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Enhancing Mechanical and Microstructural Properties of metal Alloys through Deep Cryogenic Treatment: A Comprehensive Review

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Abstract: Deep cryogenic treatment (DCT) has emerged as a promising technique for enhancing the mechanical and microstructural properties of various materials. This review provides an in-depth exploration of the significant effects of DCT on these materials. In aluminum alloys, DCT refines the grain structure, increases the strength and hardness, and enhances the fatigue strength and residual stress. The addition of alloying elements, such as silicon and magnesium, further improves the mechanical properties of these alloys. Innovative techniques, such as cryo-rolling and quenching, optimise the benefits of DCT. In magnesium alloys, DCT improves the yield strength, hardness, elongation, and creep resistance by promoting the uniform distribution of precipitates. The effectiveness of DCT in Mg alloys depends on the treatment temperature. DCT in copper alloys results in refinement of the grain structure, increasing the hardness, tensile strength, and wear resistance. DCT enhances micro hardness and reduces surface wear through dispersion strengthening and subgrain formation. In composites and nanocomposites, DCT improves the strength, compressive strength, and tribological properties by refining the microstructure and inducing phase transformations. DCT also enhances the distribution of nanoparticles in the nanocomposites. The synergistic effect of DCT and artificial aging has been observed in aluminum and magnesium alloys, resulting in fine precipitates that improve strength and wear resistance. DCT modifies the grain structure, dislocation density, and phase distribution of materials, leading to desirable improvements in strength, hardness, wear resistance, and fatigue life. However, the optimization of treatment parameters is crucial for maximizing the benefits of DCT in various materials and applications.

1. Introduction

Several centuries have passed since metals have been treated with heat-treatment methods to improve their mechanical qualities. Heat treatment methods have long been employed to enhance the mechanical properties of metals, as demonstrated by the diverse range of techniques and their effects described in the literature (Fri *et al.* 2024; Ouazzani *et al.* 2024; Karki *et al.* 2025). Various heat-treatment processes significantly affect the strength, toughness, and overall performance of different alloys (Abdelaziz *et al.* 2021). For instance, in aluminum alloys, retrogression and re-aging (RRA) treatment improves fracture toughness without sacrificing strength, whereas peak aging (T6) results in high strength but low fracture toughness (Li *et al.* 2016). Similarly, for the titanium alloy, solid solution and aging treatment at specific temperatures yield an optimal combination of high strength and ductility (Gao *et al.* 2024). Interestingly, the effects of heat treatment can vary depending on the alloy composition and desired properties. For example, in Al-Zn alloys, increasing the Zn content leads to higher hardness and tensile strength but decreased plasticity and toughness (Zhou *et al*. 2017). In contrast, for low-alloy steel weld metals, normalizing the heat treatment generally increases the toughness but significantly decreases the tensile properties (Trindade *et al*. 2005; Aichouch *et al*. 2025). Heat treatment is a crucial method for tailoring the mechanical properties of metals for specific applications. The optimal heat-treatment process depends on the alloy composition and desired property balance, as demonstrated by various studies on Al, Ti, steel, and W alloys (Wang *et al*. 2016). In additive manufacturing of Ti-6Al-4V and Ti-5Al-5Mo-5V-1Cr-1Fe alloys, post-process heat treatments effectively addressed non-equilibrium microstructures and improved mechanical properties, with specific treatments yielding optimal combinations of strength, ductility, and fracture toughness (Bai *et al.* 2021). These findings underscore the importance of continued research on heat-treatment techniques for the development of advanced materials with improved strength, toughness, and overall performance. Attention to subzero therapies, such as cryogenic treatment, began fairly early in the twentieth century; however, substantial attention and breakthroughs in this subject started near the end of the century.

Cryogenic treatment, a subzero heat treatment process, has been used since the early twentieth century for various applications in manufacturing, automotive, and aerospace industries (Slatter *et al.* 2016). While the concept of cryotherapy for treating human diseases dates back to 1845, its application to skin diseases began in the late nineteenth and early twentieth century's (Fukuma *et al*. 2016). However, despite its long history, cryogenic treatment has not gained widespread adoption owing to a lack of understanding of the microstructural changes and consensus on optimized processes (Slatter *et al.* 2016). Interestingly, the eye shows remarkable tolerance to severely low temperatures, leading to the development of cryotherapy techniques for various ocular diseases in the 1960s (LF. 1965). In contrast, psychosurgery, which includes neurosurgical treatments for psychiatric disorders, has faced significant ethical challenges and controversies, particularly due to the indiscriminate use of transorbital lobotomy in the mid-twentieth century (Staudt *et al.* 2019). Recent advances in microstructural analysis tools and techniques have enabled a better understanding of cryogenic processes (Slatter *et al.* 2016). This has led to increased research and development in cryogenic treatment, with studies focusing on its effects on the microstructure, mechanical properties, and performance of various materials, including tool steels and nonferrous metals (Elango *et al.* 2014; Sonar *et al.* 2018; Singh *et al.* 2022; Vaudreuil *et al.* 2022).

