

**ROLE OF ADDED CARBON NANOPARTICLES (CNTS) ON THE PROPERTIES OF MECHANISMS AND STRUCTURES MADE FROM AL-CU ALLOY**

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Abstract

This research work is, therefore, devoted to investigating the mechanical and structural properties of an Al-Cu alloy due to the addition of different weight ratios of carbon nanotubes (0.5%, 1.0%, 1.5%, and 2.0%). The samples were prepared in an optimal way for a better dispersion of nanoparticles into the base materials. Tensile test and Vickers hardness test were conducted along with the wear resistance test in order to check the surface properties subjected to frictional force. Microstructural analysis was done by using SEM and an XRD analysis for identifying the crystal structure of the materials. The result of the tensile test has shown a substantial increase in tensile and yield strengths when adding up to a desired ratio and marked enhancement in the Vickers hardness values, signifying enhanced resistance against plastic deformation. The wear test result indicated the decrease in wear rate and groove formation with the increase in ratios of CNTs, signifying enhanced surface wear resistance properties. The SEM result indicated that the CNTs are well dispersed in the alloy with desired ratios, representing reduced grain size and improvement in the microstructure. There was noticeable agglomeration at a desired ratio of CNTs. The XRD test revealed the stability of the main phases (Al and Cu) with the secondary phases (Al_2Cu) but without the carbide phase (Al_4C_3). In addition, the broadening of the diffraction peaks with the increase in the CNTs content was observed. The addition of CNTs to the Al-Cu alloy resulted in an improvement in the mechanical properties and wear resistance of the alloy while ensuring the stability of the structure. This composite material can therefore be considered suitable for applications where lightweight materials with high mechanical properties are needed.

Keywords: CNTs, Al-Cu alloy, Metal-based composites (MMCs), nanocomposites, wear behavior.

Introduction

Metal matrix composites (MMCs) are advanced engineering materials [1], whose properties are the combined effect of the base metal and the reinforcer to increase the efficiency of the metal in engineering applications, especially in the aerospace, automotive [2], and military sectors, where there is a need to reduce weight with increased strength and stiffness. Although the reinforcement of aluminum alloys with the right amount of copper (Al-Cu) is an efficient method of improving strength and resistance to deformation, the current need to reduce weight with increased durability has encouraged researchers to consider the use of nano-reinforcers with special properties [3]. Of the different reinforcers, the use of carbon nanotubes (CNTs) [5], with special properties, especially their strength, elastic modulus, and low density, makes CNTs the best candidates for improving the mechanical properties of metal matrices [6].

Carbon nanotubes (CNTs) have a significant effect on the improvement of the mechanical properties of metal alloys using a variety of mechanisms, including effective load transfer between the matrix and the reinforcers, dispersion of grains, and deformation density within the structure of the metal [7], and this has a positive effect on the stiffness and dynamic properties of the materials [8][9][10].

Most of the previous studies were carried out on pure aluminum alloys or their reinforcement materials [11], but recent studies have shown the addition of CNTs to aluminum-copper alloys to have the potential to greatly increase the mechanical and structural properties, especially with the help of the controlled distribution of nanotubes in the matrix and the interaction between the nanotubes and the metal [12].

In addition to this, the extent of improvement depends on the extent of dispersion and homogeneity achieved in the preparation process. CNT aggregation or heterogeneity in the accumulation of CNTs poses vulnerabilities in the regions surrounding them, hindering any enhancement of properties. This research will seek to delve into the impact of the addition of carbon nanotubes at predetermined weight percentages on the mechanical characteristics of the Al-Cu alloy. This will be achieved through a presentation of the differences in the resulting tensile strength, yield strength, and micro-structural characterization, among other factors, that have been observed. This research will seek to delve into the impact of the influence of the different mechanisms that occur as a result of the addition of carbon nanotubes on the metal alloy, which may involve mechanisms such as load, dislocation, or grain refinement. Finally, this research will seek to determine the mix that will bring about a balanced impact on the mechanical characteristics of the stability of the metal alloy's structure, thereby allowing it to be used in more advanced engineering applications that involve the use of lighter materials that have a strong mechanical efficiency.

