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Enhancing Mechanical Properties of Aluminum Matrix Composites Reinforced with Carbon Nanotubes: A Review of Fabrication Methods and Applications

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Abstract: *This study reviews the fabrication methods and compositions of aluminum matrix composites reinforced with Carbon Nanotubes (CNTs), aiming to enhance the mechanical properties of aluminum composites. The methods analyzed include ball milling, spark plasma extrusion (SPE), and chemical vapor deposition (CVD), each showing unique advantages in improving tensile strength, hardness, wear resistance, and thermal conductivity. The study highlights significant findings, such as SPE's ability to address CNT agglomeration, ensuring a more homogeneous distribution, and increasing material density. Results also reveal the effectiveness of CNT coatings in improving electromagnetic shielding performance and thermal conductivity for extreme conditions. The significance of this research lies in identifying optimal fabrication techniques and compositions, offering valuable insights for advancing lightweight, high-strength materials in automotive, aerospace, and other industries. This study emphasizes the potential of Al-CNT composites as superior materials for industrial applications and the need for further exploration of hybrid fabrication methods and CNT types.*

Keywords: *Aluminum matrix composite, Carbon Nanotubes, Mechanical properties, Fabrication methods.*

Abstrak: Penelitian ini mengulas metode fabrikasi dan komposisi komposit matrik aluminium yang diperkuat dengan Karbon Nanotube (CNT), yang bertujuan untuk meningkatkan sifat mekanis komposit aluminium. Metode yang dianalisis meliputi ball milling, spark plasma extrusion (SPE), dan chemical vapor deposition (CVD), yang masing-masing menunjukkan keunggulan unik dalam meningkatkan kekuatan tarik, kekerasan, ketahanan aus, dan konduktivitas termal. Studi ini menyoroti temuan penting, seperti kemampuan SPE untuk mengatasi aglomerasi CNT, memastikan distribusi yang lebih homogen, dan meningkatkan kepadatan material. Hasil juga mengungkapkan efektivitas pelapis CNT dalam meningkatkan kinerja pelindung elektromagnetik dan konduktivitas termal untuk kondisi ekstrem. Signifikansi penelitian ini terletak pada identifikasi teknik dan komposisi fabrikasi yang optimal, yang menawarkan wawasan berharga untuk memajukan material ringan dan berkekuatan tinggi dalam industri otomotif, kedirgantaraan, dan industri lainnya. Penelitian ini menekankan potensi komposit Al-CNT sebagai material unggul untuk aplikasi industri dan perlunya eksplorasi lebih lanjut terhadap metode fabrikasi hibrida dan jenis CNT.

Kata Kunci: Aluminum matrix composite, Carbon Nanotubes, Mechanical properties, Fabrication methods.

I. Introduction

Aluminium is a lightweight metal with good casting ability, low density, high corrosion resistance, ductility, and a high melting point, making it widely used in various industries [1]. However, in actual application processes, low wear and corrosion resistance seriously shorten the lifespan of aluminium alloys [2]. The development of nanomaterials has opened new avenues in blending composite matrix materials. Aluminium must improve its mechanical properties by creating a Carbon Nanotube (CNT) reinforced aluminium matrix composite. CNT-reinforced aluminium matrix composites have great potential for industrial applications due to their high specific strength, high thermal conductivity, and good thermal expansion coefficient [3].

In the automotive and aerospace industries, the demand for lightweight yet strong materials increases to improve fuel efficiency and reduce carbon footprints. Aluminium composites reinforced with Carbon Nanotubes (CNT) have great potential in addressing this challenge due to their high specific strength and thermal conductivity. Carbon Nanotubes are increasingly recognized in composites for their extraordinary strength, Young's modulus, thermal expansion, and superior electrical and thermal conductivity [4]. However, in practice, incorporating CNT into the aluminium matrix faces several challenges, including CNT agglomeration and uneven distribution within the matrix. This reduces the effectiveness of material reinforcement, thus requiring optimal fabrication methods to achieve a more homogeneous distribution.

In recent decades, much research has been conducted on this alloy. This journal aims to review several existing studies and analyze the percentages [5], the methods used [6], and the challenges faced in those studies. This review is hoped to provide comprehensive insights into the latest developments and opportunities for further research in the future.

Generally, aluminium reinforcement with CNTs depends on dispersion, aspect ratio, degree of alignment of CNTs, and the interfacial strength between the Al matrix and the CNT surfaces [7]. The level of homogeneity of CNT dispersion in the Al matrix is crucial in determining mechanical strength and preventing mechanical cracking. In the matrix [8]. Although significant progress has been made in the fabrication of Al-CNT, there is still an opportunity for further research to explore new methods or combinations of existing techniques to achieve more optimal and consistent mechanical properties under various application conditions.

