trend of the developed composited rose to the peak (62.92 HRB) with the addition of 8 wt% Fe-SnS reinforced phase in the matrix. This means that the addition of this hybrid reinforcement material increased the hardness of the parent-based metal processed via the stir casting technique by 24.9%. The characteristic behavior of hardness increment with the hybrid addition of the snail shell and iron fillings are traceable to their chemical make-up of hard phase element-based compositions oxides of Ca, Al, Si, and Cr as presented in Tables 2a and b. These chemical compositions tend to form the hard-phase intermetallics (ceramic compound) within the matrix that increase the hardness of the composite in this study and as also noticed in AA6061 sea sand reinforced composite in the literature [12]. This observation was in line with Alaneme et al. [42], where the aluminum matrix was reinforced with groundnut shell ash and silicon carbide hybrid particulates. They reported that the increase in hardness was due to the number of oxides of Al, Si, Ca, K, and Mg present in the composition of ground nutshell ash.

4. Conclusion

In this work, aluminum matrix scrap reinforced with discarded iron fillings (Fe) and snail shell (SnS) was successfully developed and fabricated via the stir casting technique. Mechanical property performance characterization of the composite specimen produced was carried out, and the following conclusions were presented:

1. Fe-SnS hybrid reinforcement has a less significant influence on the weight reduction of the Al-matrix composite produced, as only a 0.03% density drop relative to the parent matrix was achieved at 8 wt% Fe-SnS.

2. The yield tensile strength and hardness of the Al-matrix increased with the increasing addition of Fe-SnS particulates in the matrix. However, the impact energy of the composite only decreases after the addition of 2 wt% of reinforcement in the matrix. The maximum tensile strength (106.10 MPa) and hardness value (62.92 HRB) equivalent to 86.50% and 24.90%, respectively, was obtained at 8 wt% of the hybrid reinforcement.

3. The addition of Fe-SnS in hybrid form as reinforcement in the Al-matrix has favorably influenced the mechanical property performance of the Al-matrix composite produced via the stir casting technique. The enhancement in the properties was due to the uniform distribution of reinforcement of the duo without agglomeration and the strong bond of the intermetallic phase within the matrix phas

Competing interests

The authors declare that they have no competing interests.

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