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Article

Mechanical and Physical Properties of Al/CNT/h-BN Hybrid Composites produced via Powder Metallurgy and Hot-Rolling Techniques

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Abstract: The current work discusses the development and characterization of Al/CNT/h-BN hybrid composites using the powder metallurgy technique. This study aims to investigate the enhanced mechanical and physical properties of Al-based composites by combining CNTs and h-BN. The experimental procedures for producing the hybrid composites involve incorporating CNTs and h-BN into the Al matrix at specific concentrations and coating the surfaces of the reinforcements with Ag/Ni via electroless deposition to enhance the bonding between the matrix and reinforcements. The pure Al sample and its hybrid composites were initially produced using the powder metallurgy technique and then applied to the hot-rolling process. The results involve the characterization of the produced pure Al sample and its hybrid composites (sintered and hot-rolling samples), including their mechanical and physical properties. The main findings are that the hot-rolled Al/CNT/h-BN hybrid composites exhibit improved mechanical and physical properties compared to other sintered and hot-rolled samples. The results showed that applying the hot-rolling process improved the densification and hardness of Al and its hybrid composite of Al/CNTs/h-BN. The relative densities of sintered and hybrid composite samples revealed a high densification of over 95%. The hardness improved to approximately 108%, 38%, and 23% compared to the sintered Al, hot-rolled Al and sintered Al/CNTs/h-BN samples.

Keywords: Hybrid composites, powder metallurgy, Aluminum, Carbon nanotubes, hexagonal boron nitride, mechanical and physical properties.

1. Introduction

The pursuit of innovative materials with exceptional properties has led to the emergence of hybrid composites as promising solutions that integrate the advantages of various reinforcement materials within a single matrix [1–3]. Among these, aluminum matrix composites (AMCs) have garnered significant interest owing to their remarkable strength-to-weight ratio, thermal conductivity, and corrosion resistance [4]. Despite their potential, traditional AMCs often exhibit limitations in terms of their mechanical and thermal capabilities [4]. To address these limitations, AMCs are generally reinforced with various materials, including continuous fibers (such as carbon, alumina, or silicon carbide), whiskers (e.g., silicon carbide), and particulates (such as alumina, silicon carbide, or boron carbide) [5–9]. These reinforcements are designed to enhance the strength, stiffness, wear resistance, and thermal properties of the Al matrix. Researchers have explored the potential of carbon nanotubes (CNTs) as reinforcements in Al matrix composites owing to their exceptional mechanical properties, such as high tensile strength and modulus [10]. CNTs have been used as reinforcements in many recent studies to improve the mechanical and physical characteristics of Al metal matrix composites (AMMCs) using different production methods. Kwon and Leparoux [11] looked at composites based on hot-extruded aluminum reinforced with 1 wt.% CNTs. The conclusion drawn from the uniform distribution of CNTs was that the tensile strength of Al/1 wt.% CNT composites increased by approximately 157% compared to pure Al. Comparably, using a planetary mill and a rolling method, Esawi and El Borady [12] manufactured Al-CNT composites with 0.5, 1, and 2% by weight of CNTs. They discovered that the UTS increased by 10% over than the Al-matrix. Furthermore, Esawi et al. [12] demonstrated that extrusion-produced Al/2 wt.% CNT composites had a tensile strength enhancement of about 50%. As already shown, CNTs provide appropriate reinforcements for Al/CNT-based hybrid composites. Therefore, many scientists have been interested in creating Al/CNT-based composites with various reinforcements such as Al_2O_3 [13], TiO_2 [14], TiC [15,16], and graphene [17]. Al/CNT composites with CNT wt.% content from 0.5-1 wt.% have been produced via powder metallurgy methods based on earlier research to produce hybrid metal matrix composites (HMMCs). Several approaches have been investigated to improve the wear resistance of these composites, such as surface treatment with liquids or solid lubricants. [18,19]. However, although liquid lubricants are useless under severe weather conditions, solid lubricant coatings suffer from problems such as oxidation, poor adherence, and short lifespans. One alternative approach to minimize wear and friction without relying on liquid lubricants is to incorporate solid lubricants within the metal matrix structure. Hexagonal boron nitride (h-BN) has a low coefficient of friction and is a self-lubricating reinforcing material for MMCs [20–23]. These features are especially helpful when conventional liquid lubricants are not practical, such as in high-temperature or vacuum situations. The incorporation of h-BN into Al matrices aims to improve the tribological performance of the resulting composites by reducing the friction and wear between the sliding surfaces. This makes them ideal for applications in which minimizing friction and wear is crucial, such as bearings, gears, and sliding components. However, despite the potential benefits of incorporating CNTs and h-BN into Al matrices, previous studies have not explored the synergistic effects of combining these materials to produce Al/CNT/h-BN hybrid composites. This gap in the literature suggests an opportunity to leverage the advantages of CNTs and h-BN as a reinforcement to the Al, rendering the resulting composite suitable for a range of applications in the automotive and industrial sectors. Notwithstanding these potential benefits, the successful integration of CNTs and h-BN into Al matrices poses formidable challenges, including uniform dispersion, interfacial bonding, and prevention of agglomeration and degradation during processing. This study aims to develop and characterize Al/0.6 wt.% CNT/2 wt.% h-BN composites fabricated through the powder metallurgy technique. Notably, the surfaces of the particles for both CNTs and h-BN were modified by applying a Ni coating via electroless deposition technique, aiming to improve the wettability between the Al and CNT/h-BN particles.

2. Experimental Work

Figure 1 shows the experimental procedures for producing Al/0.6 wt.% CNTs/2 wt.% hBN hybrid composites using the powder metallurgy process.

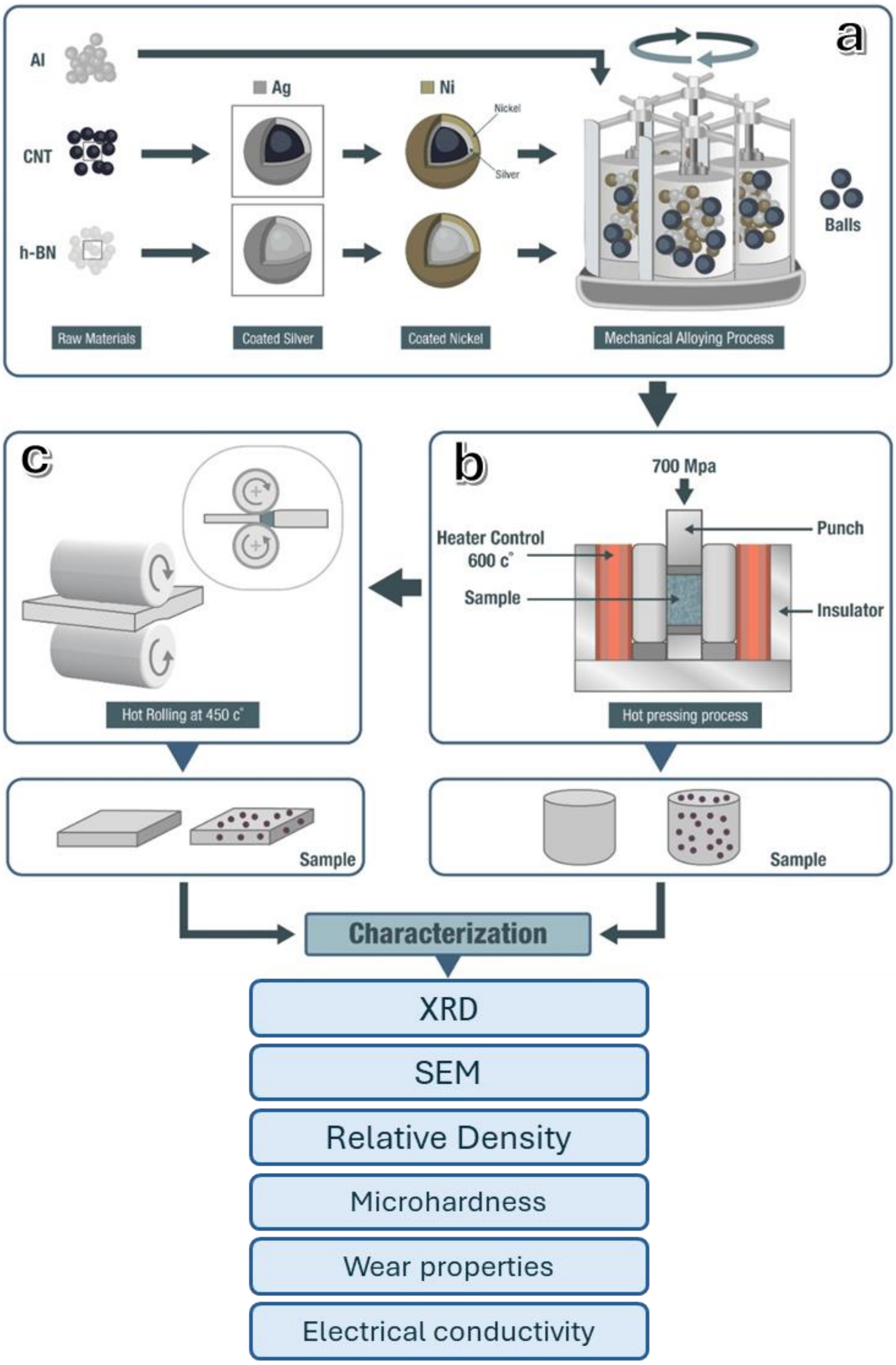

Figure 1. Schematic representation of the production of Al-based composite reinforced with the Ag/Ni coated CNT/hBN nano particles; (a) Materials preparation, (b) Synthesis of Al/CNT/hBN composites using hot pressing process, (c) Hot rolling process.

