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Article

A proposal to develop the repetitive restoring technology of rolling bearings to realize the goal of circular economy and the sustainable development

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Abstract: The pursuit of extending and restoring the fatigue life of rolling bearings represents a critical challenge in mechanical engineering, with significant implications for sustainability and industrial efficiency. This study focuses on enhancing the fatigue life of both new and remanufactured rolling bearings through innovative surface modification technologies, particularly ultrasonic nanocrystal surface modification (UNSM). By optimizing the efficiency and effectiveness of the UNSM, this research delves into the scientific mechanisms underlying these technologies to maximize their performance. Furthermore, this work aligns with circular economy principles by enabling the repeated reuse of remanufactured bearings. While current technologies permit only one additional reuse cycle, this study aims to surpass this limitation, targeting more than three reuse cycles through advanced surface modification techniques. By pushing the boundaries of current knowledge and technology, this research contributes to more sustainable industrial practices, fostering a circular economy and reducing resource consumption in mechanical industries.

Keywords: Repetitive restoring technology, Ultrasonic Nanocrystal Surface Modification (UNSM), Remanufacturing process, Prognostic Inspection and Proactive Maintenance (PIPM), Rolling bearing

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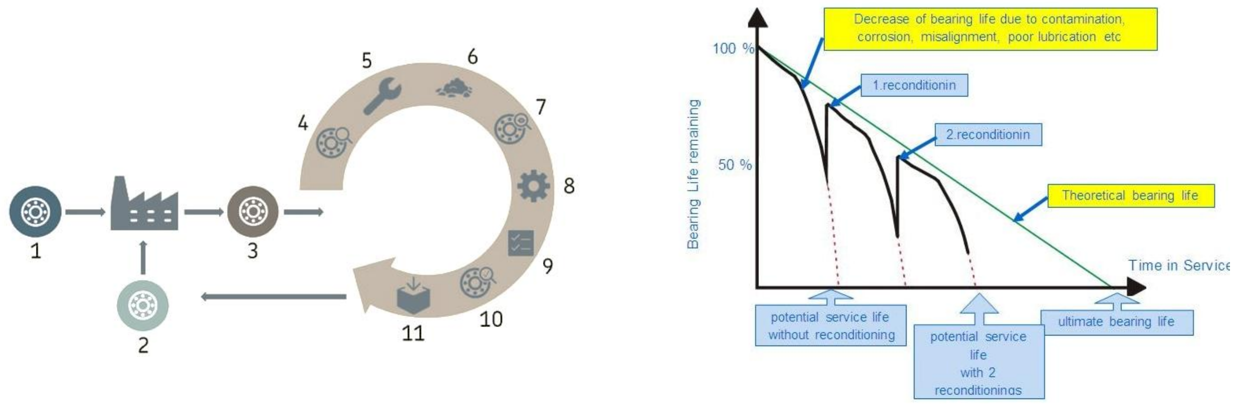
1. Introduction

The circular economy, as defined by the World Economic Forum, refers to an "industrial system that is restored or regenerated by intention and design." Unlike the traditional linear model, where raw materials are used once and then discarded, the circular economy integrates used products into a closed-loop system, enabling them to be reused, recycled, or repurposed [1]. Circular economy policies are being promoted globally to transform the linear economic structure of "take-make-consume-dispose" into a sustainable circular model [2]. For instance, the "sustainable consumption and production" initiative has been included as one of the United Nations' Sustainable Development Goals (SDGs). This initiative aims to establish a sustainable consumption and production system that promotes efficient resource management, waste reduction, and recycling [3]. Similarly, the European Union has introduced a circular economy package consisting of an action plan and legal amendments designed to transition to an economic system that maximizes resource efficiency through reuse and recycling [4]. As a resource-scarce country, the Republic of Korea faces significant challenges due to its high dependence on imported resources and limited land availability for constructing additional landfills. Consequently, transitioning to a circular economy has become an urgent priority. Since 2018, Korea has enacted the "Basic Act on Resource Circulation" to transform its economic and social structure into a sustainable resource circulation model while promoting efficient resource utilization and waste recycling [5].

