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Improving the mechanical properties of table tennis by adding nanocomposite in its polymer matrix

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Abstract. This study delves into the significant impact of integrating nanomaterials, specifically carbon and graphene nanoparticles, into the polymer matrix of aluminum alloy 356, utilizing the vortex casting technique, with the aim of improving the mechanical properties of table tennis equipment. Athletes and their coaching teams have long been on a quest for high-performance sports gear, recognizing its pivotal role in unlocking the full potential of players. The dedication of engineers to craft designs, select materials with precision, and uphold stringent testing standards reflects the commitment to meeting the demands of the sporting world. Yet, to remain at the forefront, sports engineering must continually align with contemporary technologies, and nanotechnology has emerged as a transformative force in this regard. This study not only underscores the meticulous efforts in material integration but also highlights the remarkable strides made possible by nanotechnology. Aluminum nanocomposites, particularly, showcase a groundbreaking fusion of exceptional strength and reduced weight, marking a notable achievement in sports equipment innovation. The research outcomes are compelling, revealing a substantial enhancement in the mechanical performance of the sports structures under scrutiny. This promising development hints at a potential paradigm shift in the manufacturing of sports equipment, promising a new era of elevated athlete performance and enhanced safety during the rigors of physical education training. This study stands as a testament to the tangible impact of nanotechnology on the ever-evolving landscape of sports equipment.
Keywords: mechanical properties; nanocomposite integration; nanotechnology; sports engineering; table tennis; vortex casting technique

1. Introduction

By incorporating nanocomposites into the polymer matrix of table tennis equipment, such as the rubber on the paddle, significant advancements can be made in enhancing the mechanical properties of these sporting goods. Nanocomposites, which are materials composed of a polymer matrix with nanoscale fillers dispersed within, offer unique characteristics that can improve the performance of table tennis equipment. The addition of nanocomposites can enhance properties like strength, stiffness, durability, and even control, providing players with a competitive edge on the table tennis court. This innovative approach represents a promising avenue for optimizing the design and functionality of table tennis equipment to meet the demands of modern players (Cheng *et al*. 2023, Fu *et al*. 2023, Jin *et al*. 2023, Lau and Li 2023, Li *et al*. 2023c, Wang *et al*. 2023a, Zhang and Huang 2023, Zhang *et al*. 2023e).

Sports equipment comprises various tools and apparel employed during sports and physical exercises to enhance strength and fitness (Huang and Sun 2022). Termed inter-changeably as sports goods, these items encompass an array of gear, clothing, and equipment tailored to specific sports disciplines (Lidström *et al*. 2022). They serve multifaceted roles, acting as both protective mechanisms to mitigate injuries and facilitators to optimize athletes' sporting prowess (Emery and Pasanen 2019). Throughout the course of history, sports equipment has evolved in tandem with the advancements in sports and corresponding rule changes. Athletes harness these instruments to elevate their sporting experiences and achieve optimal results. Broadly categorized into two classes, sports equipment is classified as either lightweight and geared toward aerobic activities or robust and oriented for bodybuilding and strength training (Salonen *et al*. 2020). Certain items within this category are better suited for use in sports clubs due to their substantial size and bulk. Contemporarily, the utilization of sports equipment has become ubiquitous, embraced by both professional and amateur athletes alike (Semsch 2020). Individuals increasingly employ these tools within the confines of their homes and workplaces to enhance their physical well-being, ensure proper sports technique, or augment their metabolic functions (Mileva and Zaidell 2022). It is noteworthy that the diverse array of sports necessitates distinct types of equipment, each tailored to the specific objectives of athletes in their respective disciplines (Zhu *et al*. 2017, Wang *et al*. 2020, Yang *et al*. 2022b, Wang *et al*. 2024). The cost spectrum of sports equipment varies significantly, mirroring the extensive range of available items. Furthermore, the ongoing enhancements in sports equipment predominantly center around athlete safety and injury prevention (Wu and Luo 2022).

