THE ULTRASONIC NANO-CRYSTAL SURFACE MODIFICATION TECHNOLOGY AND IT'S APPLICATION TO IMPROVE FATIGUE STRENGTH, WEAR RESISTANCE, AND SERVICE LIFE & ENERGY EFFICIENCY OF BEARINGS

Y.S. Pyoun [1, 2], C.M. Suh [3], I.H Cho [2], C.S. Kim [2], I.S. Cho [1], C.S. Lee [1], I.G. Park [1], J.S Jung [4]

[1] Sun Moon University, Tangjeong-Myeon, Asan, Chungnam, 336-708, Korea
[2] DesignMecha Co., Ltd. , Tangjeong-Myeon, Asan, Chungnam, 336-708, Korea
[3] Kyungpook National University, Sankyuk-Dong, Bukgu, Daegu, 702-701, Korea
[4] Korea Power Electric Research Institute, Munji, Yuseong, Daejeon, 305-380, Korea

ABSTRACT
The ultrasonic nano-crystal surface modification (UNSM) technology utilizes the ultrasonic vibration energy to maximize coverage and stress-field density; during the process, a tool-steel, tungsten carbide, or ceramic ball attached to an ultrasonic device strikes the surface of a workpiece 20,000 to 40,000 times per second and 1,000 to 10,000 shots per square millimeter. These strikes produce severe plastic deformation and induce a nano-crystalline microstructure in the near surface layer. The nano-structuring of the surface layer can simultaneously improve hardness and toughness of the workpiece according to the well-known Hall-Petch relationship. UNSM treatment induces deep compressive residual stresses comparable to DR, LSP and LPB, increases surface hardness, decreases surface roughness, and produces also a uniform "dimpled" surface. The effect of UNSM treatment on the fatigue and tribology characteristics was discussed in terms of rotary bending fatigue, rolling contact fatigue, and friction torque and friction coefficient in typical bearing steels. The field test results of trimming knives were also introduced.

KEY WORDS
Ultrasonic nano-crystal surface modification (UNSM), High cycle fatigue(HCF), Wear, Friction, Rolling contact fatigue(RCF)

INTRODUCTION
Reduction of fuel consumption and CO_2 emission are main goals of recent vehicle development. Weight and friction reduction of power train components are very effective method for this goal. Especially reduction of friction loss of gearing system and bearing systems at transmission and engine improves fuel consumption rate and CO_2 emission rate significantly and simultaneously(Grebe, 2006). Surface modification of gear surface and bearing race are an emerging technology for reducing friction coefficient.(Matsuyama,Toda, Kuoda, et al 2006) Compressive residual stress is a very efficient solution for improving fatigue strength and wear resistance, and thus can reduce weight of components.(Hoyashita, Hashimoto,Seto,1998, and Eckersley, Meister, 1997) But there is no attempt to adopt these two technologies, surface modification and compressive residual stress, to machine systems yet. UNSM is an emerging and very promising technology that can be used to solve fatigue and friction-related problems simultaneously.

UNSM TECHNOLOGY

UNSM technology is a patented technology which was developed and commercialized by DesignMecha. The main concept and mechanism of UNSM which is shown in Fig. 1 is as follows.(Han, Pyoun, Kim, 2002, Pyoun, 2003) A tungsten carbide ball attached to an ultrasonic device strikes the surface of a workpiece 20,000 or more times per second with 1,000 to 10,000 shots per square millimeter. These strikes, which can be described as micro cold forging, bring severe plastic deformation to surface layers and thus induce nano-crystalline structure. The nano-structural modification of the surface layer can improve both the strength (hardness) and ductility (toughness) of the workpiece simultaneously according to the well-known Hall-Petch theory.(Hall, 1951, Petch,1953) This process also improves surface integrity, and surface hardness, and induces compressive residual stress in surface layers. The UNSM effects and its anticipated benefits are summarized in Table 1.(Cho, Kim, Jin, et al, 2007)

Table 1. UNSM effects and its anticipated benefits

Effects of UNSM	Anticipated benefits
Nanocrystalline structure (Grain Sizes of 50-200 nm)	1) Increased tensile strength, 2) Increased fatigue strength, 3) Increased hardness, 4) Increased wear resistance
Deep compressive residual stresses (Greater than 1000MPa into depths of at least 1000 μm)	Improved LCF and HCF endurance limit
Dimple surface (Area: 1-2 μm^2, Depth : sub micron, Pattern pitch: few μm)	1) Reduced surface roughness 2) Decreased friction coefficient

