

Original Article

Microstructural Evolution and Mechanical Performance of Al6061-WC Composites Fabricated via Powder Metallurgy

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Abstract - Aluminium Matrix Composites (AMCs) are gaining interest for high-performance structural applications because they provide a higher Strength-to-Weight Ratio than conventional materials and superior Wear Resistance. Nevertheless, limitations like Dispersion of Reinforcement Particles, Interfacial Bonding, and Property Trade-offs hindered the broad use of these materials. In this study, the Fabrication and Characterization of an Aluminium composite based on Al6061, with Tungsten Carbide (WC) Particle Reinforcement using Powder Metallurgy (PM) and Controlled Atmosphere Sintering, is investigated. The effect of added varying percentages (0, 3, 6, 9, and 12 wt%) of WC particles to Al6061 on the Microstructural Characteristics and Mechanical Properties of the Al6061-WC Composite was investigated to optimize the optimum level of pre-milled nano-WC particles. Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-ray Diffraction (XRD) were used to confirm that the improvement in Particle Distribution and Phase Stability of the Al6061-WC Composite is directly related to the percentage of WC. Additionally, Mechanical Testing demonstrated that the mean Ultimate Tensile Strength (UTS) (151 MPa - 326 MPa) significantly improves with WC addition; however, Ductility and Impact Strength decrease due to an increase in Brittle Behaviour. Therefore, results clearly show that there is a Direct Relationship Between Strength and Ductility depending on the Content of Reinforcing Material and Quality of Interface. Analysis of Variance (ANOVA) was performed to check the data for significance, which showed a marked improvement for all properties, with a p-value of < 0.0001 . As such, this investigation has provided new knowledge regarding the optimization of Reinforcing Levels to achieve Enhanced Mechanical Performance in Al-Based Composites for Aerospace and Automotive Applications.

Keywords - Aluminium matrix composites, Tungsten carbide, Powder metallurgy, Mechanical properties, Microstructure.

1. Introduction

Advanced engineering applications (i.e., aerospace, automotive, military/defense) require new classes of materials with high mechanical properties at significantly lower weight and higher durability than traditional monolithic materials. This multi-functionality requirement has driven the development of advanced composite materials [1]. One category of materials that can potentially satisfy this requirement is AMCs. The attractive combination of low-density; high specific-strength, good corrosion-resistance, and good thermal-conductivity [2] attributes of AMCs makes them well-suited for applications requiring both high-performance-efficiency and significant weight-reduction [3]. Mostly, the improvement in the physical and mechanical characteristics of Al-based Metal Matrix Composites (MMCs) is due to a combination of ceramics that include SiC, Al₂O₃, and WC

[4]. These reinforcements improve strength and hardness, and also increase high temperature resistance and enhance the abrasion resistance [5]. Among all of these ceramic materials, WC stands out because it exhibits very high hardness values, high elastic modulus, and superior thermal stability when compared with other ceramic materials [6].

The potential benefits of developing WC-reinforced aluminium composites are offset by several inherent problems that need to be overcome [7]. A major problem is that of obtaining a homogeneous distribution of the reinforcement particles within the base metal. Because of their high surface energy, WC particles tend to agglomerate, leading to variations in the local microstructure and thus also to localized areas of high residual stresses [8]. This results in a less than desirable mechanical behaviour, especially when subjected to



tensile loads and impact loading [9]. It has been demonstrated in [10], that the ability of the reinforcement to improve the overall behaviour of the composite is strongly dependent upon the nature of the bond between the reinforcement and the matrix. Interfaces that are weak or lack continuity would impede the efficient transfer of loads from one phase to another and may lead to premature failure of the composite. There is also an apparent contradiction in terms of increasing both strength and ductility in particulate-reinforced metals. For example, while adding hard ceramic particles to a soft matrix tends to increase its hardness and tensile strength, it generally reduces its ductility and toughness as well. This is because the addition of such particles limits the extent of plastic deformation of the matrix [11]. Thus, understanding this trade-off is essential for determining the optimum amount of reinforcement required to achieve a good balance of properties for specific practical applications [12].

Although many previous studies demonstrated an increase in the mechanical properties of Al-WC composites by WC reinforcement, the current state of knowledge about how different processing parameters can lead to specific changes in microstructure and ultimately affect the mechanical properties of these materials is incomplete [13]. Moreover, a number of studies failed to take a systematic approach when investigating variations in reinforcement content while performing multi-scale characterizations of their microstructure using techniques such as SEM, TEM and XRD [14]. A combination of both systematic variation of reinforcement content and the use of multi-scale characterization techniques is necessary to establish relationships between microstructural features and corresponding mechanical properties [15]. As a result of a critical analysis of past studies regarding the subject matter at hand, it has become apparent that several areas of research remain unexplored. Specifically, although WC particles may be dispersed into the Aluminium matrix, they rarely are dispersed effectively or uniformly throughout the matrix. Consequently, poor dispersion of WC particles leads to agglomerations and the formation of non-uniform microstructures. These types of microstructures adversely affect the mechanical properties of the composite material [16]. Similarly, few studies have investigated the direct relationship between microstructural characteristics (particle distribution, bond strength at the interface between phases, and overall phase composition) and mechanical properties. Finally, most studies failed to provide a systematic means of varying the amount of reinforcement added during fabrication while maintaining consistent processing conditions. This inability to systematically vary reinforcement content has made it challenging to determine optimal composition levels [17]. Ultimately, failure to characterize the composite material's structure through multi-scale methods (using techniques such as SEM, TEM, and XRD), limits one's ability to fully understand the strengthening mechanisms and structural integrity of composite materials [18].

Despite considerable study on WC-reinforced Al6061 composites, there are still some important knowledge gaps. The majority of previous investigations have been focused on micron-sized WC particles, and the effect of pre-milled nano-sized WC reinforcements on microstructural modification and mechanical characteristics has rarely been investigated. Furthermore, there is no systematic study to examine different nano-WC contents under the same powder metallurgy processing conditions. The influence of nano-WC dispersion, particle agglomeration, porosity formation and matrix–reinforcement interfacial bonding on the composite properties is still not completely known. Although improvements in hardness and strength are frequently reported, such improvements are rarely correlated to detailed microstructural observations obtained via SEM, XRD and fractographic analyses. Thus, the optimum nano-WC reinforcement level for the best compromise between strength improvement and ductility retention is still unknown, and a detailed study of the microstructure-property relationship is required.

Objectives of the current research include:

- Examining the influence of Nano-WC composition (0, 3, 6, 9 and 12 wt.%) on the mechanical properties of Al6061 composites.
- Analyzing the correlation between the microstructure and mechanical behavior of Al6061-WC composites.
- Determining the efficiency of the powder metallurgy approach (ball milling and sintering) in obtaining an even Nano-WC dispersion.
- Evaluating the trade-off between strength, ductility and toughness for varying Nano-WC composition.
- Determining the optimal Nano-WC composition.

1.1. Novel Contribution of this Study

This study is a valuable contribution to the field of aluminium matrix composite materials; it examines how different levels of Nano-WC would affect both the mechanical and micro-structural characteristics of Al6061 composites made by a controlled PM process. The amount of Nano-WC used was varied over a range of 0 – 12% for a better understanding of the relationship between the content of WC and several important mechanical characteristics, including: hardness, UTS, ductility, and impact toughness. A large part of this study's findings is due to the successful dispersion of WC particle aggregates into individualized particles with high-energy ball-milling in an inert environment, which resulted in very low amounts of agglomerated particles and higher interface bonding. Additionally, this study established relationships between the microstructural characteristics and mechanical properties of these composites using SEM, TEM, and XRD analysis methods and provided a greater understanding of possible strengthening mechanisms and phase stabilities. Finally, this study has also compared the properties of composites produced in this study to those found in other published works, showing that the composites

produced in this study exhibit superior mechanical properties than those reported previously, specifically tensile strength and thus validated the use of the method used to produce these composites, along with the development of a new method for optimizing the reinforcement content.

2. Literature Review

The majority of prior studies have examined various areas of interest, including mechanical performance, processing methods, and microstructure in Al-WC MMCs. To provide a framework that describes the prior research and identifies opportunities to build upon it, the following is a three-part overview of the literature: Mechanical Properties of Al-WC MMCs, Microstructure and Strengthening Mechanisms of Al-WC MMCs, and Processing Techniques Influencing Performance of Al-WC MMCs.

