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Review **JoPC**

A Review on Effect of Cryogenic Treatment on Wear Resistant Bearing Materials for Automotive Application

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Abstract

Cryogenic processing has come as a successful supplementary process to common heat treatment, especially in improving the wear-resistant performance of materials employed in in-vehicle applications. This sub-zero processing is normally performed following quenching and before tempering, during which materials are subjected to extremely low temperatures, typically around -196°C, for prolonged periods of 24 hours. Cryogenic treatment, which involves subjecting materials to extremely low temperatures, has demonstrated promising results in changing the mechanical characteristics and microstructure of certain metals and alloys. Ferrous and non-ferrous alloys are among the materials whose mechanical and microstructural characteristics are drastically altered by this operation. Better hardness, dimensional stability, and wear resistance are achieved in ferrous materials like tool steel and bearing steel through the precipitation of fine carbides and the encouragement of retained austenite to convert to martensite through cryogenic treatment. Likewise, secondary phase precipitation, which boosts strength and durability, is aided by non-ferrous elements like magnesium and aluminium alloys. These changes are especially useful in the automotive industry, where items like bearings are frequently subjected to heavy mechanical loads, varying velocities, and harsh thermal environments. This article delves into the literature available on how cryogenic treatment affects bearing steels and other wear-resistant materials. In addition to qualitative microstructural changes as defined by microstructural techniques like X-ray diffraction and scanning electron microscopy, it highlights improvements in mechanical qualities like hardness, toughness, and wear resistance. The relationship between improved tribological performance in treated samples and microstructural refinement is the main focus. According to the report's conclusion, cryogenic treatment has significant promise for extending the bearing materials' operating life and dependability under challenging automotive settings. Additional research is, however, suggested to optimize treatment parameters and investigate its suitability for newer grades of material.

Keywords: Cryogenic treatment, heat treatment, alloying element, wear resistance, cryogenic materials properties, automotive applications

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INTRODUCTION

The process of heating materials in liquid nitrogen to a cryogenic temperature of -196ºC for eight to twenty-four hours is known as cryogenic treatment. It is carried out immediately following quenching, and progressive tempering comes next [1]. For automotive applications, the need to reduce fuel and energy consumption, application and operating conditions, cost savings, and maintenance all play a role in material selection. Furthermore, the market's expectations for safety, comfort, and new car designs each year give birth to a number of other requirements that the chosen material must meet. Various methods are being developed currently to improve the qualities of metallic materials in order to meet these growing needs [2]. One popular branching method is heat treatment. In order to change a material in a certain way, heat treatment involves heating or cooling it to a set temperature for a predetermined amount of time. This method is typically used on metallic materials. The most widely used heat treatment technique for automotive applications boosts the processing temperature over 0°C (>273 K). There have been intermittent attempts to use subzero treatment, also referred to as cryogenic treatment, during the past century [3]. This review gives an overview of recent developments in treatment of major classes of steel. It emphasizes the effect of treatments on microstructural modification. The review also takes into account how these changes impact corrosion behaviour, wear resistance, and mechanical qualities. The goal is to provide an overview of the current status of steel treatment, highlighting noteworthy advancements and how they affect steel performance. The importance of cryogenic treatment as a workable method for enhancing the functionality of wear-resistant bearing materials in automotive applications is the primary focus of this paper.

HISTORY OF CRYOGENIC

Swiss watchmakers had already started employing cryogenic treatment in the middle of the 1800s. They used to bury the gears and watch parts in the snow-covered alpine tunnels to make clocks that were more durable and reliable [1, 4]. Castings were often left outside to grow and set during the winter. Tool die makers discovered that freezing cutting tools maintained them sharper for longer than untreated ones, thus they started doing it in the 1930s [5].

Hugo Junkers Aircraft Company cryogenically treated engine parts for their Jumbo 1,000 HP V-12 aircraft in the 1930s. During World War II, these engines were utilized by numerous German Air Force fighter aircraft [6]. In the 1960s, NASA engineers saw that spacecraft with better mechanical properties had returned from orbit, so they shifted their attention to cryogenic processing. In the US commercial deep cryogenic treatment has been accessible since 1965. In 1966, Ed Busch started Cryotech in the US using dry steam and liquid nitrogen. This made it possible for them to control the process's temperature according to the kind and cross section of the material. To undergo sub-zero treatment, the material was initially immersed straight into the liquid nitrogen medium. However, the sudden cooling caused the components to break [7]. Ed Bush conducted additional research on the cryogenic treatment and created a CT system by the end of the 1960s. Randall Barron's pioneering research and development of microprocessor-based temperature controls in the 1960s and 1970s greatly enhanced the CT System.

