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THE EFFECTS OF NANOTECHNOLOGY ON THE MECHANICAL AND PHYSICAL PROPERTIES OF METALS OF COOLING SYSTEMS

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Abstract

Nanotechnology has revolutionized various scientific and engineering fields, including materials science. In this investigation, the focus is on examining the influence of titanium nanoparticle size on the mechanical and physical properties of metal. Incorporating nanoparticles into metal matrices presents an exciting opportunity to enhance material performance through size-dependent effects. Titanium nanoparticles have been chosen as the primary focus due to their unique properties and extensive applications. To assess the impact of nanoparticle size on mechanical properties, a series of experiments were conducted involving the production of metal composites with varying sizes of titanium nanoparticles. Mechanical properties, including yield strength and hardness, were measured using standard testing methods such as tensile testing and nanoindentation. The results indicate that smaller titanium nanoparticles contributed to improve mechanical properties, increased yield strength and hardness compared to the bulk metal. Additionally, the investigation explored the effects of titanium nanoparticle size on the physical properties of the metal composite. Thermal conductivity and coefficient of thermal expansion were measured to evaluate the thermal behavior of the composites. The findings demonstrate that the incorporation of titanium nanoparticles influences thermal conductivity and coefficient of thermal expansion, with variations that depend on nanoparticle size.

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Keywords: Nanotechnology, Titanium Nanoparticles, Mechanical Properties, Physical Properties, Metal Composites.

تأثيرات التكنولوجيا النانوية على الخواص الميكانيكية والفيزيائية للمعادن في أنظمة التبريد

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تلخيص:

أحدثت تكنولوجيا النانو ثورة في مختلف المجالات العلمية والهندسية، بما في ذلك علم المواد. في هذه الورقة البحثية تمت دراسة تأثير حجم جسيمات التيتانيوم الدقيقة على الخواص الميكانيكية والفيزيائية للمعادن. يعزز دمج الجسيمات الدقيقة مع المعدن أداء المواد وذلك بناءً على الحجم المضاف من الجسيمات. تم اختيار جسيمات التيتانيوم الدقيقة نظرًا لخصائصها الفريدة وتطبيقاتها الواسعة. ولتقييم تأثير حجم الجسيمات الدقيقة على الخواص الميكانيكية للمعدن، تم إجراء سلسلة من التجارب شملت إنتاج سبيكة معدنية بأحجام مختلفة من جسيمات التيتانيوم، وتم قياس الخواص الميكانيكية للسبيكة تحت التجربة بما في ذلك القوة والصلابة وذلك باستخدام طرق الاختبار القياسية مثل اختبار الشد والتآكل. تشير النتائج إلى أن جزيئات التيتانيوم الأصغر ساهمت في تحسين الخواص الميكانيكية وزيادة قوة التحمل والصلابة مقارنة بالمعدن السائب. بالإضافة إلى ذلك، استكشف البحث تأثير حجم جسيمات التيتانيوم الدقيقة على الخواص الفيزيائية للسبيكة المعدنية، حيث تم قياس التوصيل الحراري ومعامل التمدد الحراري لتقييم السلوك الحراري للمعدن تحت التجربة. وضحت النتائج أن دمج جسيمات التيتانيوم الدقيقة يؤثر على التوصيل الحراري ومعامل التمدد الحراري، مع وجود تباين يعتمد على حجم الجسيمات المضافة.

الكلمات المفاتيح: الجسيمات الدقيقة، الخواص الميكانيكية والفيزيائية، المعادن.

1. Introduction

In recent times, there has been increasing interest in utilizing nanotechnology to enhance the functionality of various systems and materials. One specific area that has experienced substantial progress is the application of nanotechnology to improve the mechanical and physical properties of metals utilized in cooling systems. Cooling systems play a critical role in numerous industries, including automotive, aerospace, electronics, and power generation, where efficient heat dissipation is essential for optimal performance and reliability.

Traditionally, cooling systems have relied on metals such as copper, aluminum, and steel due to their favorable thermal conductivity and mechanical strength. However, the inherent limitations of these metals have prompted researchers to explore innovative approaches to enhance their properties. Nanotechnology, with its ability to manipulate materials at the nanoscale, has emerged as a promising avenue for achieving significant improvements in the performance of cooling system metals. A key strategy in harnessing the potential of nanotechnology for cooling system applications is the integration of nanoparticles into metal matrices. Nanoparticles, typically ranging in size from 1 to 100 nanometers, possess unique physical and chemical properties that can be leveraged to enhance the mechanical and thermal characteristics of metals. By dispersing nanoparticles within metal matrices, it becomes possible to create metal-nanoparticle composites with customized properties that surpass those of conventional metals.

Incorporating nanoparticles into cooling system metals offers several advantages, particularly in terms of mechanical properties. Nanoparticles can reinforce metal matrices by impeding dislocation motion, thereby increasing the strength and hardness of the material. Studies have indicated that the addition of nanoparticles such as carbon nanotubes, graphene, or ceramic nanoparticles can significantly enhance the yield strength, tensile strength, and hardness of metals. These improvements can result in enhanced structural integrity, increased resistance to deformation, and improved load-bearing capabilities, all of which are crucial in

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cooling system applications. Moreover, the integration of nanoparticles can also impact the thermal properties of metals. High thermal conductivity is essential for efficient heat transfer in cooling systems. Nanoparticles, with their high surface-to-volume ratio, can enhance thermal conductivity by facilitating the transport of phonons across the material. Additionally, the use of nanofluids, which are suspensions of nanoparticles in a base fluid, has emerged as a potential approach to further augment the thermal performance of cooling systems. The introduction of nanofluids into heat exchangers or coolant systems has shown improvements in heat transfer rates and overall cooling system efficiency. The effects of nanotechnology on the mechanical and physical properties of cooling system metals have been studied through a combination of experimental investigations, computational modeling, and theoretical analyses. These research endeavors have provided valuable insights into the underlying mechanisms responsible for the observed enhancements in material properties. Factors such as the dispersion and interfacial interactions between nanoparticles and metal matrices, as well as the influence of grain boundaries and dislocation interactions, have been identified as crucial elements influencing the behavior of the material. The application of nanotechnology in cooling systems holds the potential to revolutionize the performance of metals utilized in these applications. By incorporating nanoparticles into metal matrices, it becomes possible to achieve remarkable improvements in mechanical strength, hardness, and thermal conductivity. These advancements can lead to more efficient and reliable cooling systems, with broad implications for industries that rely on effective heat dissipation. As the field of nanotechnology continues to evolve, further research and development are expected to uncover new opportunities and challenges in leveraging nanomaterials for cooling system applications.

1.1. Background and significance of the study

The trade-off of strength and ductility of metals has long plagued materials scientists. To resolve this issue, great efforts have been devoted over the past decades to developing a variety of technological pathways for effectively tailoring the microstructure of metallic materials. Several investigations into nano materials have yielded significant outcomes, with some nanomaterials finding practical applications in industrial production.

In [13], the utilization of Nanofluids (NF) in various energy systems was examined, revealing that NFs typically exhibit enhanced heat transfer capability compared to pure fluids. Most researchers have employed NFs containing metal oxide nanoparticles (NPs). Furthermore, the available economic and performance analyses have indicated that NFs demonstrate satisfactory performance and can be employed as industrial fluids. The challenges associated with the implementation of NFs in different industries have also been identified. These challenges primarily include the high cost of NP production, the increase in viscosity leading to higher pumping power requirements, the precipitation and agglomeration of NPs over time, the reduction in thermal conductivity coefficient at high volume fractions, increased wear in these systems, and the impact of NPs on the environment. The use of NFs has resulted in decreased energy consumption, emissions, waste generation, raw material utilization, and, consequently, reduced harm to the environment.

In [14], a recent review examined advanced strategies for designing nanostructures in crystalline and non-crystalline metallic materials. The study focused on various structural approaches, including hierarchical nanotwinned (HNT) structures, extreme grain refinement, and dislocation architectures for crystalline metals. For non-crystalline alloys, such as metallic glasses (MGs), the nanoglass structure was explored. Additionally, a series of supra-nano-dual-phase (SNDP) nanostructures were investigated for composite alloys. The manipulation of these nanostructures was found to optimize the mechanical properties, especially when multiple advanced nanostructures were combined in one material. The newly developed SNDP nanostructures, which incorporated supra-nano sized crystals and MGs, showcased unique size and synergistic effects. The review discussed the origins of these desirable properties and proposed strategies for achieving high strength and high ductility. The specific strength and ductility relationship illustrated in Figure 1 indicated that high-performance steels often contained HNT structures. Other advanced nanostructures, such as gradient structures and dislocation architectures, were also employed in conjunction with HNT. Furthermore, micro-alloying and nanostructure design played a significant role in the mechanical properties of MEAs and HEAs. The introduction of high-density multicomponent intermetallic nanoparticles and ordered oxygen complexes enhanced the mechanical properties. The manipulation of amorphous heterogeneity, although still underexplored, showed promise in fabricating multiphase metallic glasses. It summarized several superior nanostructures, along with their processing techniques and strengthening mechanisms, to achieve mechanically high-performance materials.

