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HARDNESS MEASUREMENT OF ROLLING BEARING BALLS SUBJECTED TO MULTI-CYCLE CRYOGENIC TREATMENT

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1. Introduction

Rolling bearings are essential components in a wide range of mechanical systems, where they support loads and enable relative motion with minimal friction. Their operational reliability and service life strongly depend on the mechanical properties of the rolling elements.

Among various surface and heat treatment techniques, Deep Cryogenic Treatment (DCT) is a promising method for enhancing the performance of bearing steels. DCT is a process in which materials are cooled to cryogenic temperatures (typically below −150°C), maintained at that temperature for a defined period, and then gradually reheated under controlled conditions. This process leads to several beneficial microstructural changes, such as the transformation of retained austenite into martensite, precipitation of fine carbides, and redistribution of internal stresses. These effects can contribute to improved hardness, dimensional stability, and fatigue life.

For this research, bearing balls were selected because of their distinctive cooling patterns. Unlike bearing rings, which generally cool evenly, bearing balls experience notable temperature differences between their outer surface and inner core during cooling. These thermal gradients can influence residual stress distribution and microstructural evolution, making balls an excellent subject for studying the effects of DCT.

This study investigates the influence of multi-cycle Deep Cryogenic Treatment on the hardness of bearing balls made of 100Cr6 steel, intended for use in standard deep groove ball bearings (types 6306, 6308, and 6310). The test specimens were commercially available balls, previously subjected to conventional quenching (Q) and tempering (T). The aim is to determine whether DCT, when applied as an additional treatment after Q-T, leads to significant changes in hardness and whether the treated rolling elements maintain hardness values within the range required for reliable bearing operation.

2. Literature review

Numerous studies have demonstrated that the observed increase in hardness following DCT is largely attributed to the ultra-low temperatures used in the process. These conditions promote a more complete transformation of retained austenite into martensite—a significantly harder phase—than what is typically achieved through Conventional

Heat Treatment (CHT). Moreover, DCT can trigger the precipitation of fine secondary carbides and refine the microstructure, contributing to improved hardness through dispersion strengthening mechanisms.

To achieve a more comprehensive understanding of the effects of DCT on bearing steels, researchers have explored a wide range of treatment parameters, including soaking temperature and time, sample geometry, and thermal treatment sequences.

For example, a study [1] reported that cylindrical specimens of AISI 52100 steel (18 mm diameter, 10 mm height) showed a reduction in retained austenite from 14% to 3% after DCT at −180°C for 24 hours. This transformation corresponded with a 15% improvement in hardness. Similarly, another study [2] involving the same steel, 100Cr6, found that samples of 6 mm diameter and 6 mm height, treated at −185°C for 24 hours, exhibited an 18% increase in hardness. These enhancements were attributed not only to austenite-to-martensite transformation, but also to the precipitation of secondary carbides and grain refinement of martensite.

In [3], a different experimental setup employed a heat treatment sequence of quenching, tempering, DCT, and final tempering (Q–T–DCT–T) on 10 mm × 10 mm cylindrical samples made of AISI 52100 steel. The authors identified four main mechanisms responsible for property improvements: martensitic transformation of retained austenite, formation of eta-phase carbides, precipitation of ultrafine carbides, and enhanced microstructural uniformity. This sequence improved hardness by 10% compared to CHT.

Despite significant research efforts on standard test specimens (such as plates or cylinders), experimental data on the behavior of actual rolling elements remains scarce.

In the authors' previous study [4], bearing balls were subjected to a single-cycle DCT with a soaking temperature of −160°C for 24 hours, using cooling and heating rates of 1.5 K/min. For all bearing ball types, the change in hardness after DCT was less than 1%. The present investigation extends previous work by examining the effects of multi-cycle DCT on bearing balls.

Multi-cycle deep cryogenic treatment (DCT), involving repeated cooling and heating cycles, has been less frequently studied, especially in the context of bearing materials.

In [5], high-vanadium alloy steel was investigated under various DCT conditions, including two, four, and eight cycles with short soaking times, as well as single-cycle treatments with extended durations. The results indicated that both an increased number of cycles and prolonged cryogenic exposure led to a reduction in hardness, which was attributed to stress relaxation and changes in microstructural transformations.

This study focuses on exploring the effects of multi-cycle DCT on the hardness of commercially available 100Cr6 steel bearing balls, aiming to determine the treatment's potential as an additional step following quenching and tempering.

3. Experimental samples

The test specimens used in this study were rolling elements (balls) manufactured for use in 6306, 6308, and 6310 deep groove ball bearings, which are commonly used in conveyor idlers and other industrial applications.

The average diameters of the bearing balls were approximately 12.303 mm (6306), 15.081 mm (6308), and 19.052 mm (6310). All balls were made from 100Cr6 steel (SAE/AISI 52100), a high-carbon chromium alloy steel widely used for rolling bearing elements. This steel grade is classified as ball and roller bearing steel according to the SRPS EN ISO 683-17:2023 standard [6].

Table 1. Chemical Composition [%] of Bearing Steel 100Cr6

Chemical composition [%]:	C	Si	Mn	Cr	other
	1.00	0.25	0.35	1.50	-

All bearing balls were obtained in commercially available form, having already undergone conventional quenching and tempering. As a result, the DCT was applied after these standard heat treatments, rather than between quenching and tempering as is typically the case in some DCT protocols.

4. Process Parameters for Multi-Cycle Deep Cryogenic Treatment

The bearing balls were subjected to a multi-cycle DCT with the aim of investigating the effects of repeated thermal exposure on material properties. The full temperature–time profile is shown in Figure 1.

