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INVESTIGATION OF MATERIAL PROPERTIES UNDER CRYOGENIC CONDITIONS: A REVIEW

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Purpose: The purpose of this work is to analyses the behavior and mechanical properties of metals, alloys, polymers, concrete, and composites of various materials at low and cryogenic temperatures below 123 K (-150.15°C). This review paper highlights the influence of cryogenic conditions upon material selection and design for applications where critical service conditions require exposure to extreme cold, including energy storage, aerospace, offshore structures, superconducting technologies, shipbuilding, and LNG carriers.
Design/methodology/approach: This review attempts to synthesize results from experimental studies, computational modeling, and theoretical analyses that have examined changes in material mechanical properties at cryogenic conditions. This review is focused on the fracture toughness, tensile strength, brittleness, and associated properties of the various classes of materials. In so doing, the approach is aimed at understanding how those properties evolve at low temperatures and their implications on materials selection and design for harsh environment applications.
Findings: Results show that even though cryogenic temperatures can be applied to enhance the tensile strength, modulus, ultimate strength, and fatigue resistance of materials, they simultaneously cause a significant reduction in ductility, therefore making the material more brittle with enhanced susceptibility to micro-cracking. The paper underlines the fact that material development should proceed to develop those possessing increased strength, resistance to wear and corrosion with less compromise of ductility.
Limitations/implications of the research: The complexity in testing materials at cryogenic conditions and the difficulty in directly correlating the experimental results with real applications are the limitations of the research. Further research is needed before such challenges are met and before materials with optimum performance at low temperatures, without sacrificing key properties, are developed.
Originality/value: This review gives important insight into the mechanical behavior of materials at cryogenic temperatures and points out the need for advanced material development with specific emphasis on additive manufacturing for tailoring material properties in view of superior performance and reliability in extreme cryogenic environments. The results will be an important guideline for future research and material selection of various industries, specifically aerospace and energy storage.

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Keywords: Cryogenic temperatures, mechanical properties, advanced materials.
Category of the paper: Literature review.

1. Introduction

The demand for materials that can withstand very low temperatures and cryogenic conditions is increasing across a wide range of industries, including shipbuilding, energy storage sectors, food processing and preservation, offshore structures, LNG (liquefied natural gas) pipelines, and hydrogen energy storage tanks (Luo et al., 2022; Sohn et al., 2015; Zhang et al., 2023; Xie, 2017). However, a major challenge for the engineering applications mentioned above is prolonged exposure to extreme low-temperature environments (Naser, 2019). Materials safely works under very low temperature is crucial for hydrogen turbo pumps in rocket engines (Sa´pi, Butler, 2020), superconducting magnets (Crescenzi et al., 2011), battery technology, aerospace cryogenic engines, nuclear energy, and more. While cryogenic applications are numerous, one particularly promising area that warrants further research and optimization is illustrated in Figure 1.

This literature review aims to synthesize the current state of knowledge on materials suited for cryogenic applications, such as those used in LNG carriers (operating at -163℃) and liquefied hydrogen storage tanks (operating at -253℃). By evaluating advancements in cryogenic materials, including metals, composites, concrete, and polymers, this review seeks to highlight trends, challenges, and future directions for material optimization.

A significant focus of this review is the performance of materials under cryogenic conditions, where properties such as high strength, thermal stability, corrosion resistance, and ductility are paramount. Materials that safely work at very low temperatures are mandatory in cryogenic application areas to give the desired function. This holds particular significance for liquefied natural gas (LNG) carriers, which operate at temperatures around -163°C (Kogbara et al., 2013; Krstulovic, Opara, 2007), and liquefied hydrogen storage systems, where hydrogen is stored at -253°C. At such low temperatures, the materials used for constructing LNG storage tanks, and liquefied hydrogen storage must demonstrate exceptional cryogenic properties. Several characteristics like high strength, thermal stability, corrosion resistance, and ductility, are needed for materials utilized in such circumstances. The efficient design and functioning of systems in extremely low temperatures depend on these characteristics. For example, at cryogenic temperatures, thermoplastic polymers like polytetrafluoroethylene (PTFE) and polyether ketone (PEEK) show high tensile strength. This makes them perfect for sealing applications in cryogenic fuel systems like those used in LNG carriers and liquefied hydrogen storage (Wang et al., 2024). Similarly, much research work conducted on glass fiber-reinforced epoxy shows good cryogenic properties, and it is a cornerstone in cryogenic pressure vessels for sealing purposes due to its high fatigue and corrosion resistance (Morino et al., 2001).

From another perspective, materials suited for cryogenic environments are becoming essential and transformative for industries, including hydrogen energy storage applications like cryo-compressed, liquid hydrogen storage (Barth´el´emy, Weber, Barbier, 2017), as well as for space exploration technologies. In addition, the advancement of carbon-neutral strategies has led to a rapid increase in the use of clean hydrogen as an energy vector for more efficient energy supply utilization (Guo et al., 2023; Jin et al., 2023). The novelty of this review lies in its comprehensive assessment of different materials performance across a broad spectrum of cryogenic applications and the basic mechanical properties of materials under such very low temperatures. It provides a critical analysis of the literature to identify gaps and opportunities for future research, particularly in optimizing materials for hydrogen energy storage, a key component of carbon-neutral strategies. By drawing on both foundational studies and recent advancements, this review establishes a cohesive understanding of material behavior under extreme low-temperature conditions. Hydrogen is a promising clean energy carrier particularly the liquefied hydrogen which stored at very low temperature (cryogenic temperature). Therefore the demand for containers that can securely handle, transport, and store hydrogen in cryogenic settings such as cryo-compressed and liquid hydrogen storage, which necessitates temperatures as low as (-253°C) is high. Hydrogen energy holds promise as a fossil fuel alternative due to its abundant supply, non-toxicity, and near-zero carbon emissions (Said, 2022; Bionaz et al., 2022; Singh, Altaee, Gautam, 2020).