2.1. Initial Materials

Al powder was selected as the matrix material. According to the supplier (Dop Organic Kimya, Turkey), the Al-matrix had a high purity around 99.99% and with size upto 10 µm. Al/CNT/hBN composites were formed by incorporating two ceramic powders, CNTs and hBN, into the Al matrix. The CNTs were produced using the electric arc discharge method. The quality of the CNTs produced had a purity level of over 90%, featuring diameters measuring between 10-20 nm and lengths spanning from 5-10 µm. The utilized hBN had a purity level of 99% and an average particles size ranging from 70 to 80 nm, according to the supplier. The matrix was supplemented with CNTs and hBN at a constant concentration of 0.6 wt. % and 2 wt.%, respectively, to fabricate the Al/CNTs/hBN hybrid composites.

2.2. Surface Coating of Reinforcements

An electroless Ni plating technique was applied to the surface particles of CNTs and hBN to enhance the bonding between the matrix Al and reinforcements. Prior to the Ni coating, a pretreatment involving an electroless Ag coating on CNTs and hBN was conducted. This process involved applying a layer of Ag onto the surfaces of hBN and CNTs using a two-step procedure: sensitization and silver deposition. To prepare the hBN and CNTs for plating, they were first immersed in a solution of 10% sodium hydroxide with constant stirring for one hour, followed by immersion in acetone for one hour. The hBN and CNTs were then separated and cleansed using distilled water, before being subjected to a drying process at 110 °C in an electric furnace for a duration of one hour. The electroless plating Ag on hBN and CNTs was accomplished using a chemical bath containing 3 g/L silver nitrate and 300 mL formaldehyde, with a pH adjusted to 12 using ammonia. The reaction was initiated by adding formaldehyde and the hBN and CNTs were suspended in the solution by magnetic stirring for 10 minutes at room temperature. The electroless deposition process was carried out for 30 minutes. Following this, the solution was filtered and washed with acetone. Afterward, it was dried under vacuum at 110°C for one h. The concentration of Ni deposited onto hBN and CNTs particles was 30 wt.% via electroless deposition. Numerous steps were required to complete the process. Initially, the necessary quantities of nickel chloride, potassium sodium tartrate, ammonium chlorophyte, and sodium hypophosphite were determined to be 100, 80, 50, and 100 g/L, respectively. The temperature was maintained at around 92°C, and the pH was approximately around 9.2. Subsequently, the individual ceramic granules were added to the mixture.

2.3. Production of Hybrid Composites

The methodology employed to fabricate the Al-CNT and hBN nanocomposites involved the use of a circular grinding machine for ten h at 200 rpm. The machine balls, which were ten times larger than the powder, ranged in size from 10 to 12 mm. Following mechanical alloying, the samples were hot-pressed at 600 °C for 30 minutes under 700 Mpa of pressure to form a cylindrical shape with 12 mm in diameter.

2.4. Evaluation of Produced Hybrid Composites

Scanning electron microscopy (SEM) QUANTAFEG250 coupled with Energy Dispersive X-ray spectroscopy (EDS) was used to examine the microstructures of the starting material and the Al-CNT/hBN hybrid composites produced. This method makes it feasible to measure the size, shape, and composition of the powder particles. To prepare hybrid composite samples for microstructural analysis, they were initially ground with fine sandpaper and subsequently polished with alumina paste. X-ray Diffraction (XRD) analysis was conducted with Cu K± radiation ($\lambda = 0.15406$ nm) to investigate phase analysis of the coated powders. The MPIF Standard 42, 1998, and Archimedes principle were applied to determine the densities of the fused hybrid composite samples. Prior to determining the densities of the samples, their densities were measured in air and water. The properties of the hybrid composites were analyzed via hardness and electrical conductivity. An FM-ARS 9000 Vickers Hardness machine was used to gauge the hardness of the finished hybrid composite samples. Five results are randomly selected for each sample. The hardness load was 300 g, and the rest time was 15 s.

3. Results & Discussion

3.1. Initial Materials

X-ray diffraction and SEM techniques were employed to analyze the diffraction patterns and evaluate the size, and morphology of the initial materials utilized. **Figure 2** shows the SEM analysis of the pure Al and the reinforcements of hBN, and CNTs. The SEM images confirmed the supplier's Al matrix and reinforcements sizes. Al particles, CNTs, and nano-hBN are virtually spherical, agglomerated (micron size), and uneven with sharp edges, as shown in **Figure 2**. In the case of aluminum, the XRD pattern typically shows intense peaks corresponding to the (111) plane at approximately 38.5°, (200) at 44.7°, (220) at 65.1°, and (311) at 78.2° two-theta values, which are characteristic of the face-centered cubic (FCC) crystal structure. For CNTs, the XRD pattern exhibits peaks related to the (002) plane at approximately 26° and the (100) plane at approximately 42.5° two-theta, with the relative intensities and positions of these peaks providing information about the chirality and diameter of the nanotubes. Hexagonal boron nitride (h-BN) has a layered structure similar to that of graphite, and its XRD pattern shows intense peaks corresponding to the (002) plane at approximately 26.7° and the (100) plane at approximately 41.6° two-theta values, along with other less intense peaks related to the hexagonal crystal system as shown in **Figure 3**.

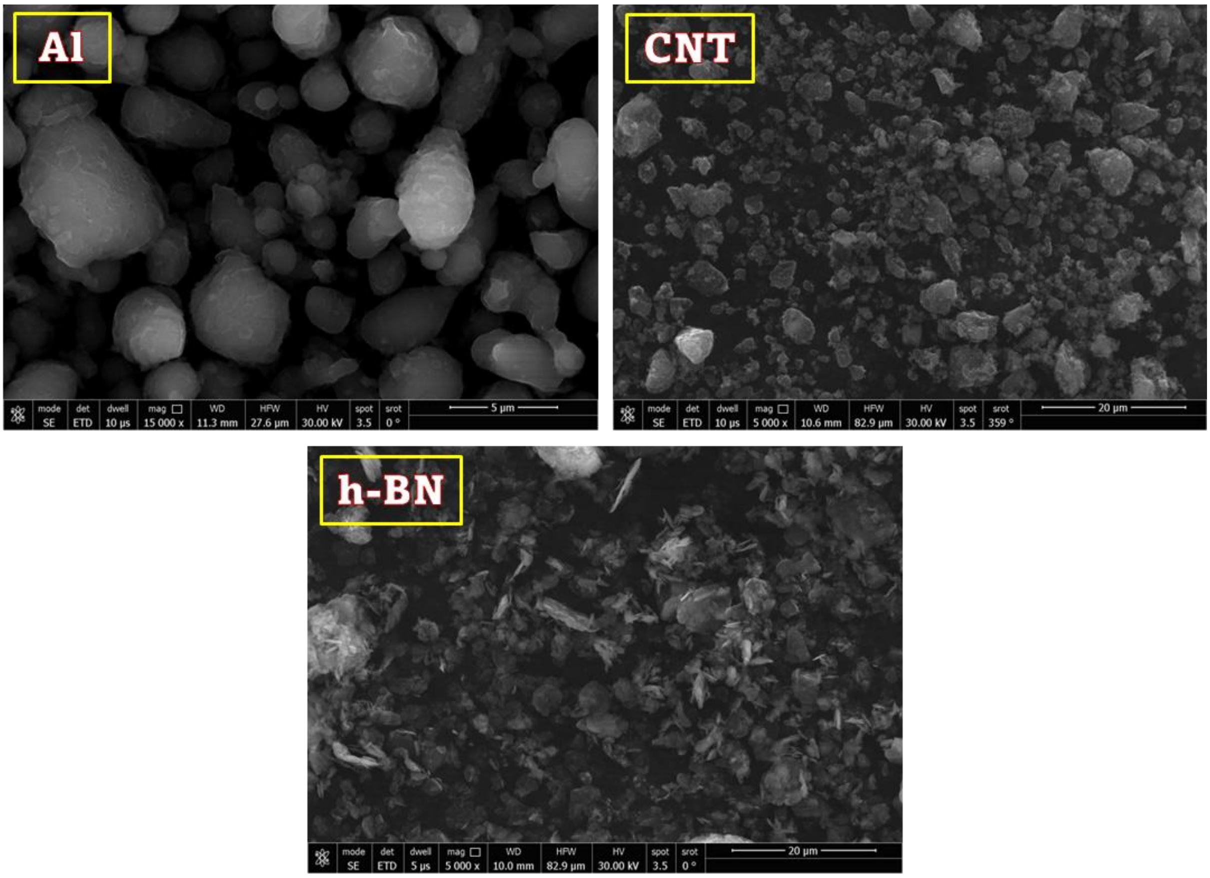

Figure 2. SEM images of the initial powders.