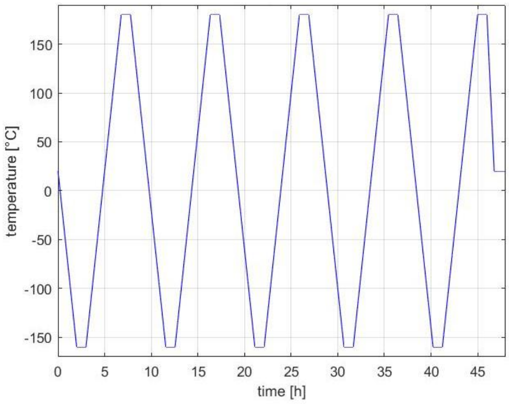

Fig. 1. Temperature Profile of Multi-Cycle Cryogenic Treatment

The process started at room temperature (~20°C) and involved a gradual cooling at a rate of 1.5 K/min down to a soaking temperature of −160°C, where the samples were held for 1 hour. After the cryogenic soak, the samples were heated to +180°C and again held for 1 hour. This cooling–heating cycle was repeated five times in total. After the final heating stage, the samples were cooled back to room temperature in a controlled manner, at a cooling rate of 1.5 K/min, to minimize thermal shock.

The treatment was performed in cryogenic chamber KK2000 using gaseous nitrogen as the cooling medium, under carefully controlled conditions to avoid thermal material shocking.

5. Hardness measurement

The hardness of the bearing balls was measured using the Zwick Roell ZHU 2.5 Universal Hardness Testing Machine, located in the accredited LIMES Laboratory (Laboratory for Testing of Machine Elements and Systems) at the Faculty of Mechanical Engineering, University of Belgrade.

Fig. 2. Zwick Roell ZHU 2.5 Universal Hardness Testing Machine (LIMES Laboratory, University of Belgrade)

The Rockwell hardness test was conducted in accordance with the latest standard SRPS EN ISO 6508-1:2024 [7], which replaced the previous SRPS EN ISO 6508-1:2017 version as of January 31, 2024. This national standard corresponds to the international EN ISO 6508-1:2023, titled *Metallic materials – Rockwell hardness test – Part 1: Test method*.

The Rockwell method determines hardness based on the depth of penetration (h) caused by a specific indenter under a controlled loading sequence, including a preload (minor) and total (major) force.

In this experiment, the HRC scale was used, employing a diamond cone (conical) indenter, which is standard for testing harder materials. The preload was 98.07 N, while the total force applied reached 1.471 kN. The HRC scale constants are N = 100 and S = 0.002 mm, leading to the following formula for calculating hardness:

$$HRC = 100 - \frac{h}{0.002}. \qquad (1)$$

According to [8], the required hardness range for bearing balls is between 58 and 66 HRC, ensuring adequate performance and resistance to wear during operation.

6. Results

The measured hardness values of the bearing balls before and after the applied multi-cycle DCT are presented in Table 2. A slight decrease in hardness was observed across all three bearing types (6306, 6308, and 6310) following the treatment. The reduction ranged from 1.7 to 2.4 HRC, corresponding to a 2.59% to 3.72% decrease in hardness.

Despite the observed reduction, all hardness values after DCT remained within the recommended range of 58–66 HRC. It is important to note that a minor reduction in hardness does not necessarily imply a loss in overall material quality.

Table 2. Initial and Post-Treatment Hardness Values of Rolling Bearing Balls

	Hardness Before DCT [HRC]	**Hardness After DCT** [HRC]	**Change** [HRC]	**Percentage change** [%]
6306	64.5	62.8	-1.7	2.64
6308	64.6	62.2	-2.4	3.72
6310	65.6	63.9	-1.7	2.59

A similar trend was observed in [4], which applied a single-cycle DCT with a soaking temperature of −160°C for 24 hours and identical cooling/heating rates of 1.5 K/min. Despite the extended soaking duration, the results also indicated a slight decrease in hardness after treatment, suggesting that DCT does not universally lead to increased hardness.

7. Conclusions

Rolling bearings are critical and widely used machine elements, making continuous improvement of their performance essential. One method employed to enhance the properties of metallic materials is DCT. Researchers have extensively investigated the effects of single-cycle DCT on bearing materials, whereas the influence of multi-cycle DCT remains relatively unexplored. Also, specimens were primarily cylindrical or disc-shaped, rather than actual rolling elements. In this study, commercially available rolling bearing balls were selected as specimens. Balls were chosen due to the significant thermal gradients between their surface and core, which are expected to make DCT effects on the material's microstructure more pronounced than in bearing rings.

This study examined the influence of multi-cycle DCT on the hardness of rolling bearing balls made of high-carbon chromium steel 100Cr6 (SAE/AISI 52100), which had previously undergone conventional quenching and tempering. The DCT process was precisely controlled, involving slow cooling and heating rates of 1.5 K/min, five repeated cryogenic cycles with a soaking temperature of −160°C held for 1 hour, followed by tempering at +180°C for 1 hour, and the use of liquid nitrogen as the cooling medium in a cryochamber.

The Rockwell hardness (HRC) measurements showed a slight decrease in hardness after DCT, ranging from 1.7 to 2.4 HRC, corresponding to a reduction of approximately 2.6–3.7%. However, all treated samples remained within the standard hardness range for bearing balls (58–66 HRC), indicating that the treatment did not compromise their applicability in rolling bearing systems.

Although a reduction in hardness was observed, this does not necessarily imply a decrease in overall performance. DCT is known to improve other material properties such as wear resistance, dimensional stability, reduction of residual stresses, and microstructural refinement. These benefits cannot be fully evaluated through hardness alone.

Future work will focus on additional characterization, including residual stress analysis, surface roughness, and dimensional stability, to gain a more comprehensive understanding of the impact of multi-cycle DCT on rolling bearing elements, as previously outlined in [9].

Acknowledgments

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