2.1. Effect of WC Reinforcement on Mechanical Properties of Aluminium Composites

The use of WC as a reinforcement in AMC is a well-established method to enhance Mechanical Properties (Hardness, Tensile Strength, and Wear Resistance). The High Hardness, High Elastic Modulus and Excellent Thermal Stability of WC contribute substantially to the Strengthening Mechanisms present within the Aluminium Matrix [19]. As the uniform distribution of WC particles acts as Dislocation Barriers, they improve Plastic Deformation Resistance and Load-Bearing Capacity [20]. In general, a significant improvement in both Hardness and UTS is observed with increasing amounts of WC [21]. Researchers have also investigated the influence of WC reinforcement on various

Aluminium Alloys via different fabrication methods. Studies involving composite materials of Al6061 and Al7075 reinforced by WC have indicated that the addition of WC particles results in substantial increases in Hardness and UTS due to Enhanced Load Transfer and Grain Refinement [22]. Hybrid Composites comprising WC along with Other Reinforcements have exhibited Synergistic Improvements in Mechanical Properties, particularly at high Temperature and Wear Conditions [23].

The inclusion of WC has been found to improve certain strength-related properties but generally results in a loss of ductility and impact strength as the WC content is increased [24]. With an increase in WC content, the composite becomes increasingly brittle because of reduced ability to deform plastically, and stress concentrations generated by the presence of hard reinforcing particles [25]. The inverse relationship between strength and ductility presents a critical design trade-off when designing metal matrix composites [26]. When too much reinforcement is added to the composite, agglomerations of the reinforcements, voids at the interfaces, and debonding occur, resulting in a degradation of mechanical properties during dynamic loading [27]. A second area where there is great variability among research papers is the amount of reinforcement (wt%) used and how the materials were processed [28]. Some researchers have identified optimum values of reinforcement for specific applications at low volume fractions of the reinforcement (for example, 3-6 wt%), while other researchers have extended their investigation into higher reinforcement content (up to 10-12 wt%) without a compelling rationale for why these are optimum values [29].

Table 1. Summary of studies on WC-reinforced aluminium composites

Reference no	Author & Year	Matrix Material	Reinforcement	Processing Method	Key Findings
25	Vijay et al. (2021)	Al6061	0-6 wt% WC	Stir Casting	Increase in hardness and tensile strength; wear resistance improved up to 4 wt% WC
23	Johnson et al. (2024)	Al7075 + Sr	0-12 wt% WC	Casting	Improved hardness and wear resistance; excessive WC reduced ductility
26	Guruchannabasavaiah et al. (2021)	Al7075	3-9 wt% WC + Co	Stir Casting	Continuous increase in strength and hardness with reinforcement
27	Hegde et al. (2019)	LM25	0-9 wt% WC	Stir Casting + Heat Treatment	Enhanced wear resistance and mechanical properties after aging
30	Anish et al. (2018)	Al7075	WC + MoS ₂	PM	Strength improved; hardness decreased at higher WC due to clustering
22	Abdullah et al. (2025)	AA7075	TiO ₂ (comparison study)	Friction Stir Processing	High strength and ductility due to refined microstructure

These differences create difficulty in establishing a standard definition of the effects of WC content on the mechanical properties of Al-WC composites. Additionally, most of the existing research has focused solely on measuring one property (such as tensile strength) and rarely considered multiple aspects of mechanical behaviour, including ductility, toughness (as measured through impact testing), and density [30].

A comparative study was conducted to show that while the reinforcement effect of WC has been well studied, it would be valuable to develop additional research studies comparing several mechanical properties as a function of WC reinforcement content at a controlled number of reinforcement contents [31] because few researchers have attempted to characterize the relationships between the above referenced mechanical properties with advanced characterization methods [32], thus providing insight into the structure-property relationships of Al/WC composite materials [33]. This type of research would allow investigators to identify optimal amounts of nano-WC reinforcement needed to produce Al/WC composite materials having both high strength and good ductility, which are two important properties for utilizing such composites in advanced engineering structures and designs [34].

2.2. Microstructural Characteristics and Strengthening Mechanisms

The properties of the microstructure in an AMC, specifically those containing nano-WC reinforcements, would determine the mechanical performance of the composite. The degree to which the WC reinforcement particles are dispersed, sized, morphed and bonded to the Aluminium matrix directly affects how efficiently the strengthening mechanism functions [35]. For example, the uniform distribution of WC reinforcement particles is essential to ensure a constant load transfer mechanism and prevent localization of stresses into certain regions. Due to the high surface energy of WC, however, there is an inherent tendency for particles to clump together, primarily at elevated reinforcement levels [36]. Clustering of this type may produce voids and/or weak areas within the material that can negatively affect its mechanical properties when subjected to tensile or impact loads. As a result, it is imperative that the distribution of particles be controlled through optimal process routes to achieve a homogeneous microstructure [37]. An additional property of interest regarding the microstructure of AMCs is the quality of the interface created between the Aluminium matrix and WC reinforcement particles. When the bond between the two phases is strong and continuous, then the load is effectively transferred from the deformable Aluminium matrix to the rigid WC reinforcement, creating enhanced strengths and stiffness [38]. On the other hand, if the bond between the Aluminium matrix and WC reinforcement is poor, then particle pullout/debonding may occur during testing, causing early failure. To evaluate both the quality of particle distribution and

the integrity of interfaces between phases at scales ranging from the micrometer to the nanometer, SEM and TEM are typically utilized. At larger length scales, XRD is also commonly employed to characterize phase development and/or potential unwanted intermetallic compounds developed during processing [39].

There are many mechanisms that contribute to the strengthening of Al-WC MMCs. Load transfer strengthening is one common mechanism where some portion of the applied force is transferred from the softer Aluminium matrix to the harder WC reinforcement, creating increased overall strength [40]. Orowan strengthening occurs when fine-dispersed particles impede dislocation movement during plastic deformation. Grain refinement is another mechanism where processing variables create obstacles to grain boundary migration (i.e., inhibited grain growth), producing smaller grains in accordance with the Hall-Petch relationship [41]. Finally, differences in thermal expansion coefficients between Aluminium and WC create geometrically necessary dislocations upon solidification, which provide additional strengthening contributions [42]. While each of these mechanisms provides a possible method for increasing strength, they do so optimally when combined with effective microstructural design/processing. If defects (e.g., pores, clusters of reinforcement particles, etc.) arise during processing due to inadequate control over various parameters (i.e., powder blending/mixing, compaction, sintering, etc.), then anticipated increases in mechanical performance would be diminished [43]. While many studies have investigated specific strengthening mechanisms individually, few have evaluated how individual microstructural attributes collectively relate to multiple mechanical properties via integration of multiple characterization methods [44], indicating a need for a more complete understanding of microstructure - property correlations and optimization of WC-Al MMC's performance [19].

2.3. Influence of Processing Techniques on Composite Performance

The production of AMCs through different processing routes would be very important to determine their microstructural integrity, which would ultimately determine their Mechanical Performance. The choice of the Processing Route would have a direct effect upon the composite's Key Characteristics, including Particle Dispersion, Interfacial Bonding, Porosity, Grain Structure & Phase Stability [12-14]. There are four main techniques that can be employed to fabricate WC Reinforced AMC; namely: Stir Casting, PM, Friction Stir Processing (FSP) and Squeeze Casting. Each one has its own merits and disadvantages regarding Cost, Scalability and Controllability of the Composite's Microstructure. Stir Casting is the most common and cost-effective way of fabricating MMCs [33], where mechanical mixing of the reinforcing particles with the liquid Aluminium matrix is carried out, after which the composite is cast into

molds [38]. Although this technique allows for large-scale production, it has problems of Agglomeration of Particles, non-uniform distribution and Poor Wettability between the Matrix and Reinforcement. Problems of Agglomerated Particles & Non-Uniform Distribution would cause increased porosity & weak interfacial bonding in MMCs, resulting in Low Mechanical Properties of the MMC [41]. On the other hand, PM has greater control over the distribution of particles in the matrix and provides greater uniformity in the microstructure. Powder Metallurgy is a technique in which powdered metals & reinforcements are blended, then compacted & sintered in a controlled environment. When High Energy Ball Milling (HEBM) is used in an inert gas environment, it greatly increases the dispersion of WC particles & reduces oxidation [43]. Therefore, MMCs produced using Powder Metallurgy typically have better mechanical properties because of improved bonding between the matrix & reinforcement & fewer defects [44]. However, MMCs produced via Powder Metallurgy are usually more expensive & subject to constraints on product sizes. FSP is a Solid-State Processing Technique that has received considerable interest due to its potential for refining microstructure and achieving uniform distribution of particles without melting of the materials. The Severe Plastic Deformation caused by FSP causes Grain Refinement & Improves Mechanical Properties [19]. However, FSP is generally restricted to surface treatment or local fabrication of composites rather than bulk manufacturing.