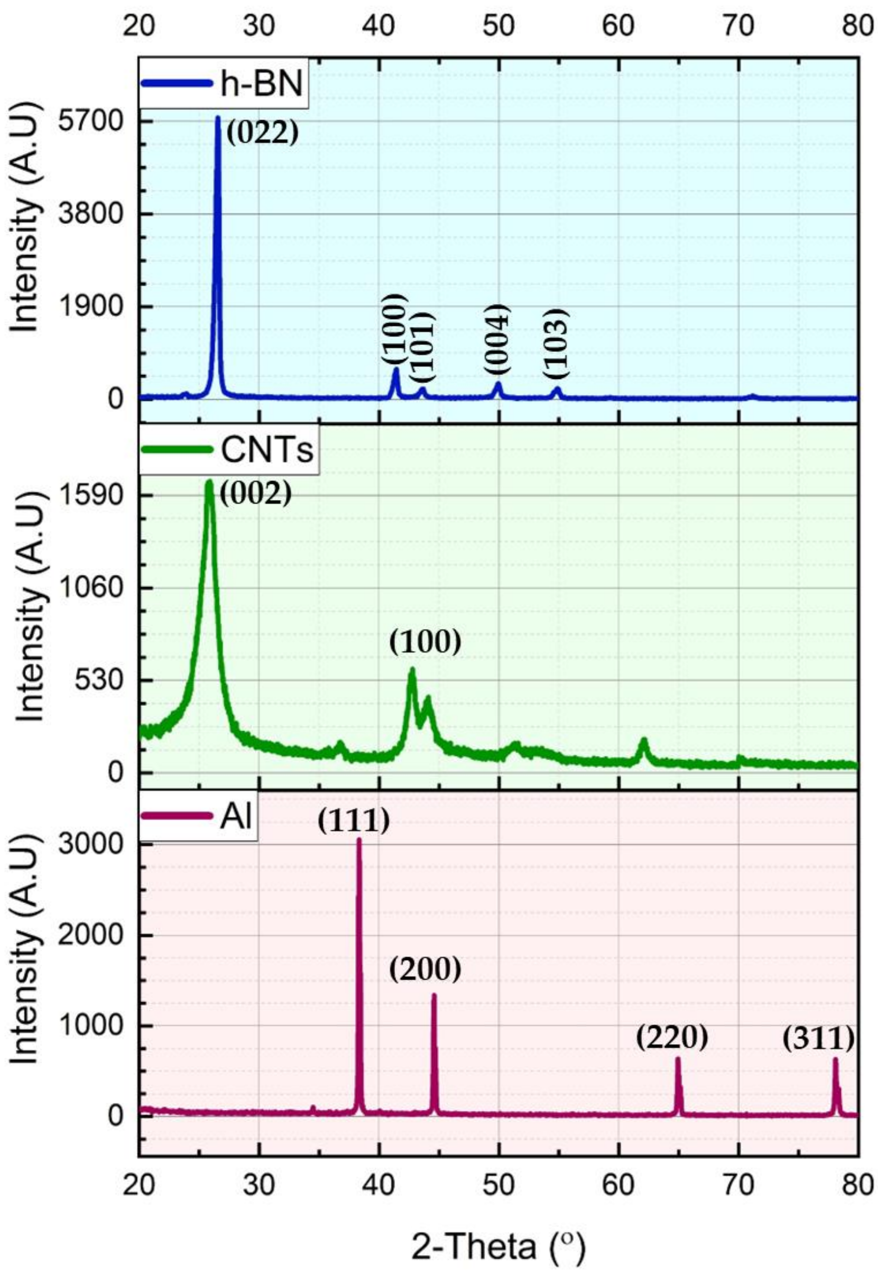

Figure 3. XRD results of initial powders.

Figure 4 features SEM images of the nano-reinforced CNTs and hBN following the Ag-Ni coating process. As illustrated in Figures 6 0% and 2%, the as-supplied nano-reinforcements provided in their original dimensions without any alterations and form after the electroless process, even when dispersed Ag/Ni existed in a nano-spherical arrangement. To verify the presence of Ni and Ag coatings, XRD was performed. The XRD patterns for both the CNTs and hBN reinforcements, both before and after the Ag/Ni coating process, along with the mixed Al/0.6 wt.% CNTs/2% wt.% h-BN, are depicted in **Figure 5**. No alterations to the citation, reference, or in-line citations are allowed. The spelling, specific terms, and phrases in American English must be strictly followed. The XRD patterns exclusively exhibit conspicuous peaks of the coated reinforcements (hBN/Ag/Ni and CNTs/Ag/Ni) utilized in the Al matrix. This feature guarantees that electroless coating and blending procedures were executed without introducing any extraneous substances into the mixture. Notably, their relatively small volume fractions hindered the detection of the CNTs, Ag, and Ni peaks.