Metals assume an indispensable role within the sports industry, where physical activity stands as a cornerstone of

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maintaining bodily health (Yang 2022). The absence of exercise invariably leads to a decline in both vitality and overall health (Wegierska *et al*. 2022). This paramount importance can be attributed to the inherent properties of metals, which encompass remarkable attributes such as high tensile strength, impact resistance, hardness, durability, and aesthetically pleasing finishes. Consequently, metals find widespread application not only in general industries but also within the realm of sports equipment (Lakshmikanthan *et al*. 2022). Lightweight alloys, categorized among the structural metals, play a pivotal role in the development of sports and recreational equipment (Fu *et al*. 2020, Hua *et al*. 2022, Su *et al*. 2023a, Wang *et al*. 2023b). Among these, aluminum, magnesium, and titanium hold the distinction of being the first, third, and fourth most abundant metals in the Earth's crust, respectively (Ahmadi *et al*. 2022). Notably, aluminum, owing to its relatively low cost and the exceptional strength exhibited by itself and its alloys, emerges as the preferred choice among non-ferrous metals for fabricating various components (Ban *et al*. 2022, Wang and Feng 2023). This versatile metal finds application in crafting a myriad of sports equipment, ranging from golf clubs to tennis rackets. In particular, Extron products, classified as part of the aluminum family, fall within the iron category of the sports industry, finding extensive use in the fabrication of football and futsal goalposts (Li *et al*. 2022, 2024, Cai *et al*. 2023, Zhao *et al*. 2023). The aluminum frame further establishes its prominence, prominently employed in bicycle frame construction. Beyond sports equipment, aluminum and iron contribute to the production of false ceilings, predominantly utilized in sports facilities, swimming pools, and moisture-prone environments (Subie *et al*. 2009, Kumar Sharma *et al*. 2020). However, perhaps the most paramount role of metals in the realm of sports lies in the production of remarkably lightweight alloys, an innovation that underpins the manufacturing of sports equipment, sporting goods, and championship medals (Pereira *et al*. 2019). It is unequivocal that advanced sports, in their current form, would be unattainable without the contributions of metals and alloys. These materials not only enhance athletic performance but also enable athletes to execute precise and controlled movements with ease (Zhao *et al*. 2021, Yang *et al*. 2022a, Wu *et al*. 2024). Thus, metals emerge as both efficient and indispensable contributors to the sports industry, endowed with unique properties and characteristics (Shalaby and Saad 2020).

Neglecting safety precautions in the realm of sports can have dire consequences, potentially resulting in injuries that can profoundly affect athletes (Fonseca *et al*. 2020). This issue becomes particularly salient when considering the crucial role of safety in sports. Among the various manifestations of safety lapses in sports, two key factors emerge prominently: inadequate sports facilities and the inappropriate design of sporting structures (Lystad *et al*. 2021). Inadequate sports facilities encompass everything from insufficiently maintained playing fields to a lack of protective barriers or surfaces. These shortcomings can expose athletes to unnecessary risks, increasing the likelihood of accidents and injuries. Similarly, improper sporting structures, such as poorly designed goalposts or uneven playing surfaces, create hazards that can have serious consequences. Another significant aspect contributing to safety concerns in sports is the use of non-standard equipment (Akaneeva *et al*. 2022). When athletes deviate from using conventional, standardized gear, they introduce an element of unpredictability and risk into their sporting activities. This can lead to unexpected accidents or injuries, as the equipment may not perform as expected. However, amidst these safety challenges, advancements in technology have provided a ray of hope (Guan 2023, Li 2023, Li *et al*. 2023b, d, Ma *et al*. 2023, Zhang *et al*. 2023b, Zhang *et al*. 2023d). The development of composites, composite materials, and nanostructured materials has revolutionized the sports equipment industry. Manufacturers have eagerly embraced these innovations, driven by the goal of not only enhancing equipment performance but also simplifying its use (Azman *et al*. 2021). These materials offer a range of benefits, from increased durability to reduced weight and improved performance. They allow athletes to push the boundaries of their abilities with greater confidence, knowing that their equipment has been engineered with safety and efficiency in mind. As technology continues to advance, the future holds promising prospects for even safer and more effective sports equipment, further mitigating the risks associated with athletic endeavors (Dai *et al*. 2023, He and Deng 2023, Jia *et al*. 2023, Li *et al*. 2023a, Song *et al*. 2023, Su *et al*. 2023b, Yang and Mao 2023, Ye *et al*. 2023).