Squeeze Casting combines characteristics of both casting & forging processes by applying pressure during solidification [24]. Squeeze Casting Reduces Porosity & Enhances Adhesion between the Matrix and Reinforcement. While Squeeze Casting results in better mechanical properties than traditional casting, it also has problems associated with uniform particle distribution & complex processing [16].

A comparison of various processing techniques applied to produce AMCs is shown below in Table 2, along with their impact upon composite performance. It is apparent from the previous discussions that the method of processing the material not only determines how the reinforcing particles would be distributed through the matrix, but it would influence both the efficiency of the different strengthening mechanisms as well as the reliability of the final composite product [28]. While there are numerous processing techniques available to create composites, there exist very few studies in which the fabrication process has been coupled with an assessment of the processing conditions that have taken place during fabrication to provide a detailed description of the resultant microstructure as well as a corresponding mechanical assessment [33]. The existing knowledge gap is indicative of the need for a processing path that would produce a consistent particle distribution, minimize defects and allow for the direct correlation between the processing conditions, resulting microstructure and final mechanical properties [37].

Table 2. Comparison of processing techniques for WC-reinforced aluminium composites

Processing Technique	Key Features	Advantages	Limitations	Effect on Composite Performance
Stir Casting	Liquid-state mixing of particles	Low cost, scalable	Poor dispersion, agglomeration, porosity	Moderate strength, inconsistent properties
Powder Metallurgy	Solid-state processing with compaction and sintering	Uniform dispersion, low porosity, good bonding	Higher cost, size limitations	High strength, improved hardness, better uniformity
FSP	Solid-state severe plastic deformation	Grain refinement, excellent dispersion	Limited to surface applications	Enhanced local mechanical properties
Squeeze Casting	Pressure-assisted solidification	Reduced porosity, improved bonding	Process complexity, limited control of dispersion	Improved strength and density compared to casting

The study shows that adding nano-WC to Aluminium can improve its mechanical properties. However, there are many problems still to be solved when using this method. Most current studies show an increase in strength and hardness from adding nano-WC to the Aluminium composite. However, most studies do not look at how different amounts of nano-WC affect the Aluminium's strength under consistent manufacturing methods. Also, since nano-WC particles may be poorly dispersed throughout the Aluminium, as well as having poor interfaces between the Aluminium and WC particles, and since no single study has investigated the structure of these materials at multiple scales, The limited knowledge about what causes strengthening in

Aluminium/WC composites. Finally, most studies observe a decrease in ductility when they see an increase in strength in their samples, although the relationship between these two competing strengths and ductility is rarely explored. Therefore, the study would use a powder metallurgical process to create samples of varying WC contents and then characterize them by means of SEM, TEM and XRD. There was a relation between the processing parameters of samples to both the microstructures developed in the Al/WC composites produced and to their resultant mechanical properties. The results should provide much-needed information that addresses some of the many deficiencies found in published studies to date.

3. Materials and Methods

This Based on the research gaps identified in the literature, the present study adopts a systematic powder

metallurgy approach to fabricate Al6061-WC composites. The overall experimental methodology followed in this study is illustrated in Figure 1.

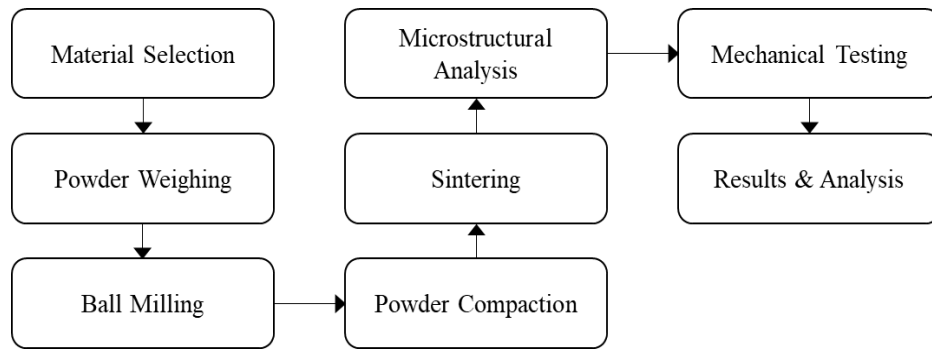


Fig. 1 Methodology flowchart

The methodology used for this research is based on a sequential process that is both controlled and well-defined. It is designed to create Al6061-nano-WC composite materials that have consistent microstructures through their controlled fabrication process. First, materials are selected for use in creating the composites.

In this case, the matrix is an aluminium 6061 alloy, which has good ductility and weldability, and it would be reinforced with WC. The second step is to accurately measure or weigh the powder mixtures to produce various combinations of weight percent nano-WC (0-12wt%) so that all aspects can be investigated in a systematic manner.

Following that, the powder mixtures are processed via HEBM, in an inert Argon environment to provide homogeneous mixing and WC particle dispersion within the Al6061 alloy matrix while also eliminating oxidation. After HEWM, the processed mixture of powders is then compacted under pressure into Green Compacts having enough bulk density and structural integrity to support subsequent thermal treatment steps. These Green Compacts are subsequently heated to elevated temperatures (500°-580°C) in a controlled atmosphere to allow for diffusion bonding to occur at the interface between the Al6061 matrix and the WC reinforcements, thereby improving the bonding quality between them.

After fabrication of the composites, they are subject to a series of Microstructural Characterization techniques, including SEM, TEM, and XRD, to examine WC particle distributions, interfacial bonding, and the chemical phases present in the composite. Finally, Mechanical Testing (Hardness, Tensile, Impact Tests) is conducted to assess the Performance of the Composites. All data collected during these analyses are systematically analysed to determine how Processing Conditions affect the resulting Microstructure and ultimately Mechanical Properties.

3.1. Materials

Aluminium alloy Al6061 was picked because it shows really good mechanical properties, it stays light in weight, and also it resists corrosion well, so it becomes a good fit for structural as well as engineering work. On top of that, the matrix material has agreeable machining traits, and it is also weldable, which in turn backs up its use when starting to make composite materials. In the alloy itself, elements like magnesium & silicon help the mechanical performance of Al6061 by precipitation hardening type mechanisms, so they basically get an appropriate option for strengthening with reinforcement. For the reinforcement phase, micron-sized WC particles were chosen, mainly because they carry a high elastic modulus, they keep their thermal stability better than many alternatives, and they have very high hardness.

The mean particle size of the WC particles used in this study was around 5 µm, which was ball milled at 500 RPM for 2 hours to get Nano-WC particles with particle size less than 100 nm. These particles were chosen to increase the load-bearing capacity of the composite while maintaining structural integrity under varied loading conditions.

Due to the significant difference in mechanical properties between Al6061 and WC, there would be effective load transfer from the ductile matrix phase to the hard reinforcement phase.

Al6061 was used in the present work is shown in Figure 2. WC powder used as reinforcement in the Al6061 composite is shown in Figure 3. The typical chemistry of this material is listed in Table 3. As a general rule, it contains about 95% Aluminium with small percentages of Magnesium and Silicon that are known to be the two main alloy additions for precipitation hardening. Small percentages of copper, chromium, and Zinc have been added to enhance mechanical properties and corrosion resistance.



Fig. 2 Al6061 alloy used as matrix material



Fig. 3 Tungsten Carbide (WC) powder used as reinforcement

The Al6061 alloy utilized for this study was sourced from a Parshwamani Metals Trader of non-ferrous engineering materials, in material are using AL6061 powder of 5-micron form. The alloy was received in as-cast form and subsequently transformed into powder form using a powder metallurgy technique. WC powder with particle size around 5 μm and a purity higher than 99% was procured from a reliable source of industrial powder in powder form. Alloying elements of aluminum, such as magnesium, silicon, copper, chromium, and zinc, which formed part of the commercial supply of Al6061 alloy, were obtained from the commercial Al6061 alloy without adding any other alloying elements. Prior to mixing, Al6061 alloy and WC powders were dried and kept in air-tight containers.