An Al2024 alloy matrix nanocomposite reinforced with different graphene contents up to 2 wt. % was synthesized using a mechanical alloying technique followed by sintering at temperatures of 460 and 560 °C in an argon atmosphere. The prepared nanocomposite powders were characterized using XRD and TEM, while the microstructure analysis of the sintered composites was performed using SEM. The relative density, corrosion rate, thermal expansion coefficient, and electrical conductivity of the sintered nanocomposites were measured. The mechanical properties of the nanocomposites, including microhardness, elastic modulus, and yield strength, were evaluated using an ultrasonic non-destructive technique. SEM and TEM analysis revealed a uniform distribution of graphene in the Al alloy matrix. As the graphene content increased to 2 wt%, the relative density, coefficient of thermal expansion (CTE), and electrical conductivity of the specimens sintered at 460 °C decreased to 90.9%, 13.6 × 10−6/°C, and 8.41 × 105 S/m, respectively. However, they increased to 93.8%, 1.5 × 10−6/°C, and 4.20 × 106 S/m when the sintering temperature was increased to 560 °C. The addition of 2 wt% graphene and sintering at 560 °C resulted in enhanced mechanical properties, with the microhardness, elastic modulus, and yield strength increasing by 155%, 134%, and 97%, respectively. Furthermore, the corrosion rate decreased from 5.74 to 2.73 and 5.34 to 2.59 for the samples with 2 wt% graphene and sintered at 460 and 560 °C, respectively, as the exposure time increased from 24 to 144 hours [15].

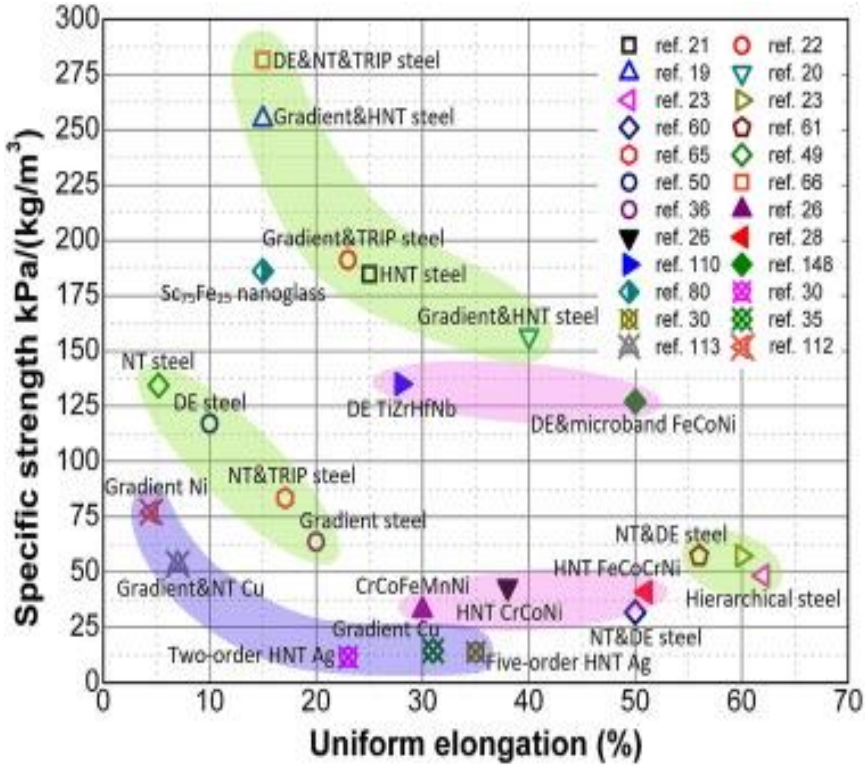

Figure 1: The Relation between Uniform elongation and Specific strength [16].

Numerous techniques have been utilized to safeguard metals in various assets against corrosion, and one cost-effective and efficient approach involves the use of organic coatings. However, the performance of organic coatings is often influenced by their inherent porosity, which can create pathways for corrosive substances or make them susceptible to mechanical harm. To enhance the engineering capabilities of coatings, nanomaterials (NMs) with diverse shapes and sizes have been employed. These NMs have demonstrated the ability to improve corrosion resistance and other coating properties through several mechanisms, some of which are not yet fully understood. a previous article provided an overview of different types of anticorrosion coatings and their protective mechanisms. This article also explored smart nanocomposite organic coatings, which can be designed to release repair or protective agents upon external triggers, primarily targeting corrosion defects or damaged areas of the coating. The findings indicated that bio-based and carbon-based nanomaterials show great promise as nanofillers for enhancing the barrier properties of organic coating [16].

The distinctive characteristics of nanomaterials provide them with extensive prospects for applications and substantial potential value in the future. Consequently, it is imperative to persist in the study of nanomaterials, delving deeper into their molding mechanism, strengthening process, and modification techniques to enhance their properties. Accordingly, the objective of this research is to investigate how the size of titanium nanoparticles influences the mechanical and physical properties of metal. The focus is on titanium nanoparticles due to their unique properties and widespread usage. The goal is to assess the simulation impact of nanoparticle size on mechanical properties with varying sizes of titanium nanoparticles using MATLAB software. Standard testing methods such as tensile testing and nanoindentation are used to measure mechanical properties, including yield strength and hardness. The research aims to determine whether smaller titanium nanoparticles can enhance the mechanical properties, leading to increased yield strength and hardness compared to the bulk metal. Additionally, the study aims to understand how nanoparticle size affects the physical properties of the metal composite, specifically thermal conductivity and coefficient of thermal expansion. By evaluating these properties, the research seeks to enhance our understanding of the relationship between nanoparticle size and the mechanical and physical properties of metal composites.

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2. Nanotechnology and its Applications in Cooling Systems

2.1. Overview of nanotechnology and its principles

Nanotechnology, a rapidly advancing field, involves the manipulation and control of matter at the nanoscale, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique properties and behaviors that differ significantly from their bulk counterparts. Nanotechnology has found applications in various disciplines, including materials science, electronics, medicine, energy, and environmental science, among others. This overview will provide insights into the principles of nanotechnology and highlight recent developments in the field.

One of the fundamental principles of nanotechnology is the ability to design and engineer materials at the atomic and molecular levels to achieve desired functionalities. Researchers utilize bottom-up and top-down approaches to fabricate nanomaterials. The bottom-up approach involves the assembly of atoms, molecules, or nanoparticles to form larger structures, while the top-down approach involves the miniaturization of bulk materials to the nanoscale. These approaches enable precise control over the composition, structure, and properties of nanomaterials, leading to unique and tailored functionalities.

Nanotechnology relies on the principles of quantum mechanics, where quantum effects dominate at the nanoscale. Quantum confinement, for example, refers to the confinement of electrons and other particles in nanoscale structures, resulting in discrete energy levels and altered electronic properties. This principle has paved the way for advancements in nanoelectronics, where nanoscale devices and components exhibit enhanced performance and novel functionalities.

Furthermore, the high surface-to-volume ratio of nanomaterials is a crucial aspect of nanotechnology. As the size of a material decreases to the nanoscale, the relative importance of the surface area increases significantly. This increased surface area provides more active sites for chemical reactions and interactions, making nanomaterials highly reactive and suitable for applications such as catalysis, sensors, and drug delivery systems.

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Recent advances in nanotechnology have been driven by breakthroughs in nanofabrication techniques. Various methods, such as chemical vapor deposition, physical vapor deposition, molecular beam epitaxy, and self-assembly, have been developed to create nanostructures with precise control over dimensions, morphology, and composition. These techniques allow researchers to engineer materials with tailored properties and structures, enabling the design of functional nanodevices and Nano systems.

Nanomaterials can be classified into different categories, including nanoparticles, nanotubes, nanowires, nanocomposites, and thin films, among others. Nanoparticles, typically ranging from 1 to 100 nanometers, exhibit size-dependent properties, such as optical, magnetic, and catalytic properties. These nanoparticles can be synthesized from various materials, including metals, semiconductors, oxides, and polymers. Nanotubes and nanowires, on the other hand, are elongated nanostructures with unique electrical, thermal, and mechanical properties, making them suitable for applications in electronics, energy storage, and sensing.

The interdisciplinary nature of nanotechnology has led to collaborations between scientists, engineers, and researchers from different fields. This multidisciplinary approach allows for the integration of expertise in physics, chemistry, materials science, biology, and engineering to address the challenges and opportunities associated with nanotechnology [17].

Figure 2 illustrates how the fracture toughness and hardness change as the nano-Al2O3 content increases. Initially, both fracture toughness and hardness increase with the addition of nano-Al2O3. However, beyond a certain point, there is a noticeable decrease in fracture toughness and hardness. Specifically, when the nano-Al2O3 content reaches 4 vol %, the fracture toughness and hardness reach their highest values. Therefore, it can be concluded that adding a large quantity of nanoparticles to the matrix can potentially decrease the mechanical properties of the nanocomposite [18]. Figure 3 showcases a transmission electron microscopy (TEM) image of gold nanoparticles. These nanoparticles exhibit unique optical and catalytic properties due to their nanoscale size.