This journal discusses the differences in various fabrication methods for adding Carbon Nanotubes (CNTs) into an aluminium matrix, as well as their effects on the mechanical and physical properties of the resulting composite materials. Various methods used in previous studies yield different results regarding tensile strength, wear resistance, and electrical and thermal conductivity of the Al-CNTs alloy. In addition, the alloy compositions used in each study also vary, significantly impacting the material's performance. Therefore, it is important to understand which fabrication methods and alloy compositions yield the best results in optimizing aluminium's mechanical and physical properties reinforced with CNTs. This research aims to identify the best methods and compositions to produce superior-performance composite materials.

II. Methods

In conducting this journal review, we used a bibliographic approach by collecting and analysing various studies that addressed the fabrication methods and composition of Aluminium Matrix Composites (AMC) reinforced with Carbon Nanotubes (CNT). The search process was conducted through the Scopus database, using keywords such as carbon nanotube reinforcement, aluminium composites, and mechanical properties enhancement. Relevant journals were then selected based on their suitability to the research topic, discussing various fabrication techniques and their impact on tensile strength, hardness, wear resistance, and thermal conductivity of aluminium composites. Furthermore, the results of the various studies were compared to identify the advantages and limitations of each method, as well as the challenges still faced in the development of these composite materials. Through this approach, this study aims to provide a more comprehensive insight into the optimal methods for improving the mechanical and thermal performance of Al-CNT composites as well as the potential for further exploration in hybrid fabrication techniques.

The use of Carbon Nanotubes (CNT) as reinforcement in aluminium matrices has been extensively researched, mainly due to their ability to enhance aluminium's mechanical and thermal properties. With advancements in material technology, various methods have been applied to strengthen aluminium using CNT to improve its wear and corrosion resistance, which are the shortcomings of this material.

Methods such as powder blending and can roll, ball milling, hot extrusion, and catalytic chemical vapour deposition (CCVD) have improved mechanical properties and thermal conductivity. For example, in particular studies, adding 0.5% CNT to aluminium through the powder blending method resulted in a 20% increase in Young's modulus and a density of up to 99%. However, there was a slight decrease in the material's ductility.

Additionally, Al-CNT composites have shown promising potential for applications requiring electromagnetic shielding and high tensile strength. Previous research has shown that using CNT with the method of coating and compressing CNT sheets can enhance mechanical and thermal performance, making this composite material suitable for environments with extreme conditions that require protection against electromagnetic interference. Although research has shown significant progress, variations in the percentage and type of CNT and fabrication methods have proven to affect the final characteristics of composite materials significantly. This indicates that there is still room for further exploration to find the best combination of composition and fabrication methods to maximize strength, wear resistance, and thermal performance in CNT-reinforced aluminium composites. This study summarizes several research efforts using a bibliographic approach to analyze various fabrication methods of Aluminum Matrix Composites (AMC) reinforced with Carbon Nanotubes. (CNT). Data was collected by searching the Scopus database using keywords such as carbon nanotube reinforcement, aluminium composites, mechanical properties enhancement, and electromagnetic shielding materials. The summarized studies will be discussed for their advantages and compared to find the best one.

III. Results

In the discussion of the results that have been conducted, they can be presented in the form of a table containing several journals and references. To facilitate understanding, please refer to Table 1.

Table 1 Previous Research on Al/CNT

No.	Nanomaterial Composition (CNTs)	Metal Matrix Composite (Al)	Fabrication Method	Advantages	Ref
1.	CNTs	Al	The mechanical destruction of Al particles in paraffin oil prevents Al oxidation.	Melting strength 60% and tensile strength 23%	[7]
2.	0-2% Maximum strength 0.5%	Al	Powder blending and can rolling process	+ yield strength 42.9% + young's modulus 20% + densification 99% - ductility 19%	[9]
3.	multi-wall carbon nanotubes (MWCNT)	Al (99.7% pure,45lm, Alfa Aesar, USA)	spark plasma extrusion (SPE)	higher hardness (33%) and compressive strength (10%)	[10]