Cryogenic treatment involves slow cooling of the component to a predetermined subzero temperature, holding it there for a specified period, referred to as freezing time, and then gradually warming it back to room temperature. The process has mainly been aimed at improving mechanical properties, such as hardness and wear resistance. Recent studies have also indicated improvements in fatigue strength, although CT targets the best balance between conflicting properties such as hardness and toughness. This potential was first demonstrated in the improvement of machinery tools where high hardness and durability have been reported. Over the last two decades, research on CT has expanded to various applications, including gears and bearings for motor racing components, oil drills, gun barrels, knives, surgical and dental instruments, brass musical instruments, and sports equipment, such as baseball bats and golf clubs. The process has attracted commercial interest, especially in the USA and Canada, where a large number of companies now offer CT services, sometimes with a guarantee that the life of some components will be enhanced or a refund will be made if none can be detected. Although CT is increasingly used, little is known about its function. Numerous theories have been proposed to explain its action, and some have been supported by microstructural analyses.

This review aims to comprehensively analyze the effects of deep cryogenic treatment (DCT) on the mechanical and microstructural properties of various materials, including aluminum alloys, magnesium alloys, copper alloys, and composites. It explores the mechanisms through which DCT enhances strength, hardness, fatigue resistance, and wear properties, with a particular focus on grain refinement, precipitate distribution, and phase transformations. Additionally, the review highlights the influence of alloying elements, synergistic treatments such as cryo-rolling and artificial aging, and the optimization of treatment parameters. By synthesizing recent advancements, this study seeks to provide insights into the potential applications of DCT and guide future research in material enhancement through cryogenic processing.

2. Methodology

2.1 Cryogenic Treatment Process

Cryogenic treatment DCT alters the microstructure of the material and improves its physical, mechanical, and sometimes even its thermal properties (Razavykia *et al*. 2019). At the pretreatment stage, the process begins with a preliminary heat treatment or stress-relief process before the actual cryogenic treatment (Carillo *et al.* 2022). This is often employed in metallic alloys, where annealing or tempering removes residual stresses or in preparation for the microstructure to undergo transformation during the cryogenic treatment process. It is a metallurgical process whereby the material undergoes low temperatures nearly below -150°C (-238 °F), for an extended period of time and then under controlled heating to room temperature as shown in fig.1.