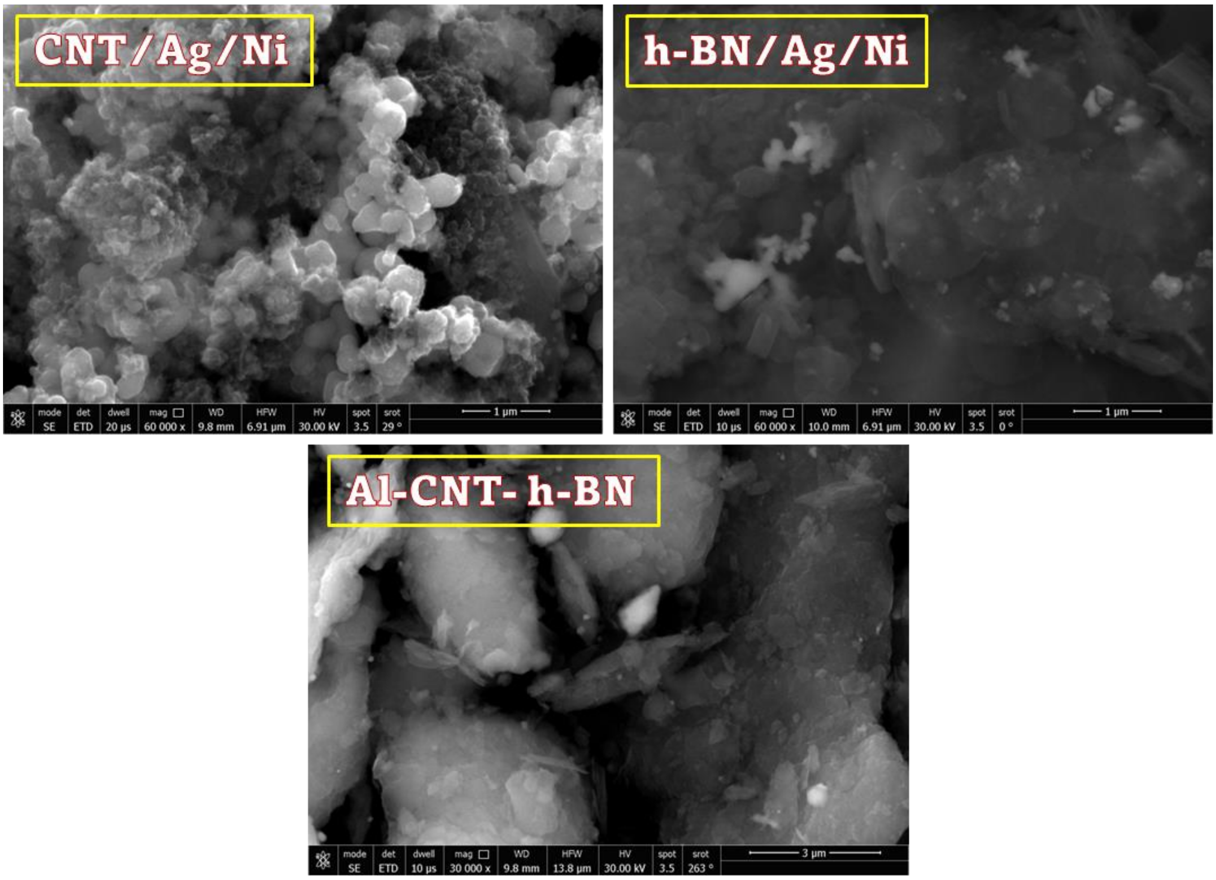

Figure 4. SEM images of Al, CNTs, and h-BN after coating

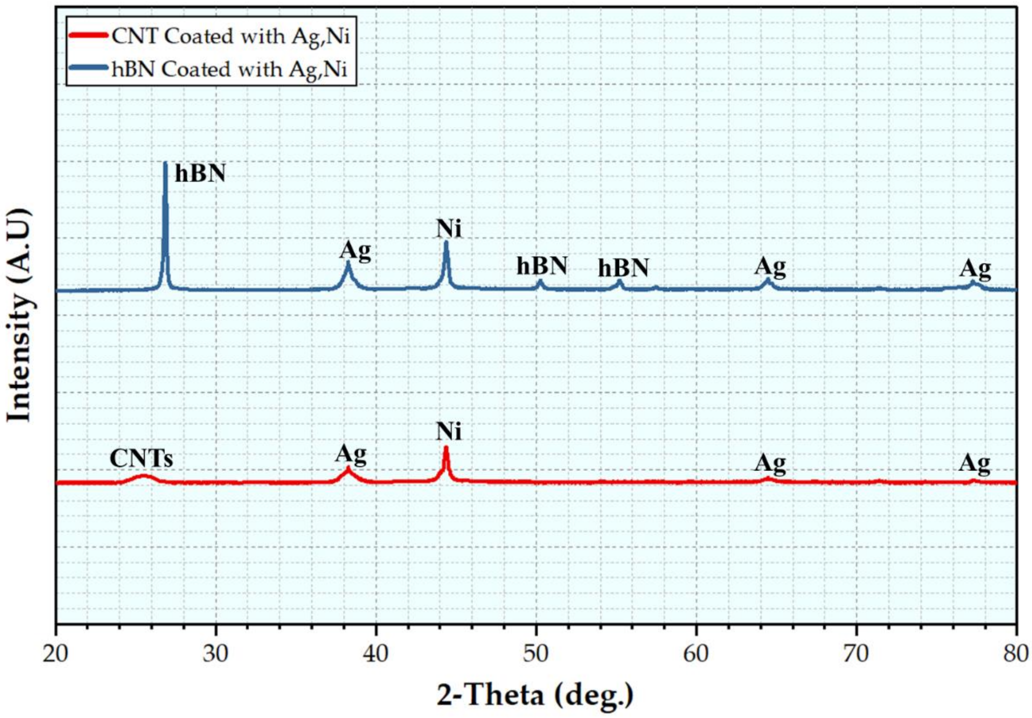

Figure 5. XRD diffraction images of CNTs, and h-BN before and after coating.

3.2 Microstructures of produced hybrid composites

Figure 6 shows the microstructures of the sintered pure Al and Al/CNT/h-BN hybrid composite. Al grains have irregular grain sizes, and their distribution displays inconsistency across the surface of the sintered pure Al sample. The microstructure significantly changed after adding CNTs and h-BN in the Al. This is because the Al grains became almost evenly distributed, and with the addition of CNTs and h-BN, the Al grains got smaller than in the sintered pure Al sample (**Figure 6**). Adding CNTs and h-BN helped organize the grains but prevented them from growing. It is noteworthy that Ni grains are irregularly dispersed between Al and h-BN grains. **Figure 7** shows the microstructure of the hot-rolled pure Al and Al/CNTs/h-BN hybrid composite. These microstructures clearly demonstrate the effectiveness of the hot-rolling process in changing the microstructure of the materials to produce them without large voids when subjected to compressive stress and the thermomechanical effect during the hot-rolling process. The microstructure changes before and after the hot-rolling process are expected to affect the physical and mechanical properties of the sintered and hot-rolled samples.

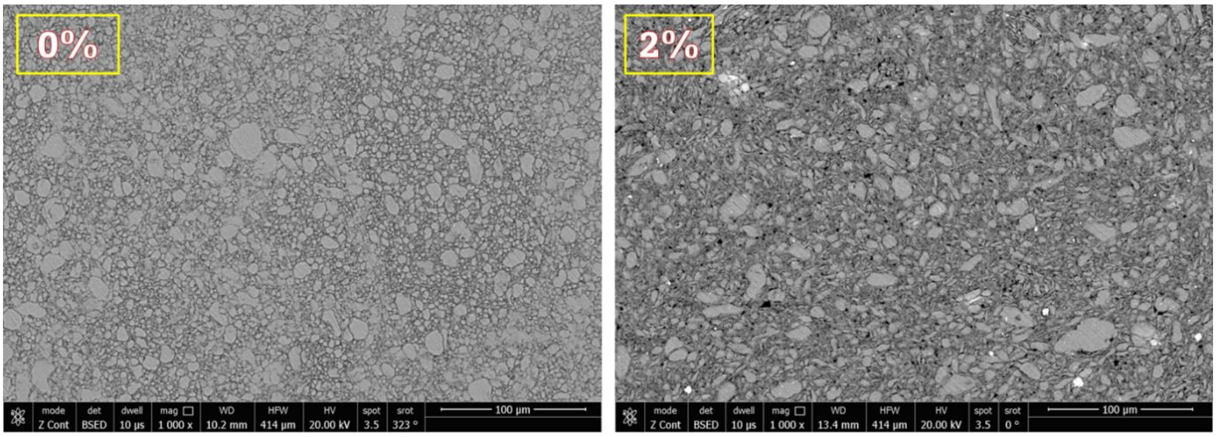

Figure 6. Microstructures of the sintered pure Al and Al/0.6wt.% CNTs/2wt.% h-BN hybrid composites.

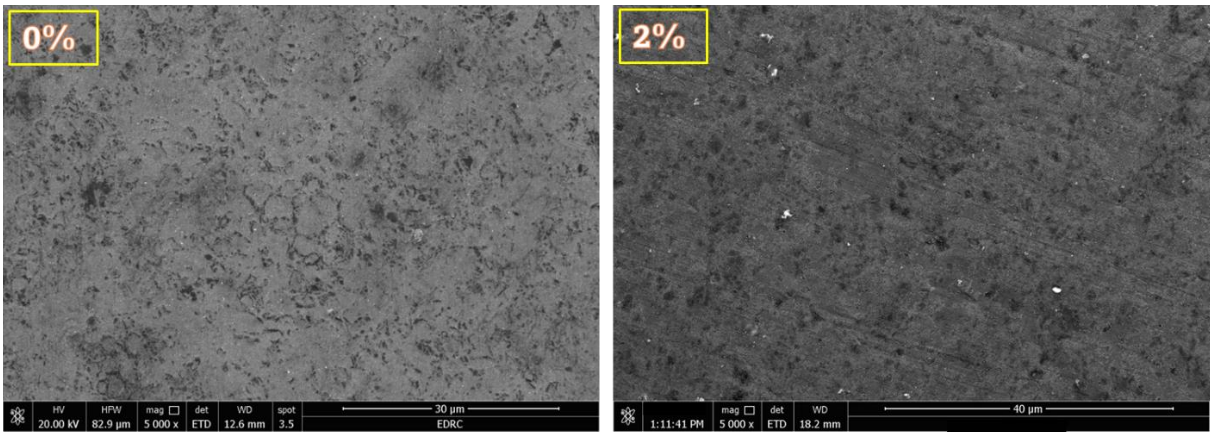

Figure 7. Microstructures of the hot-rolled pure Al and Al/0.6wt.% CNTs/2wt% h-BN hybrid composites.

3.3 Physical and Mechanical Properties

Figure 8 shows the relative densities of the pure Al and Al/0.6 wt.% CNTs/2 wt.% h-BN samples before and after the hot-rolling process. It is interesting to mention that the pure Al samples that were sintered and hot-rolled achieved relative densities close to full densification, reaching approximately 99%. Nevertheless, the incorporation of CNTs and h-BN into the sintered hybrid composites led to a slight decrease in their relative densities. In general, the relative densities of sintered and hybrid composite samples of over 95% for the sintered hybrid Al/CNT/h-BN composites can be attributed to the exceptional self-lubricating properties of h-BN. During the hot-pressing process, h-BN functioned as a solid lubricant, effectively minimizing the interparticle friction of powder particles. This allowed for particle rearrangement and effective packing, resulting in improved compaction and reduced voids or porosity. In addition, the lubricating properties of h-BN prevent grain growth and agglomeration, helping maintain the integrity of the particle boundaries [24,25]. The incorporation of h-BN nanoparticles boosts particle packing, solid-state diffusion, and interparticle bonding, ultimately resulting in a significant improvement in densification. In contrast, the hot-rolling process is a thermomechanical treatment that involves subjecting the porous rolled material to elevated temperatures and compressive forces, resulting in rearrangement and deformation of the metallic particles [4,26]. After the hot-rolling process was applied to the Al and hybrid composite samples, the densification properties improved for both samples. For the hot-rolled pure Al sample, the application of heat and pressure during hot rolling facilitated the plastic deformation of the Al particles, leading to their closer packing and elimination of residual porosity [27,28]. Consequently, the hot-rolled Al samples exhibited enhanced densification, characterized by higher relative densities and reduced porosity levels, compared to their as-sintered counterparts. This densification process is accompanied by microstructural changes (**Figures 6 and 7**), such as grain refinement, which can further affect the mechanical properties and performance of the produced Al and Al/CNT/h-BN hybrid composite samples. When the hot-rolling process is in the Al/CNTs/h-BN, the hot-rolling process exerts an effect on the densification properties of the sintered Al/CNT/h-BN hybrid composite sample. In this composite system, Al is reinforced with CNTs and h-BN. When hot rolling is performed, the simultaneous effects of increased temperatures and compressive forces enable the reorganization and deformation of the Al matrix, resulting in a more compact arrangement of the metallic particles. Simultaneously, the CNTs and h-BN underwent dispersion and alignment within the Al matrix, contributing to the densification process. The hot-rolling process effectively reduced the porosity levels and improved the interfacial bonding between the Al matrix and reinforcements, resulting in enhanced densification and consolidation of the hybrid composite. In addition, the dense structure-produced samples demonstrate the success of the production processes, including coating, mixing, hot-pressing, and hot-rolling. These high densities are expected to have a significant impact on the mechanical and wear properties of sintered composites.