4	0,5% 1% 2% 5%	Al 99,7%	Ball milling dan hot extrusion	Sifat mekanik ditemukan meningkat secara signifikan dengan peningkatan kandungan CNT.	[5]
5.	As many as 12 layers sheets of CNT measuring 7 cm × 1.5 cm	Al	• Rolling compression and acetone spraying on CNT sheets. • Chemical doping of CNT sheets with gold particles. • Compounding CNT sheets with Aluminum through Physical compression, forming C/Al composites.	• High electromagnetic shielding performance (up to 75 dB in the X-band). • Excellent mechanical strength with tensile strength reaching 95 MPa. • High conductivity (1.3 × 10^6 S/m). • Lightweight with a density of 1,1 g/cm3.	[6]
6.	Vertically Aligned Carbon Nanotubes (VACNTs)	Aluminum-doped Zinc Oxide (AZO) glass substrate	Catalytic Chemical Vapor Deposition (CCVD)	• Increasing distribution of Fe-Co catalyst nanoparticles so that VACNT growth is more uniform • Optimal synthesis temperature at 650°C with a Fe:Co catalyst ratio of 1:3 and 2:3 • VACNT growth mechanism tends to be "root-growth" rather than "tip-growth" • The synthesis process using a simple and cost-effective dip-coating method • Successfully reduces the amount of amorphous carbon formed, thereby improving the structural quality and graphitic properties of VACNT	[11]
7.	Multi-wallet carbon nanotubes (MWCNTs) diameter 10-15nm	Al Powder 99.8%	Powder metallurgy and sintering	Repeated hot rolling improves mechanical properties, especially tensile strength, without sacrificing flexibility.	[12]

8.	Carbon Nanotube 57.09%	AI	Preparation of two types of CNTs modified from carbon fiber/phenolic composites	The tensile strength of CA-CP reaches 163.86 MPa, and the wear rate is reduced by 74.31% compared to CP. Specifically, when the thickness of CA-CP is only 0.4 mm, the EMI SE in the X-band reaches over 40 dB, demonstrating exceptional EMI shielding performance. CA-CP has a thermal conductivity increase of 50.42% at 150°C compared to CP.	[13]
9.	Carbon 1,7%	Al 98%	Mechanical milling is carried out for 20 hours and followed by hot extrusion.	During extrusion at 773 K, the composite's Yield Strength and Tensile Strength were 383 ± 18 MPa and 416 ± 18 MPa, respectively. The average uniform and total elongation at fracture were 2.1 ± 0.2% and 10.8 ± 0.2%, respectively. The thermal conductivity reached 216 ± 1.6 W m^{-1} K^{-1}.	[14]
10.	(MWCNT) with various weight fractions of 0.5, 1.0, 1.5, and 2.0 wt.% were synthesized internally.	Al size ~25µm	cold compaction and sintering	• The highest relative density (94.3%) and an increase in hardness (22.85%) were observed with 0.5 wt—% CNT at a compaction pressure of 600 MPa. • Increased hardness and wear resistance	[15]
11.	carbon nanotubes (CMWCNTs) with diameters of 10–20 nm and sizes of 0.5–2 µm	AI	Utilizing the excellent photo-thermal-electric conversion properties by embedding aerogel.	In this study, the EP/CCA80 composition exhibits excellent photo-thermo-electric conversion performance through the strategic integration of CMWCNT within a 3D CNF aerogel framework, enhanced by vacuum-assisted impregnation.	[16]

12.	1 g/l, 2 g/l and 3 g/l Carbon	Al 93.65%	Non-electric coating technique	This increase reached 44.5% and 47.9% for hardness properties, 44.4% and 46.3% for elastic modulus properties, while the increase in crack growth resistance reached 83.5% and 81.6% compared to uncoated specimens.	[17]
13.	Multi-walled CNT (Baytubes C150P)	Pure aluminum 99%	Spark Plasma Sintering (SPS)	Improving the specific strength and conductivity of the material. CNT also enhances the hardness modulus of aluminum.	[18]
14.	Vertically-aligned carbon nanotube (VACNTs)	Aluminium foil	CVD (Chemical Vapor Deposition)	An increase in heat dissipation efficiency of 40% compared to copper sheets, and 20% better than pyrolytic graphite sheets.	[19]
15.	Multi-wall carbon nanotubes (MWCNTs) with a diameter of 10-30nm and a length of 5-15µm	Al Powder purity 99%	ball-milling dan solution mixing	The composite produced by the solution-mixing method shows a 50% increase in hardness and a 14% increase in tensile strength compared to pure aluminium.	[20]
16.	0,5 to 5%	Al	Mixed physical method (Physicaly Mixing Method)	Improving the performance of aluminium in engineering applications and highlighting effective and efficient synthesis approaches.	[21]

The table provides a summary comparing many studies conducted using various fabrication methods. Research shows that only the Al–0.5% weight CNT strip exhibits improved mechanical properties: tensile strength, yield strength, Young's modulus, and lower density [9]. The main obstacle to successfully combining Al-CNTs is the agglomeration and poor distribution of CNTs within the metal matrix. One of the fabrication methods that successfully consolidates powder with minimal cracking in the extrudate and achieves high green density is spark plasma extrusion (SPE) [10].

