Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 5 (2023)

Microstructure and Hardness Behaviour of Coconut Shell Ash, Silicon carbide and Carbon Nanotube in Aluminium Metal Matrix Nanocomposites

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Abstract

The current research work focuses on the fabrication of a hybrid composite of Aluminum 1050 (Al), multi - walled Carbon Nanotubes (CNTs), Silicon carbide (SiC), and Coconut Shell Ash (CSA) using a two stage stir casting technique. In the fabrication process, molten aluminum is first mixed with 0.2wt % of CNT and 0.25wt % of SiC. In addition to this, different concentrations of CSA are added in 1%, 2%, 3%, 4%, 5%, 6%, 7%, and 8% to assess the material's density, porosity and microstructure and hardness. Significantly, the Al-0.2%CNT-0.25%SiC-8%CSA composite exhibited a density 2.46% lower than that of the Al-0.2%CNT composite. The conducted hardness tests revealed a significant improvement, with a noteworthy 10.37% increase in hardness observed upon the incorporation of CSA particles up to 6%.

Keywords: Silicon Carbide, Carbon Nanotube, Coconut Shell Ash, Two stage Stir Casting.

1. Introduction

Metal matrix composites, particularly those based on aluminum, are gaining attention due to their superior operating properties compared to conventional metals and alloys. These properties include high stiffness, specific strength, wear resistance, corrosion resistance, and low density[1]. The choice of reinforcing filler plays a crucial role in determining the physical and mechanical properties of aluminum composites[2]. Hard ceramic particles like Al2O3, B4C, TiB2, TiC, SiC, and others are identified as effective fillers that significantly enhance mechanical and tribological properties[3,4]. It is emphasized that the uniform distribution of reinforcing particles within the composite and a strong interfacial bond between these particles and the aluminum matrix are of paramount importance. Uniform inclusion distribution and bonding are critical for achieving the desired composite properties. Many traditional preparation technologies are noted for their high cost, poor wetting capacity, and non-uniform particle distribution. Casting with mixing is highlighted as a promising and cost-effective method for preparing these composites, especially for large-scale production [5-10]. Unlike some other methods, casting with mixing does not require a chemical reaction between the matrix and reinforcing particles, which can reduce porosity and increase material uniformity. To create a strong bond between reinforcing particles and the molten metal matrix during composite casting, good wetting is necessary. This requires a strong interphase bond between the particles and the matrix. Achieving good wetting ensures a uniform load distribution within the composite. In general it underscores the significance of uniform particle distribution, strong interfacial bonding, and proper wetting for creating high-quality aluminum-based metal matrix composites. These composites have a range of desirable properties that make them attractive for various industrial applications, and the choice of reinforcing filler and preparation method are critical in achieving these properties. A359-Al_2O_3 MMC: The A359-Al_2O_3 MMC is mentioned to have a small grain size and a strong adhesion at the particle-matrix interface. Small grain size can be advantageous as it often leads to improved mechanical properties in materials.

Reference [16] discusses the effect of mixing duration and mixing rate when reinforcing aluminum alloy A384 with SiC particles during the preparation of MMC by casting with mixing. The way the particles are mixed with the molten aluminum alloy can influence the resulting composite's properties.

The authors of [17] synthesized an aluminum-magnesium alloy reinforced with silicon carbide (SiC) particles and found that SiC significantly enhances the mechanical properties of the composite. This reinforces the idea that SiC is an effective reinforcement material for aluminum-based composites.

Reference [18] suggests that the liquid metallurgy method is effective for producing aluminum composites. Additionally, it highlights that the casting method with mixing is highly effective for preparing aluminum composites that are reinforced with fibers or particles with random orientation. This production process involves mixing the reinforcing particles with a molten metal matrix and then pouring the mixture into a mold to create a casting. This method is recognized for its effectiveness in achieving uniform distribution of reinforcing materials.

Hybrid metal matrix composites featuring aluminum represent an innovative class of materials poised to fulfill contemporary demands in advanced engineering applications. These requirements stem from notable enhancements in mechanical properties, adaptability to conventional processing methods, and cost-effectiveness, as outlined in recent studies [19]. A highlight on various studies and methods related to the preparation of aluminum-based metal matrix composites, with a particular focus on the use of reinforcing materials like SiC. These studies and methods aim to improve the mechanical properties of these composites, making them more suitable for a wide range of industrial applications.

2. Materials and Method of Study

In this investigation, the base material for crafting hybrid composites was pure aluminum. Reinforcement materials utilized included multi-walled carbon nanotubes (MWCNT) with a purity exceeding 99% and Coconut Shell Ash (CSA) particles sized between 40 and 80 micrometers. The matrix material for the composites comprised ingots of pure aluminum obtained from PMC Corporation in Bengaluru. Additionally, reinforcement materials such as CSA were sourced from Kasturi Coconut Processings in Karnataka, while CNT was procured from Ad nano Technologies, and Silicon carbide was obtained from Gran Silica Enterprise.