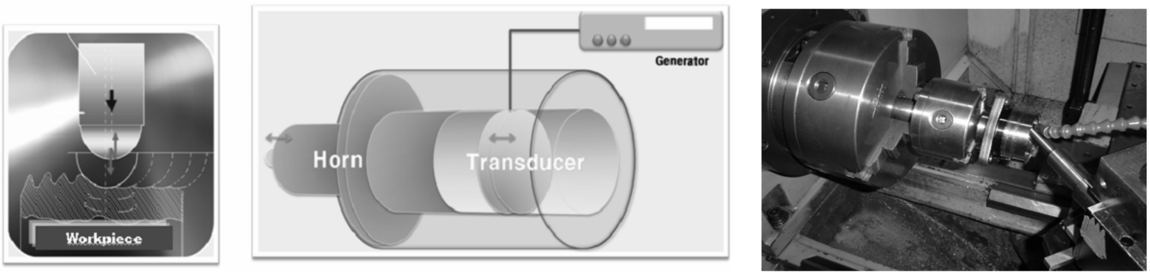


Fig. 1 UNSM Mechanism and UNSM Device with CNC Turning Machine

EXPERIMENTS

1. Fatigue characteristics of UNSM treatment

1.1 Rotary bending fatigue test

Specimens made of a SKD 61 tool steel, which is the material of the trimming knife used in the cold rolling mill, were treated using the UNSM. Fig. 2 presents the tendency of change in nano-crystal structure. The microscopic grain size is uniformly distributed on the surface before the UNSM (a), while the grain size becomes nano-scale from the surface to 100μm depth (b) after the UNSM. According to Hall-Petch equation (Hall, 1951, Petch,1953), when grain size becomes smaller, yield strength and hardness becomes greater. The hardness of the surface after UNSM was increased by 37% compared with that of before UNSM. Fig.3 shows the tendency of the change in residual stress along the depth direction for both before and after UNSM, which was measured every 20μm depth using an X-ray residual stress measurement equipment(RIKAGU).

Electro-polishing was used to cut out the constant depth. As shown in Fig.3, compressive residual stress was -443MPa at the top surface before UNSM. But the value became -811MPa after UNSM and remained until 150μm depth. It was also observed that the effective depth of UNSM was about 350μm.

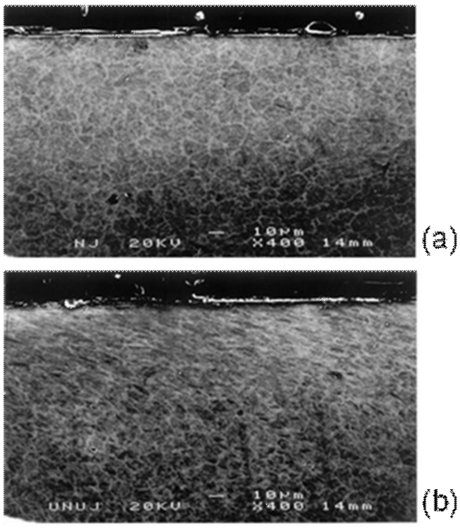


Fig. 2 Microstructure of SKD61 (a) before and (b) after UNSM

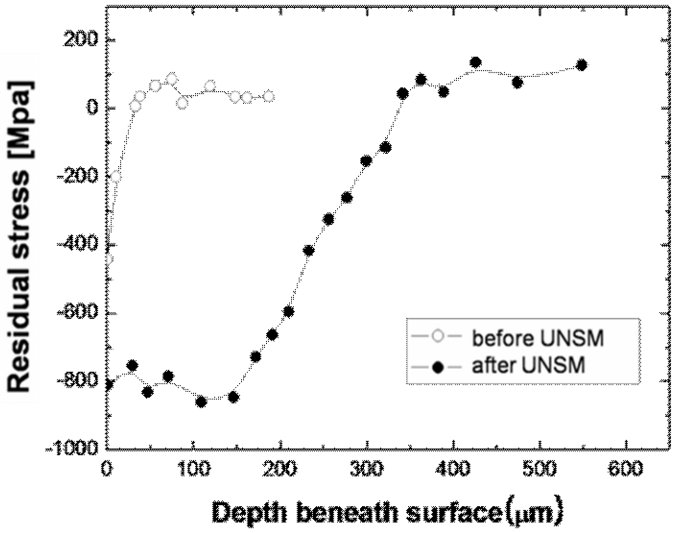


Fig. 3 Variation of compressive residual stress levels according to UNSM treatment

Fatigue tests were conducted using Ono type rotary bending machine (H5 type, 98Nm, Shimadzu Co.) at 3,400rpm of revolution at room temperature, and the specimens were prepared under the JIS Z 2274 standard. The fatigue characteristics of smooth specimen before and after UNSM are shown in Fig.4. The fatigue limit corresponding to 10^7 cycles before UNSM was 719MPa, whereas that of after UNSM was 899MPa, which represents a 25% increase.(Suh, Song, Pyoun, 2007)