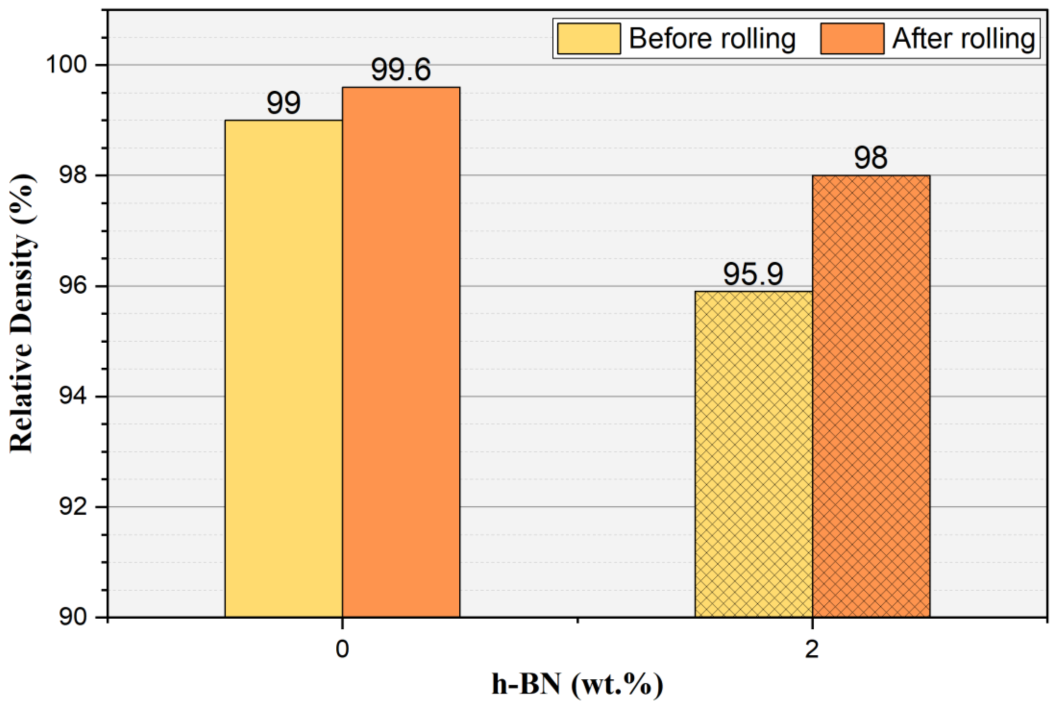

Figure 8. Relative density of sintered and hot-rolled pure Al samples

The results in **Figure 9** show the hardness values of the sintered samples compared to those of the hot-rolled samples of pure Al and its hybrid composites. The microhardness of sintered pure Al (59 HV) increased to the101.6 HV after adding the 0.6 wt.% CNTs and 2 w.% h-BN as a reinforcement to the Al-matrix. The incorporation of CNTs into the Al matrix leads to an improvement in the mechanical characteristics, including hardness, owing to the interface between the metal and CNTs and the chemical and structural stability of the CNTs. [29]. This enhancement in hardness was attributed to the strengthening factors provided by the addition of CNTs. In contrast, a study by Vorozhtsov et al. [30] indicated that while the hardness of composites increased with isothermal holding time during hot pressing, it decreased with increasing CNTs content over 1 wt. % within the material. This suggests that there may be an optimal CNTs content for maximizing the hardness, beyond which the properties may deteriorate. However, the relationship between CNTs content and hardness is not linear, and excessive CNTs may lead to a decrease in hardness [30]. However, the addition of h-BN to different matrices tends to influence the mechanical properties, including hardness. For instance, in SS316L/h-BN composites, the hardness decreases with an increase in h-BN content but it can be enhanced by raising the sintering temperature. [31]. In the case of PA66/h-BN composites, the Rockwell hardness was improved by the addition of h-BN [30]. Similarly, Al 6061-based composites reinforced with BN showed an increase in hardness [32], as did Al7050 reinforced with h-BN, which also exhibited an increased hardness [33]. These findings suggest that h-BN can enhance the hardness of MMCs. Although the specific effect of h-BN on Al/CNT composites has not been explicitly discussed, the layered structure of h-BN facilitates easy sliding of dislocations, potentially reducing hardness. Nevertheless, the incorporation of h-BN can promote grain refinement in the Al matrix during processing, leading to an increase in the grain boundary area and dislocation density, thereby contributing to hardness enhancement. The overall effect of h-BN on the hardness Al hybrid composites hardness depends on the delicate interplay between its solid lubricating effect and grain refinement ability, as well as on the optimal loading and dispersion of h-BN within the Al. Furthermore, the solid lubricating nature of h-BN may enhance the dispersion and distribution of 0.6wt.%CNTs in the Al, enhancing the load transfer efficiency and contributing to hardness enhancement. After applying the hot-rolling process, the sintered Al pure increased from 59.5 HV to 101.6 HV, and the Al/CNTs/h-BN hybrid composite sample increased from 89.8 HV to 124.3 HV (**Figure 9**). These improvements in both samples can be attributed to the elevated temperatures and compressive forces during hot rolling, which promote the recovery and recrystallization processes within the Al microstructure. This resulted in the formation of a finer and more homogeneous grain structure, leading to an increase in the grain boundary area and dislocation density. The higher dislocation density and increased grain boundary area act as barriers to dislocation motion, thereby increasing the resistance of the material to plastic deformation and enhancing its hardness [34–36]. In addition, elevated temperatures and compressive forces during hot rolling allowed particle rearrangement and effective packing, resulting in improved densification of hot-rolled samples and reduced voids or porosity, subsequently improving the hardness. It can be concluded that after applying the hot-rolling process, a higher microhardness was obtained for the hot-rolled Al/0.6 % CNTs/2% h-BN samples, with improvements of around 108%, 38%, and 23% compared to the sintered Al, hot-rolled Al, and sintered Al/CNTs/h-BN samples, respectively, as shown in **Figure 9**.

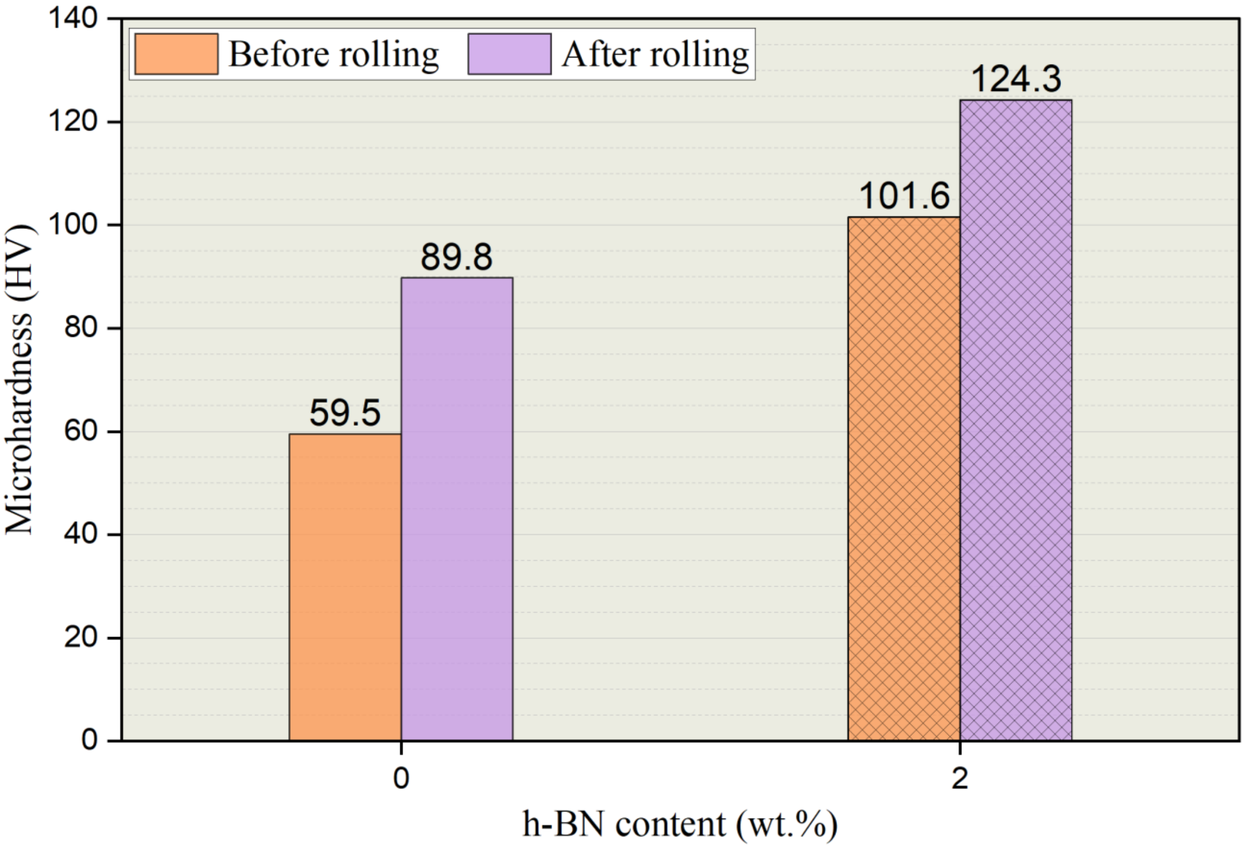

Figure 9. Microhardness of sintered and hot-rolled pure Al samples.