A nanocomposite is a complex solid material characterized by the presence of one, two, or three-dimensional phases, with dimensions all measuring less than 100 nanometers, or it may feature structures with nanoscale repetition distances between different phases within the material (Kang *et al*. 2020, Ohodnicki *et al*. 2021). These composites, including nanocomposites, find their niche in applications requiring exceptional durability and strength, particularly in situations involving high stresses, erosion processes, and multi-phase environments (Assaedi *et al*. 2019, Vinothkannan *et al*. 2021). Within this context, consider scenarios where composites and nanocomposites shine: parts subject to collisions and impacts, components in continuous rotational motion susceptible to erosion, and fluid environments, exemplified by nanofluids (Faried *et al*. 2021). In essence, the mechanical properties of these materials become pivotal. Mechanical properties denote a material's response to various forces applied to it (Liu *et al*. 2019), with forces classified into diverse categories encompassing tension, compression, bending, twisting, and more (Gonen *et al*. 2023). To illustrate the significance of nanocomposites, consider a scenario where a 1-millimeter-thick layer or plate is embedded within a soft substrate. If the reinforcing material within this composite is stronger than the substrate, such as placing sheet metal within a plastic substrate, the resulting composite becomes more robust and exhibits greater resistance to tensile forces (Mahto *et al*. 2022). However, envision scaling down this layer to a thickness of just 1 nanometer, necessitating the incorporation of a million such nanometer-thin layers. Remarkably, these one million nanometer-thick layers can be uniformly distributed across the entire surface of the polymer substrate (Pradhan and Chakraborty 2020, Melentiev *et al*. 2022). Consequently, when mechanical forces are applied to the polymer matrix, it can withstand these forces with heightened resilience and efficacy (Viscusi *et al*. 2020). This exemplifies the pivotal role of nanocomposites in engineering materials designed to withstand the rigors of various applications (Zhang *et al*. 2023a, Gao *et al*. 2024, Xu *et al*. 2024).

Mechanical properties stand as a perennial focal point for researchers and engineers, representing a pivotal aspect of material characteristics that continually undergo refinement and enhancement (Benedetti *et al*. 2021). In the contemporary landscape of material science, nanocomposite materials have emerged as a subject of substantial interest and investigation (Mollahosseini and Abdelrasoul 2021). One notable category within the realm of nanocomposites involves materials founded on graphite, specifically the remarkable graphene sheet, celebrated for its exceptional mechanical attributes (Maurya *et al*. 2023). In comparison to traditional steel, graphene possesses a compelling set of advantages: it is notably lighter, yet boasts superior strength, higher tensile strength, enhanced resistance to bending, and the potential to yield recyclable, biocompatible, and cost-effective products (Ahmed *et al*. 2021). These characteristics position graphene-based nanocomposites as promising materials with profound implications for various industries, from aerospace and engineering to biomedicine and environmental sustainability. As researchers continue to explore and harness the unique mechanical properties of graphene, its potential to revolutionize a diverse array of applications becomes increasingly evident (Qi *et al*. 2024, Wang *et al*. 2022, Zhang *et al*. 2023c, Yan *et al*. 2024).