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
Bal.	0.087	0.111	0.004	<0.005	0.011	<0.005	<0.004	0.017	---

Table 1: Chemical Composition of Aluminium 1050

Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	MnO	ZnO
15.6	0.57	12.4	0.52	16.2	0.45	45.05	0.22	0.3

Table 2: Chemical Composition CSA

Sl No.	MWCNT standards	Description	Characterization Method
1	Production Method	Chemical Vapour Deposition	Propritary method
2	Available Form	Black Powder	Visual
3	Diameter	Outer Diameter: 10-30mm	TEM, SEM
4	Length	10 Micron	TEM, SEM
5	Nanotubes Purity	98+% & above pure carbon	TGA, XRD
6	Metal Particles	<4%	TGA
7	Amorphous Carbon	<1%	TGA, XRD
8	Specific Surface Area	330 m2/g	BET

Table 3: CNT Description

SiC	SiO_2	Free Si	Free C	Fe
98.80	0.6	0.3	0.25	0.05

Table 4: Chemical Composition SiC

The Cerathermo stir casting furnace, with a capacity of 5 kg, was employed for the fabrication of the composite. Aluminum rods of predetermined weight were placed in a graphite crucible and subjected to gradual heating in an electric furnace, reaching a temperature of 750°C with a controlled increment of 5°C per minute. To maintain this temperature during the casting process, a PID controller was utilized to prevent fluctuations. The chemical

reaction inside the furnace was thwarted by keeping the temperature constant at 750°C. To enhance the melt's fluidity, 1% magnesium powder was introduced, and stirring was conducted using a stainless steel stirrer equipped with four blades.
Before introducing silicon carbide nanoparticles into the molten aluminum, the mixture was heated for 1 hour at 200°C. The addition of 0.2% CNT, 0.25% SiC took place, followed by stirring for 3 minutes, resulting in the formation of the Al-0.2% CNT-0.25% SiC composite melt. Subsequently, eight hybrid composites were generated by adding CSA in varying amounts, ranging from 1% to 8%, into the Al-0.2% CNT-0.25% SiC composite melt. A two-stage stirring method was employed to ensure the even distribution of the low-density CSA particles within the Al-0.2% CNT-0.25% SiC melt.
In this two-stage stir casting process, the Al matrix was initially heated to 750°C and transformed into a semi-solid state, followed by continuous stirring for 3 minutes. The partially solidified matrix material underwent reheating to 750°C to revert it to a molten state. During this process, CNT, SiC and CSA particles were introduced and continuously stirred for approximately 3-4 minutes. Ultimately, the resulting mixture was poured into a preheated mold, resulting in the fabrication of composite billets.

2.1. Characterization

Microstructures were examined at various magnification ranges using the Optical Microscope. Samples were prepared following the standard metallographic procedure for observing microstructures.

2.2. Density

The experimental density of the casting was determined by applying Archimedes' principle, utilizing water as the submersion medium. Simultaneously, the theoretical density of the casting was computed following the rule of mixtures [20].

The percentage of porosity within the composite was approximated by comparing the theoretical and experimental densities through the following method.

$$\%\ \text{porosity} = \frac{Theoretical\ density - Experimental\ density}{Theoretical\ density} \times 100\ \%$$

2.3. Hardness

Hardness evaluations were performed utilizing a Vickers hardness tester V1202 from Buehler, following the ASTM E-384 standard procedure. In this test, a 1 kg load was applied to the material for duration of 10 seconds. The hardness assessments were carried out at five distinct positions on the test material, and the resulting values were averaged.