Deep Cryogenic Treatment

DCT is a very helpful technique for enhancing the material's properties. How well the DCT works with the selected material and its properties depends on a number of factors, including the DCT sequence (2%), cooling and warming rate (10%), holding length (soaking period) (24%), and the selected cryogenic temperature (72%) [8].

The chemical composition of the material the temperature at which it is heated during solution treatment or austenization [9] and the temperature during tempering and aging [10] all have an impact on DCT performance. The effectiveness of DCT and the distinct evolution of particular phases in treated material are defined by these exact parameters, which have a major impact on the material's final properties.

Cryogenic treatment is not a novel concept, but (Table 1). Early in the 20th century, there were some attempts at reverse heat treatment, or cooling, mostly to enhance the performance of cutting tools. Then, in 1872, James Dewar created the vacuum flask, which allowed liquids to be chilled and stored under vacuum. Karol Olszewski liquefied oxygen in 1883, and he and James Dewar liquefied hydrogen ten years later in 1893. Later in 1908, KamerlinghOnnes also developed liquefied helium, which created additional opportunities for cryogenic treatment research [11].

Table 1. Important occasions throughout history that influenced deep cryogenic treatment (DCT).

S. No.	Year	Key events that happend
1.	1855	Invention of First Refrigeration machine.
2.	1872	Development of Vacuum flask for cooling material.
3.	1883	Successful Liquefaction of oxygen (O_2) and nitrogen (N_2).
4.	1893	Hydrogen (H_2) was liquefied.
5.	1908	Liquefaction of helium (He).
6.	1940	Early documentation of the effects of cryogenic temperatures on materials.
7.	1980	NASA studied and documented the effect of cryogenic temperatures on modern materials.
8.	2022	In the last decade, new understanding of DCT and new testing techniques emerged.

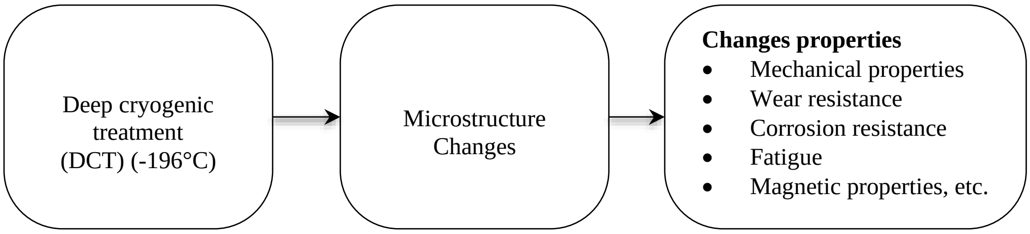

Figure 1. A schematic representation of the impact of deep cryogenic treatment (DCT) on materials [11].

The aerospace industry and research were among the first to actually see and document scientifically the effects of cryogenic temperatures on modern, complex materials, including non-ferrous alloys and specialty steels. According to documents released by NASA engineers and the Space Administration, many of the spacecraft's metal components were determined to be stronger after returning from space, where conditions are vacuum and cryogenic temperatures.

Since then, researchers and pioneers in the fields of cryogenics and cryogenic material treatment have been searching for, developing, and assessing new theories, concepts, and methods to enhance their macroscopic characteristics [12]. According to a recent study, multistage cryogenic treatment is a specific type of DCT that involves rapidly lowering to DCT temperature (below 196°C) and then heating once more to SCT temperature (80°C) or even room temperature (20°C or above). (Figure 1) [13].

Nevertheless, there is still disagreement over the precise timing and mechanisms by which DCT affects various materials. Because of this, DCT is being used to test a variety of materials and their various qualities in an effort to comprehend the underlying mechanism and offer insightful correlations to the various DCT effects with regard to particular materials (Figure 5) [11]. Although DCT has been mostly applied to metallic materials, it can also be used to non-metallic materials. Polymers, which are non-metallic materials, have gained attention recently due to their novel applications in the fields of electronics, aerospace, medical, and space exploration. Additionally, it is evident that DCT on polymers improves the material's hardness, mechanical strength, relaxation behaviour, and wear resistance [11].