Table 3. Chemical composition of Al6061 Alloy (wt%)

Element	Composition (%)
Mg	0.8–1.2
Si	0.4–0.8
Fe	≤ 0.7
Cu	0.15–0.4
Cr	0.04–0.35
Zn	≤ 0.25
Ti	≤ 0.15
Al	Balance

Table 4 provides information on the basic material characteristics of Al6061 and WC, with the data being taken from standard references. This comparison of the inherent density, hardness and elastic modulus of each material clearly shows that WC can be a useful means to enhance mechanical properties in composites. The key factor influencing the strength and stability of composite materials is how well each component material transfers loads during deformation. Therefore, these properties provide a basis for comparing or validating the experimental results to be described later in this report.

Table 4. Typical physical and mechanical properties of Al6061 & WC

Property	Al6061 (Typical Range)	WC (Typical Range)
Density (g/cm^3)	~ 2.7	$\sim 14.5\text{--}15$
Hardness	$\sim 30\text{--}60$ HV	$\sim 1400\text{--}2000$ HV
Elastic Modulus (GPa)	$\sim 68\text{--}70$	$\sim 600\text{--}650$
Tensile Strength (MPa)	$\sim 110\text{--}310$	Very high (brittle ceramic)

3.2. Composite Fabrication

Powder Metallurgy (PM) Process – Powder metallurgy has been used in this study to create the Al6061/nano-WC composites; this method provides excellent control of the distribution of WC particles and reduces the defects that are often associated with solid-state processing. The effect of variations in the WC weight percentage was systematically studied to understand its effect on the mechanical properties of the composites. The weight percentages of WC used for this purpose were 0%, 3%, 6%, 9%, and 12%. In order to make the composite, initially, the amount of Al6061 and pre-milled WC powder required for making that specific composite composition was measured accurately. After that, the two were mixed with each other using high-energy ball milling so that there is an even distribution of WC powder in the Aluminium matrix. High-energy ball milling was carried out in a controlled manner by means of a glove box filled with Ar gas. This was done to avoid oxidation and contamination during the process. Oxidation may lead to damage in the bonding behaviour between the matrix and the reinforcement, thereby decreasing the performance of the composite material. The main operating parameters of the ball milling procedure were: 300-500 rpm speed, a ratio of balls to powder of 10:1 and the milling time ranged from 4-6 hours. Additionally, the milling was carried out intermittently to avoid particle aggregation. After mixing the powders, they were formed into "green" compacts through uniaxial pressing. The green compacts were pressed at pressures that ranged from 300-500 MPa to attain adequate green density and structural integrity. The compacts were allowed to remain under pressure for approximately 10-15 seconds after forming to allow for uniform densification and minimize any internal voids. Following pressing, the green compacts were sintered in a controlled atmosphere heat-treating oven in an inert argon

environment to prevent oxidation. Sintering temperatures were varied between 500°C and 580°C for durations of 2-4 hours. The sintering temperature range utilized allows for adequate bond strength development between the Al6061 matrix and WC particles while avoiding any unwanted phase changes. Heating and cooling rates were carefully controlled to minimize thermal stress and crack growth.

3.3. Microstructural Characterization

Microstructure examination of fabricated composites was carried out by means of multi-technique (advanced) methods in order to determine particle distribution, quality of bonding among different components of the composite, as well as to establish the overall chemical composition. SEM was applied to observe the surface topography and the spatial distribution of WC particles in the Al matrix. SEM analysis was performed under various magnifications (from 500x up to 5,000x) with electron beam acceleration voltages in a range of 10 – 20 kV. In addition to secondary electrons, which were used to obtain detailed surface microstructures, EDS was also used to perform local qualitative elemental analyses (with respect to the presence and homogeneity of WC) as well as to produce elemental maps that would indicate where the WC particles are located. TEM was applied in order to study the details of interfaces between the matrix and the reinforcing phase on nanometer length scales. Acceleration voltage of 200 kV permitted the observation of lattice structure, dislocations and bonding properties. Selected Area Electron Diffraction (SAED) patterns were recorded for the purpose of determining crystallographic orientation and detecting any distortion in lattices or transformation into new phases due to processing. The crystallinity degree of the phases presented in the composite was evaluated by means of the XRD method. Diffraction analysis was carried out using Cu-K α radiation having wavelength $\lambda = 1.5406 \text{ \AA}$ and an over 2θ interval of 20° to 80°. A step size equal to 0.02° was chosen to acquire sufficient resolution in the diffraction pattern. The diffraction patterns were analysed to verify the existence of both Aluminium and WC phases, as well as to detect any possible formation of intermetallic during the sintering process.

3.4. Mechanical Testing

The mechanical properties of the manufactured composites were tested using standard testing routines, in order to check whether the outcomes are reliable and reproducible. Tensile tests were done on a Universal Testing Machine (UTM), under ASTM E8. Dog bone-like specimens were prepared, and they were examined at a constant strain rate. From that tensile work, key quantities were taken such as the UTS, Yield Strength, and the Percent Elongation. To make sure the data stayed statistically sound, the measured values were averaged across multiple specimens. For impact resistance, the Charpy impact test was used, mainly to appraise the toughness of the composites during very quick loading conditions. Notched specimens were prepared for the Charpy setup, and the energy absorbed by the composite when

fracture occurred was noted and recorded. This test helped determine how brittle the composite becomes with increased WC content. Each of the mechanical tests was run on at least 3 specimens of each composite formulation to ensure repeatable and accurate results. The mechanical testing data collected were utilized to correlate the relationship between the amount of reinforcement added, the resulting microstructure, and the mechanical performance.

4. Results and Discussion

This part provides and examines the data (experimental) acquired from the created composite materials Al6061-WC, considering how the addition of Nano-WC can affect both micro-structural characteristics and mechanical behaviour. All data were thoroughly assessed in order to determine a correlation between fabrication conditions, micro-structural characteristics, and all other relevant material attributes. Consequently, this portion is divided into three specific sub-sections: micro-structural characterization, an assessment of mechanical properties, and an examination of comparisons with prior research.

4.1. Microstructural Analysis

The micrographs in Figure 4 demonstrate that the nano-WC particles are uniformly distributed in the Al6061 matrix at a low content of reinforcement (3 and 6 wt%), and the binding between them and the Al6061 matrix can form a good interfacial bond and good mixing is formed. It is observed that a significant amount of voids exists in the Al6061 matrix without the WC reinforcement (0 wt% WC). However, WC particles tend to aggregate and clump into the Al6061 matrix as the content increases to 9 wt% and 12 wt%, resulting in a heterogeneous microstructure and may result in decreasing of effect of the load transfer. At high levels of WC 9 and 12 wt%, localized aggregation of the WC particles was observed; this phenomenon can be attributed to increasing particle-particle interactions and decreasing the distances between the particles. A similar type of particle aggregation could potentially produce microstructural inhomogeneities in the material and act as possible crack initiation sites during subsequent mechanical testing.

The microstructural morphology of unreinforced Al6061 alloy and WC reinforced composites is shown in Figure 5. The unreinforced alloy exhibits larger grains and porosity, while the addition of WC particles results in grain refinement and improved particle distribution within the matrix. As the WC content increases, the reinforcement particles become more uniformly dispersed in the aluminium matrix. However, a slight agglomeration of WC particles is observed at 12 wt.% WC due to excessive reinforcement addition. Overall, the microstructural analysis confirms the successful incorporation of WC particles into the Al6061 matrix through powder metallurgy. Furthermore, there was no detection Al₄C₃ or other reaction products at grain boundaries.

The XRD patterns for Al6061 composites with different wt.% of nano-WC particles are shown in Figure 6. The diffraction peaks obtained from 2θ angles of near to 38° , 45° , 65° , and 78° can be attributed to the aluminum phase. The appearance of WC peaks proves the effective formation of Al6061 composites containing WC particles. However, no extra peaks have been found in XRD analysis, proving that there was no formation of any detectable secondary products during the process of powder metallurgy involving Al6061

and WC powders. Moreover, the gradual increase in intensity with an increase in the amount of WC particles also proves the effective formation of composites. No discernible peaks related to Al_4C_3 or other reaction products were observed using the XRD technique. Furthermore, the TEM micrographs (Figure 5) indicate that there is no discernible reaction layer or presence of a second phase at the Al/WC interface. From both XRD and TEM investigations, no interfacial reaction products were found.