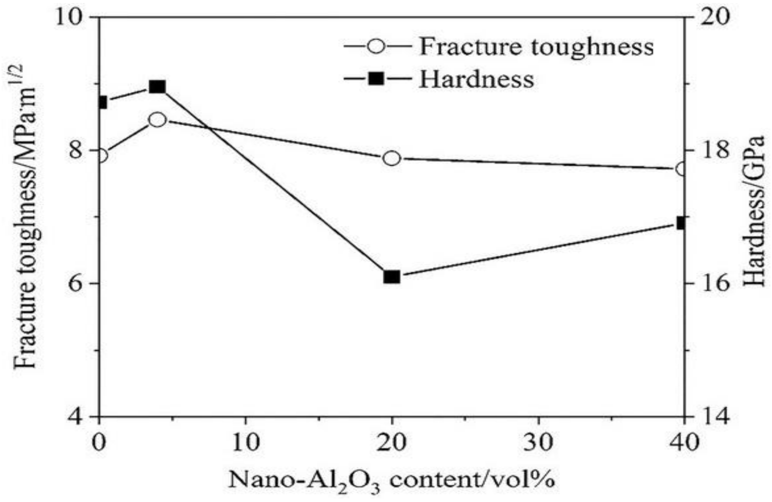

Figure 2: The Fracture Toughness and Hardness Change as the Nano-Al2O3 Content [18].

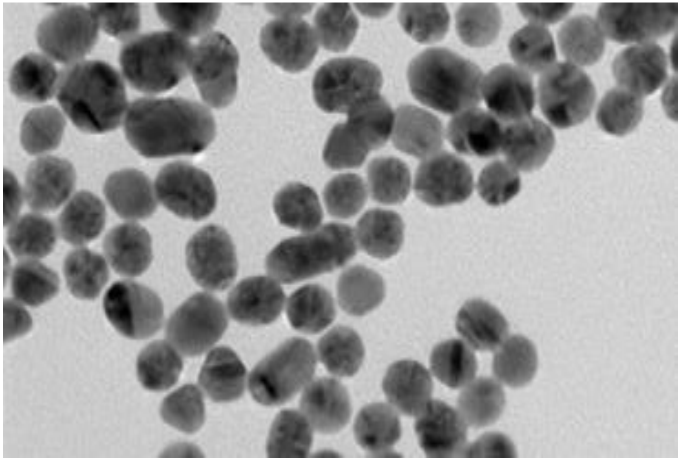

Figure 3: Transmission electron microscopy (TEM) image of gold nanoparticles [17].

Accordingly, nanotechnology offers exciting opportunities for the manipulation and control of matter at the nanoscale. The principles of nanotechnology, including precise control over materials at the atomic and molecular levels, quantum effects, and increased surface area, have allowed for the development of novel materials and devices with enhanced properties. Recent advancements in nanofabrication techniques and the interdisciplinary nature of nanotechnology have further propelled the field forward. As nanotechnology continues to evolve, it holds tremendous promise for revolutionizing various industries and addressing global challenges.

2.2. Importance of nanotechnology in enhancing cooling systems

Cooling systems play a vital role in various industries, including automotive, aerospace, electronics, and power generation, where efficient heat dissipation is crucial for optimal performance and reliability. As technology, advances and the demand for higher power densities increases, traditional cooling techniques often struggle to meet the escalating cooling requirements. Nanotechnology has emerged as a promising avenue for enhancing the performance of cooling systems by leveraging the unique properties of nanomaterials. In this article, we will explore the importance of nanotechnology in enhancing cooling systems and discuss recent developments in the field [19].

Nanotechnology offers several key advantages in the context of cooling systems. One of the primary benefits is the ability to enhance the thermal conductivity of cooling materials. Traditional cooling materials, such as metals like copper and aluminum, have relatively high thermal conductivities. However, by incorporating nanomaterials, such as nanoparticles or nanofluids, into these materials, their thermal conductivity can be significantly improved. Nanoparticles, with their high surface-to-volume ratio, can facilitate heat transfer by enhancing phonon transport, resulting in improved cooling efficiency.

Nanofluids, which are suspensions of nanoparticles in a base fluid, have attracted considerable attention in the field of cooling systems. By dispersing nanoparticles in a coolant, the thermal conductivity of the fluid can be greatly enhanced. Additionally, the unique properties of nanoparticles, such as their large surface area and

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tunable surface chemistry, enable better heat transfer and improved flow characteristics. Nanofluids have shown great potential in applications such as heat exchangers, where they can significantly enhance heat transfer rates and improve overall cooling system performance.

Another important aspect of nanotechnology in cooling systems is the development of advanced heat sink materials. Heat sinks are critical components in cooling systems that efficiently transfer heat away from heat-generating devices. By utilizing nanomaterials, heat sink performance can be significantly enhanced. For instance, the incorporation of carbon nanotubes (CNTs) or graphene into heat sink materials can increase their thermal conductivity and provide better heat dissipation capabilities.

Figure 4 illustrates a schematic representation of a nanomaterial-enhanced heat sink. The incorporation of nanomaterials, such as carbon nanotubes or graphene, improves the thermal conductivity and enhances heat dissipation.

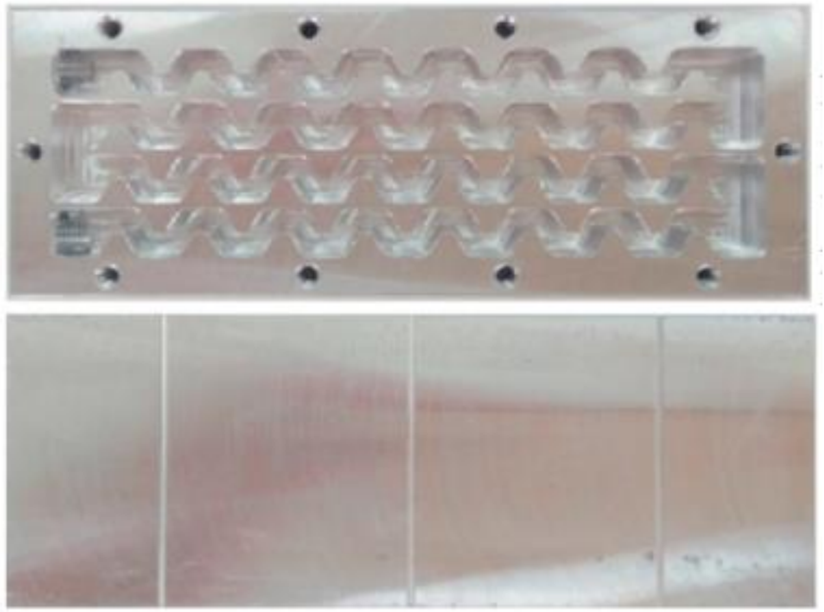

Figure 4: Schematic representation of a nanomaterial-enhanced heat sink [20].

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Furthermore, nanotechnology enables the development of lightweight and compact cooling systems. As industries strive for miniaturization and improved portability, traditional cooling systems face challenges in meeting these demands. Nanomaterials, with their exceptional mechanical properties and high aspect ratios, can be utilized to create lightweight heat sinks, heat pipes, and other cooling components. These materials offer improved thermal performance while reducing the weight and size of cooling systems, making them more suitable for compact and mobile applications.

In addition to thermal enhancements, nanotechnology also offers opportunities to improve other aspects of cooling systems. For example, the incorporation of nanoparticles in cooling materials can enhance their mechanical strength and hardness, leading to improved structural integrity and durability. Nanocoatings can provide corrosion resistance, reduce fouling, and improve the overall efficiency of cooling systems.

Accordingly, nanotechnology plays a crucial role in enhancing cooling systems by leveraging the unique properties of nanomaterials. The ability to improve thermal conductivity, develop advanced heat sink materials, create lightweight cooling components, and enhance mechanical properties has significant implications for various industries. Recent developments in nanofluid technology, nanomaterial synthesis, and nanocoatings have demonstrated the potential of nanotechnology to revolutionize cooling system performance. As research in this field progresses, we can expect further advancements that will drive the development of more efficient, compact, and reliable cooling systems to meet the evolving demands of modern industries [20].

Nanoparticles, with their unique size-dependent properties, have garnered significant attention in various fields of science and engineering. One area of interest is the study of nanoparticles' effects on the physical properties of materials. In this article, we will focus on the changes in the coefficient of thermal expansion (CTE) induced by nanoparticles.

The coefficient of thermal expansion is a material property that quantifies how its dimensions change with temperature. It represents the fractional change in length (or volume) per unit change in temperature. A positive CTE implies expansion with increasing temperature, while a negative CTE indicates contraction.

The introduction of nanoparticles to a material can significantly alter its CTE. The underlying mechanisms responsible for these changes can be attributed to various factors, including the nanoparticle size, shape, composition, and dispersion within the matrix.