CRYOGENIC TREATMENT

From the Greek words "genics," which means to generate, and "cryo," which means extremely cold, the English word "cryogenic" is derived. Cryogenic therapy, then, is the technique of cooling a material to a temperature below 0°C (<273 K) in order to create particular properties in the material [3, 14]. The literature commonly uses the following terms to describe cryogenic treatment: low temperatures, cryogenics, cryogenic processing, cryoprocessing, cold therapy, cryogenically treated, cryogenating, cryogenic stress reduction, cryogenic hardening, cryogenic thermal cycling treatment, subzero, low temperatures, and cryogenic techniques [15].

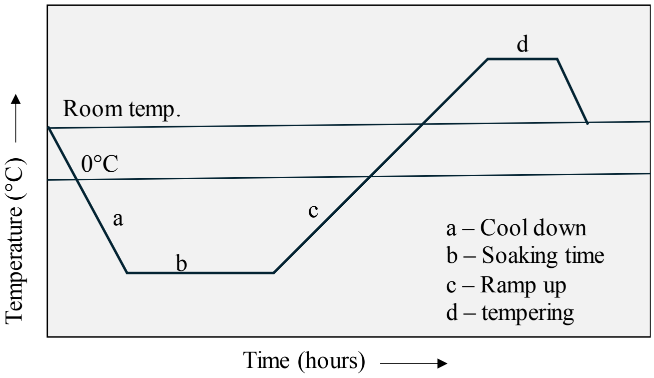

Figure 2. Steps involved in cryogenic treatment [3, 18].

Cryogenic treatment, which exposes wear-resistant bearing materials to extremely low temperatures, usually below -150°C, is beneficial for automotive applications. Through this procedure, the material's microstructure is altered, improving hardness, durability, and wear resistance while also fine-tuning grain boundaries. Because of this, cryogenic-treated bearings in automotive systems function better, last longer, and are more reliable, which lowers maintenance costs and increases overall efficiency. Proper design, material selection, production accuracy, and application of a chosen heat treatment are the main factors that define an automobile component's lifespan and usefulness; these factors are eventually impacted by production costs [3].

Both non-ferrous alloys (such as aluminum, titanium, magnesium, nickel, etc.) and ferrous metals (such as steel) are used as component parts in the automotive sector, and both metals may undergo cryogenically.

Differential turns, crankshafts, kingpins, axles, connecting rods, pinion shafts, bevel pinions, and bevel wheels are all made from this basic material [16]. Cryogenic treatment not only lessens wear but also enhances other mechanical characteristics like fatigue, toughness, residual stress, ductility, hardness, and dimensional stability [3, 17].

The following are the steps in cryogenic treatment [18] as shown in Figure 2:

1. Gradual cooling to a set temperature (gradient, gradual cooling minimizes stress).
2. Immersion period with constant or fluctuating temperature profile for predefined duration [19].
3. Gradually bringing the temperature down to room temperature (ascend; gradual warming rate minimizes stress).

TYPES OF CRYOGENIC TREATMENT

Three systematically different temperature systems make up the cryogenic treatment. Conventional cryogenic treatment (CCT), which lowers the temperature to about 80°C (193 K), is the primary method employed. [10, 33] The operating temperature range for shallow cryogenic treatment (SCT) is -80 to -160 °C (193 to 113 K) [20]. Some research indicates that deep cryogenic therapy (DCT) occurs at temperatures lower than -160°C (113 K) [21] and below -153°C (120 K) [22], in Celsius. The metallic material is quenched and then quickly cooled to 80 °C for a predetermined period of time in order to reach thermal equilibrium in SCT. By turning leftover austenite into martensite, SCT hardens the material, increases the quantity of precipitated carbides in the microstructure, and decreases the size of carbides [23]. Figure 3 provides a schematic illustration of the many forms of cryogenic therapy. To avoid thermal shocks from abrupt freezing and heating, the instruments were gradually cooled to and heated from the shallow cryogenic temperature (-110 °C) and deep cryogenic temperature (-196 °C) over the course of four and seven hours, respectively. A thermocouple attached to the device was used to monitor the temperature. Thus, 0.5 °C/min is the average rate of heating and cooling. After that, two tempering cycles were used to boost the temperature to 150°C [24].