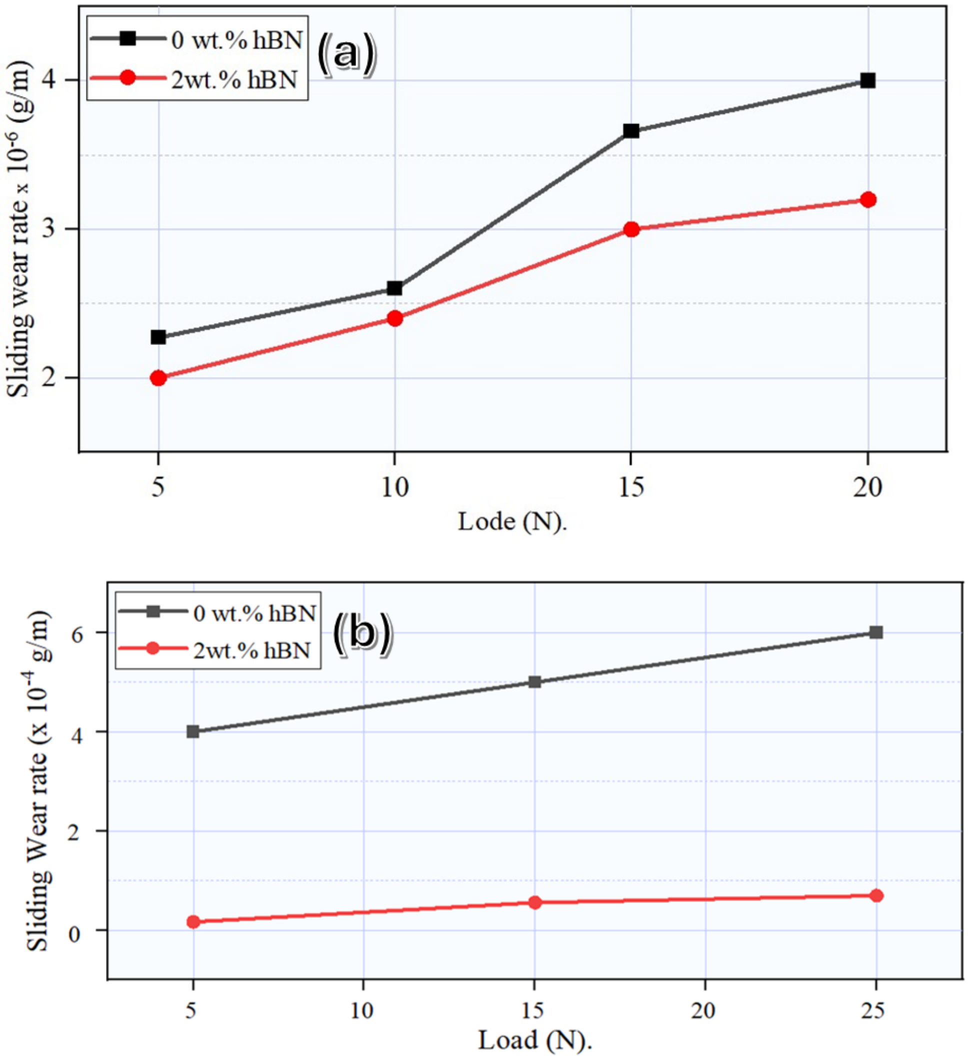

Figure 10 (a, b) illustrate the wear rate of the sintered samples, both before and after the hot rolling process, respectively.

The results presented in Figure 10a depict the variations in wear rates observed in both the aluminum matrix and the aluminum-carbon nanotubes/hexagonal boron nitride (Al-CNTs/h-BN) nanocomposites when subjected to dry sliding wear conditions at varying loads while keeping other parameters constant. The findings of the study consistently demonstrate an increase in wear rates as the applied load increases across all the samples examined. This suggests a direct correlation between the depth of wear penetration in the consolidated specimens and the magnitude of the applied loads during the wear tests. With an increase in load, the indenter penetrates deeper into the material, consequently leading to a higher rate of wear [37,38,39]. While Figure 10 (b) shows a noticeable decrease in the wear rate compared to Figure 10 (a), due to the increase in the h-BN content to 2%wt, in addition to the effect of the hot rolling process. Hot rolling process enhances the surface hardness, wear resistance, and impact wear behavior of Al-CNTs/h-BN samples. addition the lower finishing rolling temperature refines the microstructure, increases grain boundary and dislocation densities, and promotes precipitation strengthening, all of which improve wear performance. Surface rolling can improve the rolling contact fatigue behavior and failure mechanism of PM Al-CNTs/h-BN samples compared to unrolled samples.in finally the combination of increased h-BN content and the application of the hot rolling process has resulted in a significant reduction in the wear rate of the Al-CNTs/h-BN nanocomposite samples. The hot rolling process plays a crucial role in refining the microstructure and improving the surface properties, ultimately enhancing the overall wear resistance of the PM-produced nanocomposite materials.[40]

Figure 11 depicts the conductivities of the pure aluminum and hybrid composite samples before and after hot rolling. It is evident that the conductivity of both pure Al samples decreased after the addition of 0.6wt.%CNTs and2wt.% h-BN as reinforcements to create the Al/06wt.%CNT/2wt.%h-BN hybrid composite. This decrease in conductivity can be attributed to the poor conductivity of 2wt.% h-BN, which acts as an insulating barrier and disrupts the continuous conductive network of pure Al [41]. Additionally, the presence of these reinforcements introduces interfaces and grain boundaries within the composite, which act as electron scattering sites, thereby increasing the overall electrical resistivity. Although h-BN is an electrical insulator, it can enhance certain properties when added to the composites. For example, it has been shown to increase the threshold voltage between the ohmic and space-charge-limited current (SCLC) regions in epoxy composites, indicating a modification of the electrical conductivity within certain field ranges [42]. However, this does not contradict the observed decrease in electrical conductivity in the aluminum matrix, as the mechanisms of electrical conduction in the epoxy and aluminum composites differ. The addition of h-BN to Al results in decreased electrical conductivity owing to its insulating nature, which interrupts the conductive pathways within Al [41]. Despite its ability to modify the electrical properties of other composite systems [42], the fundamental insulating characteristics of h-BN dominate when mixed with conductive matrices, such as Al. On the other hand, after applying the hot-rolling process to both samples of sintered pure Al and its hybrid composite, it was observed that the electrical conductivities of both samples increased (**Figure 11**). This can be attributed to several factors. During the hot-rolling process, the composite undergoes plastic deformation, which leads to the alignment and orientation of the CNTs and h-BN along the rolling direction. This alignment creates preferential conductive pathways within the composite, allowing more efficient electron transport [43,44]. Additionally, the hot rolling process promotes interfacial bonding between the Al matrix and reinforcements, reducing the interfacial resistance and facilitating better electron transfer across the interfaces [43]. Furthermore, the hot-rolling process can help reduce the agglomeration of CNTs and h-BN, resulting in a more uniform dispersion within the Al matrix [43]. This improved dispersion further enhances the electrical conductivity by minimizing the formation of resistive regions [42,45]. Consequently, the electrical conductivity of the material was enhanced during the hot rolling process. This is attributed to various microstructural changes, such as the improved alignment of the reinforcements, enhanced interfacial bonding, and better dispersion. These factors collectively contribute to the observed increase in the electrical conductivity after hot rolling. It can be concluded that higher (41.2 IACS) and lower (17.1 IACS) conductivities of the produced samples were observed in the hot-rolled pure Al sample and sintered Al/CNTs/h-BN hybrid composite sample, as shown in **Figure11**.