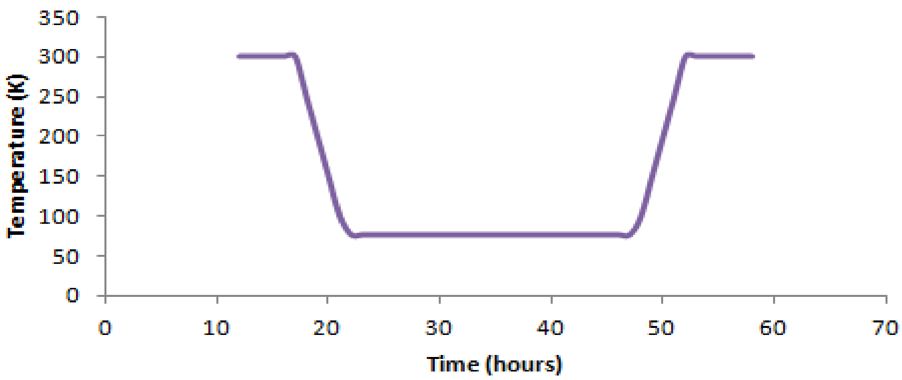

Fig. 1. Cryogenic Treatment Graph

Cooling Stage (Sub-Zero Treatment): The cooling stage in deep cryogenic treatment (DCT) involves gradually lowering the temperature from room temperature to cryogenic levels, typically between -150°C and -196°C. Liquid nitrogen is commonly used as the coolant medium due to its extremely low boiling point of -196°C. The slow cooling process is essential to prevent thermal shock, residual stresses, and potential fractures in the material. To ensure uniform temperature distribution throughout the specimen, cooling is often conducted in stages over several hours. Cryogenic Soaking: Once the material reaches the target cryogenic temperature, it is held at that temperature for an extended period, typically between 24 to 72 hours, depending on the material type and the intended mechanical improvements. During this soaking phase, significant transformation processes take place that enhance the material's properties (Parikh *et al.* 2024). Changes during Soaking: One of the key transformations that occur during soaking is the conversion of retained austenite into martensite. Retained austenite is a relatively softer phase in steels, but when subjected to cryogenic temperatures, it transforms into martensite, a harder and more brittle phase. This transformation significantly increases hardness and wear resistance. Another critical microstructural change is grain refinement. The extreme cold enables atomic structures to reorganize into more stable configurations. Although grain refinement is considered a minor structural alteration, it improves mechanical properties such as tensile strength, hardness, and fatigue resistance.

Gradual Heating to Room Temperature: Following the cryogenic soaking stage, the material must be carefully returned to room temperature. This gradual heating process is essential to prevent sudden thermal expansion, which could introduce internal stresses or even cause cracking. In certain materials, such as steels, rapid temperature increase may lead to temper embrittlement. Therefore, controlled heating in stages is commonly practiced to maintain structural integrity.

Thermal Treatment: Tempering (Optional): For some materials, particularly tool steels, an additional tempering process is conducted after cryogenic treatment. This tempering step is crucial for relieving internal stresses induced by the martensitic transformation, thereby improving toughness without excessively reducing hardness. By applying post-treatment tempering, the material achieves a balanced combination of hardness and impact resistance, ensuring that it does not become excessively brittle after cryogenic treatment.

2.2 Benefits of Cryogenic Treatment

a) Enhanced Hardness and Wear Resistance: Cryogenic treatment can enhance the hardness of materials such as steel, especially with magnesium alloys, to make them resist wear and fatigue. This proves to be very suitable for applications like cutting tools and automobile parts.
b) Reduction of Internal Stresses: Cryogenic treatment stabilizes the microstructure, thus reducing the internal stresses. In this regard, the long-term dimensional stability of parts becomes important otherwise, and critical dimensional stability can be lost. This is especially important in precision items, such as aerospace and engine parts.
c) Increase in Tensile Strength and Toughness: AZ91 magnesium alloy and several types of steels undergo appreciable tensile strength enhancement after treatment owing to the improved microstructure and phase transformations. Low Electrical Resistance: In studies on alloy AZ91, cryogenic treatment also reduces its electrical resistance; hence, it can be applied in electronics or conductive devices.

Recently, cryogenic treatments of various aluminum alloys have attracted intense scrutiny owing to the excellent improvement in their mechanical properties. The effects of DCT on the metallurgical and mechanical microstructures of Al6061-T6. The treatment involved exposure of the alloy to a cryogenic temperature of -196 ºC for 36 h. in DCT, the hardness and material quality significantly improved owing to precipitation solidification and increased separation thickness (Theja *et al.* 2020). A comparison of the fracture topologies of the treated specimens versus control samples by electron microscopy revealed denser striations that resulted from the refined microstructure of the treated specimens. Following this, Padmini et al. studied the wear resistance of aluminum alloys, specifically Al 2024, 6082, and 7075, after 64 h of deep cryogenic treatment. The results confirmed a minor increase in hardness for all three alloys, although Al 6082 attained the highest improvement. At room temperature, the resistances under different loads increased by 25% and 40%, respectively (Padmini *et al.* 2019). These results were further confirmed and evaluated solution treatment combined with aging and subsequent cryogenic treatment on 7050 aluminum alloy. The results showed that not only were the fine precipitates enhanced owing to the combined treatments but also led to lower residual stress and uniformity, which improved the dimensional stability (Weng *et al.* 2020).

Additional research on alloy composition and treatment can be found in both ferrous and nonferrous alloys treated by DCT. The results of these studies indicate improvements in toughness, ductility, electrochemical corrosion resistance, and dimensional stability for every type of material and composition via different mechanisms (Jovičević *et al.* 2021). Similarly, AA6082 aluminum alloy subjected to a treatment involving both solution heat and cryogenic treatments. The results indicate that extended exposure to cryogenic treatment results in a significant augmentation of hardness and tensile strength.