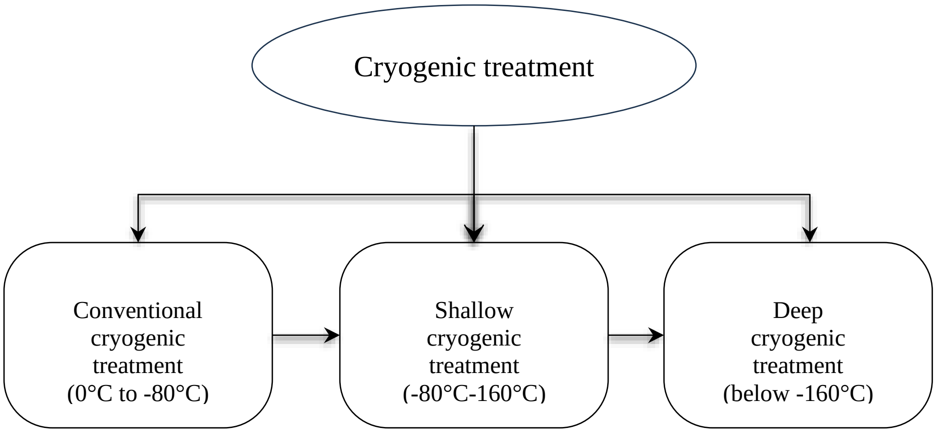

Figure 3. A schematic representation of the types of cryogenic treatment [15].

CRYOGENIC TREATMENT EQUIPMENT

Equipment for cryogenic treatment is employed in many fields, including research, freezing, and preservation. The following is a list of typical cryogenic therapy tools.

- *Cryogenic chamber:* The primary vessel used to hold the material to be treated is a cryogenic chamber or tank. It is linked to the rest of the system by pipes and valves.
- *Liquid Nitrogen storage tank:* The liquid nitrogen needed for cooling is kept in this tank. It has safety features including valves for relieving pressure.
- *Vacuum pump:* Prior to adding liquid nitrogen, a vacuum is created inside the chamber using a vacuum pump.
- *Transfer Hoses and Fittings:* These enable for the regulated transfer of the cryogenic fluid by joining the cryogenic chamber and the liquid nitrogen storage tank.
- *Temperature Monitoring Devices:* Throughout the treatment procedure, sensors installed inside the chamber keep an eye on the temperature.
- *Safety valves:* By ensuring pressure release in the event of an overpressure, these valves help to avoid mishaps.
- *Insulation:* To reduce heat transmission and preserve low temperatures, insulation materials are placed around the cryogenic chamber.
- *Control Panel:* A control panel allows users to adjust temperature, pressure, and other system parameters. It also controls how the system operates.
- *Thermocouples:* Thermocouples are extensively utilized in cryogenic apparatus to regulate and measure temperature. Thermocouples are a vital component of cryogenic equipment since they provide temperature information that is needed for research, safety, and process control.
- *Solenoid valves:* Solenoid valves are essential components of cryogenic systems because they provide safety, improve operational efficiency, and offer precise and dependable control over the flow of cryogenic fluids [1, 25].

The arrangement and wiring of different components are usually included in a cryogenic equipment schematic design. Figure 4 shows the cryogenic equipment's schematic design.

CRYOGENIC TREATMENT CYCLE

The cryogenic processing cycle is not the same in most studies. The cryogenic cycles used by the researchers varied, even for the same material. The generalized cycle for cryogenic treatment is displayed in Figure 5.

Steps involved in cryogenic treatment are as follows:

1. *Preparation:* To prepare materials for cryogenic processing, they are cleaned and degreased to get rid of any impurities. Prior to cryogenic treatment, parts may also be examined for flaws or damage.

2. *Cooling phase:* Liquid nitrogen or other cryogenic fluids are usually used to progressively chill the materials or components down to cryogenic temperatures. To guarantee equal temperature distribution and prevent thermal shock, cooling may take place in stages.
3. *Soaking phase:* The materials are maintained at the intended cryogenic temperature, which is normally between -120°C and -196°C, for a predefined amount of time known as the soaking or dwell time. The microstructure of the material can change and internal stresses can be relieved during the soaking period.
4. *Tempering:* To further improve the material's qualities, a tempering process could occasionally come after the cryogenic treatment, particularly for specific kinds of steel. In order to stabilize the material's microstructure, tempering entails heating it to a particular temperature range and then cooling it once more.
5. *Post Processing:* The materials may go through further processing procedures including machining, grinding, or surface finishing after they have warmed back up to room temperature.
6. *Testing and Inspection:* Many tests and inspections are typically carried out to evaluate the mechanical properties, dimensional accuracy, and overall performance of treated materials. Microscopy, tensile testing, hardness testing, and other analytical techniques may be used.