The storage and transportation of hydrogen as a liquefied gas impose greater demands on the design and construction of storage tanks (Gu et al., 2020; Kumar et al., 2011) because of its great storage density and efficiency of delivery, liquid hydrogen (LH2) is especially preferred. Comparing liquefied hydrogen storage to compressed gaseous hydrogen storage improves safety and addresses low energy density caused by space limitations in compressed hydrogen storage techniques. But storage of liquid hydrogen is a challenge due to its very low temperature needs Sarangi, 1987. Containers for LH2 storage must endure temperatures down to 20 K (Zu¨ttel, 2004). These containers' materials must be carefully chosen to guarantee that they are compatible with such low temperature of liquid hydrogen, resistant to hydrogen embrittlement, and have the best possible mechanical and thermophysical qualities. While LH2 storage tanks are commonly made of stainless steel (Yatsenko et al., 2022), hydrogen embrittlement is a concern (Qiu et al., 2021). Various grades of stainless steel have been tested for resistance to this issue.

Aluminum, with its high strength and reduced susceptibility to embrittlement, is another option for LH2 storage tanks. Additionally, titanium and composite materials are being explored as alternative materials to store in such a very low temperature (Aziz, 2021; Qiu et al., 2021).

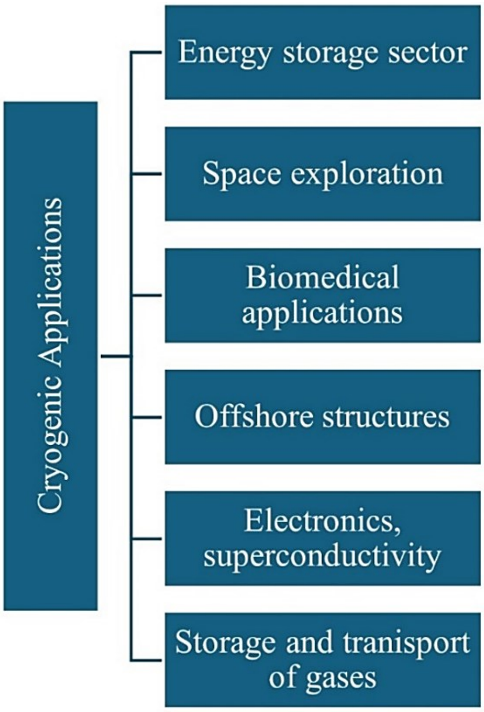

Figure 1. Applications area of cryogenic temperature.

A deep understanding of how materials behave in cryogenic conditions is crucial to building safe and effective systems for storage and transportation purposes, like liquid hydrogen storage tanks. The choice of materials for these extremely low temperatures remains a significant challenge. At low temperatures, materials must maintain their desired properties without breaking down. Because of their advantageous strength-to-weight ratios, metals, composites, and alloys like aluminum alloys are particularly interesting and could be used in cryogenic applications (Xu, Roven, Jia, 2017; Dong et al., 2020).

The materials used in cryogenic environments must ensure both safety and reliability. Although no precise temperature strictly defines cryogenics, it is generally considered to be temperature below (-150℃). Below this threshold, gases such as oxygen, nitrogen, hydrogen, and helium begin to reach their boiling points (Sa´pi, Butler, 2020). The cryogenic temperature enhances the physical and mechanical properties of materials such as tensile strength, yield strength, and fatigue.

According to the literature source, cryogenic temperature improves resistance to corrosion, erosion, wear, and abrasion while also increasing durability and stabilizing strength characteristics. This process refines and stabilizes the crystal lattice structure and ensures a more uniform distribution of carbon particles throughout the material, resulting in stronger and more durable materials (Kalia 2010). Refrigeration and cryogenics have a shared common history, with the main distinction between them being the temperature range they operate within. The various application areas of temperature ranges connected to low temperatures (LT) and cryogenic temperatures (CT) are shown in Table 1. For example, due to aircraft operating in diverse temperature ranges, particularly in low-temperature conditions, components must be engineered to endure extremely low temperatures. At high altitudes, aircraft can frequently experience temperatures below (-50°C). To ensure reliability and safety, electronic components, hydraulic systems, and fuel systems must be specifically designed to withstand these harsh conditions.

The methodology employed for this literature review involves a systematic approach to identifying, evaluating, and synthesizing peer-reviewed studies and industry reports. Key publications were selected based on their relevance, scientific rigor, and contribution to the field. The review is structured to provide an overview of cryogenic applications, material performance, and emerging trends, followed by an analysis of challenges and future research directions. By consolidating knowledge from a wide range of studies, this literature review aims to support researchers and engineers in selecting and developing materials for cryogenic applications. It underscores the critical role of material science in enabling advancements in energy storage, transportation, and other cryogenic technologies, paving the way for more sustainable and efficient systems.

Table 1.
Temperature Ranges and Categories for Different Substances

Explanation	**[K]**	**[°C]**	**Category**
Room temperature	296	23	RT
Design for aircraft components temperature	216	-57	LT
Lowest temperature measured on Earth	184	-89	LT
Liquid methane (LCH4) or natural gas (LNG)	111	-162	CT
Liquid nitrogen (LN2)	77	-196	CT
Liquid hydrogen (LH2)	20	-253	CT
Liquid helium (LHe)	4.2	-269.95	CT
Absolute Zero	0	-273.15	CT

Source: (Sapi, Butler, 2020).