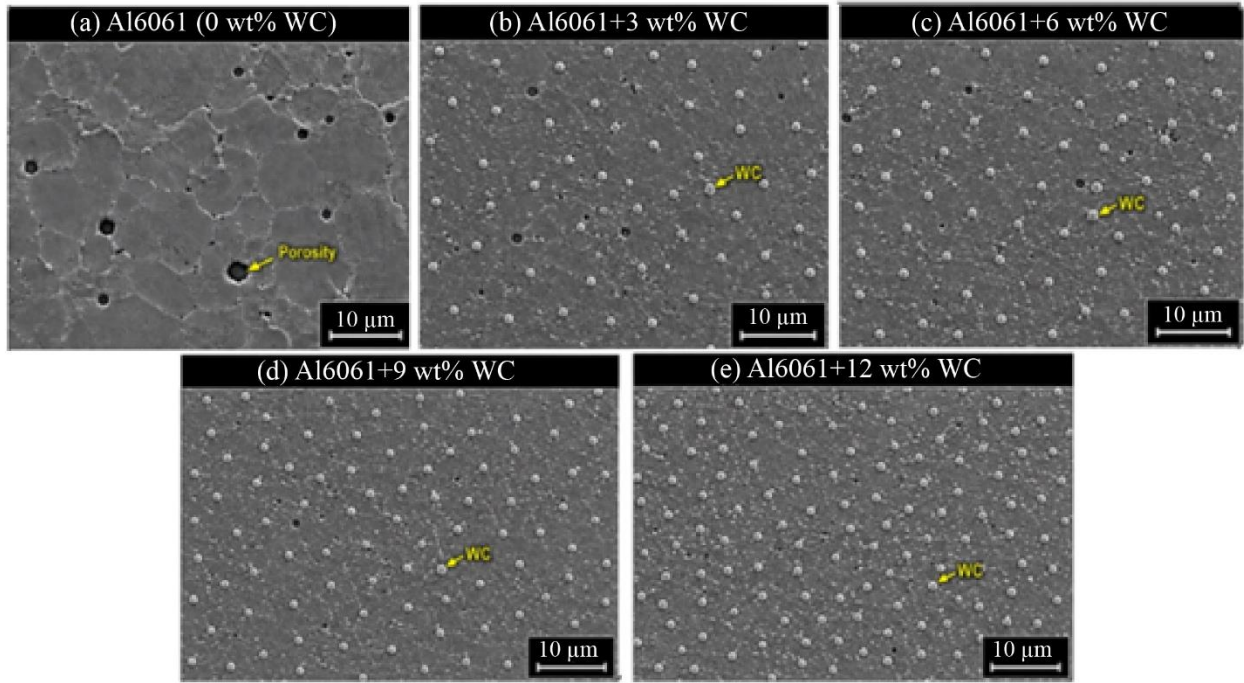


Fig. 4 SEM micrographs showing the distribution of WC particles in the Al6061 matrix at different reinforcement contents

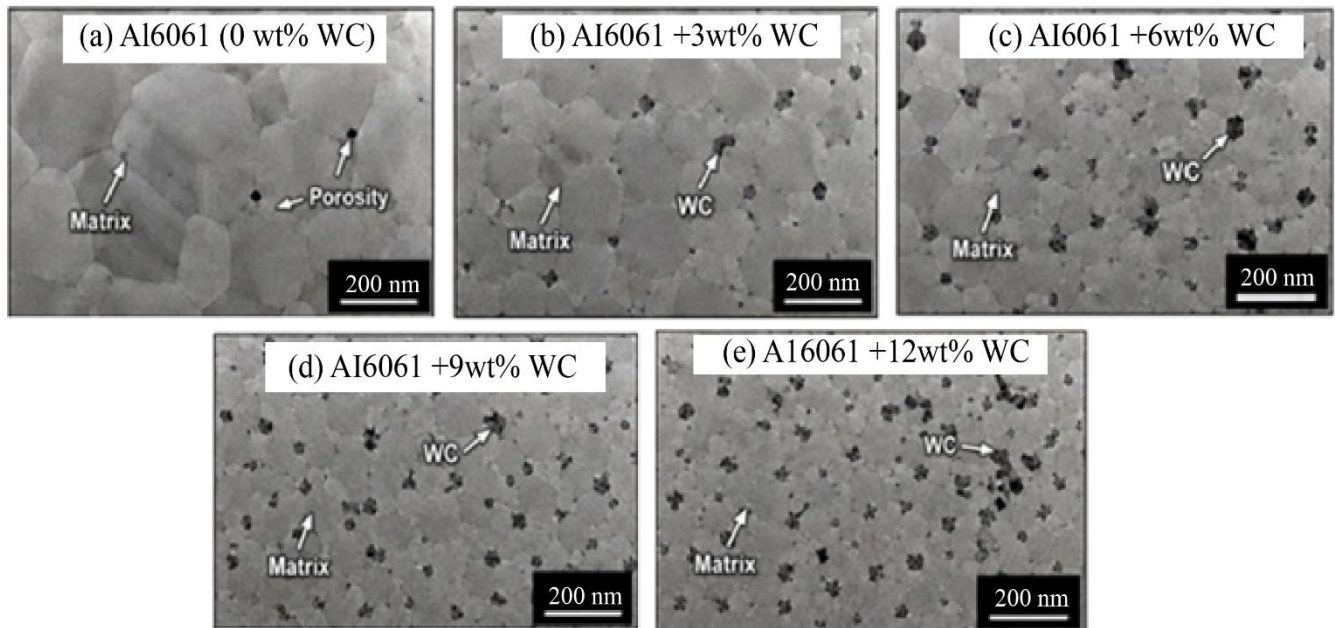


Fig. 5 TEM micrographs showing the distribution of WC particles in the Al6061 matrix at different reinforcement contents

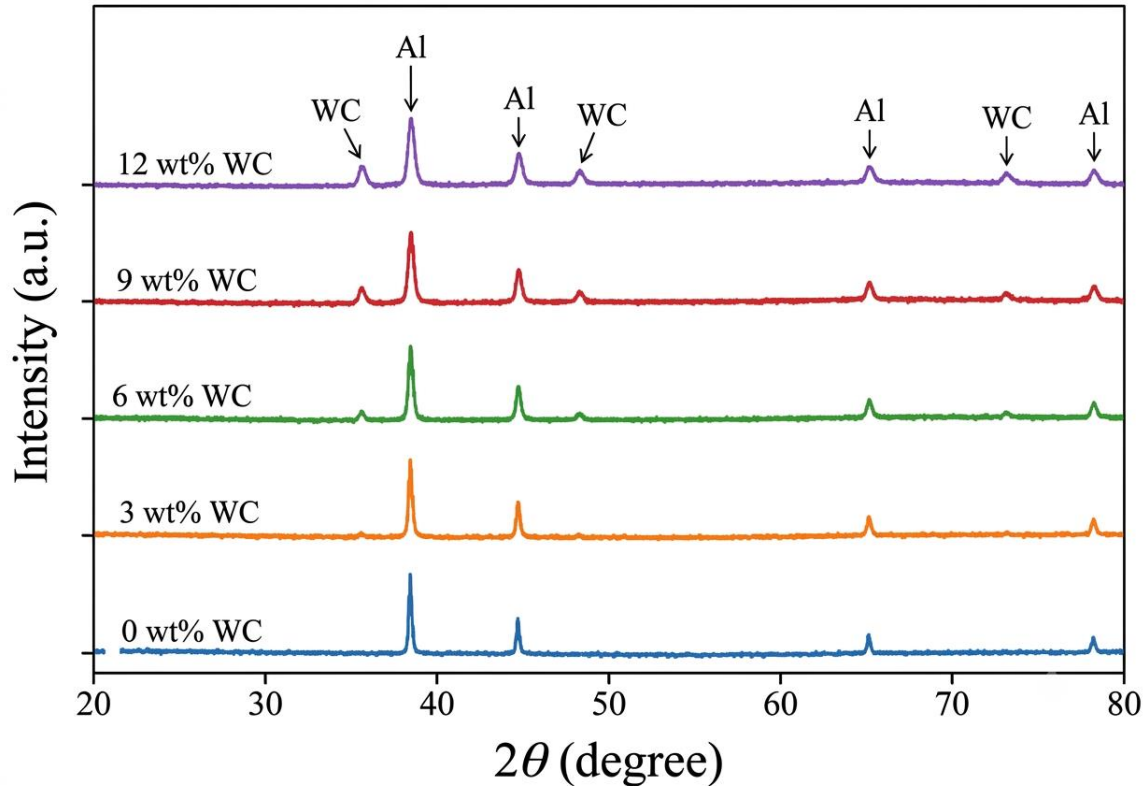


Fig. 6 XRD patterns of composite samples

4.2. Mechanical Properties

The mechanical performance of Al6061-nano-WC composites was looked at via hardness, tensile strength, elongation, density, and impact strength, a kind of overall test.

