Application of Ultrasonic Nanocrystalline Surface Modification Technology for Prolonging the Service Life of Double Row Angular Contact Bearings and for Reducing Friction Loss

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Abstract
Double row angular contact ball bearings (DRACBB) - are capable of carrying high radial and thrust loads in both directions and need small space comparing to two single row angular contact bearings. A newly developed magnetic clutch of compressor needs higher dynamic load rating without increasing space for bearings. Therefore, Ultrasonic Nanocrystalline Surface Modification (UNSM) technology is applied to bearing raceways in order to improve rolling contact strength and to reduce friction loss. The rolling contact fatigue and friction test specimens which are treated by UNSM technology are performed in order to find proper surface hardness, topology and compressive residual stress. Comparison test of service life and friction coefficient between UNSM-treated and untreated bearings were carried out in the bearing test rig. After UNSM treatment, the friction coefficient was reduced and the service life was extended at room temperature due to the UNSM treatment. Life tests data showed that the life of the UNSM-treated bearings was much longer than that of the untreated bearings. The basic mechanism and effects of UNSM technology were also explained.

Keywords Double row angular contact ball bearing (DRACBB), friction, fatigue, ultrasonic nanocrystalline surface modification (UNSM).

Introduction

Recently, technological practice, particularly in the spring-manufacturing, automotive and aerospace industries, is hardly imaginable without mechanical surface treatment processes. Mechanical failures, especially tribological failures of components, such as friction and wear related failures, are today one of the main reasons for unavailability. That`s the reason why these phenomena are interesting for tribologists.

When double row angular contact ball bearings operate under loading, the raceways of their inner and outer rings and rolling elements are subjected to repeated cyclic stress. Due to the metal fatigue of the rolling contact surfaces between the raceways and rolling elements, scaly particles may separate from the bearing material as shown in Figure 1.

Figure 1. Flaking on the Bearing Raceway Surface

UNSM technology was applied to DRACBB in order to extend the service life and to reduce friction coefficient. The UNSM technology is a patented technology, which was developed and commercialized by DesignMecha Co., Ltd. [1]. It is a method of metal improvement that utilizes ultrasonic energy.

The principles of UNSM are based on the instrumental conversion of harmonic oscillations of an acoustically tuned body into resonant impulses of ultrasonic frequency. The acoustically tuned body is brought to resonance by energizing an ultrasonic transducer. The energy generated from these high frequency impulses with the total force ($F=P_{st}+P_{dy}$) on a workpiece surface 20,000 to 40,000 times per second and 1,000 to 4,000 shots per square millimeter [2].

This technology has aroused considerable interest due to its economical effectiveness, possible fine adjustment of effects upon the workpiece. In addition, it is a safe, simple and effective method for application in production of machine components and machinery of various purposes [3].

The UNSM technology controls the quality, properties and characteristics of the surface, modifies material properties in the treatment area, improves the fatigue and corrosion resistance, as well as the resistance to abrasion and contact failures, induces compressive residual stress, refines grain size into nanocrystalline, stabilizes and improves static quality and reliability characteristics in mechanical engineering [4].

The objective of this paper is to prolong the service life and to reduce friction coefficient of DRACBB through UNSM technology.

The associated results showed that the lower friction coefficient can yield because of the UNSM treatment effect resulted from a greater separation between the mating surfaces and the service life can be improved by induced residual stress and increased hardness. The commendable works, along with previously mentioned researches, help greatly to improve the tribological and mechanical properties of bearings.

Experimental Methods

Table 1 shows the mechanical parameters of the UNSM technology for SAE 52100 bearing steel treatment. Both friction and fatigue tests specimens were treated under the same UNSM conditions as shown in Table 1.

Table 1. Details of UNSM Treatment Conditions.

Amplitude [μm]	Load [N]	Lathe Spindle Speed [rpm]	Feedrate [mm/rev]	Tip Diameter [mm] and Material
30	60	30	0.07	2.38 & WC

The material used in this study was SAE 52100 bearing steel and its chemical composition is given in Table 2. Specimens were made for rolling contact and the geometries of the roller specimens were illustrated in Figure 2. All specimens were manufactured through super fine finishing because surface finishing condition affects the test results. Overall fatigue test specimens were annealing treated for 2.5 hours at 850^0C and then quenched in oil bath. Table 3 shows the test condition for rolling contact fatigue test.

Table 2. Chemical Composition of SAE52100 Bearing Steel (in wt.%).

Material type	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
SAE52100	0.98	0.23	0.28	0.025	0.008	0.025	1.44	0.06	0.35

Table 3. Test Conditions for Rolling Contact Fatigue Test.