Low temperatures are usually defined as those in the range from 0 C (273 K) to about -150°C (123 K), and are usually in application in such fields as aerospace engineering, refrigeration, and atmospheric studies. Cryogenic temperatures, on the other hand, define any state below -150°C (123 K) in which materials such as nitrogen, oxygen, hydrogen get in liquid form and their cryogenic handling and storage is what a study discipline named as cryogenics constitute. Materials exposed to cryogenic conditions exhibit special properties, such as superconductivity a very important issue in different scientific research and technological applications. Known differences and characteristics of materials in both temperature ranges are a must for the development of technology in areas depending on low and cryogenic temperatures.

2. Literature Review: Effect of Cryogenic Temperature on Material Properties

Cryogenics is the scientific study of materials at very low temperatures, typically below-150°C, where significant alterations in their physical and mechanical properties occur due to temperature-dependent phenomena and material composition. At cryogenic temperatures, a material's microstructure can change, enhancing properties such as tensile strength, hardness, and durability. For instance, many metals experience increased yield and tensile strength as atomic vibrations decrease, which suppresses dislocation movement, while ductility may decline, leading to a transition from ductile to brittle behavior. Similarly, certain polymers retain flexibility and toughness at low temperatures, making them suitable for cryogenic applications. The performance of materials is also influenced by their composition; for example, the addition of elements like nickel in alloys can improve toughness and reduce brittleness in cryogenic conditions. Understanding these intricate relationships is essential for advancing technology in fields such as aerospace, energy storage, and superconducting technologies, where material performance under extreme conditions is crucial. In addition, cryogenic treatment like deep cryogenic treatment is a technique used to process materials at ultra-low temperatures to enhance their performance characteristics of traditional alloys (Gu et al., 2018; Yang et al., 2006). This review work highlights how various materials such as metals, composites, ceramics, and polymers, behave under cryogenic conditions and explores their mechanical characteristics.

2.1. Effect of Cryogenic Temperature on Metals and Alloys

In recent years, the study of the properties of metals at low temperatures has emerged as a key focus in materials science. Traditional metals and alloys, especially stainless steels, show outstanding tensile qualities, such as resistance to oxidation, corrosion, and wear in the cryogenic environments (Cao et al., 2023; Zhu et al., 2017). Notably, face-centered cubic (FCC) metals exhibit an enhanced hardening rate at cryogenic temperatures due to several factors, including the inhibition of dynamic recovery, microstructural changes, and an increase in defect density. These characteristics make them ideal for cryogenic applications.

Austenitic stainless steels, especially the 300 series (AISI 304L, 316L, 321, and 347), are highly suitable for use in very low-temperature application areas like liquid natural gas (LNG) storage and nuclear facilities. Their effectiveness is particularly notable in applications such as LNG cargo barriers, as illustrated in Figure 2, austenitic stainless steel. However, it is important to note that cryogenic temperatures significantly affect their mechanical properties. Numerous studies show that at cryogenic temperatures, the tensile strength, and ultimate strength of various metals increase. For instance, AA6061-T6, an aluminum alloy, showed improved mechanical characteristics at cryogenic temperature (Jin et al., 2024). This improvement is attributed to increased resistance to dislocation movement resulting from reduced thermal energy.

Figure 2. LNG applications of austenitic stainless steel, image of an LNG carrier.

Source: (Park et al., 2010).

The mechanical properties of high-strength and high-toughness (HSHT) steels have shown significant improvement at cryogenic temperatures, according to recent studies. (Xia et al., 2023), reported that when tested at -196℃, HSHT steel exhibits a yield strength of 1200 MPa and a tensile strength of 1620 MPa. These steels maintain both strength and ductility in harsh environments, as evidenced by the marked improvement in strength accompanying enhanced uniform elongation. Such characteristics are crucial for applications that require high-performance materials. In the context of bulk metallic glasses, a study by (Li et al., 2013), demonstrates that reducing the temperature from 293 K to 77 K increases the compressive yield stress from 1791 MPa to 2217 MPa, illustrating a substantial enhancement in strength. Additionally, cryogenic treatment of metals, such as Cr8-type cold work die steel, enhances hardness by reducing retained austenite and improving wear resistance through the precipitation of specialized carbides (Chi et al., 2010).

Research on stainless steels reveals that while they maintain corrosion resistance, their toughness decreases markedly at temperatures approaching liquid nitrogen levels (77 K). Conversely, titanium alloys have been shown to retain good strength and toughness as well as excellent corrosion resistance at cryogenic temperatures (Zhao et al., 2021), making them suitable for specific aerospace and cryogenic storage applications. Most metals become inherently brittle at low temperatures. Nevertheless, conventional titanium exhibits a consistent trade-off between strength and ductility at cryogenic temperatures (Huang et al., 2022; Zang et al., 2022; Zherebtsov et al., 2013). Leskovˇsek, Kalin, and Viˇzintin (2006) investigated the influence of cryogenics on the wear resistance of steel and demonstrated that cryogenically treated samples exhibit improved wear resistance. Additionally, research on copper proves that it exhibits greater strength and ductility at cryogenic temperatures (77 K) than at room temperature during uniaxial tensile tests. This implies that cryogenic conditions noticeably improve the mechanical properties of copper (Zhang et al., 2021).