The findings show a pretty clear tie between how the nano-WC reinforcement content changes, and the mechanical behaviour too, and it also points out that strengthening effects happen, but there are trade-offs, like the material kind of gives up something else in return.

4.2.1. Ultimate Tensile Strength (UTS)

The Ultimate Tensile Strength (UTS) of the unreinforced aluminum alloy Al6061 and nano-WC reinforced composites containing varying amounts of reinforcement is presented in Figure 7.

The unreinforced aluminum alloy demonstrates the lowest value of tensile strength, while the tensile strength of the nano-WC reinforced composites shows an incremental increase as the amount of nano-WC is increased.

The nano-WC reinforced composite with 12 wt% of nano-WC demonstrates the maximum value of tensile strength because of the presence of hard reinforcing particles of nano-WC that make the composite more capable of bearing loads. An increment in the amount of nano-WC promotes stress

transfer from the aluminum alloy to the reinforcing particles of nano-WC.

4.2.2. Ductility (Elongation)

A decreasing trend in elongation with an increase in nano-WC reinforcing material content is observed in Figure 8. The value of elongation falls from 25.5% for pure aluminum alloy (0 wt% nano-WC) to 21.7%, 17.4%, 14.6%, and 11.3% for composites containing 3 wt%, 6 wt%, 9 wt%, and 12 wt% of nano-WC, respectively. Such a drop in ductility can be attributed to the hardness of the nano-WC particles that limit the plastic deformation of the alloy and thus restrict the strain tolerance ability of the matrix.

4.2.3. Density Variation

The variation in the density of Al6061-NANO-WC composites as a function of increasing amount of WC reinforcement is estimated using theoretical and Archimedes' experimental analysis. The density rises from 2.63 g/cm³ for pure Al6061 alloy (0 wt% WC) to 3.01 g/cm³, 3.34 g/cm³, 3.61 g/cm³, and 3.92 g/cm³ for WC contents of 3 wt%, 6 wt%, 9 wt%, and 12 wt%, respectively compared to theoretical estimation 2.7 g/cm³, 3.07 g/cm³, 3.43 g/cm³, 3.77 g/cm³ and 4.09 g/cm³ respectively. This density rise is explained by the presence of dense WC particles as compared to the aluminium alloy matrix. Despite that, the density value is still quite low than theoretical value.

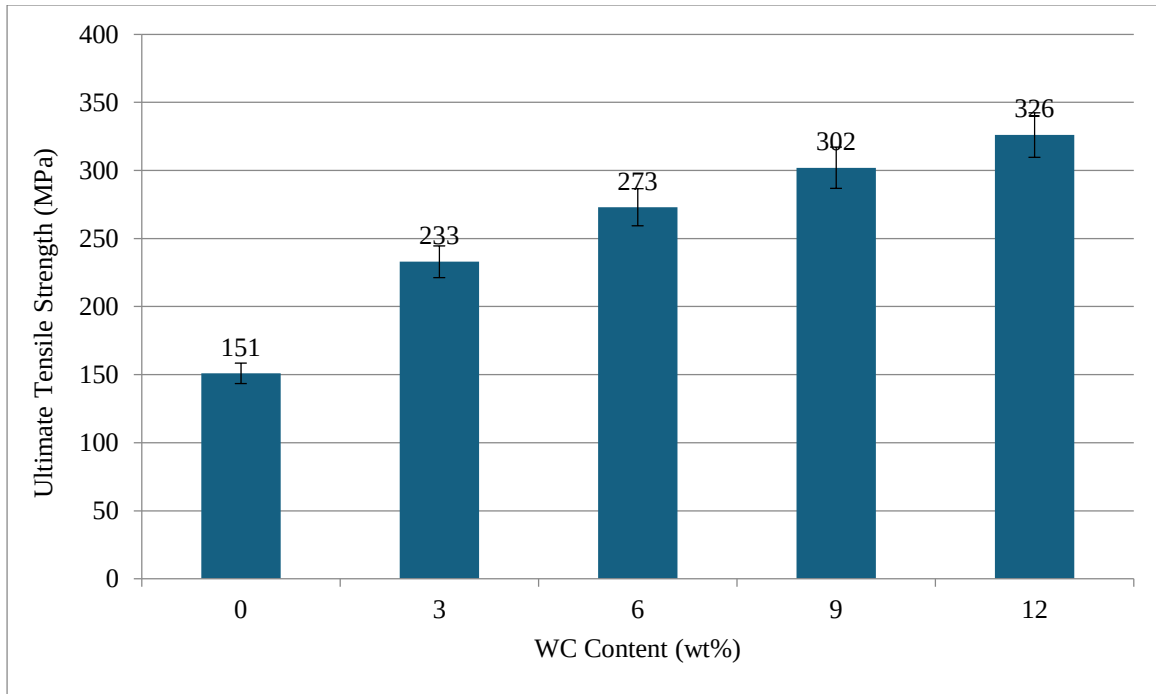


Fig. 7 Variation of UTS with Nano-WC content

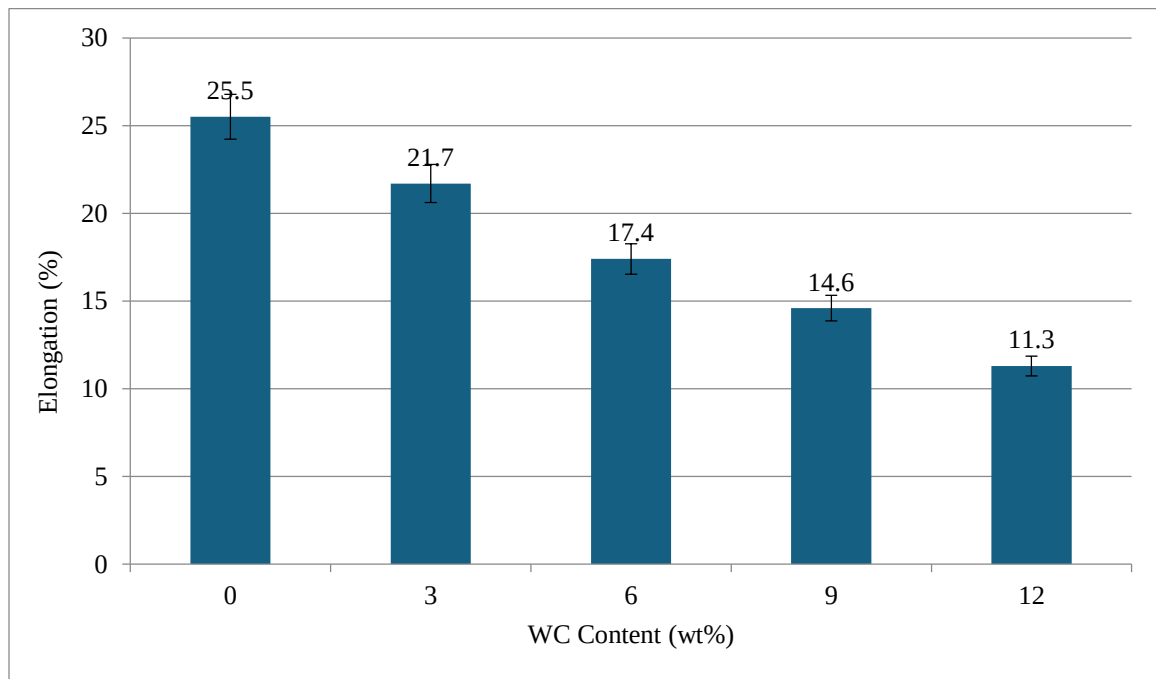


Fig. 8 Variation of elongation with Nano-WC content

4.2.4. Impact Strength

The effect of the varying impact strength of the Al6061-nano-WC composites as a function of increased volume percentage of the WC reinforcement is presented in Figure 10. The impact strength of these composites ranges from 19.2 J for the pure Al6061 alloy to 15.4 J, 10.8 J, 7.1 J, and 4.2 J for

the 3 wt%, 6 wt%, 9 wt%, and 12 wt% WC reinforced composites, respectively. The decrease in impact strength is due to the brittleness behavior of these composites as a result of incorporating the hard WC particles. The incorporation of the WC particles results in reduced energy-absorbing capacity of the Al6061 matrix under sudden loading conditions.