Load [N]	Roller size [mm]	Rotation speed [rpm]	Lubrication oil
1500 ~ 3700	300 mm	8000	Drop oil per 3 sec

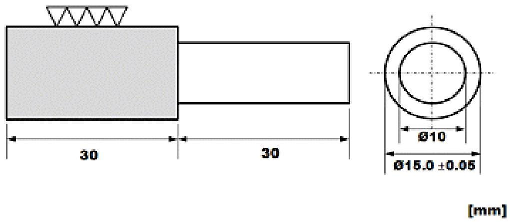


Figure 2. Dimension of Specimen for Rolling Contact Fatigue Test.

The friction test disk specimen was prepared as disk 60 mm in diameter and 5 mm in thickness, with a ball of 11 mm in diameter. The experimental tests were performed on the tribometer using ball-on-disk contact geometry. Table 4 lists the experimental conditions of the ball-on-disk test. Prior to the each test, the disks were aged with a normal force of 10 N in order to provide contact between ball and disk surfaces.

Table 4. Test Conditions for Friction Test.

Test Parameters	Values
Normal force, [N]	20, 40, 60, 80 and 100
Rotational speed, [rpm]	100
Sliding distance, [m]	100
Testing (scar) track radius, [mm]	45
Oil lubrication	Tonna Oil 32, 0.13 Ns/m^2 @ 40^{0}C

The comparison of micro-hardness before and after UNSM of SAE 52100 is shown in Figure 3. It can be seen that the hardness of UNSM-treated surface increases from 726 HV up to 870 HV.

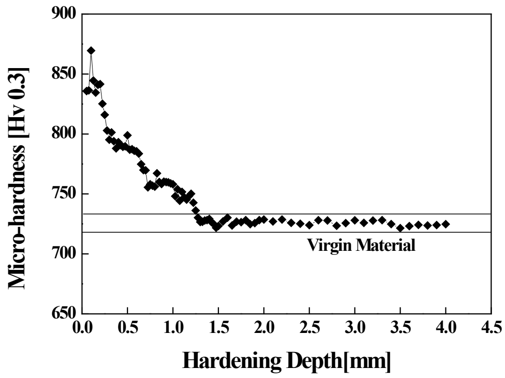


Figure 3. Near-surface Hardness vs. Depth Profile of SAE52100 after UNSM.

The comparison of EBSD cross-sectional micrographs shows that UNSM technology produced nanocrystalline structure of about 100 μm thick in the surface layer as shown in Figure 4. The grain size is about 30 nm in the top surface layer, and it increases with an increase of depth from the UNSM-treated surface. And it was measured by analyzing EBSD observations of the studied material utilizing TSL OIM Analysis 5 program (Software for EBSD data acquisition and processing).

Change of grain layer on metal surface into plastic deformation layer improves strength and hardness of metal surface layer significantly. Owing to the plastic deformation in the surface layer induced by UNSM, the coarse-grained structure in the surface layer is refined into the nanometer scale without changing the chemical compositions.

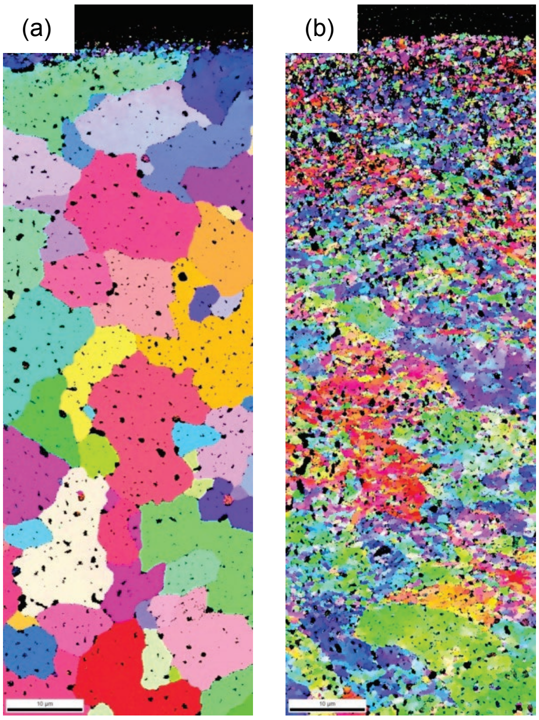
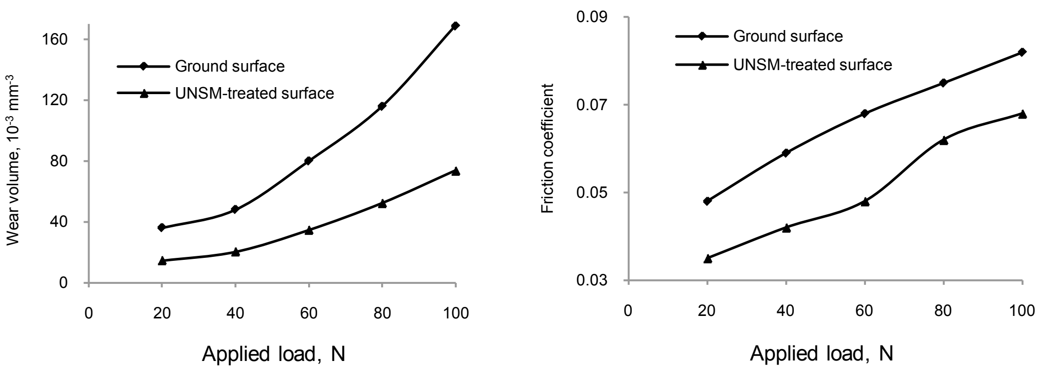


Figure 4. EBSD Cross-sectional Morphologies Before (a) and After (b) UNSM.