Global bearing manufacturers such as SKF, Schaeffler, and Timken have actively embraced circular economy principles and carbon emission reduction strategies. These companies recognized the importance of bearing remanufacturing early on and have been continuously implementing remanufacturing processes [6-8]. Medium- and large-sized rolling bearings are predominantly used in industries such as steel mills, power plants, paper mills, construction equipment, railway vehicles, and aircraft. In a linear economy model, single-use medium- and large-sized rolling bearings represent a significant waste of resources, environmental impact, and cost. Thus, remanufacturing these bearings is critical for sustainability. NASA has been utilizing remanufactured bearings in commercial and military aircraft for approximately 40 years. The L10 life of remanufactured bearings—achieved by removing fatigue stress-affected areas where maximum shear stress occurs and replacing worn parts—ranges from 87% to 99% of new bearings [9]. However, conventional bearing remanufacturing processes cannot completely eliminate accumulated fatigue layers. As a result, remanufactured bearings often fail to achieve their theoretical service life and can typically only be reused up to two times. In contrast, Design Mecha Co., Ltd.'s patented ultrasonic nanocrystal surface modification (UNSM) technology introduces compressive residual stress and nanostructures into the surface layer through severe plastic deformation (SPD) combined with elastic deformation. This process significantly enhances mechanical properties such as fatigue resistance and wear characteristics, enabling bearings to be reused more than three times. As society transitions toward a circular economy model, steady demand for remanufacturing medium- and large-sized rolling bearings is anticipated from domestic steel mills and power generation companies. This demand aligns with efforts to promote resource recycling and sustainability.

2. Technical limitations and verification test

A typical rolling bearing remanufacturing process is as shown in Figure 1(a), which proceeds in the following steps: 1 new bearing, 2 remanufactured bearing, 3 removed bearing, 4 pre-inspection, 5 disassembly, 6 cleaning, 7 inspection, 8 machining, 9 reassembly, 10 final inspection and 11 packaging. In general, even if the damaged parts such as wear, corrosion, cracks, and dents on the surface of the rolling bearing raceway are finished by machining, the accumulated fatigue layer cannot be completely removed. Therefore, as shown in Figure 1(b), not only does it not reach the theoretical service life, but it can only be reused up to two times at most [6, 10]. In addition, the recyclability of the ring part of large-sized rolling bearings decreases depending on the severity of the damaged area, which also causes problems in remanufacturing the entire bearing.



(a) (b)

Figure 1. Current status of remanufactured bearings: (a) Bearing remanufacturing process [6]; (b) Service life of remanufactured bearings [10].

In the study by Pyun et al. (2013) [11], UNSM technology was investigated for restoring fatigue-damaged bearing surfaces. The UNSM technology induces SPD on the material surface by utilizing ultrasonic vibration superimposed on a combination of static and dynamic loads [12]. This generates high hardness and compressive residual stress in the surface layer, which is used to improve the wear resistance, corrosion resistance, and fatigue properties of various materials. The properties and performance of each material are improved by changing the values of process parameters such as frequency, number of strikes, amplitude, static load, tip diameter, and tip material [13].

As shown in Table 1, the restoration of the accumulated fatigue layer was confirmed through two types of test methods. As a result, in all test methods, when the fatigue-accumulated surface layer was modified by UNSM treatment, the fatigue life was significantly increased compared to the untreated material. It was determined that the compressive residual stress and nanostructure formed in the surface layer due to UNSM treatment had a great effect on the restoration of the fatigue layer. Based on these results, a patent for "Bearing Remanufacturing Method" using UNSM technology was registered in 2013.