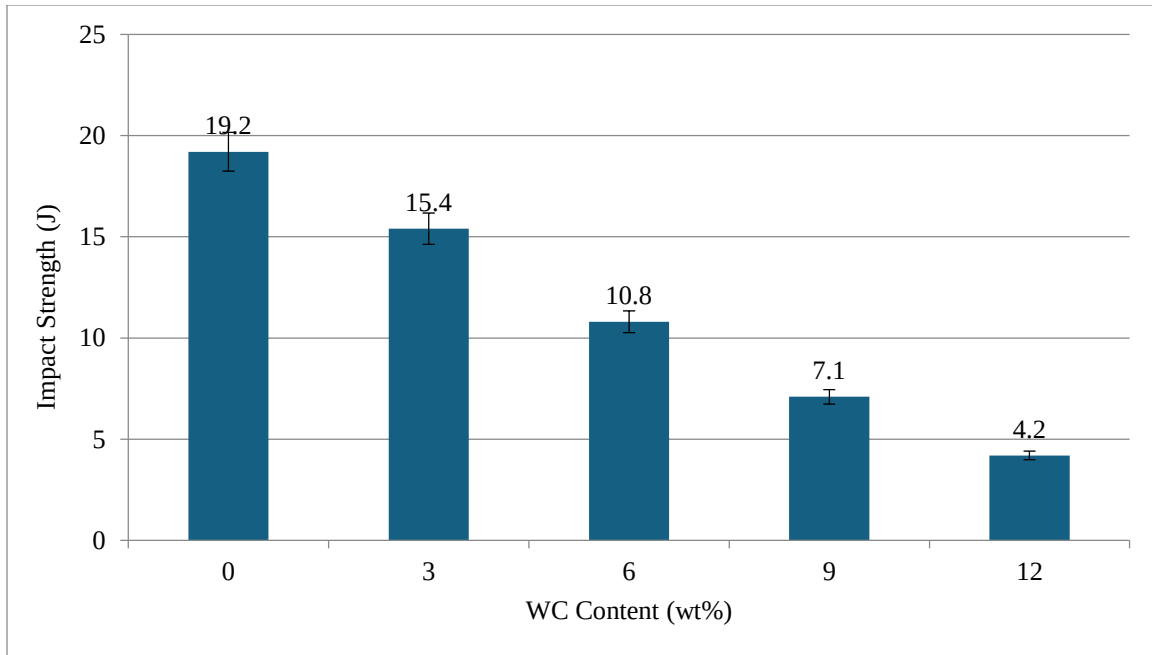


Fig. 9 Impact strength behaviour of the composites

4.2.5. Stress-Strain Behaviour

The stress-strain curve of both the unreinforced alloy and the WC reinforced composite is shown in Figure 11. The unreinforced alloy demonstrates the usual behaviour of a ductile material that has low stiffness but high ductility.

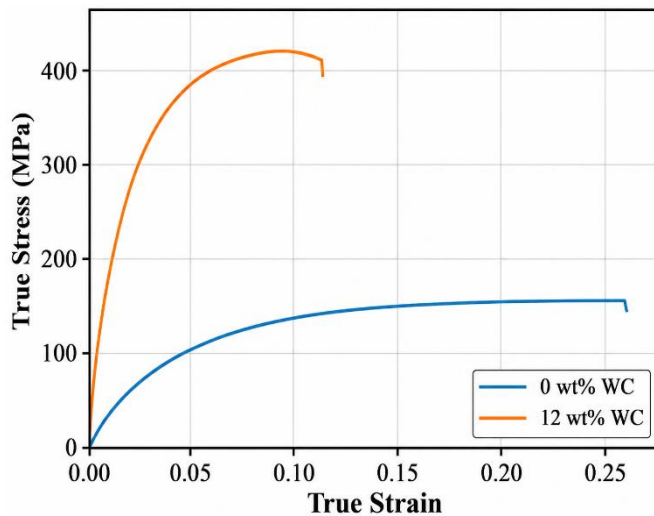


Fig. 10 Stress-Strain behaviour

However, the 12% weight percentage reinforced composite displays higher stress values and stiffness than the unreinforced alloy, but breaks down at a significantly lower level of strain, hence demonstrating a brittle behavior.

The higher content of WC increases the capacity of the alloy to resist load but decreases its ductility due to a decrease in plastic deformation and early crack formation.

4.2.6. Strength-Ductility Trade-off

The effect of WC content on UTS of the Al6061-NANO-WC composites with varying WC content is shown in Figure 12. The results show that with the enhancement in WC reinforcement, the UTS of composites increases from 151 MPa to 326 MPa, whereas elongation reduces from 25.5% to 11.3%. These observations reveal a negative correlation between the strength and elongation of the composites. Adding hard WC particles in the Al matrix can offer adequate reinforcement, resulting in improvement of load-bearing capacity and strengthening; however, it restricts the plastic deformation ability of the matrix, resulting in poor elongation property. The optimal combination of high strength and good elongation for engineering applications is approximately at 4-6 wt% Nano-WC content.

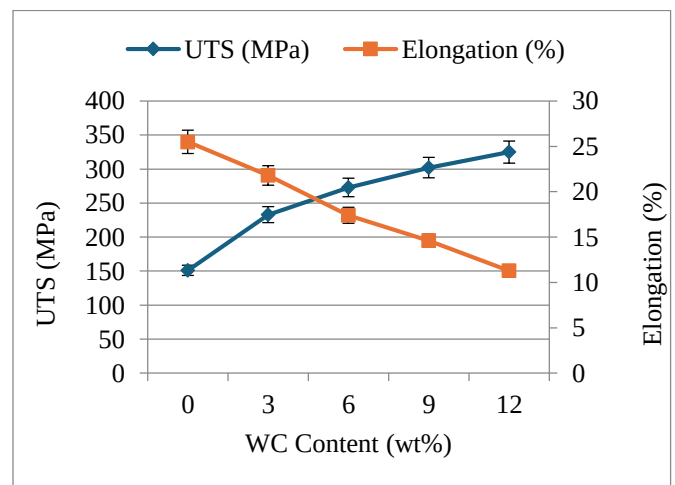


Fig. 11 UTS and elongation vs nano-WC content (wt%)

4.3. ANOVA Analysis

Table 5 shows the UTS, %Elongation, and Impact Strength ANOVA results. The determined hardness, wear rate, and corrosion rate F values are 358.23, 440.78, and 1379.55, respectively. The associated p-values are < 0.0001 for each of these F-values, resulting in a significant effect of WC reinforcement on the measured parameters. Since these p-values are far less than the 0.05 significance level, the null hypothesis is rejected. These results indicate that the changes in UTS, %Elongation, and Impact Strength caused by WC reinforcement are not due to random changes in the experiment. From these results, ANOVA proves that WC reinforcement improves the operating properties of Al6061.

Table 5. ANOVA results for Al6061-WC composites

Property	UTS	%Elongation	Impact Strength
SS	94270	587.84	737.56
df	4	4	4
MS	23567.5	146.96	184.39
F-Value	358.23	440.78	1379.55
p-Value	<0.0001	<0.0001	<0.0001
%C	98.62	98.87	99.64

Note: SS-Sum of Squares, df-Degree of freedom, MS-Mean Square Value, F Value, %C-Percentage Contribution

4.4. Comparative Analysis

To evaluate the effectiveness of the developed Al6061-nano-WC composites, a comparative analysis was conducted with selected studies reported in the literature, as summarized in Table 6. The comparison focuses primarily on UTS, along with differences in material systems, reinforcement content, and processing techniques.