According to the laws of thermodynamics, the lowest temperature that can be achieved is absolute zero.

Molecules are in their lowest and most limited energy state at absolute zero. On the thermodynamic or absolute temperature scale, absolute zero is the zero point. That is equal to -273.15 ºC, or -459.67 ºF.

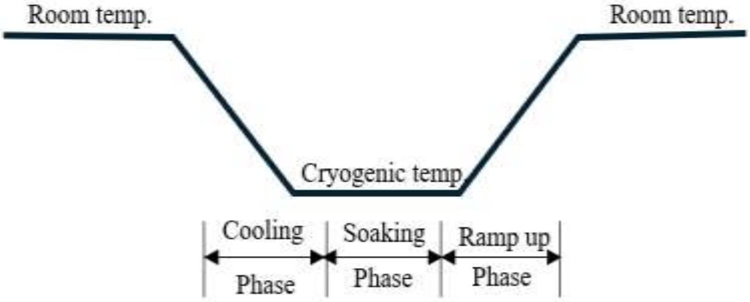

Figure 5. Cryogenic treatment cycle [27].

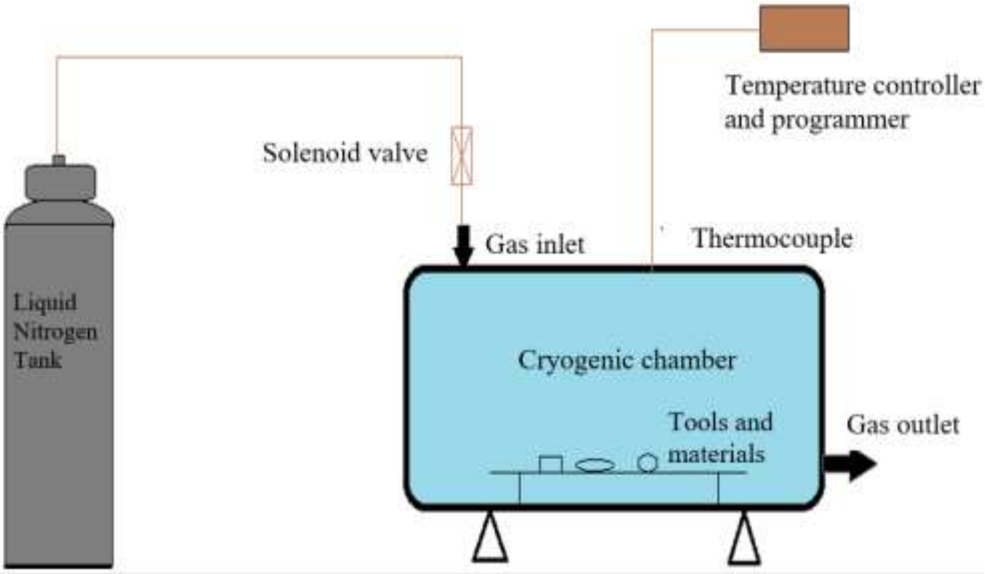

Figure 4. Cryogenic equipment schematic design [26].

Table 2. Common cryogenic fluids' normal boiling points [28].

S.N.	Cryogen	(K)	(ºC)	(ºF)
1.	Absolute zero	0	-273.15	-459.67
2.	Helium	4.2	-269.0	-452.1
3.	Hydrogen	20.3	-252.9	-423.2
4.	Nitrogen	77.4	-195.8	-320.4
5.	Oxygen	90.2	-183.0	-297.3
6.	Methane	111.7	-161.5	-258.6

The cryogenic region is commonly defined as the area below around 120 K (-153ºC) on the Kelvin scale. The normal boiling point (NBP) of common permanent gases is the temperature at which they transition from a gas to a liquid under atmospheric pressure as indicated in Table 2. Cryogenic liquids, also referred to as cryogens, are such liquids [28].