In examining the integration of nanocomposites into the polymer matrix of table tennis equipment, it is evident that the existing literature provides a comprehensive overview of the potential benefits in terms of mechanical properties enhancement (Zhang *et al*. 2020, Liu *et al*. 2024, Zhao *et al*. 2024). However, certain shortcomings and gaps persist. Firstly, while the broader context of sports equipment evolution is discussed, there is a lack of specific emphasis on the state-of-the-art developments in table tennis equipment, leaving a notable gap in understanding the current landscape. The literature predominantly focuses on the general categories of sports equipment, and more nuanced details pertaining specifically to table tennis gear are underrepresented. Moreover, the presented information extensively covers the significance of metals, especially aluminum, in sports equipment manufacturing, but falls short in directly connecting this with the nanocomposite integration explored in the study. This leaves room for a more explicit exploration of the transition from traditional materials to innovative nanocomposites in the context of table tennis. The safety concerns highlighted in the literature primarily address generic issues in sports, with limited emphasis on the safety implications specifically related to the mechanical properties of table tennis equipment. Additionally, while advancements in technology and materials are acknowledged, there is a need for a more nuanced exploration of how nanocomposites specifically address safety concerns in table tennis equipment. In essence, the literature presents a robust foundation but lacks the granularity required to fully appreciate the state of the art and the novel contributions that this study aims to bring to the forefront. The novelty of this research lies in bridging these gaps, offering a focused exploration of the state-of-the-art developments, safety implications, and the transformative potential of nanocomposite integration in optimizing table tennis equipment for enhanced mechanical performance and player safety. This study serves as a valuable contribution to the nuanced understanding of materials engineering in the context of table tennis, fostering innovation and addressing specific gaps in the current literature.

2. Materials and equipment

The comprehensive inventory of materials and equipment employed in this study is detailed in Table 1. All chemicals utilized in this research were procured with the highest degree of purity from Merck Company.

3. Research methodology

3.1 Synthesis of graphene nanoparticles

The synthesis process of graphene nanoparticles involved several precise steps. Initially, 0.3 grams of graphite powder was meticulously mixed with 15 ml of H_2SO_4 at a temperature of 70°C for a duration of 3 hours. Subsequently, 3 grams of KMnO4 were slowly introduced into the solution and subjected to sterilization for 2 hours. Following this phase, 30 ml of deionized water was added, and a solution containing 3 ml of H2O2 dissolved in 100 ml of deionized water was incorporated into the mixture. To eliminate any residual acids and salts within the solution, thorough filtration was employed. To facilitate the revival of the graphene oxide solution via a hydrothermal process, the pH level was initially raised to 9. Subsequently, 100 milliliters of the graphene oxide solution were transferred into a hydrothermal autoclave featuring a 150 milliliter Teflon chamber. The hydrothermal regeneration process was carried out for a duration of 5 hours at a temperature of 120 degrees. The resulting nanoparticles were then subjected to analysis through Atomic Force Microscopy (AFM) for a comprehensive evaluation of their characteristics and quality.

3.2 Green Synthesis of Carbon Nanoparticles

The process of green synthesizing carbon nanoparticles commenced with the cleansing of clover flowers using distilled water. Subsequently, an aqueous extract was prepared from these flowers using an ultrasonic bath, employing a temperature of 50°C for a duration of 30 minutes. The resulting solution was then separated from any residual plant matter through the use of filter paper. This solution served as the basis for the hydrothermal synthesis of carbon dots. To facilitate the synthesis, an Erlenmeyer flask was sealed entirely with a screw cap. The prepared plant extract was carefully poured into the Erlenmeyer flask, and the synthesis process was set to occur at a temperature of 100°C for a duration of 3 hours. Accordingly, the sealed flask was placed within an oven under the aforementioned conditions. Upon the completion of the designated time, the Erlenmeyer flask was removed from the oven and allowed to cool. Subsequently, the flask was opened, resulting in the discharge of a dark brown solution. To further process the solution, it was subjected to centrifugation at 500 rpm for a period of 10 minutes. This centrifugation process led to the separation of the transparent upper solution. Finally, the separated material was left at room temperature to undergo drying. The synthesized carbon dots typically exhibit significant absorbance in the Ultraviolet-visible spectrum. To investigate this property, carbon dots produced from the clover extract were analyzed using a UV-Vis spectrometer, specifically the Cary 4000 model, to gain valuable insights into their optical characteristics and quality.