Table 1. Verification test for fatigue restoration [11]

Test method	Specimens		Number of cycles [cycles]		Note
	No.	Name	Fatigue accumulation	Result	
Rotary Bending Fatigue (RBF)	1	Untreated	-	6,400,000	Failure
	2	UNSM after fatigue accumulation	1,600,000 (25%)	22,500,000	Run out
	3	UNSM after fatigue accumulation	3,200,000 (50%)	22,100,000	Run out
	4	UNSM after fatigue accumulation	4,800,000 (75%)	22,700,000	Run out
Rolling Contact Fatigue (RCF)	1	Untreated	-	4,641,000	Failure
	2	UNSM treated	-	10,119,000	Failure
	3	Fatigue accumulation	4,000,000 (86%)	2,340,000	Failure
	4	UNSM after fatigue accumulation	4,000,000 (86%)	8,323,000	Failure

3. Repetitive restoring technology of rolling bearings

The bearing remanufacturing process using UNSM technology proceeds in the following steps: 1 bearing collection, 2 classification, 3 disassembly, 4 washing, 5 inspection, 6 polishing, 7 UNSM treatment, 8 clearance/roughness/hardness/residual stress inspection, 9 reassembly, 10 final inspection and 11 packaging as shown in Table 2 [14]. The difference from the typical bearing remanufacturing process is that the UNSM treatment restores the accumulated fatigue layer, which can extend the product replacement and maintenance cycle due to the improved service life of the bearing. Based on a roller bearing raceway with dimensions of 100 mm inner diameter and 50 mm width, the UNSM treatment requires approximately 70 minutes and achieves a strike density of around 2,730 strikes/mm^2. The UNSM technology forms large and deep compressive residual stresses required for improving fatigue properties compared to other surface modification technologies, while simultaneously reducing surface roughness. Furthermore, the product service life is significantly extended compared to the UNSM process time, contributing to the circular economy.

Table 2. Bearing remanufacturing process including UNSM technology [14]

Process order	Process Contents
1	Collect used / damaged / discarded the bearings
2	Inspect and classify the bearings
3	Disassemble the bearings
4	Clean the bearing parts
5	Inspect the bearing parts
6	Polish the raceway and balls / Polish the raceway and rollers

7	UNSM treat the raceway and balls / UNSM treat the raceway and rollers
8	Inspection: tolerance / clearance / roughness / hardness / residual stress etc.
9	Reassemble the bearings
10	Check the reassembly status and performance of the bearings
11	Pack the bearings

As an example, a spherical roller bearing (FAG 24020, ID 100mm × OD 150mm × W 50mm) used by a domestic steel company was remanufactured and delivered. A total of four products (New, UNSM treated, Used, Remanufactured) were prepared and surface property and durability tests were performed [15]. The detailed results are shown in Table 3. The durability test results showed that the remanufactured bearings had a 95.7% longer life than accumulated fatigue bearings and a 7.1% longer life than new bearings. Remanufactured bearings with a lifespan equivalent to or greater than that of new bearings satisfy resource conservation, high efficiency, and cost reduction. It has been confirmed that they will be of value in various related industrial fields in the future.

Table 3. Surface property and durability test results of spherical roller bearings [15]

Sample		Roughness (Ra) [μm]	Hardness [HRC]	Residual stress [MPa]	Life [cycles]
New	Inner ring raceway	0.090	61.3	-516.3	645,400 (failure)
	Outer ring raceway	0.185	-	-	
UNSM treated (Based on 'New')	Inner ring raceway	0.073	62.3	-1,095.7	1,000,000 (run out)
	Outer ring raceway	0.070	-	-	
Used	Inner ring raceway	0.154	60.5	-401.5	353,200 (failure)
	Outer ring raceway	0.096	-	-	
UNSM treated (Based on 'Used')	Inner ring raceway	0.084	63.6	-1,356.1	691,500 (failure)
	Outer ring raceway	0.127	-	-	