The size of nanoparticles plays a crucial role in modifying the CTE of materials. As the nanoparticle size decreases, a higher surface-to-volume ratio is achieved. This increased surface area promotes stronger interactions between nanoparticles and the matrix, leading to enhanced CTE modifications. Smaller nanoparticles exhibit larger surface areas, resulting in stronger particle-matrix bonding and increased CTE reduction.

In Figure 5, the relationship between nanoparticle size and CTE modification were observed in [21]. As the nanoparticle size decreases, the CTE reduction becomes more pronounced, ultimately leading to a lower overall CTE.

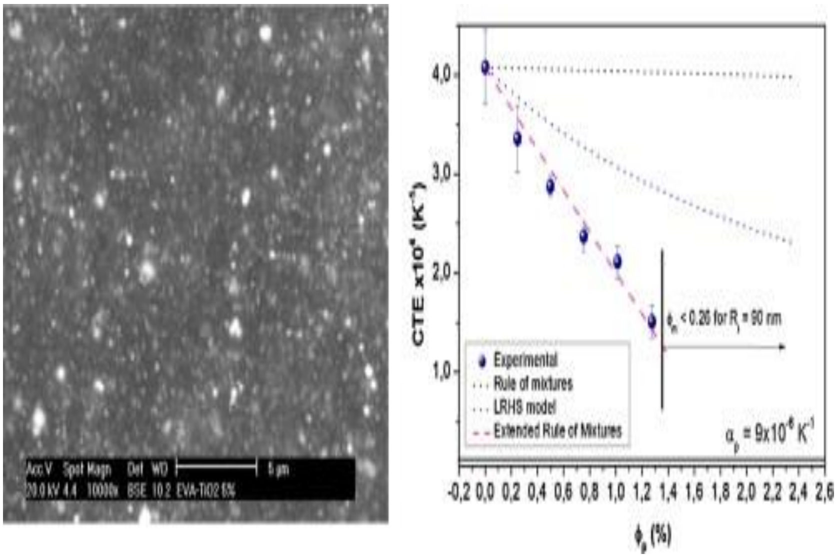

Figure 5: Effect of Nanoparticle Size on CTE Modification [21]

2.3. Effect of Nanoparticle Shape and Composition:

Apart from size, nanoparticle shape and composition also influence CTE modifications. Anisotropic nanoparticles with elongated or plate-like shapes tend to align within the matrix, resulting in directional CTE changes. Additionally, nanoparticles with high thermal conductivities, such as metallic nanoparticles, can influence the heat transfer pathways within the material, thereby affecting thermal expansion behavior.

As shown in Figure 6, anisotropic nanoparticles (represented by ellipsoidal shapes) induce directional CTE changes, while metallic nanoparticles enhance CTE reductions due to their high thermal conductivities [22].

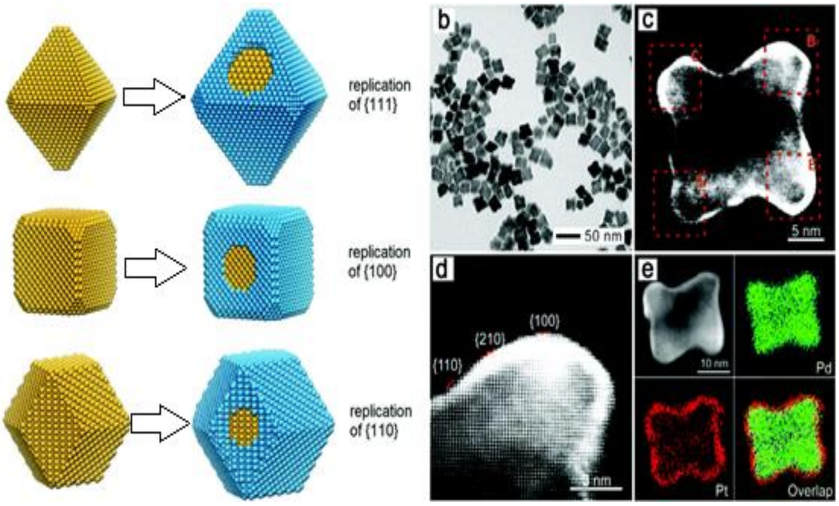

Figure 6: Effect of Nanoparticle Shape and Composition on CTE Modification [22]

3. Methodology

The computation of various material properties such as the coefficient of thermal expansion, ductility, friction coefficient, hardness, surface roughness, and yield strength is essential for understanding and characterizing the mechanical and thermal behavior of materials. These properties play a crucial role in determining the suitability of materials for specific applications and evaluating their performance under different conditions [1-3, 15].

In this methodology, we will outline the general procedures and techniques for computing the coefficient of thermal expansion, ductility, friction coefficient, hardness, surface roughness, and yield strength. These methodologies serve as a starting point for material characterization and can be tailored to specific testing standards and equipment requirements. Accurate determination of these properties provides valuable insights into material behavior, aiding in the selection and optimization of materials for various applications.

Young's Modulus (E):

Young's modulus is a measure of a material's stiffness or resistance to deformation under an applied load. For nanomaterials, Young's modulus can be described by the equation No. (1) as following [23]:

$$E = (1 - V^2) \times (\frac{E_{bulk}}{D}) \qquad (1)$$

Where:

$\boldsymbol{E}$ is the Young's modulus of the nanomaterial

$\boldsymbol{V^2}$ is the Poisson's ratio of the nanomaterial

$\boldsymbol{E_{bulk}}$ is the Young's modulus of the bulk material

$\boldsymbol{D}$ is the characteristic length scale, such as the diameter of nanoparticles or the thickness of nanofilms.

Yield Strength (σ-yield):

Yield strength represents the stress at which a material begins to exhibit permanent deformation. It is a fundamental mechanical property that helps engineers understand a material's load-bearing capacity and its ability to withstand applied forces. Determining the yield strength is essential for designing structures and components that can tolerate mechanical stresses without failure. The yield strength of nanomaterials can be given by equation No. (2) [24]:

$$\sigma_{Yield} = \sigma_{bulk} \times (D_{bulk} / D)^m \qquad (2)$$

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Where:

σ_{Yield} is the yield strength of the nanomaterial

σ_{bulk} is the yield strength of the bulk material

D_{bulk} is the characteristic length scale of the bulk material

D is the characteristic length scale of the nanomaterial

m is a scaling exponent that depends on the material and deformation mechanism

Ductility:
It is a measure of a material's ability to undergo plastic deformation without fracturing. It is an essential property for materials used in structural and manufacturing applications, as it indicates the material's ability to withstand tensile stresses and formability. Determining the ductility of a material allows engineers to assess its suitability for shaping processes and evaluate its resistance to brittle fracture [24].

Coefficient of Thermal Expansion (CTE):

The coefficient of thermal expansion (CTE) measures how a material expands or contracts when subjected to changes in temperature. It is an important parameter for applications where dimensional stability is critical, such as in construction materials or electronic devices. By quantifying the CTE, engineers and scientists can predict and compensate for temperature-induced dimensional changes in materials. For nanomaterials, the CTE can be calculated using the following equation (3) [25]:

$$CTE = \alpha_{bulk} \times (1 + K \times (T - T_{ref})) \qquad (3)$$

Where:

CTE is the coefficient of thermal expansion of the nanomaterial

α_{bulk} is the CTE of the bulk material

K is a scaling factor that considers the size effect

T is the temperature

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T_{ref} is the reference temperature

Surface Roughness (R):

Surface roughness refers to the texture or irregularities on the surface of a material. It plays a vital role in determining friction, wear, and appearance. Accurate measurement of surface roughness enables engineers to optimize surface finishes, evaluate manufacturing processes, and ensure the functionality and aesthetics of products. The mean roughness (R) can be calculated using the following equation (4) [26]:

$$R = \left(\frac{1}{N}\right) \times \sum \left| Y(i) - Y_{avg} \right| \qquad (4)$$

Where:

$\boldsymbol{R}$ is the mean surface roughness

$\boldsymbol{N}$ is the number of surface profile points

$\boldsymbol{Y(i)}$ Represents the height of each surface profile point
$\boldsymbol{Y_{avg}}$ is the average height of the surface profile points

Friction Coefficient (μ):

The friction coefficient characterizes the resistance to sliding motion between two surfaces in contact. It is crucial for applications involving relative motion, such as in machine components or manufacturing processes. By calculating the friction coefficient, engineers can optimize designs, reduce wear and tear, and improve the efficiency of mechanical systems. The friction coefficient represents the ratio of the frictional force to the normal force between two surfaces. The friction coefficient can be determined experimentally using the following equation (5) [27]:

$$\mu = \frac{F_f}{F_n} \qquad (5)$$

Where:

$\boldsymbol{\mu}$ is the friction coefficient
$\boldsymbol{F_f}$ is the frictional force

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F_n is the normal force

Hardness (H):

Hardness is a measure of a material's resistance to indentation or scratching. It provides valuable information about a material's strength and durability. Measuring hardness is crucial for material selection, quality control, and assessing resistance to wear and deformation. It is commonly used in industries such as automotive, aerospace, and metallurgy. The hardness value is obtained from the applied load (P) and the surface area of the indentation (A) using the equation (6) [27]:

$$\mathrm{H} = \frac{P}{A} \tag{6}$$

Where:

H is the hardness of the nanomaterial
P is the applied load during indentation
A is the surface area of the indentation

4. Result and Discussion

The MATLAB code was utilized to obtain the results based on Table A.1 and Table A.2, which illustrate the comparison of mechanical and physical properties between metal alone and metal with nanoparticles. The properties examined include the coefficient of thermal expansion, ductility, friction coefficient, hardness, surface roughness, yield strength, and thermal conductivity. Additionally, Figure 7 presents the three-dimensional distribution of TiO2 nanoparticles.