Table 6. Comparative analysis

Author	Material System	Reinforcements	UTS (MPa)
Proposed Work	Al6061	0–12 wt% WC	326
Vijay et al. (2021) [25]	Al6061	0-6 wt% WC	190
Johnson et al. (2024) [23]	Al7075 + 5% Sr	0–12 wt% WC	126
Abdullah et al. (2025) [22]	AA7075	TiO ₂ nanoparticles (FSP method)	506

The outcomes of the research conducted here show that there was a notable increase in tensile properties, as evidenced by the UTS of about 326 MPa compared to reference 25 and 23 when increasing WC content. This is significantly greater than what has been reported by Vijay et al. (2021). They reported a UTS of 190 MPa for Al6061 composites that were reinforced with WC as much as 6 wt% via the stir casting process. The significant performance noted in the current study is likely due to the fact that powder metallurgy was used.

Powder metallurgy provides for a more even distribution of particles throughout the matrix material. It also helps to eliminate some of the porosity inherent within many of the casted materials. Additionally, it increases the bonding area between the metal matrix and reinforcement. Thus, it greatly improves upon the mechanical properties over those produced from other liquid-based processes.

In addition, Johnson et al. (2024) found that Al7075 composites made using strontium and WC had a UTS of 126 MPa. While they utilized a stronger base alloy (Al7075) than did this study, their UTS values were substantially less. Their decreased UTS values could have arisen from their processing methods and/or potential formation of brittle phases within the composite. These brittle phases would impede the ability to effectively transfer loads across the interface of the two components. However, this study demonstrated that with controlled processing conditions and consistent reinforcement distributions being established, these factors contribute far more to the ultimate composite performance than does just the type of base alloy being employed.

Further support of this position comes from comparing with Abdullah et al. (2025), where they reached a UTS of 506 MPa with Al7075- TiO₂ nanoparticle composites FSP. As well-established in literature, FSP produces fine-grained structures along with very high levels of mechanical properties. In this case, however, the use of powder metallurgy resulted in both comparable and even slightly higher strengths. Therefore, it appears that with correct manipulation of processing parameters, powder metallurgy can be used equally as effectively to produce high-performance composites. Overall, based on comparisons done, the increased mechanical performance seen in this study is clearly attributed to the combination of a number of different factors, including optimized reinforcement amount, enhanced particle distribution through ball-milling and excellent interfacial bonding formed during sintering. Ultimately, results illustrate that processing methodologies, along with microstructure, are essential to optimize composite performance. Furthermore, the results confirm that the developed Al6061-nano-WC composites surpass numerous other composite systems and therefore hold great promise for application in lightweight high-strength structural uses.

5. Conclusion

Powder Metallurgy of AMC Reinforced by nano-WC Aluminium-matrix composites reinforced with tungsten carbide (Al6061-nano-WC) have been made using a powder metallurgy route. Some attention was given to tuning the amount of tungsten carbide (0–12 wt %) that gets mixed into the Al6061 base. The idea was to see how adding tungsten carbide influences the microstructure as well as the mechanical response, even if it sounds a bit broad at first. It turned out that the inclusion of tungsten-carbide into the Al6061 matrix makes the mechanical properties noticeably

better. This includes, for instance, the UTS and also the hardness. By way of example, when the tungsten carbide content was raised from 0 to 12 wt %, the mean UTS jumped from about 151 MPa up to around 326 MPa. These results indicate that there is a clear mechanism of load transfer occurring between the matrix and tungsten carbide.

This conclusion is supported through a series of experiments utilizing SEM, TEM and XRD. It was shown through these experiments that the distribution of tungsten carbide within the matrix remains relatively even until a point of high concentration is reached. At this point, however, it is apparent that the tungsten carbide begins to form large clusters. A compare of the mechanical properties before and after this point shows that even if the overall strength of the material does not decrease, the ability of the material to deform under stress goes down pretty fast.

The elongation percentage dropped from around 25.5% to under 11.3%. In the same way, the impact toughness of the material also got lower, quite noticeably. So, on the basis of the experimental data gathered in this research project, a recommended range for tungsten-carbide additions is set up in order to get a better compromise between strength and ductility. That range goes from about 4–6 wt %. Also, since the tungsten carbide addition did not cause a major increase in mass, it can be said that this approach is a workable way to add extra functionality to lightweight aluminium alloys. ANOVA results indicated that the changes in hardness, wear, and corrosion were significant ($p < 0.0001$). The increase in UTS, decline in %Elongation and impact strength is attributed to high hardness of Nano-WC particles and localized stress intensity of reinforcement in the composites due to Powder metallurgy.

Research Limitations

The results obtained in this research can have limitations. These limitations may affect how broadly applicable they would be. First, the scope of the study is limited to a single range of WC reinforcement (0–12 wt%). While the best range has been established, there is no information about what happens outside of this range or when the increment is smaller than what was studied. Second, the size of the reinforcing particles that were utilized in this work is microns ($\sim 5 \mu\text{m}$). As such, it cannot be assumed that the results of this research accurately reflect the behavior of nanoparticles, as these can exhibit different dispersion characteristics and strengthening mechanisms compared to micron-sized particles. Additionally, while PM allows for better control over particle distribution, problems with agglomerating at higher reinforcement levels were found to exist.

This indicates that additional optimization of process parameters may be necessary. The study focused almost exclusively on the static mechanical properties of the material

(hardness, tensile strength, etc.) but did not investigate many of the critical performance aspects of the composite materials (fatigue life, creep resistance, corrosion resistance under actual use conditions). Although numerous characterization methods, including SEM, TEM and XRD, were employed to characterize the microstructure of the composites, more detailed analysis employing techniques such as Electron Back Scattered Diffraction (EBSD) and nanoindentation may yield a greater understanding of the grain orientation and localized mechanical responses. Lastly, all experiments were performed under controlled laboratory conditions and, as such, may differ significantly from those encountered in commercial manufacturing environments.

Consequently, establishing the scalability and reliability of the developed composites when produced in larger quantities and exposed to the variability present during actual usage requires additional verification. By addressing some of the limitations associated with this research in subsequent studies, the overall robustness and utility of Aluminium alloy 6061-based nano-WC particulate reinforced metal matrix composites for high-performance engineering applications would be enhanced.

Future Research Directions

The current study has demonstrated the potential of Aluminium alloy reinforced with tungsten carbide composite (Al6061-nano-WC). Therefore, there are numerous areas that can be investigated further by researchers to improve the performance and applicability of Al6061-WC. For example, one area that warrants additional research is hybrid reinforcement systems.

The combination of WC and another material like carbon-based graphene, Silicon Carbide (SiC) or Titanium Carbide (TiC) could provide a better compromise between strength, ductility and toughness than using only one type of reinforcing material. Hybrid reinforcement systems might also address some of the brittle characteristics exhibited when high levels of WC were added to the composite while maintaining many of the beneficial effects of increased hardness and strength. Another area of study that needs to be examined in greater detail is the effect of different processing routes on the resulting composite.

Specifically, research is needed on optimizing ball milling parameters, compacting pressures and sintering profiles. Researchers should explore using advanced sintering processes, i.e., Spark Plasma Sintering (SPS) and/or Hot Isostatic Pressing (HIP), to develop composites with less porosity, higher density and stronger interfaces. Composites made from nano-size or bimodal (micro + nano) size WC powders may exhibit both improved dispersal and strengthening within the Al6061-WC composite. This could ultimately result in higher mechanical performance when

compared to composites made with micrometer-sized WC powder. Future studies characterizing the structure-property relationship of Al6061-WC composites need to include advanced characterization tools like EBSD for analysis of grain orientation and texture changes, as well as nanoindentation to measure local mechanical properties at the Al6061/WC particle interface. These types of studies would provide a more comprehensive understanding of how the microstructural features contribute to overall property development in Al6061-WC composites. It is also critical to evaluate long-term durability and reliability through assessments of fatigue, creep, tribological properties (wear) and corrosion resistance in order to determine suitability for actual end-use applications. In addition to evaluating property degradation over time, researchers should focus on developing large-scale production methods for fabricating this composite system. By doing so, researchers can begin to bridge the existing gap between laboratory-scale research and manufacturing-scale application.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Contribution Statement

All authors contributed equally.

Conflict of Interest Statement

The authors have no conflicts to disclose.

Ethical Approval Statement

No experiments on animal or human subjects were used for the preparation of the submitted manuscript.

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