In a more explicit expression, a 69.5% higher hardness was recorded compared to the solution-treated specimens, thereby underlining the capabilities of cryogenic treatment for refining the material properties (Sonia *et al.* 2020). Further research highlighted the mechanical behavior and wear resistance of alloys that are cryogenically treated. The results from the study on Al6061 by Kumar showed an 8.9% improvement in tensile strength and yield strength with an 18% increase, respectively, for this alloy post-cryogenic treatment, while elongation decreased (Kumar *et al*. 2021; Syed *et al*. 2022). In contrast, Syed reported that cryogenic heat treatment significantly enhanced the wear resistance of Al 6101 closed-cell foam, thus supporting the view that cryogenic treatment may improve the performance metrics of most aluminum forms (Syed *et al*. 2022). Cumulatively, evidence seems to suggest that the application of cryogenic treatment usually results in crucial gains in the mechanical properties of aluminum alloys, making it an important treatment in material engineering. Finally, the most recent studies conducted explained the micro and mechanical strengthening resulting from cryogenic treatment. Li's work with automotive 6063 aluminum alloy showed remarkable grain refinement and raised mechanical strength with hardness increased by 34.17% and significant tensile strength after applying a 36-hour cryogenic treatment (Li *et al.* 2024).

Meanwhile, the investigation by Jin on grain size and aging conditions highlighted microstructural regulation as playing a critical role in optimizing the fatigue performance of aluminum alloys (Jin *et al.* 2024). Collectively, these studies affirm how transformative cryogenic treatments are applied to aluminum alloys so that aluminum alloys have crucial applications where improved mechanical properties are necessary. Mechanical testing of engineering materials plays a critical role in the evaluation of material qualities, innovations in new material designs, and assurance of reliability for construction and design applications.

The selection of material is of extreme importance in engineering applications exposed to loads of various intensities and motives have been underlined on the strength and rigidity test. The influence of silicon on the mechanical properties of aluminum alloys; the five selected alloys were in the silicon content range of 5–14%. The silicon content was directly related to the mechanical properties, and the yield strength and ultimate tensile strength increased with increasing silicon levels. However, with increased silicon levels, there was a corresponding loss in ductility and elongation; such compromises are inherent in alloy design (Kalhapure and Dighe, 2015).

Further, extension of the cryogenic treatment the microstructural, mechanical, and wear characteristics of Al 6061 and Al 8011 alloys. Cryogenic treatment has resulted in better improvement in wear resistance by 25% compared to untreated aluminium (Khanna *et al*. 2020). This study incorporates different time intervals as well as rotational speeds during the process of treatment and presented extremely significant changes in microstructure with drastic enhancement in the performance of the alloys. The need and benefits of cryogenic cooling in engineering applications in terms of enhancement in wear resistance in critical components.

The mechanical properties of the AlSi10Mg alloy after cryogenic treatment, with tensile testing at different times of treatment. The results show a significant increase in tensile and compressive strength for longer times of treatment, peaking at certain intervals, and it then degrades. The authors also found a ductile-to-brittle transition that occurred during the treatment time from 12 to 24 hours, as a result of the precipitation of second-phase particles. The above explanation about the dynamic behavior of aluminum alloys under cryogenic conditions has further explained the subtleties of mechanical properties as a function of the treatment time (Desai *et al.* 2016).

The tensile properties and microstructures of aluminum alloys treated by liquid nitrogen cryogenic treatment. Zhou's study showed that cryogenic treatment improved the ultimate and yield strengths of the 2024-T351 alloy without decreasing elongation (Zhou *et al.* 2016), while Araghchi claimed an utmost rise of up to 75 MPa in ultimate tensile strength as compared to T6 heat-treated alloys by using a newly adopted process for cryogenic treatment that involves rapid heating (Araghchi *et al.* 2017). These studies collectively illustrate the transformative potential of cryogenic treatments in optimizing the mechanical performance of aluminum alloys, reinforcing the importance of innovative approaches in material engineering.

Cryogenic treatment has gained attention for its ability to improve mechanical characteristics, including hardness, tensile strength, and elongation. The effects of Deep Cryogenic Aging Therapy (DCAT) on 6082 aluminum alloy, comparing it with Artificial Aging Treatment (AAT) and Solid Solution Treatment (SST). Results revealed that DCAT increased yield strength and elongation compared to AAT, with SST samples showing lower yield strengths (less than 200 MPa) and higher elongation (16%) (Xia *et al.* 2024). Similarly, the influence of low temperatures on aluminum alloy (AA6061-T6) under dynamic stress. The strain rate depended with stress measurements increasing by 5-10% at 80°C, highlighting the alloy's ability to retain its microstructure while absorbing more energy at lower temperatures (Kopec *et al.* 2024).