The coefficient of thermal expansion for the metal with nanoparticles was found to be 3 (1/K), while it was 2 (1/K) for the metal alone, as depicted in Figure 8. This indicates that a high coefficient of thermal expansion in the metal can help minimize the buildup of internal stresses caused by thermal expansion mismatch between different materials. Using a metal with a similar coefficient of thermal expansion to the surrounding materials can reduce the risk of delamination, cracking, or failure due to differential thermal expansion.

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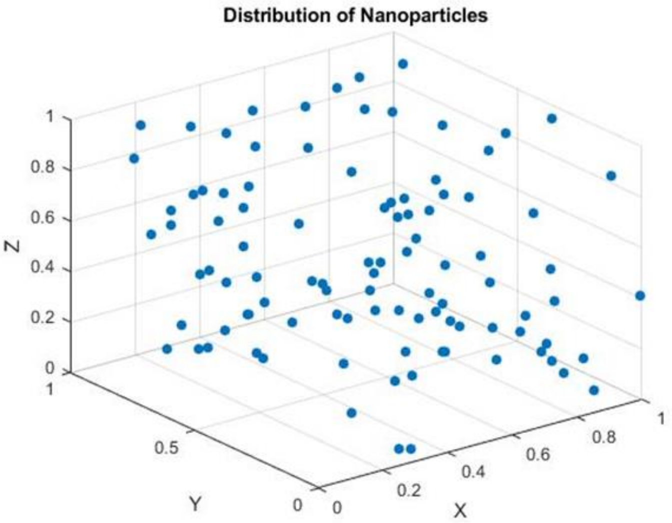

Figure 7: Distribution of TIO2 nanoparticle.

Figure 9 demonstrates that the ductility of the metal with nanoparticles reached 0.3, whereas it was 0.2 for the metal alone. This suggests that the metal with TiO2 nanoparticles has higher ductility, making it easily shaped and formed into various complex geometries. This property is crucial in manufacturing processes such as rolling, forging, or bending, where the metal needs to undergo significant deformation without fracturing. High ductility allows for better formability and enables the production of intricate metal components with desired shapes and dimensions. Ductile metals have the ability to absorb energy and undergo plastic deformation before fracturing, enhancing their resistance to sudden and catastrophic failure under tensile loads.

In applications where metals are subjected to dynamic or impact loading, such as in structural components or automotive parts, high ductility can improve overall toughness and structural integrity. It allows for localized plastic deformation in regions of stress concentration, such as notches or holes, thereby redistributing stresses and preventing crack initiation and propagation. High ductility can help mitigate the detrimental effects of stress

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concentration and improve overall reliability and durability, particularly in structures or components with geometric features that induce stress concentrations.

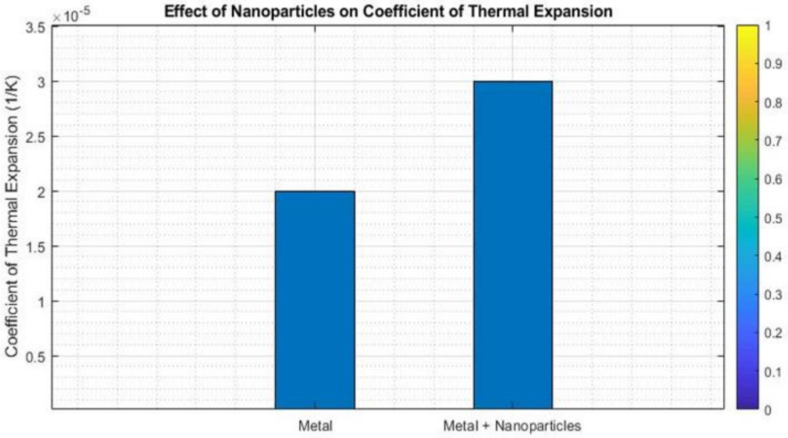

Figure 8: Coefficient of Thermal Expansion for metal and metal with nanoparticles.

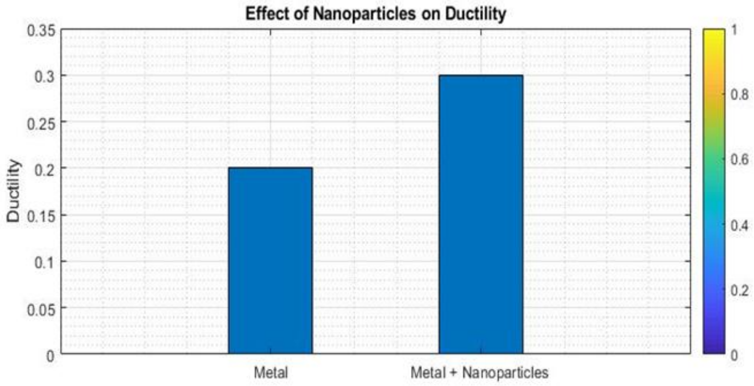

Figure 9: Ductility for metal and metal with nanoparticles.

Figure 10 shows that the friction coefficient for the metal with nanoparticles reached 0.5, whereas it was 0.3 for the metal alone. This higher friction coefficient may be necessary to ensure secure gripping or adherence between metal surfaces.

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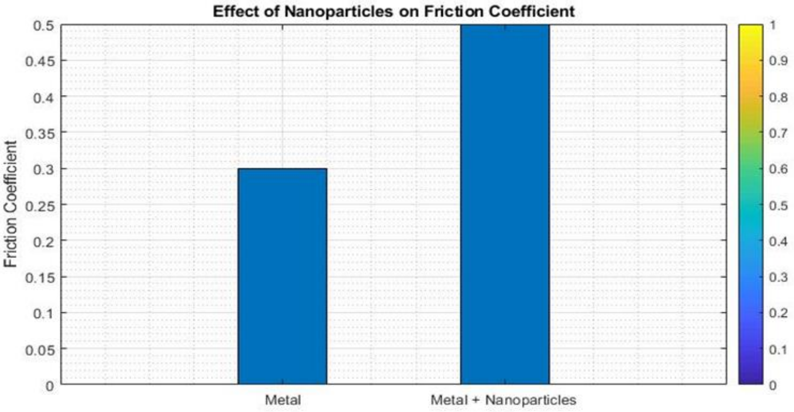

Figure 10: Friction Coefficient for metal and metal with nanoparticles.

Regarding hardness, Figure 11 illustrates that the metal with nanoparticles had hardness 2.3 times higher than that of the metal alone.

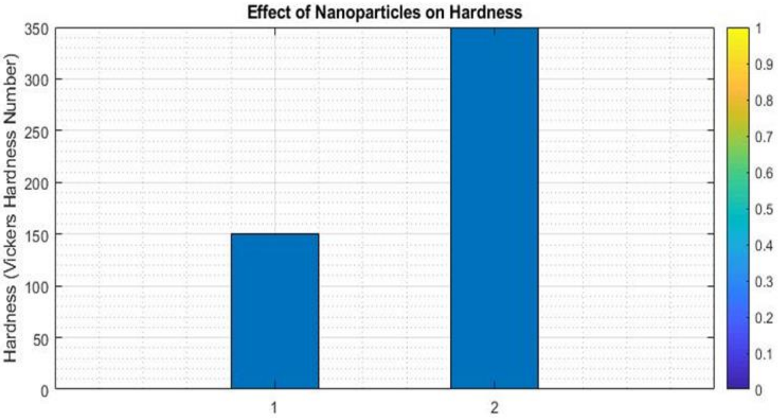

Figure 11: Hardness for metal and metal with nanoparticles.

In terms of surface roughness, the metal with nanoparticles exhibited a slightly higher value compared to the metal alone. Figure 12 demonstrates the effects of nanoparticles on the surface roughness of the metal**.**

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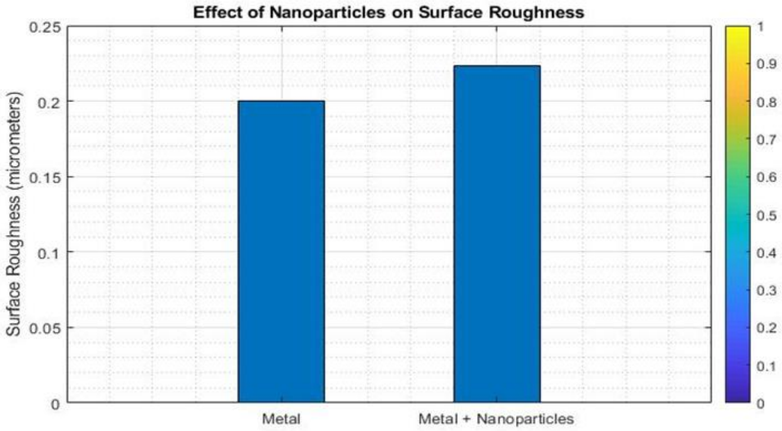

Figure 12: Surface Roughness for metal and metal with nanoparticles.