2. Materials and Methods

Aluminum-copper alloys containing carbon nanotubes were synthesized via the melt-and-stir process, with pure aluminum and copper considered as the main components, while carbon nanotubes (CNTs) as reinforcing agents. Initially, the aluminum was melted in the electric furnace at a temperature of 750-780°C for a uniformly thorough melting process. Copper was then added to the liquefied aluminum with a flowing process of stirring in a ratio of 4 wt. %, enabling a homogenous mixture to be obtained. The carbon nanotubes were also suspended in the liquid compound of aluminum and copper in varying weight percentages of either (0.5, 1, 1.5, or 2%) with steady mechanical stirring to inhibit the clustering of the nanoparticles in the metal matrix. The liquid compound was transferred to the metal castings as the process cooled slowly to room temperature. As shown in table (1) the composite was subjected to the solution heat treatment process in the electric furnace at a temperature of 520°C for a duration of two hours, followed by a fast-cooling process in the water bath method for a few minutes for thorough cooling of the substance. The process was followed by artificial aging processes in the electric oven set at a fixed temperature of 170°C for a period.

Table 1. The percentage of samples used

Sample	Al%	Cu%	CNTs (wt.%)
Al-Cu	96	4	0
Al-Cu-CNTs	95.5	4	0.5
Al-Cu-CNTs	95	4	1
Al-Cu-CNTs	94.5	4	1.5
Al-Cu-CNTs	94	4	2

3. Results and Discussion

3.1 tensile strength

To determine the essential properties of the alloy from the tensile test, which may include ultimate tensile strength, yield strength, and elongation properties, a tensile test was carried out. The specimen used for the tensile test followed the requirements of ASTM E8/E8M. A universal testing machine with constant loading velocity was used for the experiment. This experiment is crucial to evaluate the effectiveness of CNTs on loading transfer within the metal matrix and their efficacy on resisting plastic loading. The specimen reinforced with CNTs had high tensile strength compared to the regular alloy. From the tensile test result, there was an improvement in ultimate tensile strength (UTS) and yield strength (YS) of the specimen reinforced with CNTs compared to the regular alloy [13]. This can be attributed to the effective loading mechanism of carbon nanoparticles to transfer the mechanical loading from the metal matrix to the high-strength CNTs as shown in Table (2) The maximum properties were observed at CNT addition levels ranging from 1-1.5 wt.%, at which the homogeneity of the particles was high. However, beyond 2 wt.%, there was a slight decrease in elongation because of the nanoparticle agglomeration and formation of stress concentrations [14], which decreases the ductility of the alloy. As shown in figure (1)