Cryogenic treatments have also shown beneficial effects in enhancing specific mechanical properties. It improved the toughness, ductility, and dimensional stability of both ferrous and non-ferrous alloys, with mechanisms differing based on the material type (Jovičević and Podgornik, 2020)

3 Results and Discussion

3.1. Effect of Cryogenic Treatment and Aluminum Alloys

The cryogenic treatment of aluminum alloys, including 6063, has been shown to significantly improve their mechanical properties. The severe strain induced during plastic deformation at cryogenic temperatures produces ultrafine microstructures with improved strength and hardness (Panigarhi *et al.* 2008). For example, cryorolling of Al-Si-Mg alloys, such as 6082, resulted in enhanced fatigue strength compared to bulk alloys (Kumar *et al.* 2014). Cryogenic treatment also facilitates the precipitation of fine, densely distributed precipitates, which enhances the pinning effect of dislocations and improves tensile strength (Qiu *et al.* 2024).

Interestingly, the addition of silicon to aluminum alloys, such as 6063, can further enhance their properties when combined with cryogenic treatment. In the A356.2 aluminum alloy (which contains silicon), solution treatment at cryogenic temperatures causes eutectic silicon to undergo disintegration, spheroidization, and coarsening, affecting the mechanical properties of the alloy (Ding *et al.* 2018). However, the optimal cryogenic treatment duration varies, as both the tensile strength and elongation first increase and then decrease with extended cryogenic treatment (Qiu *et al.* 2024). In conclusion, the combination of silicon addition and cryogenic treatment can significantly improve the mechanical properties of the aluminum alloy 6063. Cryogenic treatment enhances the strength and hardness through microstructural refinement and precipitation hardening, whereas silicon contributes to the overall performance of the alloy. However, careful optimization of the treatment parameters is necessary to achieve the best balance of properties (Park *et al.* 2011).

The effects of deep cryogenic treatment on 7075-T651 aluminum alloy by treating specimens at -196°C for two different durations, 2 h and 48 h, revealed that the 2-hour treatment showed no significant impact, the 48-hour treatment led to slight increases in strength and toughness, with a minor reduction in hardness. The results indicate that prolonged exposure to cryogenic temperatures can enhance certain mechanical properties of the 7075-T651 alloy, making it beneficial for applications that require high strength and (Lulay *et al.* 2002). The thermal conductivity of various aluminum alloys, such as 6082 and the 1000 series, across a temperature range from near the superconducting transition (~ 1 K) to room temperature. The low-temperature measurements were closely aligned with the actual thermal conductivity values, differing by only approximately 10%. The importance of precise thermal conductivity data for aluminum alloys, particularly in extreme environments such as cryogenic systems (Woodcraft, 2005).

An innovative quenching method to reduce the residual stresses in the 2024 aluminum alloy during cryogenic treatment. Immersing the samples in liquid nitrogen followed by rapid reheating in hot oil at 180°C led to a 71% reduction in residual stress, which was significantly higher than that of traditional methods. Additionally, the treated sample experienced a 75 MPa increase in strength. This advanced cryogenic approach for mitigating residual stress not only reduces distortion but also enhances mechanical performance, offering significant benefits for industries that use high-strength aluminum alloys in stress-critical applications (Araghchi *et al.* 2017). The mechanical properties of aluminum-lithium alloy AA2195 after tensile testing at 7% cold working and cryogenic temperatures down to liquid hydrogen at -20 K. lower temperatures resulted in higher tensile and yield strengths, with minimal loss in ductility (Nayan *et al.* 2014).

The addition of magnesium to aluminum alloys and subsequent cryogenic treatment can significantly impact the microstructure and properties of these alloys. Magnesium addition to aluminum alloys, such as the 5A06 aluminum alloy, can lead to the formation of Al_3Mg_2 phases. When subjected to cryogenic treatment, the amount of this phase increases noticeably in the microstructure (Jin and Ji, 2021). This phase formation contributes to improved hardness and mechanical properties. For instance, the combination of 16% cold deformation and 72 h cryogenic treatment so the optimal process for enhancing the hardness of the 5A06 aluminum alloy (Jin and Ji, 2021).

3.1. Effect of Cryogenic Treatment on Magnesium Alloys

Deep cryogenic treatment (DCT) has been shown to have significant positive effects on the properties of Mg alloys. Studies have demonstrated that DCT can improve the micromechanical,

mechanical, and tribological properties of magnesium alloys with rare earth metals such as WE43 and WE54 (Barylski and Aniołek, 2022). Treatment time plays a crucial role in the effectiveness of DCT, with optimal results typically achieved between 12-24 hours (Fangwei and Xueying, 2020). DCT has been found to enhance various properties of Mg alloys, including density, ignition temperature, compressive yield strength, ductility, and microhardness (Gupta *et al.* 2023).