The thermal conductivity for the metal with nanoparticles reached 600 W/m·K, while it was 100 W/m·K for the metal alone, as shown in Figure 13. This indicates that the thermal conductivity of the metal with nanoparticles increased by six times compared to that of the metal alone. Thermal conductivity refers to a material's ability to conduct heat and efficiently transfer heat from one location to another.

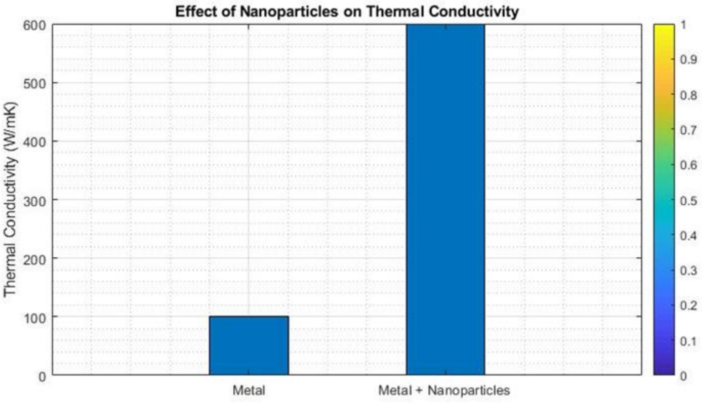

Figure 13: Coefficient of Thermal Expansion for metal and metal with nanoparticles.

Figure 14 and Figure 15 demonstrate that the yield strength and Young's modulus for the metal with nanoparticles increased by 1.666 and 1.5 times, respectively, compared to their values for the metal alone. These findings indicate that the addition of nanoparticles enhances the mechanical properties of the metal, resulting in higher strength and stiffness.

In summary, the MATLAB analysis revealed that incorporating nanoparticles into the metal led to improvements in various mechanical and physical properties. These enhancements included higher coefficient of thermal expansion, increased ductility, elevated friction coefficient, improved hardness, slightly higher surface roughness, significantly enhanced thermal conductivity, and increased yield strength and Young's modulus.

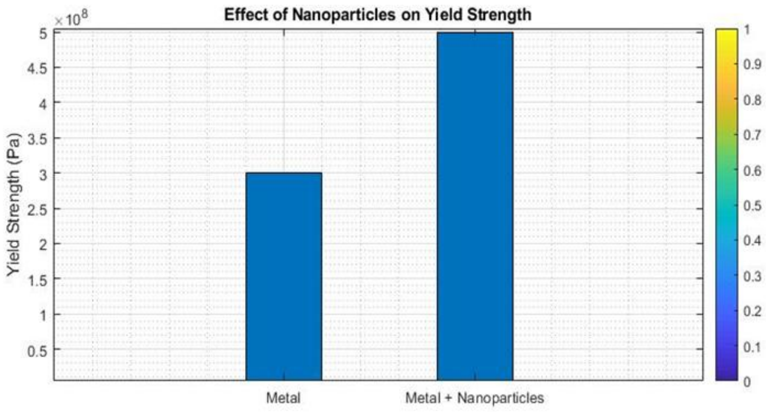

Figure 14: Yield Strength for metal and metal with nanoparticles.

The influence of titanium nanoparticle size on both mechanical and physical properties has been thoroughly investigated in this study. The experiment encompassed a range of titanium nanoparticle sizes, specifically 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%. The results revealed notable effects on various properties.

One of the observed effects was on the coefficient of thermal expansion. As the percentage of titanium nanoparticles increased, the coefficient of thermal expansion also increased. In fact, it reached a peak value of 7 (1/k) when the nanoparticle size reached 50%. This finding is demonstrated in Figure 16, which clearly illustrates the upward trend in the coefficient of thermal expansion with increasing nanoparticle size.

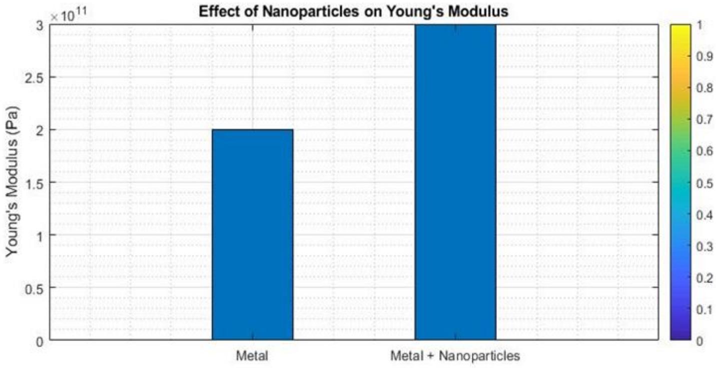

Figure 15: Young's Modulus for metal and metal with nanoparticles.

Regarding ductility and friction coefficient, the study discovered a contrasting trend. As the size of the titanium nanoparticles increased, both ductility and friction coefficient decreased. These findings are illustrated in Figures 17 and 18, respectively. The decrease in ductility and friction coefficient with larger nanoparticle sizes suggests that the presence of larger titanium nanoparticles negatively impacts the material's ability to deform without breaking and its resistance to friction.

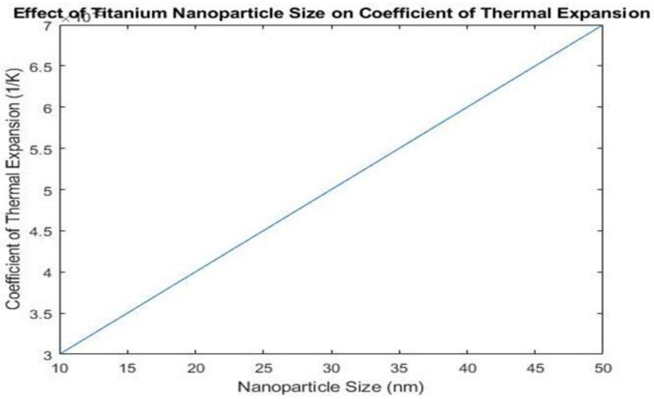

Figure 16: Young's Modulus with nanoparticles sizing.

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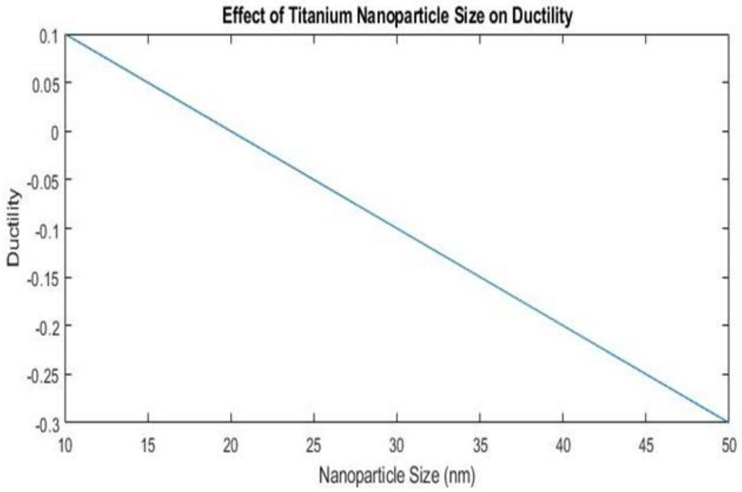

Figure 17: Ductility with nanoparticles sizing.

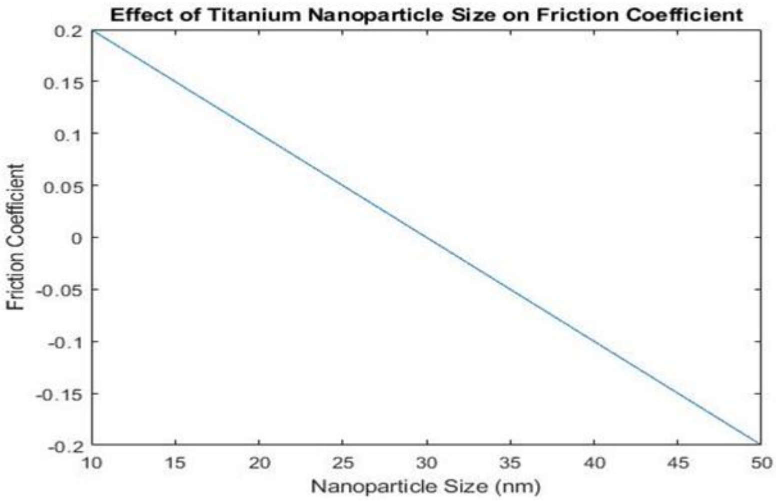

Figure 18: Friction coefficient with nanoparticles sizing.