3.3 Aluminum-based alloy

The choice of A356 as the primary aluminum alloy in this study stemmed from its ready availability and the potential for generalizing results. To validate the chemical composition of the primary aluminum alloy A356, an elemental emission spectroscopic test was conducted. The results of this analysis are presented in Table 2, providing a comprehensive overview of the chemical composition of this pivotal alloy.

3.4 Nanocomposite production via vortex flow method

A cutting-edge approach for fabricating nanocomposites involves the creation of a vortex flow within the molten mixture using a specialized stirrer. The initial step involved slicing the primary alloy A356 ingots into 100-gram segments using a band saw. To prepare the primary melt, 900 grams of this alloy were meticulously placed within a resistance furnace, with the temperature set at 800°C, and housed in a graphite crucible. Incorporation of graphene nanoparticles and carbon nanoparticles occurred at concentrations of 0.01%, 0.1%, and 0.15% by weight. These nanoparticles were systematically added to the molten alloy in 14 equal portions, each with a precisely measured time interval of 1 minute, within an aluminum foil enclosure. Following the introduction of each portion of the refractory powder, stirring was executed using a preheated graphite stirrer, maintained at a temperature of 300°C. The stirring process was executed at a consistent speed of 400 rpm for 1 minute. Throughout the stirrer’s rotation, argon gas was applied to the molten surface as a protective measure against oxidation. Subsequent to the completion of the stirring process, the crucible containing the molten mixture was promptly removed from the furnace. The molten alloy was then subjected to the melting process within a cylindrical mold, preheated to 400 degrees Celsius. Microstructural images were meticulously captured utilizing a scanning electron microscope, providing

Table 2 Chemical Composition of primary A356 alloy

Element	Weight percent
Si	8.21
Mg	0.35
Mn	0.01
Fe	0.01
Cu	0.09
Al	Residual

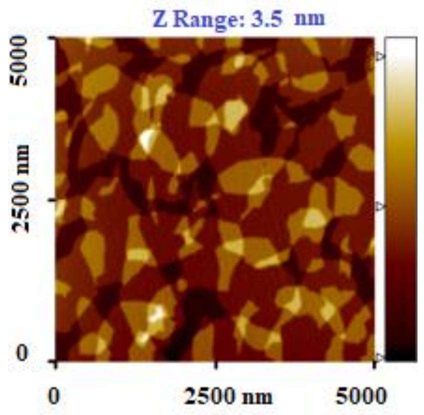

Fig. 1 Graph obtained from AFM analysis results

magnifications of up to 1000 times. To assess the mechanical properties of the resulting nanocomposites, both tensile and static pressure tests were employed. These comprehensive analyses allowed for an in-depth evaluation of the structural and mechanical attributes of the newly fabricated nanocomposites.

4. Results and discussion

4.1 Results of graphene synthesis

The outcomes of the graphene synthesis process are presented in Fig. 1, showcasing Atomic Force Microscopy (AFM) results. Notably, the figure clearly illustrates the overlapping of graphene sheets, providing valuable insights into particle size. As discerned from the figure, the thickness of graphene particles measures approximately 0.785 nanometers. These results offer essential information about the quality and characteristics of the synthesized graphene, which will be instrumental in understanding its performance in subsequent applications and within nanocomposite structures. Further analysis and discussion of these findings will shed light on their implications for the overall research objectives.

4.2 UV-Vis Test

The UV-Vis test served to explore the optical characteristics of the fabricated carbon dots. Fig. 2 presents the findings, revealing that the sample exhibits absorbance within the wavelength range of 252 to 279 nanometers. This