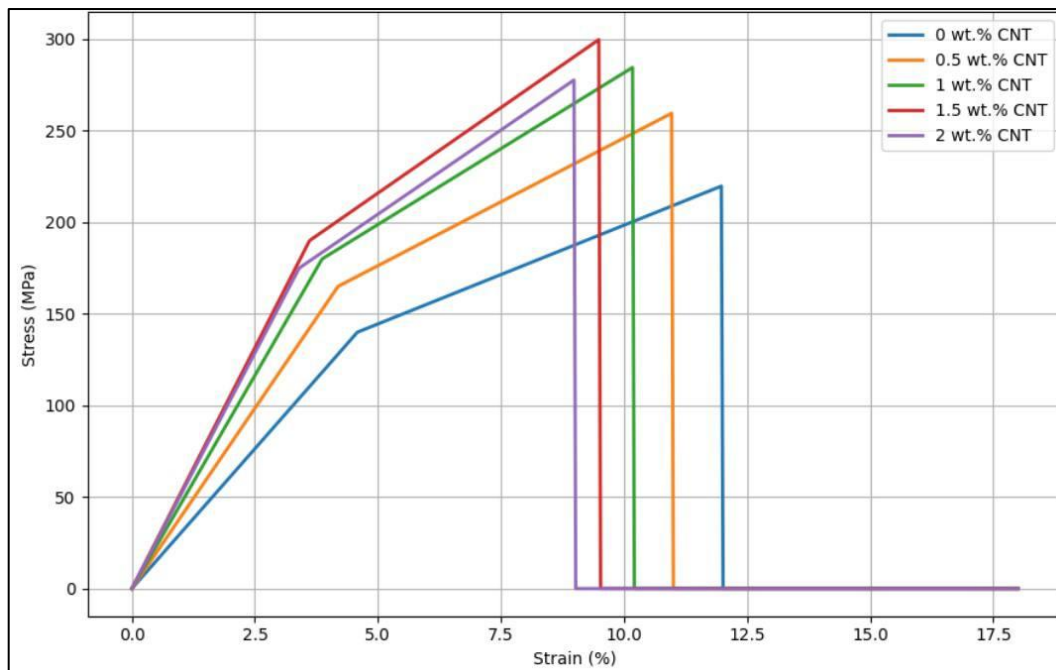


Figure 1. Stress–strain curve for Al-Cu/CNTs sample

Table 2. The tensile test results for all samples

Sample	CNTs (wt.%)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation %
Al-Cu	0	140	220	12.0
Al-Cu-CNTs	0.5	165	260	11.0
Al-Cu-CNTs	1	180	285	10.2
Al-Cu-CNTs	1.5	190	300	9.5
Al-Cu-CNTs	2	175	278	0.5

3.2 Hardness Test

The Vickers Hardness Test was carried out to determine the resistance to localized deformation of the alloy. A load of 100 was placed on the polished surface of the specimen, and the impact diameter(s) formed were measured to determine the value of the hardness. This test indicates the strength of the microstructure due to the presence of CNTs, as the nanoparticles restrict the movement of the dislocations and enhance the surface strength against deformation [15]. The Al-Cu specimens with CNTs showed a remarkable increase in the value of hardness compared to the base metal. The value of hardness continuously increases with the increase in the content of CNTs due to the reasons given below: enhancement of the metal matrix, decrease in the grain size, and hindrance to the movement of the dislocations. This phenomenon is associated with the Orowan strength mechanism [16], in which the nanoparticles act as a mechanical barrier to the deformation process, as depicted in figure (2).