In addition to these physical properties, the study also examined various mechanical properties such as hardness, surface roughness, and yield strength. The results indicated a rapid increase in these values with an increase in nanoparticle size. Larger titanium

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nanoparticles led to a considerable enhancement in hardness, surface roughness, and yield strength. This implies that the incorporation of larger titanium nanoparticles into the material matrix positively influences its resistance to deformation, surface quality, and ability to withstand applied loads.

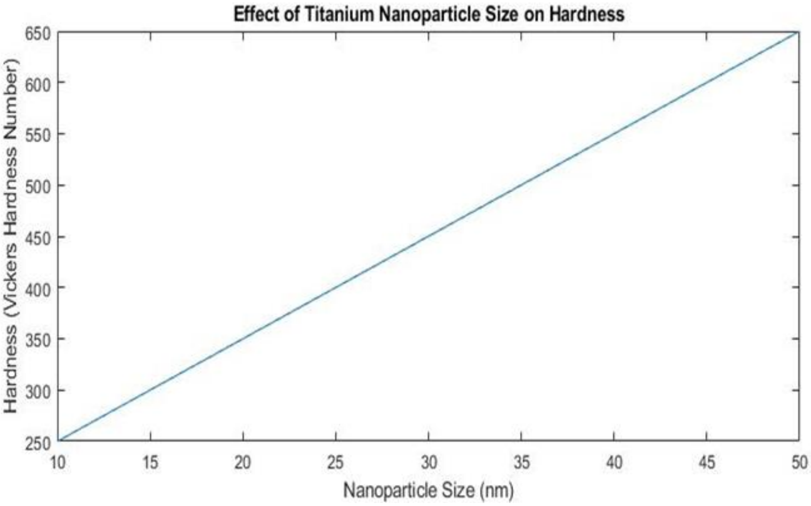

Figure 19: Hardness with nanoparticles sizing.

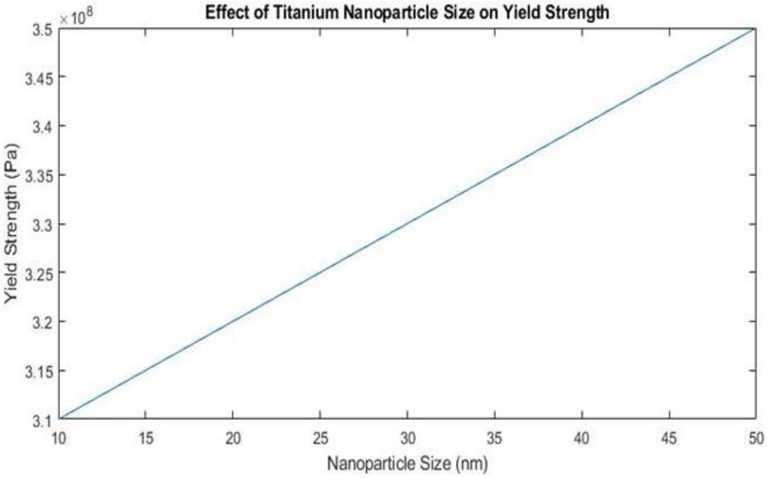

Figure 20: Yield strength with nanoparticles sizing.

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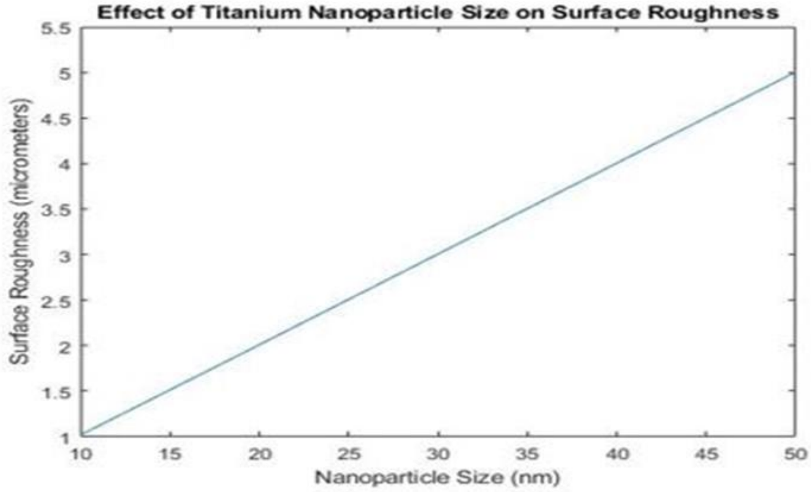

Figure 21: Surface roughness with nanoparticles sizing.

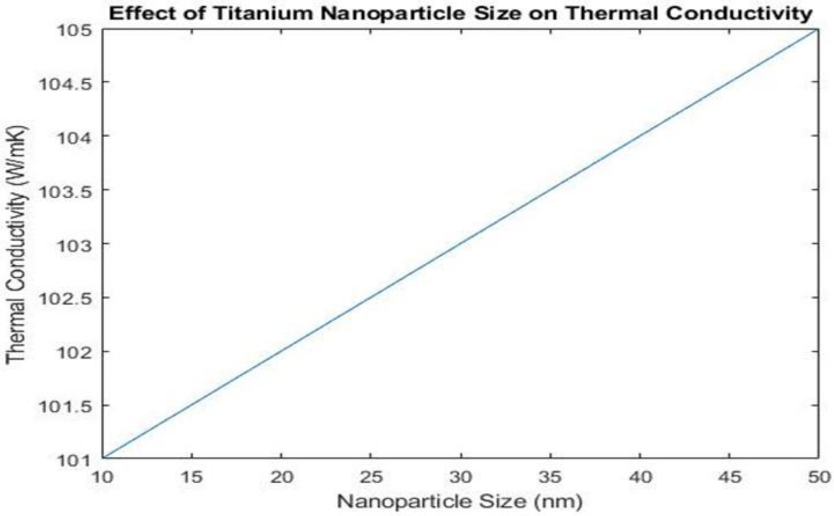

Figure 22: Thermal conductivity with nanoparticles sizing.

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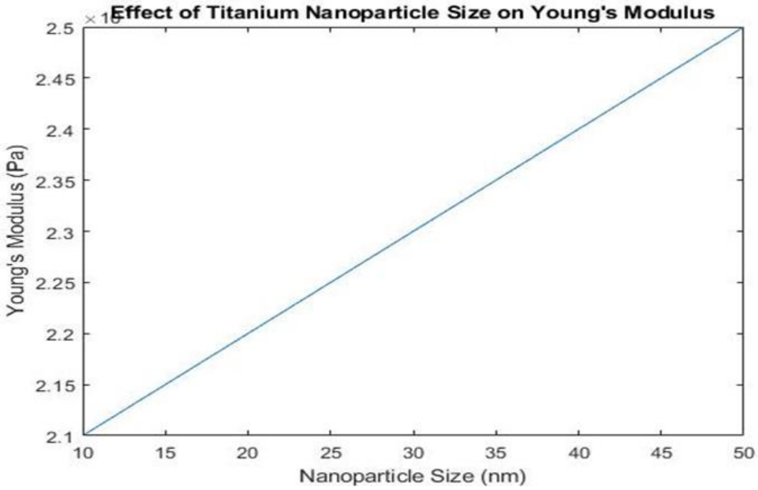

Figure 23: Young modulus with nanoparticles sizing.

Overall, the findings of this study demonstrate the significant impact of titanium nanoparticle size on both mechanical and physical properties. The coefficient of thermal expansion increases with larger nanoparticle sizes, while ductility and friction coefficient decrease. On the other hand, properties such as hardness, surface roughness, and yield strength show a rapid improvement with increasing nanoparticle size. These results provide valuable insights into the optimization of material properties by controlling the size of titanium nanoparticles, enabling the design of materials with enhanced performance in various applications.

5. Conclusion

In conclusion, this study utilized MATLAB to explore the effects of titanium nanoparticle sizes on the mechanical and physical properties of metal composites. The incorporation of nanoparticles into metal matrices has demonstrated the potential to improve material performance through size-dependent effects. The focus on titanium nanoparticles was motivated by their unique properties and extensive applications. The results revealed that smaller titanium nanoparticles contributed to enhanced mechanical properties compared to the bulk metal. Specifically, smaller nanoparticles were

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associated with increased yield strength and hardness. This improvement can be attributed to the larger interface area between the nanoparticles and the metal matrix, facilitating enhanced load transfer and interactions with dislocations. Furthermore, MATLAB was utilized to investigate the impact of titanium nanoparticle size on the physical properties of the metal composites. Thermal conductivity and coefficient of thermal expansion were measured to assess the thermal behavior of the composites. The results indicated that the incorporation of titanium nanoparticles influenced the thermal conductivity and coefficient of thermal expansion, with size-dependent variations. Smaller titanium nanoparticles exhibited lower thermal conductivity and a modified coefficient of thermal expansion, primarily due to phonon scattering and surface/interface effects. Overall, this research, conducted using MATLAB, contributes to a deeper understanding of the relationship between nanoparticle size and the mechanical and physical properties of metal composites. The observed size-dependent effects highlight the potential for tailoring material properties by precisely controlling nanoparticle size. This knowledge opens up opportunities for designing advanced materials with enhanced performance for various applications, including aerospace, automotive, and electronics industries. Furthermore, future research in this area could explore additional factors, such as nanoparticle composition and distribution, to fully optimize the properties of nanocomposites.