3. Result and Discussion

3.1 Morphology of Al-0.2% CNT-0.25% SiC and its composites

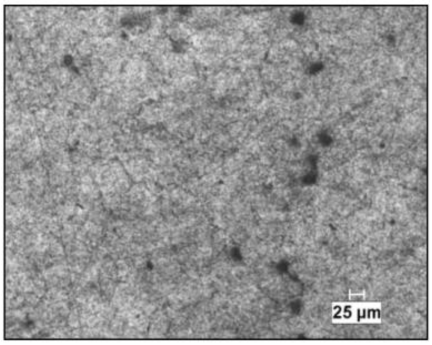

Fig 1(a) Al-0.2%CNT-0.25%SiC-2%CSA

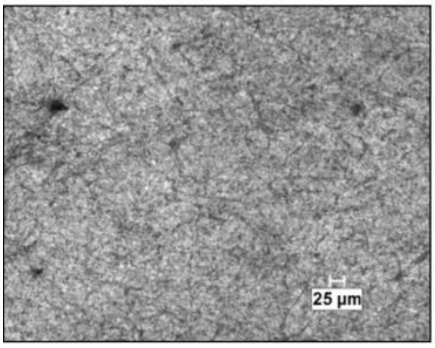

Fig 1(b) Al-0.2%CNT-0.25%SiC-4%CSA

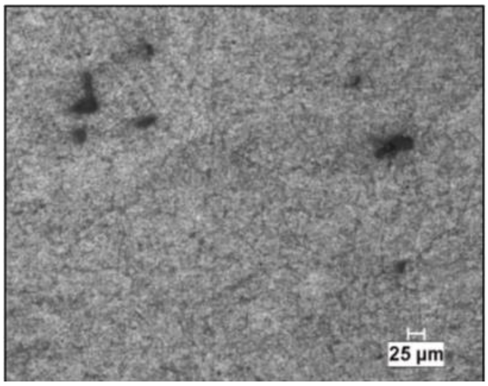

Fig 1(c) Al-0.2%CNT-0.25%SiC-6%CSA

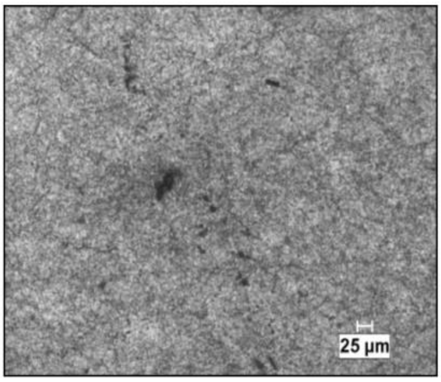

Fig 1(d) Al-0.2%CNT-0.25%SiC-8%CSA

From the graphs, it is evident that the CSA, which is a very fine mixture, is evenly spread throughout the Aluminium Matrix. The dark spots indicate constituent compounds of Coconut Shell Ash such as CaO, SO_2, K_2O etc. The brighter spots indicate the presence of the Ceramic particles such as Al_2O_3 and SiO_2 among other constituents present in CSA. Signs of particle clusters are minimal but present. This particle segregation and agglomeration tendencies maybe arising from the vast difference between the matrix and reinforcement particle's sizes. As intended, clarity of microstructure WRT grain structure and other surface characteristics is increased significantly with usage of etchant. The microstructure is devoid of defects such as voids and cracks. However, some porosity is noticed which could have been a consequence of stir casting process. As this imaging was done on a metallurgical microscope, the particle size ranges are not highly discernible as compared to what would have been obtained using a Scanning Electron Microscope.

3.1. Density of Al-0.2% CNT-0.25% SiC and its composites

Sl. No	Composition	Theoretical Density (g/cm3)	Experimental Density(g/cm3)	% Porosity
Sample 0	Al +0.2% CNT+0.25% SiC	2.787	2.69	3.480444923
Sample 1	Al +0.2% CNT+0.25% SiC + 1% CSA	2.84	2.73	3.873239437
Sample 2	Al +0.2% CNT+0.25% SiC + 2% CSA	2.79	2.69	3.584229391
Sample 3	Al +0.2% CNT+0.25% Sic + 3% CSA	2.67	2.59	2.996254682
Sample 4	Al +0.2% CNT+0.25% SiC + 4% CSA	2.63	2.582	1.825095057
Sample 5	Al +0.2% CNT+0.25% SiC + 5% CSA	2.624	2.559	2.477134146
Sample 6	Al +0.2% CNT+0.25% SiC + 6% CSA	2.612	2.546	2.526799387
Sample 7	Al +0.2% CNT+0.25% SiC + 7% CSA	2.594	2.491	3.970701619
Sample 8	Al +0.2% CNT+0.25% SiC + 8% CSA	2.543	2.431	4.404246952

Table 5: Density of Al-0.2%CNT-0.25%SiC and its composites

Table 5 provides a comprehensive comparison between theoretical predictions and experimental results concerning the density of the samples. It is apparent that, in both instances, the density of the specimens decreases with an augmentation in the quantity of reinforcing particles. Notably, both theoretical and experimental densities are observed to be below the density of aluminum, which stands at 2.71 g/cm³. The level of porosity in the composites, outlined in Table 1, is determined to be relatively low, ranging from 2.4 to 2.75%. As outlined in the table, it is noticeable that the theoretical density of the composite decreases with an increasing amount of reinforcement, attributed to the inherently low density of the Ceramic Self-lubricating Agents (CSA). However, a consistent trend is challenging to discern in the case of experimental density due to varying percentages of porosity. The data presented in the table highlights that experimental density values are consistently lower than their theoretical counterparts, a consequence of the presence of pores or irregularities introduced during the casting process.