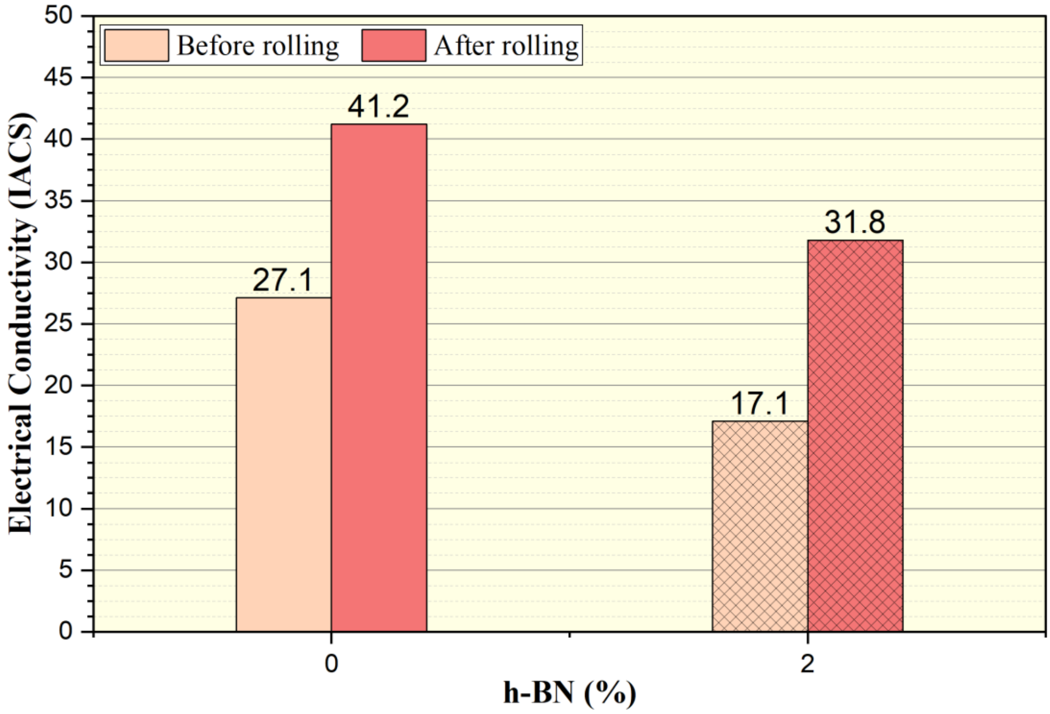

Figure 11. Electrical conductivity of sintered and hot-rolled Aure Al samples

5. Conclusions

The study focused on investigative the microstructures, mechanical properties, and physical properties of the Al/CNT/hBN hybrid composites, which were fabricated through hot compaction and hot rolling. The investigation resulted in the following conclusions:

1. The main findings are that the hot-rolled Al/CNT/hBN hybrid composites exhibit improved mechanical and physical properties compared to other sintered and hot-rolled samples.

2. The results showed that applying the hot-rolling process improved the densification and hardness of Al and its hybrid composite of Al/CNTs/h-BN. The relative densities of sintered and hybrid composite samples revealed a high densification of over 95%.

3. The hardness improved to approximately 108%, 38%, and 23% compared to the sintered Al, hot-rolled Al and sintered Al/CNTs/h-BN samples.

4. The electrical conductivity of pure Al decreased after the addition 0.6wt.%CNTs and 2wt.% h-BN. This reduction in electrical conductivity can be considered as the main factor contributing to lower conductivity of h-BN. The results showed that the hot-rolled pure aluminum sample had a higher conductivity of 41.2 IACS, while the sintered Al/CNTs/h-BN hybrid composite sample had a lower conductivity of 17.1 IACS.

References

1. Barakat, W.S.; Habba, M.I.A.; Ibrahim, A.; Fathy, A.; Elkady, O.A. The Effect of Cu Coated Al2O3 Particle Content and Densification Methods on the Microstructure and Mechanical Properties of Al Matrix Composites. *J. Mater. Res. Technol.* **2023**, *24*, 6908–6922.
2. Fouad, R.A.; Ibrahim, A.A.; El-Sayed Seleman, M.M.; Ataya, S.; Habba, M.I.A. Mechanical Properties and Wear Performance of Denture Base Polymethyl Methacrylate Reinforced with Nano Al 2 O 3. *J. Thermoplast. Compos. Mater.* **2024**, *0*, 1–26, doi:10.1177/08927057241241500.
3. El-Sayed Seleman, M.M.; Ataya, S.; Ahmed, M.M.Z.; Hassan, A.M.M.; Latief, F.H.; Hajlaoui, K.; El-Nikhaily, A.E.; Habba, M.I.A. The Additive Manufacturing of Aluminum Matrix Nano Al2O3 Composites Produced via Friction Stir Deposition Using Different Initial Material Conditions. *Materials (Basel).* **2022**, *15*, doi:10.3390/ma15082926.
4. Wang, W.; Heydari Vini, M.; Daneshmand, S. Mechanical and Wear Properties of Al/TiC Composites Fabricated via Combined Compo-Casting and APB Process. *Crystals* **2022**, *12*, 1–11, doi:10.3390/cryst12101440.
5. Tang, B.; Jiang, X.; Jin, P.; Wang, H.; Peng, H. Effects of Hot Extrusion Deformation on Microstructure and Mechanical Properties of the Spray-Deposition 17 Vol.% SiCp/7055Al Composite. *Mater. Res. Express* **2021**, *8*, doi:10.1088/2053-1591/ac128b.
6. Barakat, W.; Elkady, O.; abuoqail, A.; Yehya, H.; EL-Nikhaily, A. EFFECT OF Al2O3 COATED Cu NANOPARTICLES ON PROPERTIES OF Al / Al2O3 COMPOSITES. *J. Pet. Min. Eng.* **2020**, *0*, 0–0, doi:10.21608/jpme.2020.19110.1017.
7. Chenrayan, V.; Parthiban, M.; Venkatachalam, C.; Gelaw, M. Experimental and Optimised Data Set for Hot Extrusion of B4C/Al 6061 Composite Using Taguchi Coupled GRA Technique. *Data Br.* **2020**, *29*, 105389, doi:10.1016/j.dib.2020.105389.
8. Roy, S.; Schell, K.G.; Bucharsky, E.C.; Weidenmann, K.A.; Wanner, A.; Hoffmann, M.J. Processing and Characterization of Elastic and Thermal Expansion Behaviour of Interpenetrating Al12Si/Alumina Composites. *Mater. Sci. Eng. A* **2019**, *743*, 339–348, doi:10.1016/j.msea.2018.11.100.
9. Wagih, A.; Abu-Oqail, A.; Fathy, A. Effect of GNPs Content on Thermal and Mechanical Properties of a Novel Hybrid Cu-Al2O3/GNPs Coated Ag Nanocomposite. *Ceram. Int.* **2019**, *45*, 1115–1124.
10. Yang, X.; Zou, T.; Shi, C.; Liu, E.; He, C.; Zhao, N. Effect of Carbon Nanotube (CNT) Content on the Properties of in-Situ Synthesis CNT Reinforced Al Composites. *Mater. Sci. Eng. A* **2016**, *660*, 11–18, doi:10.1016/j.msea.2016.02.062.
11. Kwon, H.; Leparoux, M. Hot Extruded Carbon Nanotube Reinforced Aluminum Matrix Composite Materials. *Nanotechnology* **2012**, *23*, doi:10.1088/0957-4484/23/41/415701.
12. Esawi, A.M.K.; Morsi, K.; Sayed, A.; Gawad, A.A.; Borah, P. Fabrication and Properties of Dispersed Carbon Nanotube-Aluminum Composites. *Mater. Sci. Eng. A* **2009**, *508*, 167–173, doi:10.1016/j.msea.2009.01.002.
13. Khani, M.; Ezatpour, H. reza; Ebrahimi, G. Mechanical and Microstructure Properties of Al/CNT-Al2O3 Hybrid Nanocomposite Produced by Accumulative Roll Bonding Process. *mdrsjrns* **2018**, *17*, 56–64.
14. Irhayyim, S.S.; Hammood, H.S.; Abdulhadi, H.A. Effect of Nano-TiO2 Particles on Mechanical Performance of Al-CNT Matrix Composite. *AIMS Mater. Sci.* **2019**, *6*, 1124–1134, doi:10.3934/matersci.2019.6.1124.
15. Nayim, S.M.T.I.; Hasan, M.Z.; Seth, P.P.; Gupta, P.; Thakur, S.; Kumar, D.; Jamwal, A. Effect of CNT and TiC Hybrid Reinforcement on the Micro-Mechano-Tribo Behaviour of Aluminium Matrix Composites. *Mater. Today Proc.* **2020**, *21*, 1421–1424, doi:10.1016/j.matpr.2019.08.203.
16. Nyanor, P.; El-Kady, O.; Yehia, H.M.; Hamada, A.S.; Hassan, M.A. Effect of Bimodal-Sized Hybrid TiC–CNT Reinforcement on the Mechanical Properties and Coefficient of Thermal Expansion of Aluminium Matrix Composites. *Met. Mater. Int.* **2021**, *27*, 753–766, doi:10.1007/s12540-020-00802-w.