At cryogenic temperatures, the microstructure of materials can be enhanced, which is important for improving their overall performance. Also, stress relaxation can be significantly slowed, resulting in increased material strength and stability (Feng et al., 2014; He et al., 2018; Li et al., 2016). Therefore, cryogenics is a crucial science to improve the mechanical properties of metals. In general, as the temperature decreases, a material's elastic modulus, tensile strength, and yield strength tend to increase, along with improvements in its fatigue strength and endurance limit (Duthil, 2015; Qiu et al., 2021), but its plasticity diminishes. The substantial reduction in plasticity at low temperatures can lead to the initiation of brittle cracks and increase the risk of fracture. Anjaria et al. (2024) reported that, at cryogenic temperatures, materials experience a typical localized plastic deformation resulting from the concurrent activation of multiple deformation mechanisms.

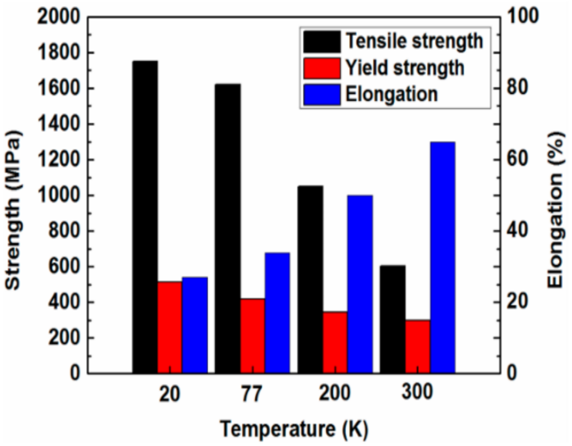

Figure 3. Cryogenic behavior of 18Cr–8Ni stainless steel across various temperatures.
Source: (Qiu et al., 2021).

Many studies have confirmed the dependency of material mechanical properties on cryogenic temperatures, with most metals exhibiting an increase in tensile strength as temperature decreases. This phenomenon is supported by the findings of (Xia et al., 2023), as illustrated in Figure 4. Microstructural analysis reveals that deformation at cryogenic temperatures leads to a high dislocation density and the formation of mechanical twins, suggesting the presence of complex deformation mechanisms critical to understanding material performance.

The influence of cryogenic temperatures on the mechanical properties of metals is well-documented, with a general trend of increasing tensile strength at lower temperatures. This behaviour can be largely attributed to reduced thermal agitation, which minimizes atomic vibrations and restricts dislocation movement. In addition (Xia et al.,2023; Umezawa, 2021) corroborate this trend. Ghosh et al. (2023) conducted experiments on various alloys under cryogenic conditions and observed significant increases in tensile strength accompanied by a reduction in ductility. Their study highlighted the roles of deformation twinning and high dislocation density as critical factors influencing the mechanical response of metals in such environments.

Microstructural analysis across these studies consistently demonstrates that deformation mechanisms at cryogenic temperatures are complex, involving the simultaneous occurrence of twinning and dislocation activity. According to (Umezawa, 2021), these mechanisms enhance material strength by creating barriers to further dislocation motion, thereby increasing the stress required for continued deformation. This phenomenon is essential for understanding the behaviour of metals in cryogenic environments, such as aerospace applications or cryogenic storage systems, where materials are subjected to extreme conditions.

Furthermore Ma et al. (2023) employed axial tensile testing and scanning electron microscopy to investigate the strength and fracture mechanisms of aluminium plate-fin structures at cryogenic temperatures. Their analysis revealed a quasi-cleavage fracture mode characterized by distinct morphological features, including dimples, tear ridges, and microscopic cleavage zones. Similarly, Zheng et al. (2022) found that pure magnesium specimens demonstrated enhanced strain-hardening tendencies and increased tensile strength under cryogenic conditions. However, these specimens also exhibited reduced elongation to failure, along with the suppression of grain boundary sliding.