In the AZ91 magnesium alloy, DCT combined with T6 heat treatment resulted in improved elongation by 20% due to the promotion of continuous precipitation (Monica *et al.* 2023). The treatment also affects the distribution of β-precipitates in the AZ91 alloy, leading to significant improvements in its mechanical properties and creep behaviour (Asl *et al.* 2009). DCT is a valuable technique for enhancing the properties of magnesium alloys. It can be effectively combined with other heat treatments to achieve optimal results (Barylski *et al.* 2024). The improvements in mechanical properties, wear resistance, and corrosion performance make DCT-treated magnesium alloys promising candidates for various applications, including degradable metallic implants (Shishir *et al.* 2020). However, it is essential to note that the optimal treatment parameters may vary depending on the specific alloy composition and the desired properties.

The deep cryogenic treatment of AZ91 magnesium alloy, including its high-temperature behavior. Specimens of a high-pressure die-cast alloy were tested for creep at both 100 and 200°C. The mechanical properties and microstructural stability of the alloy were investigated using optical and scanning electron microscopy, supplemented with differential scanning calorimetry analysis. The results show no evidence of structural variation; therefore, the mechanical behaviour remains unchanged after cryogenic treatment. Deep cryogenic treatment does not seem to have a remarkable effect on the high-temperature performance of AZ91 (Gariboldi *et al.* 2012).

A more comprehensive study on the AZ91 magnesium alloy by considering the microstructural evolution and physical properties after cryogenic treatment. Optical microscopy, X-ray diffraction (XRD), resistance, and mechanical testing were performed on the specimens. At temperatures below 143 K, the alloy had an ordered microstructure, increased peak stress, reduced electrical resistance, and variation in the lattice constants based on the crystallographic changes. The results showed the richness of the quality regarding the cryogenic treatment ability for enhancing the mechanical properties of AZ91, especially its tensile strength behaviour (Junwie *et al.* 2012).

The effects of deep cryogenic treatment (DCT) on AZ91 magnesium alloy at elevated temperatures (100°C and 200°C), observing no significant alterations in mechanical properties or microstructure after conducting creep tests, optical and scanning electron microscopy (SEM), and differential scanning calorimetry (DSC). Their findings suggest that DCT exerts minimal influence on the high-temperature performance of AZ91 and has limited effects on its structural and mechanical behaviours (Gariboldi *et al.* 2012). In contrast, Liu et al. conducted a more comprehensive study, revealing that at temperatures below 143 K, DCT induced an ordered microstructure, increased peak stress, reduced electrical resistance, and altered lattice constants in AZ91, ultimately enhancing its tensile strength. This indicates that while DCT does not significantly impact AZ91's high-temperature properties, it can improve its low-temperature mechanical performance by modifying its microstructure (Junwie *et al.* 2012). Thus, the two studies elucidate the differing effects of DCT on AZ91 depending on the temperature range, with no substantial impact at high temperatures but notable improvements in mechanical behaviour at cryogenic temperatures.

A novel process for addressing cracking issues in the laser welding of AZ91D magnesium alloy. By combining cryogenic treatment with heat treatment, they successfully enhanced the tensile strength and hardness of the weld joint while eliminating cracks between the fusion zone and heat-affected zone (HAZ). This approach introduces new possibilities for laser welding applications, improving both the mechanical properties and weld integrity of AZ91D, thereby increasing its viability in industrial settings where magnesium alloys are employed (Shen, 2016).

An extensive study on multiple magnesium alloys, including AZ91, AZ31, and ZK60, to investigate the effects of DCT on their microstructures and mechanical properties. The study examined temperatures below 77 K, which transformed the retained austenite into martensitic structures. The ultimate tensile and yield strengths of the treated alloys were significantly higher than those of the untreated samples, with no reduction in ductility, even at very low temperatures. This comprehensive analysis confirmed that cryogenic treatment considerably improves the mechanical properties of Mg alloys, enhancing their suitability for use in extreme environments (Dieringa, 2017).