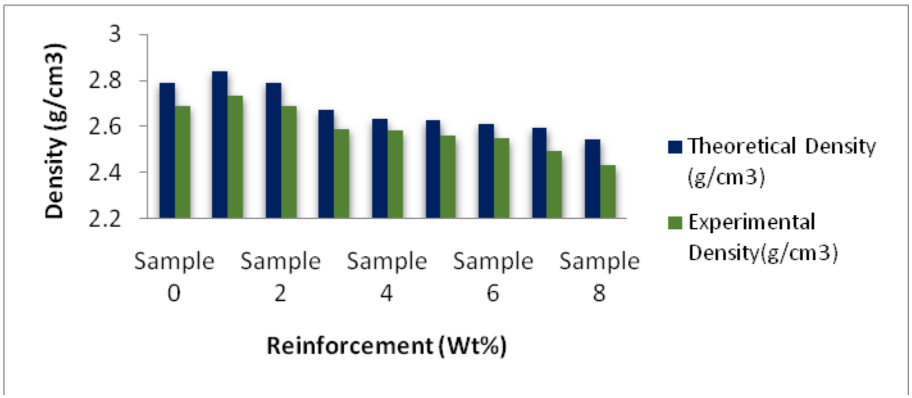

Fig. 5: Density(Theoritical Vs. Experimental) of Al-0.2%CNT-0.25%SiC and its composites

3.2. Hardness of Al-0.2% CNT-0.25% SiC and its composites

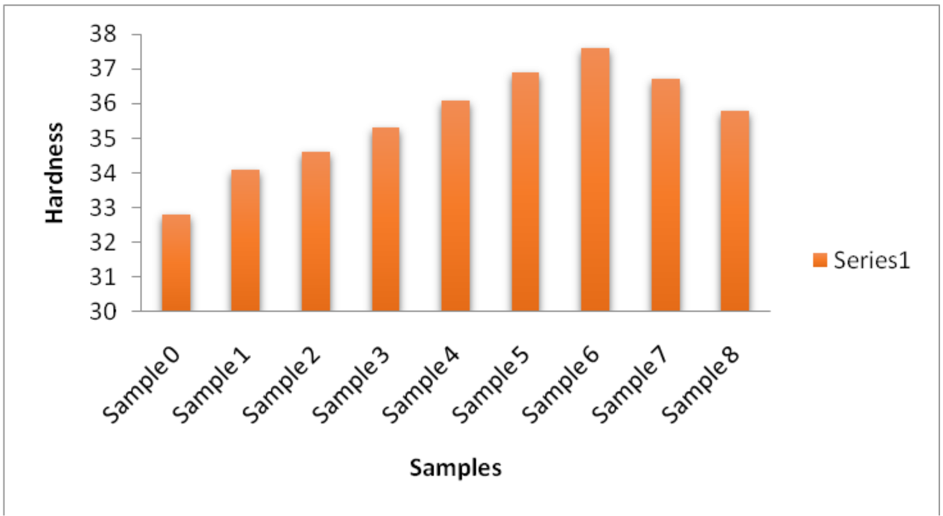

Fig. 5: Hardness of Al-0.2%CNT-0.25%SiC and its composites

The presented figures depict the hardness characteristics of Al-0.2% CNT-0.25% SiC and its composites, revealing a noteworthy trend. The hardness of the hybrid composites demonstrates an upward trajectory with increasing weight percentage (wt %) of Ceramic Self-lubricating Agents (CSA) particles in the matrix. The base hardness of Al-0.2% CNT-0.25% SiC stands at 32.8 HV, and the inclusion of 8% CSA results in a substantial hardness augmentation of 10.37%. Furthermore, the incorporation of CSA into the Al-0.2% CNT matrix leads to gradual enhancements in micro-hardness, showing increments of approximately 3.96%, 5.48%, 7.62%, 10.06%, 12.5%, and 14.63%, respectively, as CSA content rises from 1 to 6 wt% in 1 wt% increments. Despite these improvements, a reduction in hardness is observed at 7% and 8% CSA, registering declines of approximately 2.74% and 5.49%, respectively. Notably, the hardness of the Al-0.2% CNT-8% CSA composite is lower than that of the Al-0.2% CNT-6% CSA hybrid composite, potentially attributed to the formation of reinforcement particle agglomerations during the casting process.

4. Conclusion

The fabrication of Al-CNT-CSA-SiC hybrid composites was achieved through a Stir Casting process, involving systematic adjustments in CSA proportions in 1% increments from 1% to 8%. Notably, the density of the Al-0.2%CNT-0.25%SiC-8%CSA composite was found to be 2.46% lower than that of the Al-0.2%CNT-0.25%SiC composite. Morphological examination unveiled a consistent and uniform dispersion of reinforcement particles throughout the hybrid composites. The conducted hardness tests demonstrated a notable enhancement, with a 10.37% improvement in hardness observed by incorporating CSA particles up to 6%. This underscores the potential benefits of controlled CSA content in optimizing the hardness properties of the hybrid composites produced through the Stir Casting process.

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