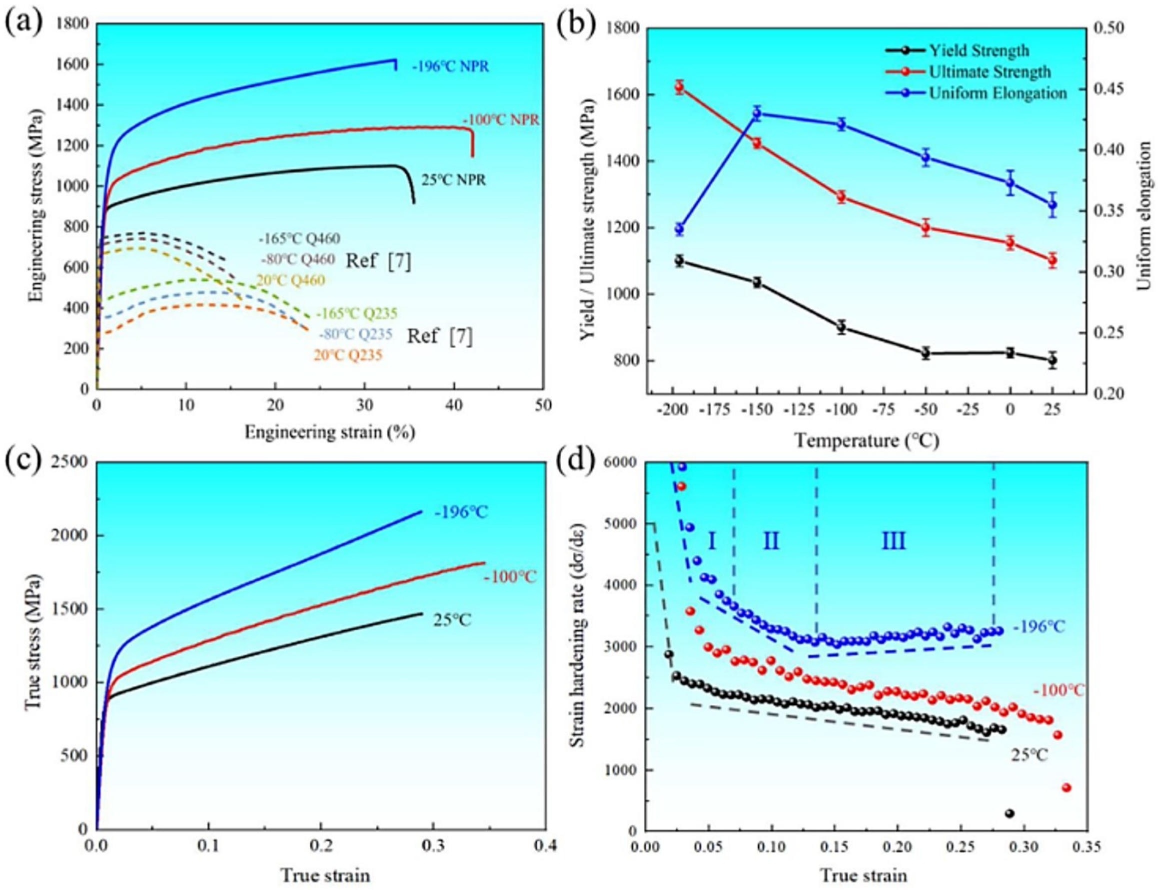

Figure 4. The graph presents the mechanical responses of HSHD steel at various temperatures: (a) engineering stress-strain curves of HSHD, Q235, and Q460 steels, (b) temperature- dependent trends in HSHD steel's mechanical properties, (c) true stress-strain curves for HSHD steel, and (d) strain hardening rate curves for HSHD steel at different temperatures.

Source: (Xia et al., 2023).

Together, these studies (Xia et al., 2023; Umezawa, 2021; Ghosh et al., 2023; Ma et al., 2023; Zheng et al., 2022) provide consistent evidence that cryogenic temperatures significantly enhance the mechanical properties of metals. These enhancements are driven by microstructural phenomena such as twinning and dislocation interactions, which are pivotal for optimizing materials for high-performance applications in cold environments.

2.2. Effect of Cryogenic Temperature on Composite Materials

Understanding the cryogenic behavior of composites is essential for their effective use in real world applications at cryogenic temperatures, ensuring they meet the specific performance requirements for cryogenic conditions. Advanced composites, including fiber reinforced polymers and metal matrix composites, are increasingly explored for cryogenic applications such as space applications (especially for pressure vessel or tanks), superconducting devices, and the storage of propellant gases in liquid form, all of which are pertinent to the energy sector, especially for green transition, due to their customizable properties. Composite materials, with higher strength and lower density, offer the potential to reduce tank weight by up to 25% compared to aluminum alloy tanks (Verstraete et al., 2010; Schutz, 1998). The composites encompass thermo- plastic and thermosetting polymers reinforced with fibers and particles. The literature suggests that composites can be engineered to maintain structural integrity at low temperatures while minimizing weight. Designing composite components for working under cryogenic conditions presents a substantial challenge because of the complex stress fields that develop within the materials. Chen et al. (2021), Hohe et al. (2021), S´api, Butler (2020) commenced from rheological changes the material experiences during curing and cooling to cryogenic temperatures (Baran et al., 2017), and due to the dissimilar nature of the constituents and dissimilar properties.

Cryogenic temperatures pose a significant challenge to the mechanical performance of composites, as extreme conditions can induce microstructural changes that affect mechanical properties and may lead to fracture. While most research has focused on room temperature behavior, some researchers have specifically studied the cryogenic characteristics of composite materials (Kliauga, Sordi, 2021; Cheng et al., 2020). According to reported by Sa´pi and Butler (2020) as temperature decreases, the Young's modulus and tensile strength of the matrix increase due to reduced polymer chain mobility, which enhances the binding forces between molecules and strengthens the material. The mechanical properties of composites at low temperatures are influenced by the resin, fiber, and interface. Hence, as the temperature decreases, the bonding strength of the polymer molecular chains increases, leading to higher Young's modulus and tensile strength in the resin matrix. However, this decrease in temperature also results in reduced toughness of the resin matrix (Hohe et al., 2021). Additionally, based on the time temperature superposition principle, lower temperatures slow stress relaxation over time. For instance, carbon fiber reinforced polymers have shown promise in maintaining their strength and stiffness even at cryogenic temperatures, although they may still suffer from matrix cracking. Metal matrix composites, particularly those reinforced with ceramics, offer a balance of strength and toughness, making them suitable for use in cryogenic fuel tanks and structural components in space vehicles. Also, SiC/Al composites have gained increasing attention due to their well-rounded properties, including a high specific modulus, impressive hardness, and strong corrosion resistance (Wang et al., 2014; Chen et al., 2014). Numerous studies have identified SiC/Al as a promising material for use in cryogenic applications (Liu et al., 2019; Feng, Liang, Jianfu Zhang, 2014; Zulfia, Hand, 2002; Yan, Lifeng, Jianyue, 2008; Guoju Li et al., 2014; Shen et al., 2015). SiC/Al composites are used in spacecraft for long-duration remote sensing satellites, but their mechanical properties in cryogenic conditions remain largely unexplored.

In general, a review of composite materials at cryogenic temperatures shows that cold conditions generally enhance strength, modulus, fatigue, and thermal properties. However, they also reduce ductility, leading to lower failure strain, fracture toughness, and impact resistance.