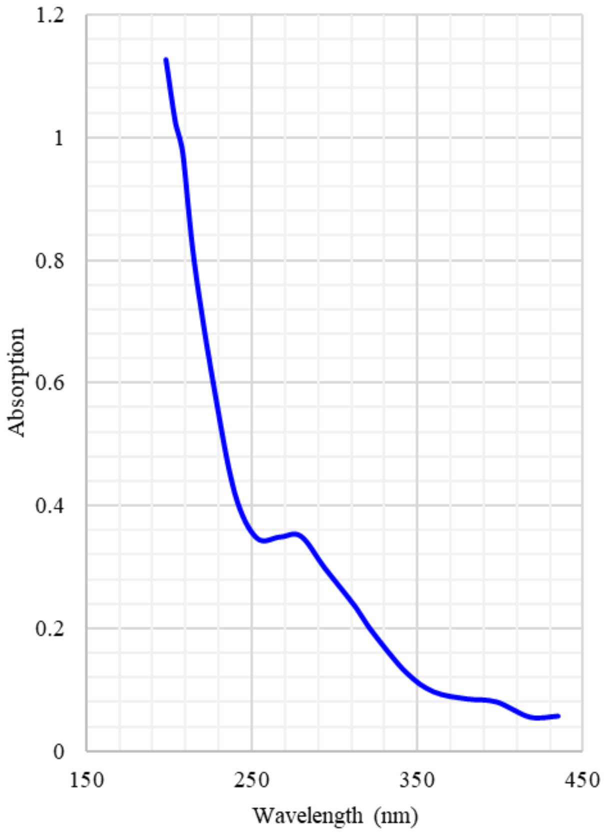

Fig. 2 Absorption spectrum of carbon particle

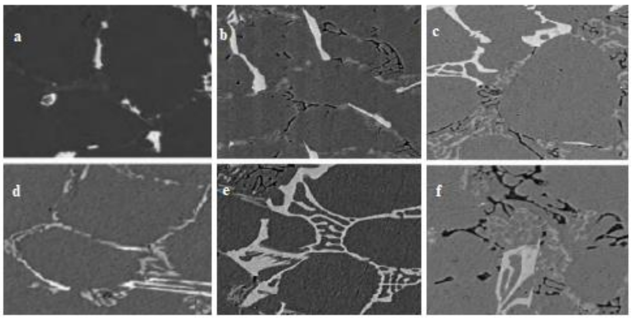

Fig. 3 Scanning electron microscope images

absorption spectrum aligns with the characteristic absorption patterns observed in other carbon dots, validating the successful synthesis of these nanoparticles. The UV-Vis test results provide crucial insights into the optical properties of the carbon dots, laying the foundation for further discussions and analyses of their performance and potential applications in nanocomposites and related fields.

4.3 Scanning electron microscopy results

Fig. 3 offers a revealing glimpse into the microstructure of each of the produced nanocomposites, as observed at a magnification of 1000. Notably, an intriguing trend emerges with increasing weight percentages of the stabilizer, where the presence and dispersion of the phase characterized by a dark color, indicative of the carbon phase, exhibit an upward trajectory. This pattern is particularly pronounced among the three samples incorporating graphene nano-particles. Consequently, to achieve more uniform dispersion within both resistors, it becomes evident that increasing the weight percentage to 0.15 is a promising avenue. In terms of the dispersion and morphology of the resistive phase, subtle differences are observed between the two types of reinforcements. In samples featuring carbon nanoparticles, the formation of carbon streaks is noticeable, typically occurring in proximity to the Al7Si phases (Fig. 3a-c). In contrast, for samples reinforced with graphene, these carbon streaks manifest away from the secondary phases and within the background (Fig. 3d-f). This distinction in the location of carbon streak formation between the two types of nanocomposites introduces variations in their mechanical behavior. It is anticipated that in graphene-reinforced nanocomposites, the creation of carbon streaks and their increased dispersion within the matrix will contribute to enhanced mechanical strength. This improvement is not solely anticipated to surpass the strength of the unreinforced sample (primary alloy A356) but may potentially outperform samples reinforced with carbon nanoparticles. This expectation is rooted in the formation of graphene veins within the matrix, positioned away from areas of stress concentration, such as the Al_7Si phase. Consequently, this redistribution of carbon veins holds the potential to bolster the overall strength of the nanocomposite, promising intriguing possibilities for advanced materials in various applications.