Experimental Results

Figure 5 plots the wear volume loss and friction coefficient as a function of load under a sliding distance of 100 meter and rotating speed of 100 rpm of UNSM-treated and ground specimens. Wear volume loss and friction coefficient of the ground and UNSM-treated disk specimens were measured by using a tribometer. As shown in Figure 5, the wear volume loss of UNSM-treated specimen is lower than that of the ground surface. The coefficient values of UNSM-treated specimen are also evidently smaller than that of the ground surface. These observations indicate that the friction and wear properties of the bearing steel disk and ball combination can be improved by means of the formation of the nanostructured surface layer and the induced compressive residual stress. In addition, the improved friction and wear properties can be attributed to the strong surface layer with nano-size grains and a gradient variation in the microstructure and properties along the depth in the top surface.



(a) (b)

Figure 5. Variations of the Wear Volume (a) and the Friction Coefficient (b) with Load for the UNSM-treated and Ground Surfaces.

Figure 6 compares the residual stress before and after UNSM treatment. It can be seen that a tensile residual stress below 20~40 μm from the surface presents in the grinding material, which is caused by machining effect for specimen preparation. On the contrary, a compressive residual stress of -700 MPa presents on the surface of the UNSM treated specimen. In addition, a value of -400~-500 MPa is produced at the depth of 240 μm. Therefore, it was identified that there is a difference of -500~-700 MPa of compressive residual stress before and after UNSM treatment. Compressive residual stress is a very important factor for fatigue life improvement.

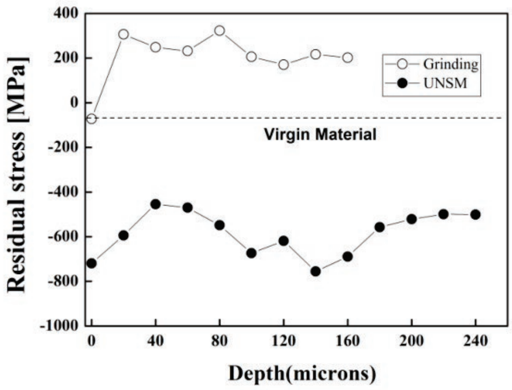


Figure 6. Residual Stress as a Function of Depth into the Surface.

Figure 7 shows the results of force (F) vs. number of cycles (N) for SAE 52100 specimens obtained from the fatigue tests under the test conditions as shown in Table 3. It can be seen from Figure 7 that the service life of the UNSM-treated specimens was prolonged by 10 times comparing to the untreated specimens. The main reason for this improvement is due to the compressive residual stress produced by UNSM technology (see Figure 6).

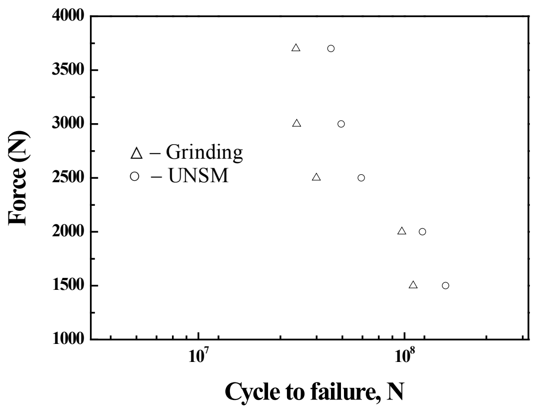


Figure 7. Force vs. Number of Cycles Results Before and After UNSM

Conclusions

In this paper, two experiment results were presented and the following conclusions could be drawn:

- A nanocrystalline structure was successfully produced on bearing steel by means of the UNSM treatment.
- The grain size is about 30 nm in the top surface layer, and it increases with an increase of depth from the UNSM-treated surface.
- Hardness of the specimens is increased by 20% after UNSM, which can help to increase the friction coefficient and service life of DRACBB.

- The comprehensive friction and wear properties of the UNSM-treated surface are remarkably improved by about 40% comparing to the untreated surface.
- UNSM technology managed to induce compressive residual stress by about -700 MPa which is the main factor to improve the service life of DRACBB.
- Fatigue life of the UNSM-treated specimens was prolonged by about 10 times comparing to untreated specimens.

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