2.3. Effects Cryogenic temperature on Concrete Properties

Nowadays, the application of concrete materials at cryogenic temperatures is on the rise due to their strong mechanical properties, good design flexibility, relatively low cost, and durability (Lin et al., 2022; Mottaghi, Benaroya, 2015), particularly at extremely cold temperatures in space and energy sector. However, a challenge with concrete is that it has traditionally been used in normal temperature and pressure applications, and its performance in harsh environments has not been extensively investigated by researchers and engineers. Concrete properties can be severely compromised when exposed to cryogenic temperatures, which can, in turn, reduce the lifespan of structures. A growing number of containment tanks or vessels for the storage and transportation of liquefied natural gas (LNG) have been built worldwide as a result of the LNG market's expansion.

Concrete has been used as the primary structural material in the majority of LNG tanks (Cheng et al., 2022; Kogbara et al., 2013). These tanks are made up of an inner tank of 9% nickel (Ni) steel and an outside tank made of prestressed concrete (Ludescher, Næss, Bjerkeli, 2011). It is evident that very low temperatures can affect the mechanical properties of concrete. Therefore, it is of great importance to have a good understanding of the properties of concrete at cryogenic temperatures. Every study in the literature to date shows that concrete exhibits significantly higher compressive strength at cryogenic temperatures as a result of ice formation within the pores of the concrete (Zhengwu et al., 2018; Liu et al., 2016), even double of that of room temperature (Dahmani et al., 2007). Some studies, such as those by Wang et al. (2021) and Zhang (2018), have attempted to quantify the aforementioned strengthening effects using micro, and mesoscale models of ice formation in concrete pores and cracks. The compressive strength of concrete at low temperatures is heavily influenced by its water content (Xie, Yan, 2018; Zhengwu et al., 2018. Xiong et al., 2022) demonstrated that the compressive strength of geopolymer paste increased from 50.0 MPa to 80.0 MPa at -30°C.

Moreover, Unlike metals, alloys, and some composites, concrete's compressive strength does not continuously increase as temperature decreases. Literature source indicate that as temperature decreases, compressive strength initially increases to a peak, but then decreases with further temperature decline as shown in Figure 5. Zhang et al. (2023) reported that the flexural properties of ultra-high-performance concrete (UHPC) significantly improved at -170ºC, however, this enhancement was accompanied by a marked reduction in ductility, a phenomenon referred to as the thermal dependent brittleness effect. Additionally, Liu et al. (2016) showed that temperature drops had no effect on the final strain.

In general, the mechanical properties of concrete have been evaluated in various studies (Zhang et al., 2023; Kogbara et al., 2013, 2015), it is widely recognized that the compressive strength of these materials significantly improves at cryogenic temperatures. Furthermore, a trend has been observed where compressive strength increases as the temperature decreases further into the cryogenic range. The moisture content and exposure to cryogenic temperatures have a major impact on the thermal characteristics of concrete. As temperatures drop, the pore water in concrete migrates and changes phases, leading to temperature induced deformation that causes initial shrinkage, followed by expansion, and then further shrinkage.

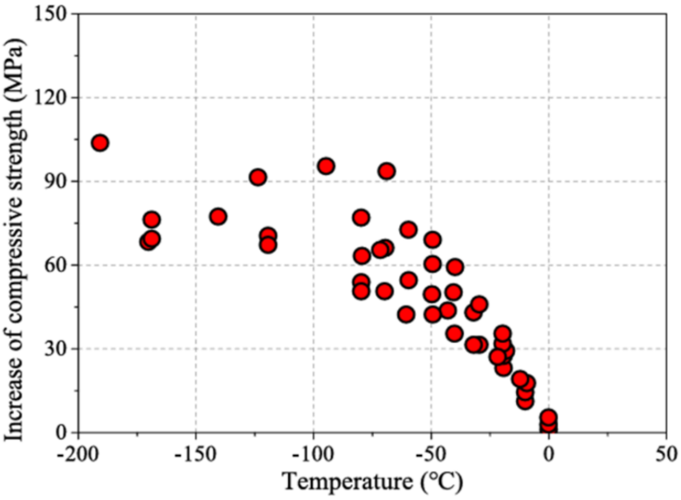

Figure 5. Increase in compressive strength of concrete at sub-zero temperatures.
Source: (Lin et al., 2022).

2.4. Effect of Cryogenic Temperature on Ceramics

Ceramics are known for their good mechanical properties, high temperature stability and are often considered for cryogenic applications where thermal insulation and structural stability are required. Ceramics are effective insulation materials due to their exceptional vacuum sealing properties and hygroscopic nature, which result in minimal degradation over time (Xie et al., 2011). In addition ceramics possess essential functional properties, including piezoelectricity, magnetism, and high temperature superconductivity (Porz et al., 2021; Ritchie, 2011). However, at cryogenic temperatures, ceramics typically exhibit increased brittleness due to their low fracture toughness. The literature reports that materials like alumina and zirconia, while maintaining their thermal stability, are prone to sudden failure under stress at cryogenic temperatures. Research has focused on improving the toughness of ceramics through composite materials or novel processing techniques to make them more suitable for cryogenic environments like advanced ceramics (Webber et al., 2017; Gumbsch et al., 2001). High entropy transition metal carbide (HETMC) ceramics, made from multiple primary components, usually deliver superior performance due to their high configurational entropy (Han et al., 2023). High entropy transition metal carbide (HETMC) ceramics are a class of advanced materials composed of multiple transition metals in near equimolar ratios, yielding high configurational entropy that lowers Gibbs free energy. This complex, multi component design provides exceptional benefits, including improved mechanical strength due to atomic scale lattice distortions that resist dislocation motion, superior thermal stability, and enhanced oxidation and corrosion resistance. Additionally, the diverse elemental makeup allows for the precise tailoring of properties such as thermal conductivity, hardness, and wear resistance making HETMC ceramics ideal for demanding applications in extreme environments like aerospace and power generation. By leveraging the high-entropy effect, these materials can achieve both durability and adaptability beyond the limitations of traditional ceramics.