5. Results of tensile and compression mechanical tests

The outcomes of the tensile and compression mechanical tests are graphically depicted in Figure 4. The incorporation of both types of reinforcement into the primary aluminum alloy A356 has led to a notable increase in tensile ductility (Figure 4a). In the most favorable scenario, the addition of 0.15% of carbon nanoparticles results in a remarkable enhancement of ductility, reaching a level of 3.31%. This boost in ductility can be attributed to several factors, including the presence of nanoparticles and their influence on grain size modification within the background phase. This, in turn, retards nucleation and crack propagation, postponing failure. Additionally, the presence of carbon nanoparticles contributes to the delay in dislocation movement, effectively increasing ductility. It's worth noting that at lower concentrations, carbon nanoparticles exhibit a more pronounced effect compared to graphene. However, as the reinforcement content increases to 0.15%, the impact of graphene and carbon nanoparticles becomes nearly equal. This can be attributed to the lower density and superior wettability of graphene, which results in a more substantial impact on ductility at higher weight percentages.

Moreover, the inclusion of the reinforcing agent has had a significant influence on both tensile and compressive strength, as depicted in Figs. 4b and 4d. This strength enhancement is attributed to the impact of the reinforcing

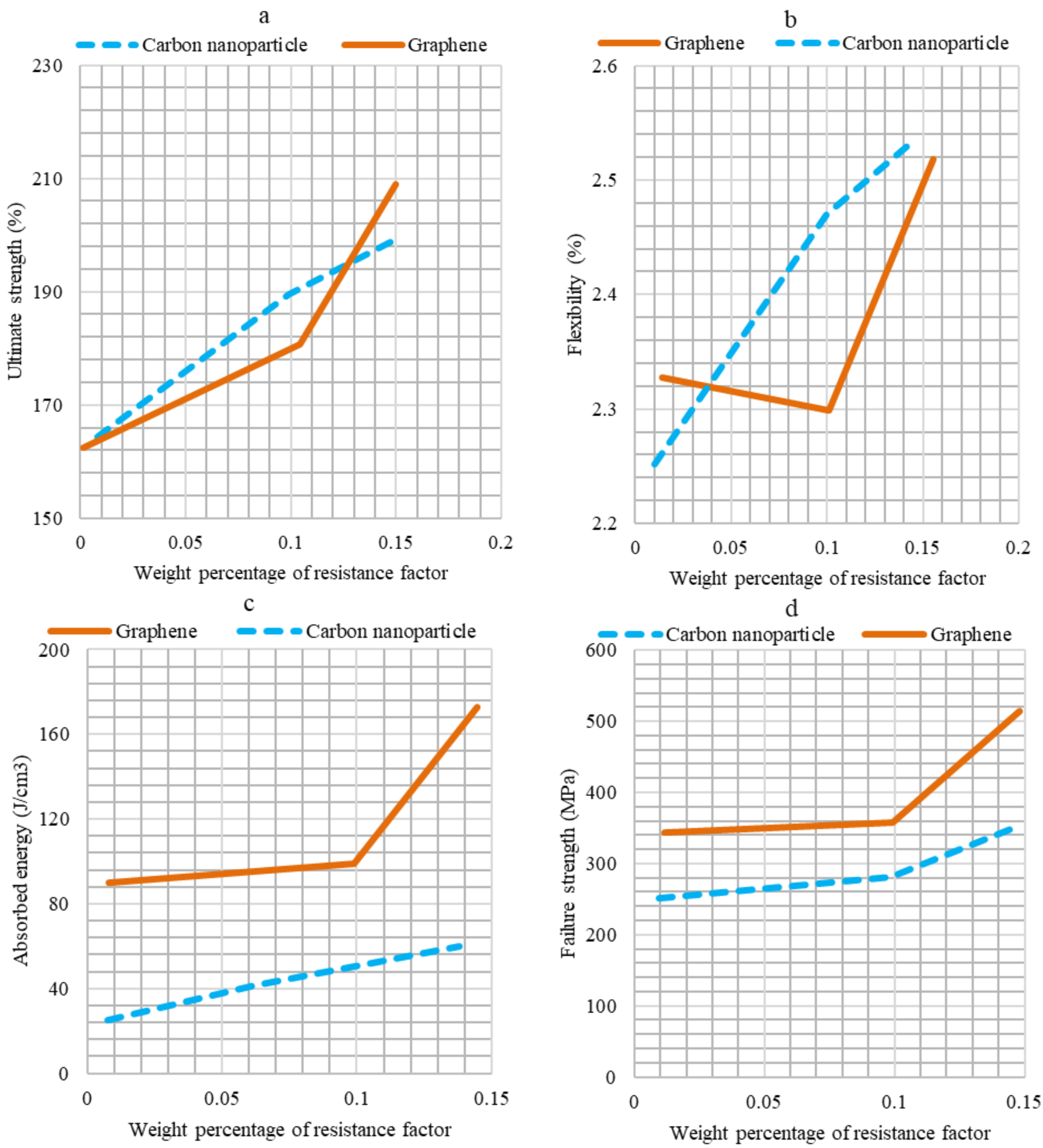

Fig. 4 Results of tension and pressure tests of nanocomposites. a. Flexibility b. Ultimate strength c. Absorbed energy d. Failure strength

agent on dislocation mobility, impeding both the initiation and propagation of dislocation movement, consequently bolstering strength. Furthermore, a reduction in grain size, especially in terms of yield strength, contributes to the observed increase in strength. This phenomenon is linked to a growth-limiting factor in the context of phase transformations. For aluminum alloys, carbon elements play a notable role in this context, rationalizing the increase in strength in the presence of carbon agents. Comparative analysis reveals a substantial increase in tensile strength for the produced nanocomposites when compared to the strength of the primary aluminum alloy. Even at the lowest concentration, the presence of carbon-based nanoparticles has induced a significant strength increase.