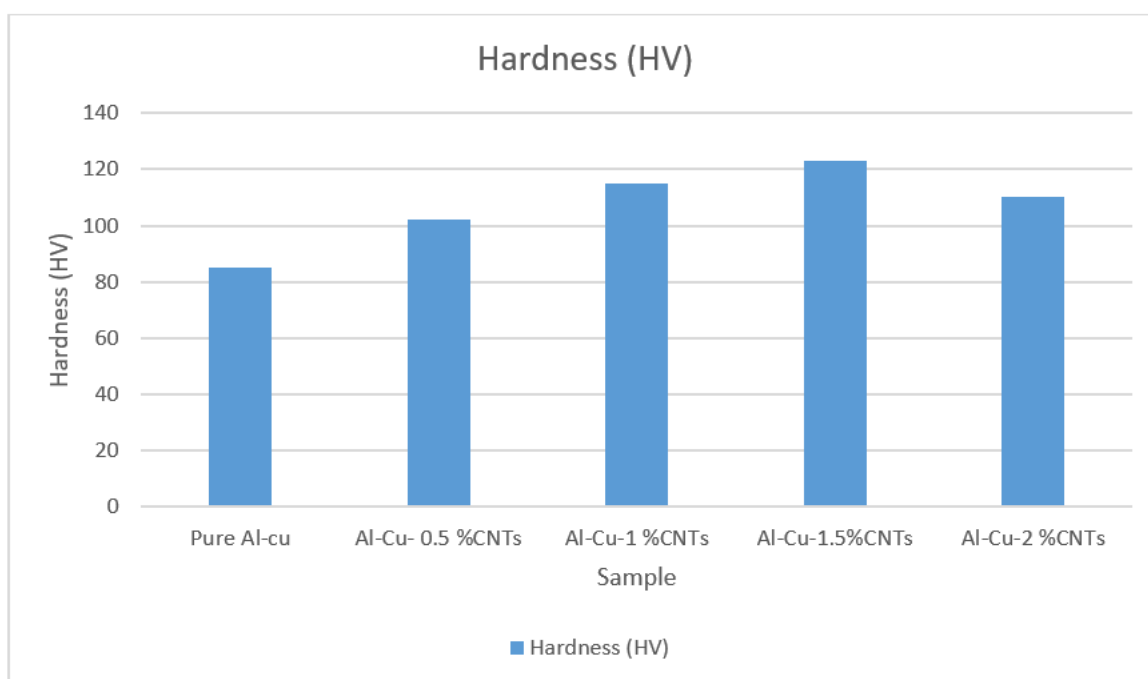


Figure 2. Hardness for Al-Cu/CNTs sample

3.3 Wear Test

The wear test was conducted using the pin-on-disc apparatus to assess the resistance of the alloy to frictional wear. The force is applied to the sample with a constant weight for a predetermined period of time while rotating at a predetermined speed. The wear test is useful in examining the effect of carbon nanotubes in lowering the wear rate, because carbon nanotubes have the property of being self-lubricating, thus increasing the wear resistance of the resulting alloy [17]. The wear test revealed that the weight loss rate of the carbon nanotube-reinforced alloy is lower compared to the unreinforced alloy [18]. The reduction in the weight loss rate is attributed to the following: the increase in the hardness of the surface, the self-lubricating effect of the carbon nanoparticles, and the reduction in the contact between the two surfaces in contact. The wear resistance increases with the increase in the concentration of carbon nanotubes to the optimum ratio, as indicated in figure (3). And then stabilizes or decreases at higher ratios because of the surface irregularities created due to agglomeration.