17. Naik H R, M.; L H, M.; Malik, V.; Patel GC, M.; Saxena, K.K.; Lakshmikanthan, A. Effect of Microstructure, Mechanical and Wear on Al-CNTs/Graphene Hybrid MMC'S. *Adv. Mater. Process. Technol.* **2022**, *8*, 366–379, doi:10.1080/2374068X.2021.1927646.
18. Jeyasimman, D.; Sivasankaran, S.; Sivaprasad, K.; Narayanasamy, R.; Kambali, R.S. An Investigation of the Synthesis, Consolidation and Mechanical Behaviour of Al 6061 Nanocomposites Reinforced by TiC via Mechanical Alloying. *Mater. Des.* **2014**, *57*, 394–404, doi:10.1016/j.matdes.2013.12.067.
19. Khakbiz, M.; Akhlaghi, F. Synthesis and Structural Characterization of Al-B4C Nano-Composite Powders by Mechanical Alloying. *J. Alloys Compd.* **2009**, *479*, 334–341, doi:10.1016/j.jallcom.2008.12.076.
20. Murugadoss, P.; Jeyaseelan, C. Enhancing Tribo-Mechanical and Corrosion Properties of A383 Aluminum Matrix Composites through Stir-Cum-Squeeze Casting with Marble Dust and Hexagonal Boron Nitride Reinforcement. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2024**, doi:10.1177/14644207241235784.
21. Jiang, C.; Zou, Y.; Wang, S.; Wang, Y.; Ouyang, J.; Jia, D.; Zhou, Y. A HBN/B-Si-Al-O-Glass Composite Coating Growth on SiCp/Al Composite Using One-Step PEO with Nanoparticle Addition for Outstanding Electrical Insulation Performance. *Surf. Coatings Technol.* **2023**, *475*, doi:10.1016/j.surfcoat.2023.130147.
22. Mahto, N.K.; Shafali, K.; Tyagi, R.; Sharma, O.P.; Khatri, O.P.; Sinha, S.K. Friction and Wear of Ni3Al-Based Composites Containing Ag and Cu Modified HBN at Elevated Temperatures. *Wear* **2023**, *530–531*, doi:10.1016/j.wear.2023.205065.
23. Zhang, P.; Yao, C.; Yu, L.; Zhao, X.; Zhao, L.; Lan, L.; Dong, S. Large-Scale Plasma Grafts Voltage Stabilizer on Hexagonal Boron Nitride for Improving Electrical Insulation and Thermal Conductivity of Epoxy Composite. *High Volt.* **2023**, *8*, 550–559, doi:10.1049/hve2.12261.
24. Loganathan, P.; Arivalagar, A.A.; Nadanakumar, V.; Christu Paul, R.; Godwin John, J. Study on Microstructure, Mechanical and Wear Behavior of AA7075/HBN Composites Fabricated via Liquid Metallurgy. *Mater. Today Proc.* **2023**, doi:10.1016/j.matpr.2023.03.478.
25. Palanivendhan, M.; Chandradass, J. Fabrication and Characterization of ADC-12 Hybrid Composites Utilizing Lemon Grass Ash and Boron Nitride through Stir-Squeeze Casting Method. *Mater. Res. Express* **2023**, *10*, doi:10.1088/2053-1591/ad076f.
26. Banijamali, S.M.; Najafi, S.; Sheikhani, A.; Palizdar, Y. Dry Tribological Behavior of Hot-Rolled WE43 Magnesium Matrix Composites Reinforced by B4C Particles. *Wear* **2022**, *508–509*, 204487, doi:10.1016/j.wear.2022.204487.
27. Yuan, C.; Tan, Z.; Fan, G.; Chen, M.; Zheng, Q.; Li, Z. Fabrication and Mechanical Properties of CNT/Al Composites via Shift-Speed Ball Milling and Hot-Rolling. *J. Mater. Res.* **2019**, *34*, 2609–2619, doi:10.1557/jmr.2019.219.
28. Guo, B.; Ni, S.; Yi, J.; Shen, R.; Tang, Z.; Du, Y.; Song, M. Microstructures and Mechanical Properties of Carbon Nanotubes Reinforced Pure Aluminum Composites Synthesized by Spark Plasma Sintering and Hot Rolling. *Mater. Sci. Eng. A* **2017**, *698*, 282–288, doi:10.1016/j.msea.2017.05.068.
29. Tajzad, I.; Ghasali, E. Production Methods of CNT-Reinforced Al Matrix Composites: A Review. *J. Compos. Compd.* **2020**, *2*, 1–9, doi:10.29252/jcc.2.1.1.
30. Vorozhtsov, S.; Kvetinskaya, A.; Khurstalyov, A.; Promakhov, V. Influence the Carbon Nanotubes on the Structure and Mechanical Properties of Aluminum-Based Metal Matrix Composites.; 2016; p. 030021.
31. Mahathanabodee, S.; Palathai, T.; Raadnui, S.; Tongsri, R.; Sombatsompop, N. Effects of Hexagonal Boron Nitride and Sintering Temperature on Mechanical and Tribological Properties of SS316L/h-BN Composites. *Mater. Des.* **2013**, *46*, 588–597, doi:10.1016/j.matdes.2012.11.038.
32. Keshavamurthy, R.; Saravanan, R.; Bharathesh, T.P.; Mukesh, Y.B. Effect of Hot Extrusion on Mechanical Behaviour of Boron Nitride Reinforced Aluminium 6061-Based Metal Matrix Composites. *Int. J. Mater. Eng. Innov.* **2019**, *10*, 135, doi:10.1504/IJMATEI.2019.10021339.

33. Srivallirani, K.; Venkateswara Rao, M. Fabrication and Mechanical Characterization of Al 7050/ TiO2/ BN Hybrid Metal Matrix Composites. In Proceedings of the Materials Today: Proceedings; Elsevier Ltd, 2020; Vol. 39, pp. 1750–1753.
34. Zhao, J.-R.; Hung, F.-Y.; Chen, J.-H. Effects of Heat-Treatment and Cold-Rolling on Mechanical Properties and Impact Failure Resistance of New Al 6082 Aluminum Alloy by Continuous Casting Direct Rolling Process. *Materials (Basel).* **2024**, *17*, 805, doi:10.3390/ma17040805.
35. Wang, C.S.; Wang, H.X.; Li, J. Bin; Zhang, J. Experiment on Hot Rolling Deformation Resistance of Aluminum Alloy and Mathematical Modeling. *Adv. Mater. Res.* **2011**, *314–316*, 409–414, doi:10.4028/www.scientific.net/AMR.314-316.409.
36. Cepeda-Jiménez, C.M.; García-Infanta, J.M.; Pozuelo, M.; Ruano, O.A.; Carreño, F. Impact Toughness Improvement of High-Strength Aluminium Alloy by Intrinsic and Extrinsic Fracture Mechanisms via Hot Roll Bonding. *Scr. Mater.* **2009**, *61*, 407–410, doi:10.1016/j.scriptamat.2009.04.030.
37. Sadoun, A.M.; Najjar, I.M.R.; Wagih, A. Electroless-Plating of Ag Nanoparticles on Al2O3 and Graphene Nano Sheets (GNs) for Improved Wettability and Properties of Al–Al2O3/GNs Nanocomposites. *Ceram. Int.* **2021**, *47*, 10855–10865.
38. Fathy, A.; Abu-Oqail, A.; Wagih, A. Improved Mechanical and Wear Properties of Hybrid Al-Al2O3/GNPs Electro-Less Coated Ni Nanocomposite. *Ceram. Int.* **2018**, *44*, 22135–22145.
39. Sadoun, A.M.; Fathy, A.; Abu-Oqail, A.; Elmetwaly, H.T.; Wagih, A. Structural, Mechanical and Tribological Properties of Cu–ZrO2/GNPs Hybrid Nanocomposites. *Ceram. Int.* **2020**, *46*, 7586–7594.
40. Chen, D.; Li, D.; Peng, J.; Wang, T.; Yan, B.; Lu, W. The Effect of Rolling Temperature on the Microstructure and Mechanical Properties of Surface-Densified Powder Metallurgy Fe-Based Gears Prepared by the Surface Rolling Process. *Metals (Basel).* **2017**, *7*, 420.
41. Wang, J.; Ma, F.; Liang, W.; Sun, M. Electrical Properties and Applications of Graphene, Hexagonal Boron Nitride (h-BN), and Graphene/h-BN Heterostructures. *Mater. Today Phys.* **2017**, *2*, 6–34, doi:10.1016/j.mtphys.2017.07.001.
42. DESMARS, L.; GALY, J.; BACHELLERIE, D.; CRISTIANO-TASSI, A.; HALLER, S.; PRUVOST, S. High Voltage Electrical Properties of Epoxy / h-BN Microcomposites. In Proceedings of the 2018 IEEE 2nd International Conference on Dielectrics (ICD); IEEE, July 2018; pp. 1–5.
43. Wu, C.; Ma, W.X.; Chen, Y.P.; Li, Y.; Chen, Y.; Li, J. Progress of the Current Interface Research on Carbon Nanotubes Reinforced Aluminum-Matrix Composites. *Adv. Mater. Res.* **2013**, *842*, 196–200, doi:10.4028/www.scientific.net/AMR.842.196.
44. Su, Z.; Wang, H.; Ye, X.; Tian, K.; Huang, W.; He, J.; Guo, Y.; Tian, X. Anisotropic Thermally Conductive Flexible Polymer Composites Filled with Hexagonal Born Nitride (h-BN) Platelets and Ammine Carbon Nanotubes (CNT-NH2): Effects of the Filler Distribution and Orientation. *Compos. Part A Appl. Sci. Manuf.* **2018**, *109*, 402–412, doi:10.1016/j.compositesa.2018.03.021.
45. Ng, H.Y.; Lu, X.; Lau, S.K. Thermal Conductivity, Electrical Resistivity, Mechanical, and Rheological Properties of Thermoplastic Composites Filled with Boron Nitride and Carbon Fiber. *Polym. Compos.* **2005**, *26*, 66–73, doi:10.1002/pc.20076.