CRYOGENIC TREATMENT'S IMPACT ON MATERIAL'S MECHANICAL PROPERTIES

Cryogenic treatment improves a material's mechanical qualities and increases the lifespan of mechanical components [1] over time, CCT, SCT, and DCT have been introduced to materials and components utilized in the automotive sector. CCT improves fatigue strength by turning most of the residual austenite in steels into martensite, even if it also increases material strength [26]. and the formation of pin-dislocating delicate martensitic structures [29]. It has been demonstrated that DCT of metallic materials decreases site reduction and carbon redistribution [21], decreases free energy of crystal structure [30], precipitates tiny submicroscopic carbides [31], precipitates secondary and tertiary carbides [1, 21] and transforms retained austenite into martensite. The cryogenic treatment procedure exposes materials to extremely low temperatures, which can significantly alter the mechanical characteristics of certain materials. The cryogenic treatment sequence is frequently used after metallic material has been quenched [32]. Nevertheless, a number of studies [33] and even [34] applied the treatment following tempering or even annealing.

The DCT enhances the following properties of alloys: impact toughness [13], free energy absorption [27], ductility [35], hardness [12, 27], wear resistance [12, 27], dimensional stability [36], resistance to electro-chemical corrosion [36], machining time and machinability [37], and smooth surface [38]. Additionally, it offers a better and more uniform dispersion of precipitated secondary carbides [17, 39]. Evaluations of the DCT influence on microstructure and carbide precipitation are emphasized, and they are based on the distribution of carbides, their morphology, density, volumetric fraction, size, and chemical composition.

According to the research, the modified carbide nucleation and $M_{23}C_6$ precipitation altered the chemical composition of the residual M_2C through DCT, resulting in distinct DCT decomposition behaviors.

This offers a distinct perspective and explanation for the various microstructure and correct growth stages of HSS using DCT [15, 40]. The DCT effect is examined by altering the alloying elements phase change, binding state, chemical composition, and microstructure. The HSS material that was chosen, AISI M2. Because it is generally believed that DCT affects a material uniformly throughout its volume and surface, there hasn't been much focused research done on how DCT affects a material's surface and qualities up until now. Nonetheless, this study offers the first evidence that surface characteristics are customized differently from the bulk of the material under investigation [15].

The austenitic Fe-18Cr-8Ni stainless steel used in the test in [29] had previously 2% strain to raise the density of dislocations. The findings indicate that in the low-cycle regime (less than 104 cycles), the CT has no effect on fatigue life. However, CT samples in the high cycle regime (> 104 cycles) have demonstrated a longer longevity. CT samples, however, have shown a longer lifespan in the high cycle regime (> 104 cycles). CT specimens exhibit four to five times as many cycles to failure as untreated ones, with a maximum stress of 350 MPa. The identical material underwent the same subzero treatment after being pre-strained by 10%. In [41], which led to a fatigue life extension that was more than ten times longer. Similar outcomes have been reported for AISI 304 (pre-strained at 2% and 10%) and AISI 316 samples [42].

This work examined the impacts of various cryogenic treatment parameters on Ti-6Al-4V alloy and the effects of varying cryogenic treatment durations on sample hardness [43]. The authors reached the maximum hardness level after 72 hours of storage. The mechanical characteristics of tool steels following cryogenic treatment are the particular focus of this investigation. The authors discovered that compressive residual stress, wear resistance, and hardness were all enhanced by cryogenic treatment. These occurrences are explained by the precipitation of microscopic carbides and the conversion of leftover austenite into martensite during the cryogenic treatment procedure. [44].

APPLICATION OF CRYOGENIC TREATED MATERIAL

Many materials' microstructures have been found to be altered by cryogenic treatment, which enhances their mechanical properties and functionality. Typical applications for cryogenically treated materials include the following:

- *Cutting Tools:* Cuttings tools are among the many products that are made using the cryogenic process. It prolongs tool life and increases machining efficiency by improving these tools' toughness, wear resistance, and general performance [1, 45].
- *Engine Parts:* In automotive, aviation, and marine engines, cryogenic treatment is used on parts such as crankshafts, pistons, valves, and connecting rods. They become stronger, harder, and more fatigue resistant as a result, which increases their dependability and longevity under demanding circumstances [1].
- *Aerospace Components:* Engine parts, structural elements, and turbine blades are among the parts of aircraft that are subjected to cryogenic treatment. It improves the material's resilience to thermal stress, corrosion, and fatigue, which raises the overall performance and dependability of aeronautical systems [1, 46].
- *Tool and Die Making:* Molds, dies, and other tooling required in a variety of manufacturing processes are produced using cryogenic treatment. It prolongs tool life and increases productivity by enhancing these components' surface polish, dimensional stability, and wear resistance.
- The study's findings showed a notable improvement in the cryo-treated cutting tools flank wear and crater wear. The scientists stated that the tools' chemical stability through cryogenic treatment was responsible for this improvement [47].
- *Medical Applications:* It has been demonstrated that cryogenic treatment can help a material's resistance to corrosion. Medical equipment including needles, scissors, knives, and the like can have their service lives extended by using cryogenic treatment [45].