3.1 Deep Cryogenic Treatment on Copper Alloys

Deep cryogenic treatment has greatly improved the mechanical properties of copper alloys. For a Cu-Al-Si alloy prepared by cold metal transfer technology, DCT led to an enhancement in micro-hardness values by around 10%. Tensile yield and ultimate strengths were also improved by ~20% for both cases. Microstructural evolutions mechanisms found to be crucial drivers of these enhancements included grain refinement, texture randomization, and development of subgrains and fine grains along with deformation twins (Liu *et al.* 2019). Similarly, in beryllium copper alloy (CuBeZr), DCT led to the transformation of the precipitates into rod shapes and an improvement in the dispersion of CuNi and CuNiZr precipitates in the matrix α. These led to an as much as 11% rise in hardness and a very good 60% reduction in surface wear after 48 hours soaking time (Wannaprawat and Tuchinda, 2020). An overall improvement of microstructure and mechanical properties in copper alloys can be disclosed from the results of DCT through improved precipitate distribution and grain structure changes.

Deep cryogenic treatment proves to be an effective method for enhancing the mechanical and microstructural properties of copper alloys. The treatment's ability to refine grain structure, modify precipitate distribution, and improve wear resistance makes it a valuable technique for optimizing the performance of these alloys in various applications. An investigation on the microstructural behavior and mechanical properties of pure copper sheets under the influence of cryogenic rolling. From their investigation, they found that nanomechanical twins and zigzag structures were the precipitates at the central sheet after the application of sub-zero temperature treatments. Additionally, the yield strength and ultimate tensile strength increased with cryogenic rolling treatment, which suggested benefits from cryogenic treatment for the mechanical performance of pure copper (Li *et al.* 2020).

The effects of cryogenic rolling, low-temperature annealing, and aging treatment on Al-Cu alloy 2219. The investigation concluded that there was minimal variation in the microstructure and mechanical properties but, under the optimal conditions, the alloy possessed excellent ductility with tensile elongation of about 11% and improved tensile strength up to 540 MPa. These studies seem to indicate that cryogenic treatments may be utilized for the enhancement of mechanical properties in Al-Cu alloys without imparting major changes in their microstructure (Shanmugasundaram *et al.* 2006). The machinability of Beryllium-Copper alloy through EDM treated at cold and cryogenic conditions. Cold and cryogenic treatments have been carried out on test specimens at -150F and -

300F, respectively. The machined samples showed the material removal rate increasing by 20-30% with slight variations in the wear rate, surface roughness, and white layer thickness. Cryogenic treatment thus seemed to have a good prospect of improving the machinability of Beryllium-Copper alloys (Yildiz *et al.* 2012).

Wang Ping et al. studied thermal physical properties of $Cu_{76.12}$ $Al_{23.88}$ alloy both in the state of before and after cryogenic treatment. The researched properties included: thermal diffusion coefficient, heat capacity, thermal conductivity, and coefficient of thermal expansion (Wang *et al.* 2011). It was concluded that the application of cryogenic treatment influenced the coefficient of thermal expansion since it became more sensitive to the growth of temperature and concurrently increased thermal conductivity while reducing the heat capacity. All these improvements showed a promising application of cryogenic treatment in the improvement of thermal properties of copper and aluminum based alloys.

3.4 Deep Cryogenic Treatment on Composite and Nanocomposites

Deep cryogenic treatment (DCT) has shown significant effects on the properties of various composite and nanocomposite materials. In magnesium-based nanocomposites, DCT has been found to increase density, ignition temperature, compressive yield strength, compressive ductility, and microhardness (Gupta *et al.* 2023). Similarly, for aluminum silicon composites, DCT improved compressive strength and hardness, supported by microstructural changes (Rasool *et al.* 2011).

Interestingly, DCT's effects can vary depending on the material and application. For TiC/water nanofluids, DCT led to decreased viscosity due to homogeneous distribution of TiC nanopowder (Senthil, 2018). In self-lubricating iron matrix composites, DCT induced martensite phase transformation and fine carbide precipitation, resulting in significantly improved hardness and tribological properties (Peng *et al.* 2018).

DCT has potential to enhance various properties of composite and nanocomposite materials. The improvements are generally attributed to microstructural changes, such as phase transformations, carbide precipitation, and homogeneous distribution of nanoparticles. DCT could be a valuable tool for tailoring the properties of composite and nanocomposite materials for specific applications.

Aluminum composites have also benefited from cryogenic treatments. S. Gupta et al. investigated Mg/2wt. %CeO_2 nanocomposites subjected to shallow and deep cryogenic treatments. Deep cryogenic treatment at -196°C demonstrated an improvement in porosity, ignition resistance, and mechanical properties; though the cost-benefit ratio may not justify the deep treatment over shallow ones (Gupta *et al.* 2024).