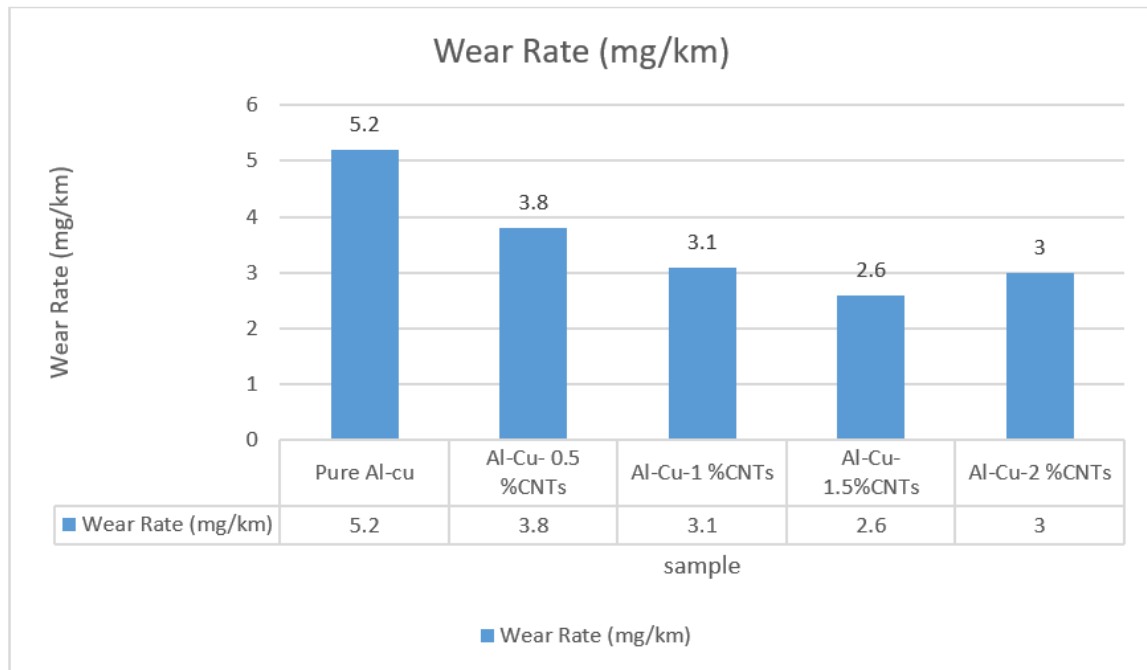


Figure 3. wear for Al-Cu/CNTs sample

3.4 Scanning electron microscopy Analysis

Scanning electron microscopy (SEM) images of the base Al–Cu alloy indicated a microstructure with a relatively distinct aluminum grain size and a rather heterogeneous distribution of copper and interfacial compounds with micropores due to the fabrication technique. Such a microstructure can be held accountable for the poor mechanical properties of the unreinforced material. The SEM images of the material reinforced with carbon nanotubes (CNTs), on the other hand, indicated a much greater homogeneity in their microstructure. A better distribution of nanoparticles in the aluminum grain was also evident, especially when the addition levels were low to moderate (0.5–1.0 wt.% CNT). Such a phenomenon was accompanied by a refinement in the size of the aluminum grains, a reduction in porosity, and also an increased intensity of the interface between the nanoparticles and the aluminum alloy, as shown in figure (4). The morphology also indicated the formation of micro-network CNTs, which essentially behaved as strong barriers to the movement of dislocations, and also increased the effectiveness of reinforcement mechanisms such as loading and Orowan. The addition of CNT with a higher wt.% of 1.5 and 2 wt.% caused localized agglomeration thereof, with irregular distribution and some zones with low interfacial strength. This may cause localized stress and might not allow proper utilization of the distinct properties exhibited by CNT. There were no observable cracks and defects in the structure along the interface between CNT and matrix, thus ensuring proper processing conditions and avoiding adverse reactions and structural segregation in CNT [19]. The SEM analysis results support that proper CNT addition enables effective microstructural refinement and structural homogeneity in the alloy, thus promoting an enhancement in tensile strength, hardness, and wear resistance in the fabricated composite materials.