2.5. Effect of Cryogenic Temperature on Polymer

Cryogenic characteristics of polymers are increasingly important with advancements in space, superconducting, electronics, defense, and cryogenic engineering. In fiber-reinforced polymer composites, unequal thermal expansion between fibers and matrix can cause internal stresses, leading to micro-cracking in the polymer matrix at cryogenic temperatures (Nobelen, et al., 2003). Polymers generally have poor performance at cryogenic temperatures due to their tendency to become brittle (Lau et al., 2013). The literature highlights that most polymers, such as polyethylene and polytetrafluoroethylene (PTFE), suffer from significant reductions in flexibility and toughness when cooled to cryogenic levels. However, some high-performance polymers, such as polyimides, demonstrate better retention of mechanical properties, though they still experience some embrittlement. The insulating properties of polymers, particularly their low thermal conductivity, remain advantageous in cryogenic applications, such as insulation in superconducting magnets and space exploration equipment. Plastics, which are classified under polymers, are widely used in various applications due to their versatility. Understanding their behavior at cryogenic temperatures is critical for advancing low-temperature technologies. Previous studies on polymers, particularly polyimides have shown that cryogenic temperatures significantly affect their mechanical properties, with both the elastic modulus and ultimate tensile strength increasing as temperatures drop, while failure strain decreases. Additionally, fracture toughness improves moderately at lower temperatures, with no detectable sample size dependence, and detailed fracture behavior has been analyzed using optical and scanning electron microscopy.

Research on polymers like ABS, PE, and PVDF (Kim et al., 2022), battery separators in lithium ion batteries, and epoxy transposed wire in reactors highlights the impact of low temperatures on tensile strength, fracture strain, and brittleness. Studies on polyethylene variants like HDPE, LDPE, and LLDPE emphasize the importance of parameters like relative elongation at break and impact strength at subzero temperatures in assessing frost resistance properties. The data from these research papers collectively demonstrate that low temperatures generally lead to increased tensile strength but decreased ductility, impacting the overall mechanical behavior of materials used in various industries. The tensile strength and modulus of the matrix increase at cryogenic temperature due to reduction in polymer chain mobility.

2.6. High entropy alloys as cryogenic materials (HEAs)

High-entropy alloys (HEAs) are extremely interesting prospects for technical applications because of their exceptional flexibility, extraordinary corrosion resistance (Pao et al., 2023), fatigue endurance (Gludovatz et al., 2014), wear resistance (Cantor et al., 2004). In high-entropy alloys (HEAs), the principal components do not vary significantly; instead, five or more metallic elements are combined in Equi atomic ratios, melted, and subsequently solidified to create a uniform solid solution structure. Recent studies underscores their potential in areas such as superconductivity and applications in extreme environments. In recent studies, high-entropy alloys (HEAs) such as Fe27Co24Ni23Cr26 have demonstrated remarkable strength and ductility at cryogenic temperatures. Tai et al. (2024) reported that this alloy achieves impressive tensile strengths of up to 1211 MPa, with an elongation of 87.2% at -150°C. These properties highlight the potential of HEAs for low-temperature applications, where both strength and flexibility are critical. Jiang et al. (2023) observed that the FeNiAl0.1Ti0.05 alloy achieves a yield strength of 575 MPa and a tensile strength of 1145 MPa at 77 K. This alloy demonstrates a well-balanced combination of strength and ductility, attributed to modified deformation mechanisms at cryogenic temperatures. These findings underscore the adaptability of HEAs to extreme conditions, further supporting their suitability for cryogenic applications. In addition, HEAs have been found to exhibit superconductivity, with the Ta1/6Nb2/6Hf1/6Zr1/6Ti1/6 alloy achieving a critical current density exceeding 100 kA cm^2 at 4.2 K (Jin et al., 2024). The exploration of high-entropy superconductors has opened new avenues for applications in high-field magnets and nuclear fusion reactors. This development underscores the potential of these materials in advancing technology for demanding energy applications.

3. Methods

This literature review followed a systematic approach to identify, evaluate, and synthesize relevant peer-reviewed studies and industry reports. The search strategy was designed to capture a broad spectrum of knowledge related to cryogenic applications, material performance, and emerging trends in the field, with a focus on how these aspects support cryogenic application areas particularly, the improvement of energy storage and transportation systems.

The initial sources of information were established academic databases, such as Scopus, Web of Science, and Google Scholar. They were chosen for their wide coverage of peer-reviewed literature, conference proceedings, and industry reports. This search was further narrowed down to include publications between 200 and 2024 to cover recent developments and aggregate formative studies that have guided the field for the past two decades. Only English-language publications were included to ensure both consistency and accessibility to the broadest possible international audience.

The review focused on peer-reviewed journal articles, conference proceedings, and high-quality industrial reports. Such publication types were chosen for their scientific rigor, relevance to the field, and contribution to advancing material science in cryogenic technologies. Search terms were chosen to reflect the major themes of the review: cryogenic applications, material performance, cryogenic technologies, and energy storage systems. The search terms were then iteratively refined in an attempt to strike a balance between key areas. All told, both broad and specific keywords had to be used, capturing sources from foundational research in cryogenic materials to the leading edge. This is with clear definition to the inclusion/exclusion criteria so that only works focusing squarely on material properties, performance, and application under a cryogenic environment would be gathered. This work hence removes any publications on matters relating to non-cryogenic applications and further non-theses from material science and publishes instead the final study which embodies both scientifically well-designed methods and highly important conclusions of significant knowledge that aid in revealing and interpreting material phenomena. When multiple were found to deal with the same or closely related topics, priority was given to more recent and highly cited works, so that breadth of research could be presented in the review, including a look at the most highly influential studies of the field.