3.5. Deep Cryogenic Treatment on Artificial Aging Synergies

Deep cryogenic treatment (DCT) combined with artificial aging has shown synergistic effects on various alloys, enhancing their mechanical properties and microstructural characteristics. In aluminum alloys, DCT promotes the formation of fine, densely distributed precipitates during artificial aging. For instance, in Al-Mg-Si alloy, DCT accelerates the precipitation of β'' phase while retarding the formation of larger β' precipitates (Jovičević *et al.* 2021). Similarly, in Al-Cu-Mg-Ag alloys, DCT facilitates the nucleation and growth of Ω phase, resulting in improved mechanical properties (Gupta *et al.* 2024).

Interestingly, the effects of DCT on aging processes can vary depending on the alloy composition and treatment parameters. In ZK60 magnesium alloy, DCT before solution treatment and artificial aging significantly enhances the length and density of rod-like β′1 precipitates, improving strength while maintaining elongation (Hu *et al.* 2023). For the WE54 magnesium alloy, a combination of DCT and precipitation hardening resulted in accelerated precipitation and improved tribological properties (Barylski *et al.* 2020). Combining cryogenic treatment with artificial aging presents further opportunities for enhancing aluminum alloys. For example, Abbas Sadeghi et al. focused on AA6061 and discovered that cryogenic rolling followed by artificial aging at 150°C for 50 hours resulted in a 40% increase in strength. This treatment also improved formability, particularly under multi-axial forming conditions (Sadeghi *et al.* 2023). Despite these enhancements, elongation remained unchanged, suggesting that specific properties can be targeted without compromising others.

3.6 Impact on Microstructure and Strength

Various studies have delved into the microstructural changes induced by cryogenic treatments. Deep cryogenic treatment (DCT) significantly impacts the microstructure and strength of various materials, leading to improved mechanical properties. DCT involves exposing materials to extremely low temperatures, typically around -196°C, for extended periods. The microstructural changes induced by DCT include grain refinement, uniform distribution of secondary phase particles, and increased dislocation density. In steels, DCT promotes the formation of fine carbides and a martensitic microstructure (Senthilkumar, 2016; Zhang *et al.* 2023). For aluminum alloys, DCT results in finer grains and better distribution of secondary phase particles (Kumar *et al.* 2023). In WC-Co cemented carbides, DCT refines WC grains into triangular prisms and induces phase transformation in the Co binder (Xie *et al.* 2015).

3.7 Residual Stress and Fatigue Resistance

Cryogenic treatments are also effective in reducing residual stresses and improving fatigue life. This process also increased the ultimate tensile strength by 75 MPa in comparison to T6 heat-treated alloys. Aluminum alloys at cryogenic temperatures and found improvements in yield stress, ultimate tensile strength (UTS), and elongation at failure. The increased resistance to dislocation movement at cryogenic temperatures contributed to better fatigue resistance and longer fatigue life, with a 143% improvement compared to room temperature.

Conclusion

This review paper discusses and explores in depth the highly significant effects of Deep Cryogenic Treatment (DCT) on improvement in mechanical and microstructural properties of materials generally including Aluminum, Magnesium, Copper alloys, and composites.

Aluminum Alloys: DCT refines grain structure, strength, and increases the hardness. The fatigue strength and residual stress especially in alloys such as 6082, 6063, A356.2, and 2024 get enhanced. Silicon and magnesium alloying elements enhance the mechanical properties of the alloys. Cryorolling along with innovative quenching techniques ensures better achievement of the outcomes.

Magnesium Alloys: The yield strength, hardness, elongation, and creep resistance of AZ91, WE43, and WE54 grades are improved through the DCT process. The uniform distribution of precipitates is promoted; hence, the benefit depends on the treatment temperature.

Alloys of Copper: DCT in copper alloys results in the refinement of grain structure that leads to higher hardness, tensile strength, and wear resistance. For example, microhardness increases and surface wear decreases in cases like Cu-Al-Si and CuBeZr due to dispersion strengthening and the formation of sub-grain.

Composites and Nanocomposites: In composites, DCT is known to improve the strength, compressive strength, and tribological properties through microstructural refinement and phase transformation. It also improves the nanoparticle distribution in cases of nanocomposite materials such as Mg/CeO_2.

Synergy with Artificial Aging: DCT and artificial aging together confer superior mechanical properties in the aluminum and magnesium alloys. For example, artificial aging following DCT produces fine precipitates that improve strength and wear resistance.

Overall, DCT modifies and enhances the grain structure, dislocation density, and phase distribution of materials, leading to desirable strength, hardness, wear resistance, and fatigue life in those materials. However, the treatment parameters play the key role in accomplishing the maximum possible benefits in various materials and applications.

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