The life restoration technology utilizing UNSM can have a great effect on the transition to a circular economy and carbon-neutral society. This technology can be used not only in bearings but also in fields using industrial knives, valves, and molds. By adding the prognostic inspection and proactive maintenance (PIPM) system, a new concept of repetitive restoring technology can be developed. The PIPM system has already been announced in the Kim et al. (2024) [16] and is a system that integrates UNSM technology and non-destructive inspection technology with the remanufacturing process. As shown in Figure 2, the service life of the product is compared with the L10 remaining life, and then the hardness, residual stress, and surface integrity are inspected. After that, it is compared with the reference value of each characteristic and determined whether to restore it using UNSM technology or continue to use it. Of course, crack initiation and crack growth are not easy to determine because they require a lot of data and failure criteria for each material. However, it is clear that this repetitive restoring technology is helpful and meaningful for the circular economy [17]. Compared to typical remanufacturing processes, the PIPM remanufacturing process can reduce purchasing costs by about 40% and lead times by about 50%.

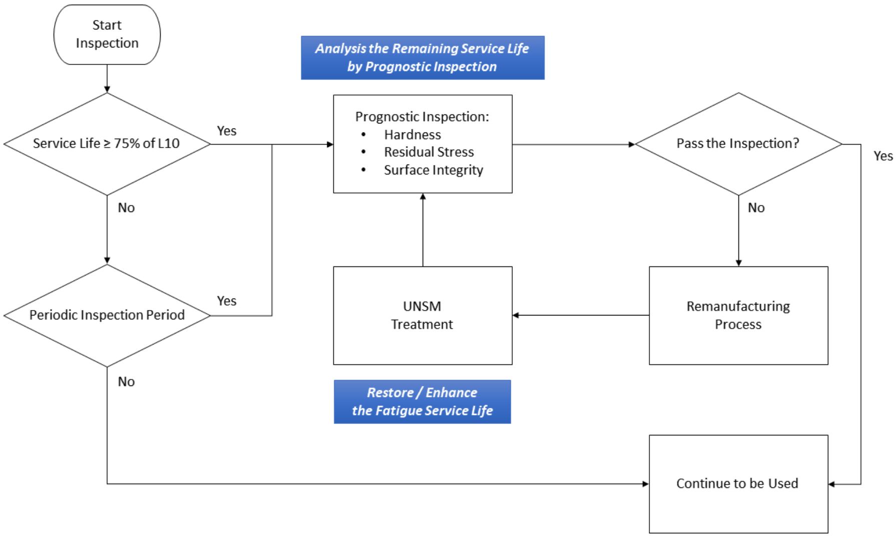


Figure 2. Flow of the PIPM remanufacturing process [16].

4. Concluding Remarks

The bearing remanufacturing technology currently utilized by global manufacturers is limited to a maximum of two reuse cycles. Furthermore, remanufactured bearings fail to achieve the service life of new bearings, typically retaining only up to 95% of their original fatigue life. These limitations highlight the need for improved economic feasibility and technological advancements in the remanufacturing process. By adopting the PIPM system integrated with UNSM technology, significant improvements can be achieved. Bearings treated with this remanufacturing process can be reused more than three times, enabled by the formation of large and deep compressive residual stresses. The environmental impact of this advanced remanufacturing approach is substantial. If 10% of all bearings worldwide are remanufactured more than three times using this technology, it is estimated that raw steel manufacturing could be reduced by 10 million tons, while CO_2 emissions could decrease by 20 million tons. These reductions represent significant contributions to global sustainability efforts. Moreover, this repetitive restoration technology aligns closely with international sustainability objectives. It supports the United Nations SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). Additionally, it complements the European Union's Circular Economy Action Plan, which aims to increase material circularity and achieve carbon neutrality under the European Green Deal by 2030. In conclusion, the repetitive restoration technology utilizing UNSM provides a practical and scalable solution that simultaneously addresses critical environmental challenges and advances circular economy principles. Its ability to extend bearing reuse cycles and reduce resource consumption makes it a pivotal innovation for sustainable manufacturing systems worldwide.

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