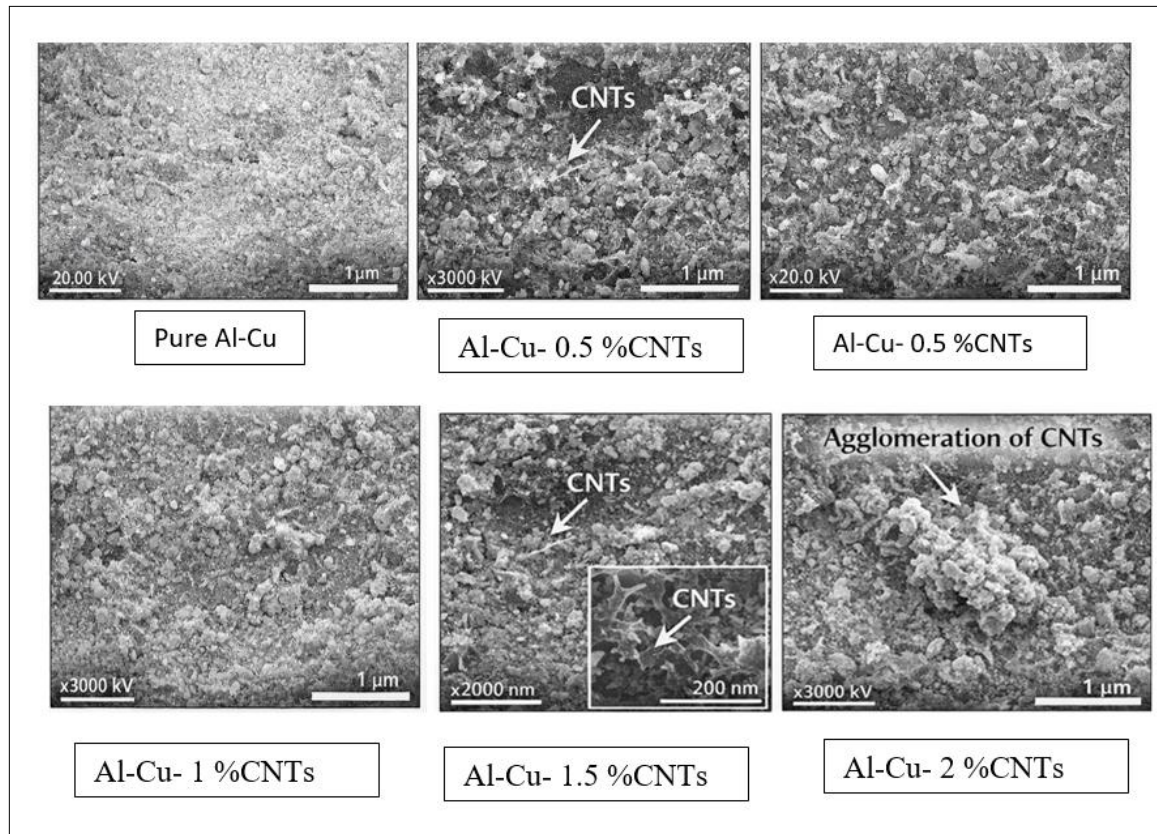


Figure 4. SEM images of samples

3.8 XRD diffraction Analysis

The X-ray diffraction (XRD) patterns obtained for all samples, including the base Al-Cu alloy and the alloys containing carbon nanotubes (CNTs) at percentages of 0.5, 1, 1.5, and 2 wt.%, revealed the appearance of clear diffraction peaks that belonged to the base face-centered cubic aluminum phase. These peaks were recorded at 2θ positions of approximately 38° , 44° , 65° , and 78° , for the (111), (200), (220), and (311) lattice planes, respectively. Other weak peaks also appeared in the patterns, belonging to the Al_2Cu interfacial compounds formed by the reaction between the aluminum matrix and copper, signifying that the phase structural integrity in the alloy was maintained. Moreover, the incorporation of the CNTs did not provoke the appearance of any new peaks and did not change the base crystal structure, signifying a complementarity and suitability in the choice of the nano-reinforcement material and the metal matrix. An increase in the diffraction peak broadening was noticed with an incremental rise in the amounts of the incorporated CNTs. This was related to the refinement in the crystal size and the rise in the micro-stresses in the crystal lattice provoked by the suppression and restriction in the movement of the dislocations in the aluminum matrix. On the other hand, there were no observable distinct diffraction peaks attributed to the CNTs due to the low addition percentage and nanoscale sizes. Moreover, there were no observable peaks due to the Al_4C_3 phase; hence, there were no undesirable chemical reactions between the aluminum and carbon during the preparation of the alloy. This is a crucial requirement for the preservation of the alloy's strength and mechanical properties. Regarding the highest addition percentage of 2 wt.% CNTs, there was a relative decrease in the intensity of the peaks and irregular expansion of the amplitude range [20]. This can be related to the localized agglomeration of the

nanoparticles. This could be a negative consequence of the regularity of the crystal structure as shown in figure (5). On a general perspective regarding the XRD results, the presence of a moderate amount of CNTs enhances the crystalline structure of the alloy. This is due to the grain refinement and the micro-stress without the destabilization of the phases. This enhances the positively related qualities of the wear resistance and mechanical properties of the resulting materials.