The research using the non-electrolytic coating technique by adding carbon with concentrations of 1g/l, 2g/l, and 3g/l to the Al coating with a purity of 93.65% shows a significant improvement in mechanical properties. As a result, the material hardness increased by 47.9%, and the modulus of elasticity improved by 44.4%. Additionally, there was a significant increase in the material's resistance to crack growth, reaching an improvement of 83.5%[17]. Developing carbon fiber/phenolic composites by adding carbon nanotube (CNT) structures on the fiber surface to enhance strength, wear resistance, EMI protection, and thermal management. With CNTs in array form penetrating the resin matrix, these composites show significant improvements in mechanical properties and EMI efficiency compared to regular carbon fibers [13].

In the mechanical milling process followed by hot extrusion at a temperature of 773 K, with the addition of 1.7% carbon into Al with a purity of 98%, it shows a yield strength and tensile strength of 383 ± 18 MPa and 416 ± 18 MPa, respectively. The average uniform and total elongation at fracture measured reached 2.1 ± 0.2% and 10.8 ± 0.2%. This composite composition also produces a thermal conductivity of 216 ± 1.6 W m -1 K-1[14]. Epoxy composites reinforced with cellulose nanofibers and carbon nanotubes to enhance photothermal-electric conversion efficiency. This composite has an expansive light absorption range (200-2500 nm) and a solar energy conversion efficiency to heat of up to 54.35% with only 0.65% carbon nanotube content. With a maximum temperature difference reaching 25.3 °C and a voltage of up to 160.29 mV at a light intensity of 1.0 kW/m², this composite can power small devices, offering a practical, sustainable energy solution for remote areas [16].

IV. Discussion

This research reviews various fabrication methods used to add CNT to the aluminium matrix and their effects on the mechanical and thermal properties of the resulting composite materials. Some commonly used methods include ball milling, spark plasma extrusion (SPE), and catalytic chemical vapour deposition (CCVD), each having advantages in enhancing Al-CNT composites' strength, hardness, wear resistance, and thermal conductivity. Among the various methods tested, the results show that methods like SPE and ball milling consistently improve the tensile strength and hardness of the material. For example, the ball milling method followed by hot extrusion resulted in a hardness increase of 33% and a compressive strength increase of 10%, especially in composites with a CNT content of around 0.5% to 2%. This technique also maintains the material's flexibility, indicating potential in applications requiring strength and ductility.

However, the main challenge in mixing Al-CNT lies in the difficulty of distributing CNTs uniformly within the aluminium matrix, which often leads to agglomeration or clumping. Methods such as spark plasma extrusion have effectively addressed this issue by increasing density and reducing cracks in the resulting composites. For example, the SPE method with a low CNT ratio results in better mechanical strength and higher density, although it slightly reduces the material's ductility.

This study also found that variations in composition and fabrication methods significantly affect the composite's thermal characteristics and wear resistance. Several studies have shown that using CNT as a coating in the rolling compression technique can enhance the electromagnetic interference (EMI shielding) performance of composites up to 75 dB in the X-band, making them suitable for electromagnetic protection applications.

In future studies, it is important to continue exploring fabrication methods that can maximize the homogeneity of CNT distribution and enhance the interaction between materials. Combining the ball milling method with the rolling compression process can improve mechanical properties without sacrificing ductility. Additionally, exploring various types of CNTs (such as multi-walled or vertically-aligned CNTs) and their influence on the properties of composite materials can provide deeper insights into optimizing aluminium applications in extreme environments.

V. Conclusions

This research reviews various fabrication methods and compositions to enhance carbon nanotube-reinforced aluminium composites' mechanical and thermal properties. (CNT). The review found that several methods, such as ball milling followed by hot extrusion and spark plasma extrusion (SPE), consistently improve the material's tensile strength, hardness, and wear resistance. SPE, in particular, shows an advantage in addressing the issue of CNT agglomeration, resulting in a more homogeneous distribution and increased material density.

Although many fabrication methods show positive results, the main challenge still lies in the difficulty of evenly distributing CNTs within the aluminium matrix and avoiding agglomeration, which can reduce the effectiveness of the composite. Further development of techniques for more homogeneous CNT integration will be highly beneficial in enhancing the performance of composite materials.

This research also highlights the potential applications of Al-CNT composites in electromagnetic interference (EMI) shielding and industries that require a combination of high strength, lightweight, and good thermal conductivity. Further studies are needed to explore variations of CNTs, such as multi-walled and vertically-aligned CNTs, and the potential of hybrid fabrication methods to achieve optimal mechanical and thermal properties.

Overall, CNT-reinforced aluminium composites show great potential as superior materials in various industrial applications, especially under extreme conditions.

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