In the compressive state, the highest strength achieved reached 600 MPa, marking a substantial 58% improvement (Fig. 4d). The simultaneous enhancement of strength and ductility has a profound impact on the remarkable improvement in energy absorption during the compression test, as illustrated in Fig. 4c. Graphene, in particular, exerts a more pronounced influence on elevating this quantity compared to carbon nanoparticles. The most striking improvements in this parameter for both reinforcement agents were observed at the 0.15 weight percent concentration, emphasizing the pivotal role of the reinforcement content in achieving these remarkable mechanical advancements.

4. Conclusions

Significant progress was achieved in this study's pursuit of advancing nanotechnology for the fabrication of sports equipment, dedicated to enhancing athletes' performance during physical education training. The exploration of production conditions for aluminum-based nanocomposites resulted in the introduction of an innovative material with immense promise within the realm of sports engineering. Specifically, the influence of two key reinforcing agents, graphene and carbon nanoparticles, on the microstructure and mechanical characteristics of sports equipment and structures was investigated. The successful production of these nanocomposites stood as a pivotal achievement, with subsequent microstructural assessments revealing the attainment of optimal morphology and particle distribution at a concentration of 0.15% by weight for both graphene and carbon nanoparticles. These findings directly contributed to the development and assessment of nanotechnology-enabled sports equipment.

Furthermore, the synergistic enhancement in strength and ductility, brought about by the presence of both reinforcement agents, marked a significant milestone. This simultaneous improvement in vital mechanical properties translated into a notable augmentation in energy absorption capacity, a crucial attribute for sports equipment tasked with enduring mechanical loads while efficiently absorbing and dissipating energy. This, in turn, contributed to the enhancement of athletes' performance and safety. The study underscored the potential of aluminum nanocomposites as a class of materials boasting exceptional attributes, including a remarkable strength-to-weight ratio, corrosion resistance, and versatility across diverse sporting applications. The investigation, particularly the incorporation of carbon nanoparticles into aluminum alloy 356 through the vortex casting method at varying weight percentages, held great promise for advancing the development and utilization of nanotechnology in sports equipment, ultimately propelling athletes to new heights in their physical education training endeavors.

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