EFFECT OF CRYOGENIC TREATMENT ON WEAR RESISTANT BEARING MATERIALS FOR AUTOMOTIVE APPLICATION

Cryogenic treatment is utilized in automotive usage to enhance durability, hardness, and wear resistance of bearing material. The motor industry is being confronted with expanding demands every year with the progress of society. Such demands range from cost reductions to environmental protection, performance increase, longer cycles of materials, and improved component recycling [3]. It is estimated that 32% of the entire 83 EJ of energy used by road vehicles and 30% in other transport sectors is used to overcome friction each year. Through the production of materials with better wear resistance and better lubrication systems, remanufacturing and replacement of components can be minimized, thereby reducing vehicle wear [48].

Automotive components treated with cryogenic processes are more reliable, require less maintenance, and last longer. Cryogenic treatment is a process of immersing materials or components in a cryogenic fluid at temperatures between 0 and -269 °C for a given period of time. Over the past three decades, cryogenic treatment has been in the spotlight for its ability to enhance the performance of engineering components [49]. In machining operations, cryogenic cooling improves surface finish, extends tool life, reduces operating temperatures, saves energy, and reduces tool wear. This ultimately leads to improved productivity. Cryogenic chilling is also in demand for its capability to change and refine the nanostructure of metals [50].

ANALYSIS OF STUDY

It has been studied whether the wear resistance of bearing materials used in automotive applications can be increased by employing cryogenic treatment, which exposes materials to extremely low temperatures.

This review explores how cryogenic treatment affects several kinds of materials. To guarantee lifespan and dependability, the automotive sector requires bearings with outstanding wear resistance. Heat treatment, surface coatings, and material composition modifications are examples of conventional techniques for improving wear resistance. Cryogenic treatment, however, offers a viable substitute strategy. Bearing materials' resistance to wear can be significantly increased by cryogenic treatment. The process results in microstructural changes, such as the reduction of residual stresses, the refinement of carbide particles, and the conversion of residual austenite into martensite. These changes result in increased durability, hardness, and strength for the materials.

Furthermore, fatigue, adhesion, and abrasive wear are prevalent wear processes in automotive bearings that have been shown to be lessened by cryogenic treatment. This process may reduce wear rates and increase bearing service life, which could save costs and improve performance in automotive applications.

Even with encouraging outcomes, more investigation is required to completely comprehend the mechanics underlying cryogenic treatment's impacts on bearing materials. For broad acceptance in the automobile sector, practical factors like scalability, cost-effectiveness, and environmental impact also need to be taken into account.

The review concludes by highlighting the possibility of cryogenic treatment as a workable strategy for improving bearing materials wear resistance in automotive applications. The potential for enhancing material characteristics and mitigating wear mechanisms renders this field meriting further exploration and possible integration into vehicle manufacturing processes.

CONCLUSION

- The cryogenic treatment of wear-resistant bearing materials for use in automobiles is a practical way to increase performance and longevity in critical components.
- Cryogenic treatment enhances the mechanical properties and microstructure of bearing materials, boosting their hardness, fatigue strength, and wear resistance, as demonstrated by a comprehensive review of the literature. These improvements are especially helpful in automobile settings where bearings must withstand high loads, fast speeds, and temperature changes.
- The evaluated research also highlight how cryogenic treatment may be used to lessen wear-induced failures, extending the life of automobile bearings and lowering maintenance expenses. Even though cryogenic treatment has several established advantages, practical use must take cost-effectiveness, material selection, and process parameters into account.
- Further research and development efforts in this field are required to thoroughly examine the feasibility and potential of integrating cryogenically treated bearings into automotive systems and, eventually, enhance sustainability, efficiency, and dependability in the automobile industry.

Declaration of Interest

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- *Conflict of interest:* The authors declare no competing interests.

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