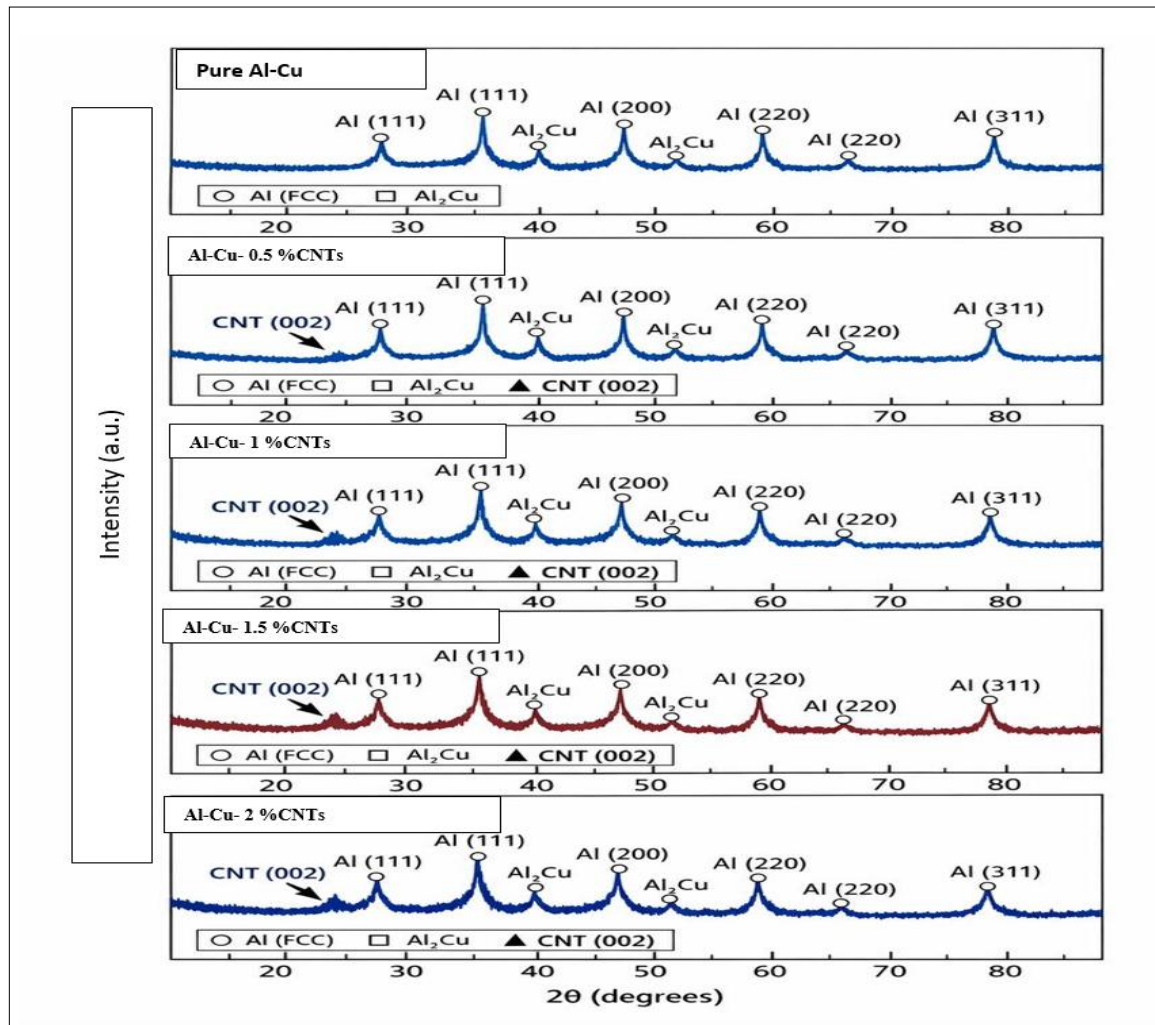


Figure 5. XRD patterns of composites Al-Cu/CNTs


4. Conclusion

1. Enhanced Mechanical Strength: Addition of CNTs into the aluminum-copper alloy showed a substantial improvement in the value of tensile strength and yield strength of the material compared to the base material.
2. Increased Hardness: With the rise in the concentration of CNTs, there was a corresponding rise in Vickers' hardness values.
3. Enhanced Wear Resistance: The wear rate decreased in the CNT-reinforced samples, with a smoother wear surface and shallower grooves compared to those in the unreinforced alloy.
4. Good Nanoscale Distribution at Optimal Ratios: From the SEM images, there was a good nanoscale distribution of CNTs at optimal ratios with smaller grain sizes and better microstructure.

5. Agglomeration Effect at High Ratios: The increase in the amount of CNTs introduced certain areas of agglomeration, which worked as a hindering effect for homogeneity, thus limiting the further enhancement in the properties. 6. Stability of crystal structure and improvement of microstresses: The XRD analysis revealed the lack of formation of the undesirable brittle phase in the given ratios, while the observation of the widening of the diffraction peaks indicated the reduction in the crystal size along with the increase in microstresses.

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