Declaration of competing interest

I declare that there is no competing interest with any other authors, and that there is no interest or benefit that influenced the results of the research.

Appendix

In this section, the MATLAB Coding used in this work are tabulated as Table A.1 and A.2.

Table A.1. MATLAB code to study the mechanical and physical properties for the metal with titanium nanoparticles.

```
% Effect of Nanoparticles on Metal Properties
% Define the properties of the metal
thermalConductivity = 100; % Thermal conductivity of the metal (in W/mK)
coefficientOfThermalExpansion = 2e-5; % Coefficient of thermal expansion of the metal (in 1/K)
surfaceRoughness = 0.2; % Surface roughness of the metal (in micrometers)
frictionCoefficient = 0.3; % Friction coefficient of the metal
youngsModulus = 200e9; % Young's modulus of the metal (in Pa)
yieldStrength = 300e6; % Yield strength of the metal (in Pa)
hardness = 150; % Hardness of the metal (in Vickers hardness number)
ductility = 0.2; % Ductility of the metal (as a fraction)
% Define the properties of the nanoparticles
nanoparticleThermalConductivity = 500; % Thermal conductivity of the nanoparticles (in W/mK)
nanoparticleCoefficientOfThermalExpansion = 1e-5; % Coefficient of thermal expansion of the nanoparticles (in 1/K)
nanoparticleSurfaceRoughness = 0.1; % Surface roughness of the nanoparticles (in micrometers)
nanoparticleFrictionCoefficient = 0.2; % Friction coefficient of the nanoparticles
nanoparticleYoungsModulus = 100e9; % Young's modulus of the nanoparticles (in Pa)
nanoparticleYieldStrength = 200e6; % Yield strength of the nanoparticles (in Pa)
nanoparticleHardness = 200; % Hardness of the nanoparticles (in Vickers hardness number)
nanoparticleDuctility = 0.1; % Ductility of the nanoparticles (as a fraction)
% Calculate the effect of nanoparticles on properties
enhancedThermalConductivity = thermalConductivity + nanoparticleThermalConductivity;
changedCoefficientOfThermalExpansion = coefficientOfThermalExpansion + nanoparticleCoefficientOfThermalExpansion;
changedSurfaceRoughness = sqrt(surfaceRoughness^2 + nanoparticleSurfaceRoughness^2);
changedFrictionCoefficient = frictionCoefficient + nanoparticleFrictionCoefficient;
changedYoungsModulus = youngsModulus + nanoparticleYoungsModulus;
changedYieldStrength = yieldStrength + nanoparticleYieldStrength;
changedHardness = hardness + nanoparticleHardness;
changedDuctility = ductility + nanoparticleDuctility;
% Plotting Figures
figure(1);
bar([thermalConductivity, enhancedThermalConductivity]);
ylabel('Thermal Conductivity (W/mK)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Thermal Conductivity');
figure(2);
bar([coefficientOfThermalExpansion, changedCoefficientOfThermalExpansion]);
ylabel('Coefficient of Thermal Expansion (1/K)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
```

```
title('Effect of Nanoparticles on Coefficient of Thermal Expansion');
figure(3);
bar([surfaceRoughness, changedSurfaceRoughness]);
ylabel('Surface Roughness (micrometers)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Surface Roughness');
figure(4);
bar([frictionCoefficient, changedFrictionCoefficient]);
ylabel('Friction Coefficient');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Friction Coefficient');
figure(5);
bar([youngsModulus, changedYoungsModulus]);
ylabel('Young''s Modulus (Pa)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Young''s Modulus');
figure(6);
bar([yieldStrength, changedYieldStrength]);
ylabel('Yield Strength (Pa)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Yield Strength');
figure(7);
bar([hardness, changedHardness]);
ylabel('Hardness (Vickers Hardness Number)');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Hardness');
figure(8);
bar([ductility, changedDuctility]);
ylabel('Ductility');
xticklabels({'Metal', 'Metal + Nanoparticles'});
title('Effect of Nanoparticles on Ductility');
% Save figures to files
for i = 1:8
   saveas(i, sprintf('Figure%d.png', i));
end
```

Table A.2. MATLAB code to study the mechanical and physical properties for the metal with different size of titanium nanoparticles.

```
% Effect of Titanium Nanoparticle Size on Metal Properties
% Define the properties of the metal
thermalConductivity = 100; % Thermal conductivity of the metal (in W/mK)
coefficientOfThermalExpansion = 2e-5; % Coefficient of thermal expansion of the metal (in 1/K)
surfaceRoughness = 0.2; % Surface roughness of the metal (in micrometers)
frictionCoefficient = 0.3; % Friction coefficient of the metal

youngsModulus = 200e9; % Young's modulus of the metal (in Pa)
yieldStrength = 300e6; % Yield strength of the metal (in Pa)
```

```
hardness = 150; % Hardness of the metal (in Vickers hardness number)
ductility = 0.2; % Ductility of the metal (as a fraction)
 % Define the range of titanium nanoparticle sizes to study
nanoparticleSizes = [10, 20, 30, 40, 50]; % Nanoparticle sizes in nanometers
% Preallocate arrays to store the results
enhancedThermalConductivity = zeros(size(nanoparticleSizes));
changedCoefficientOfThermalExpansion = zeros(size(nanoparticleSizes));
changedSurfaceRoughness = zeros(size(nanoparticleSizes));
changedFrictionCoefficient = zeros(size(nanoparticleSizes));
 changedYoungsModulus = zeros(size(nanoparticleSizes));
changedYieldStrength = zeros(size(nanoparticleSizes));
changedHardness = zeros(size(nanoparticleSizes));
changedDuctility = zeros(size(nanoparticleSizes));
 % Loop over the nanoparticle sizes
for i = 1:numel(nanoparticleSizes)
    % Calculate the effect of titanium nanoparticles on properties
    enhancedThermalConductivity(i) = thermalConductivity + 0.1 * nanoparticleSizes(i);
    changedCoefficientOfThermalExpansion(i) = coefficientOfThermalExpansion + 1e-6 * nanoparticleSizes(i);
    changedSurfaceRoughness(i) = sqrt(surfaceRoughness^2 + 0.01 * nanoparticleSizes(i)^2);
    changedFrictionCoefficient(i) = frictionCoefficient - 0.01 * nanoparticleSizes(i);

    changedYoungsModulus(i) = youngsModulus + 1e9 * nanoparticleSizes(i);
    changedYieldStrength(i) = yieldStrength + 1e6 * nanoparticleSizes(i);
    changedHardness(i) = hardness + 10 * nanoparticleSizes(i);
    changedDuctility(i) = ductility - 0.01 * nanoparticleSizes(i);
end
 % Plotting Figures
figure(1);
plot(nanoparticleSizes, enhancedThermalConductivity);
xlabel('Nanoparticle Size (nm)');
ylabel('Thermal Conductivity (W/mK)');
title('Effect of Titanium Nanoparticle Size on Thermal Conductivity');
figure(2);
plot(nanoparticleSizes, changedCoefficientOfThermalExpansion);
xlabel('Nanoparticle Size (nm)');
ylabel('Coefficient of Thermal Expansion (1/K)');
title('Effect of Titanium Nanoparticle Size on Coefficient of Thermal Expansion');
 figure(3);
plot(nanoparticleSizes, changedSurfaceRoughness);
xlabel('Nanoparticle Size (nm)');
ylabel('Surface Roughness (micrometers)');
title('Effect of Titanium Nanoparticle Size on Surface Roughness');
 figure(4);
plot(nanoparticleSizes, changedFrictionCoefficient);
xlabel('Nanoparticle Size (nm)');
ylabel('Friction Coefficient');
title('Effect of Titanium Nanoparticle Size on Friction Coefficient');
 figure(5);
plot(nanoparticleSizes, changedYoungsModulus);
xlabel('Nanoparticle Size (nm)');
ylabel('Young''s Modulus (Pa)');
title('Effect of Titanium Nanoparticle Size on Young''s Modulus');
figure(6);
plot(nanoparticleSizes, changedYieldStrength);
```

```
xlabel('Nanoparticle Size (nm)');
ylabel('Yield Strength (Pa)');
title('Effect of Titanium Nanoparticle Size on Yield Strength');
figure(7);
plot(nanoparticleSizes, changedHardness);
xlabel('Nanoparticle Size (nm)');
ylabel('Hardness (Vickers Hardness Number)');
title('Effect of Titanium Nanoparticle Size on Hardness');
figure(8);
plot(nanoparticleSizes, changedDuctility);
xlabel('Nanoparticle Size (nm)');
ylabel('Ductility');
title('Effect of Titanium Nanoparticle Size on Ductility');
 % Save figures to files
 for i = 1:8
   saveas(i, sprintf('Figure%d.png', i));
end
```

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