This review summarizes the state of knowledge in cryogenic materials and related technologies by consolidating information from this carefully selected body of literature, bringing into light not only the achievements so far but also areas that require further investigation. The methodology followed will also provide a transparent and reproducible framework for researchers and engineers involved in the selection and development of materials for cryogenic applications.

4. Summary and Main Conclusion

At cryogenic temperatures, materials undergo significant changes in their microstructure, influencing mechanical properties such as tensile strength, hardness, and durability. Reduced atomic vibrations in metals at these temperatures limit dislocation movement, resulting in increased yield and tensile strength. However, this improvement is often accompanied by reduced ductility, shifting materials from ductile to brittle behaviour. While this phenomenon enhances resistance to deformation under stress, it raises concerns about sudden, catastrophic failures due to brittleness. The reviewed literature reveals both benefits and challenges associated with material performance in cryogenic environments.

Research indicates that cryogenic conditions enhance properties like tensile strength, fatigue strength, hardness, and corrosion resistance. However, critical limitations exist. Metals exhibit a trade-off between strength and ductility, which poses risks in applications such as cryogenic fuel tanks and aerospace components. This balance is not fully addressed in existing studies, leaving a gap in methods to mitigate brittleness while maintaining strength. Research on concrete shows that its compressive strength initially increases at cryogenic temperatures due to ice formation in its pores, but further cooling leads to strength degradation. However, the variability in these findings, often linked to differences in moisture content and composition, highlights the need for standardized testing methodologies. Additionally, while traditional materials like stainless steel and aluminium alloys have been extensively studied, there is limited exploration of emerging materials such as advanced superalloys and hybrid composites, which show potential for improved performance.

Several important lessons emerge from the literature. Materials like composites and polymers demonstrate improved modulus and fatigue resistance at low temperatures, yet their impact resistance and fracture toughness decline. The unique influence of moisture content on concrete's cryogenic behaviour suggests opportunities to tailor its composition for optimized performance. Furthermore, the renewed focus on lightweight and high-strength materials, such as titanium alloys and composites, underscores a shift toward solutions that meet the demands of space exploration, energy storage, and delivery systems where traditional materials may fall short. These insights provide a deeper understanding of material behaviour and help identify opportunities for improvement in cryogenic applications.

The importance of this research extends to numerous critical industries. In aerospace applications, the enhanced strength-to-weight ratios of advanced alloys and composites at cryogenic temperatures improve the safety and efficiency of cryogenic fuel tanks and spacecraft components. In the energy sector, advancements in hydrogen embrittlement resistance and improved material properties facilitate the design of reliable storage systems for LNG and liquefied hydrogen, contributing to the global push toward carbon-neutral energy solutions. For infrastructure, understanding concrete's cryogenic behaviour offers valuable guidelines for the construction of storage facilities and structures operating in extreme environments.

Future research should focus on addressing current limitations and expanding the knowledge base. Developing alloys that retain ductility while enhancing strength at cryogenic temperatures will reduce the risk of brittle failures. Standardizing testing protocols for concrete performance under extreme conditions will ensure consistent and reliable results. Expanding the use of composites, given their thermal and fatigue resistance, could lead to lightweight, high-performance systems for cryogenic applications. Furthermore, exploring novel materials and coatings, particularly for hydrogen storage and aerospace technologies, could unlock new opportunities. By addressing these challenges and building on the lessons learned, the field can make meaningful advancements, supporting innovation across industries that depend on cryogenic technologies.

5. Future Research direction

The study should focus on developing new materials capable of functioning in cryogenic environments, which pose particularly harsh and challenging conditions. At these extremely low temperatures, materials are prone to losing ductility, becoming brittle, and suffering from micro-cracking. To address these issues, it is essential to optimize or develop new materials that retain high strength, hardness, corrosion resistance, and wear resistance without compromising ductility or experiencing a significant shift in the ductile-brittle transition temperature. These kinds of materials ought to be impervious to the development of microcracks brought on by mechanical strains and thermal contraction, which are frequent in cryogenic applications. Moreover, it is imperative that these materials retain their stiffness and ductility under all circumstances and avoid losing volatile components. Applications where mechanical integrity must be maintained in harsh settings, such as the building of cryogenic tanks, aerospace com- ponents, and energy systems, call for this in particular. Moreover, the study should prioritize the development of new alloys and composite materials that can overcome the challenges associated with the ductile-brittle transition in cryogenic conditions.

Many conventional materials experience a drastic loss of ductility at very low temperatures, leading to a higher risk of sudden fracture. The research should focus on creating materials that can withstand this transition, retaining their ability to deform plastically rather than fracturing suddenly. This would substantially enhance the reliability and safety of systems operating in cryogenic environments, such as liquefied natural gas (LNG) storage tanks, cryogenic fuel tanks for space exploration, and superconducting technologies. Future research could explore the potential of high-entropy alloys (HEAs), amorphous metals, and nano-structured materials, which show promise for maintaining suitable mechanical properties at cryogenic temperatures. These materials may provide improved ductility, strength, and fracture resistance, creating new opportunities for cryogenic applications.

Additionally, advancements in additive manufacturing may allow for the development of highly customized materials tailored for specific cryogenic needs, further pushing the boundaries of what can be achieved in low-temperature environments.

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