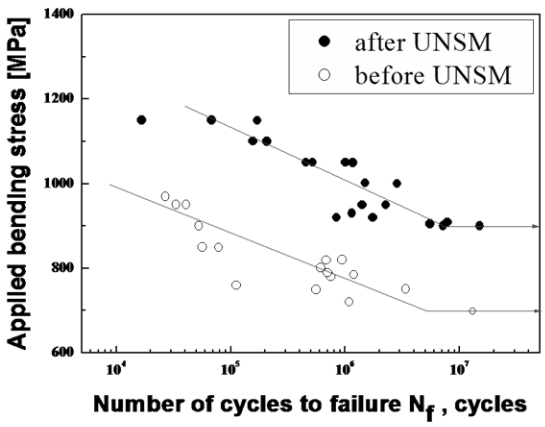


Fig. 4 S-N curves of the smooth specimen

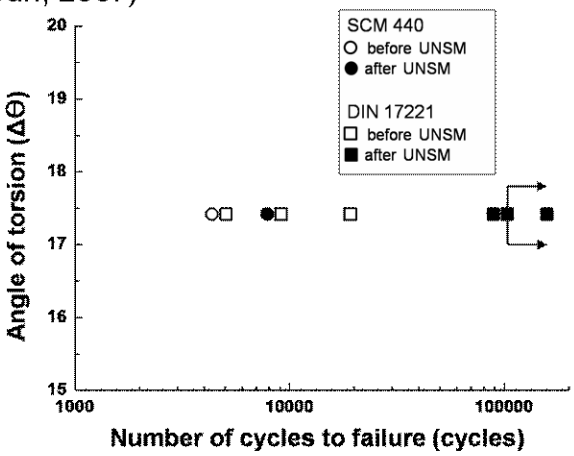


Fig. 5 Θ-N in case of SCM440 and DIN 17221 specimens at ΔΘ=1.4~18.8°

1. 2 Torsional fatigue test

Cr-Mo(SCM440) steel and spring steel(DIN17221) specimens were prepared for torsional fatigue test. The hardness of the surface after UNSM was increased as shown in Fig. 6 by more than 10~30%. Torsional fatigue test was carried out by axial-torsional material test system(646 JUS, MTS System). The tendency of the increased fatigue cycles by UNSM is shown in Fig. 5. In DIN17221, the fatigue failure cycle was increased about 10 times, whereas in SCM440, it was increased about twice only.

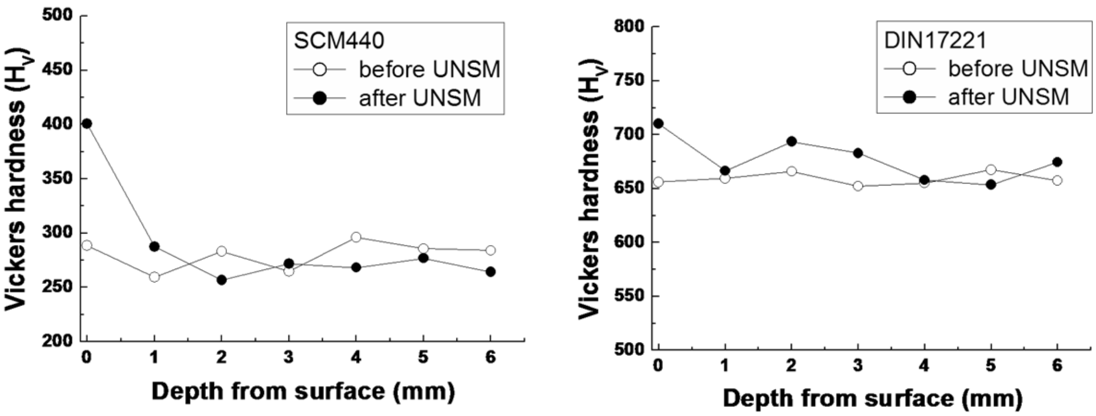


Fig. 6 Variation of micro Vickers hardness by UNSM : SCM440 (Left) and DIN17221 (Right)

2. Tribological characteristics of UNSM treatment

2.1 Rolling contact fatigue strength in 6 ball RCF test

The effects of the UNSM technology are observed by comparing measurements before and after application of UNSM treatment on bearing steels SAE52100(JIS SUJ2R). The variation of micro hardness, compressive residual stress, and surface topography after UNSM are shown in Figs.8-10, respectively. The roughness was improved from before UNSM Ra=0.19 to Ra=0.10 after UNSM, and the micro hair cracks formed before UNSM were removed and micro dimpled surface were created as shown in Fig. 8. The schematic diagram of rolling contact fatigue tester is shown in Fig. 7

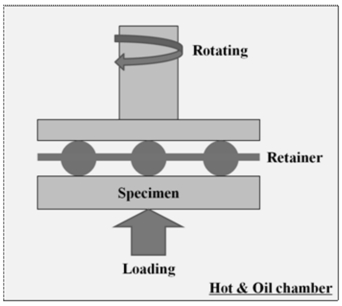


Fig. 7 Scheme of 6 ball type RCF tester

Table 2 Results of 6 ball type RCF testing

	Before UNSM	After UNSM
Cycles to failure	6,380,000	26,000,000

Test conditions are as following. Load : 550Kgf, Ball size and number : 3/8 inch & 6pcs, Rotation Speed : 1,000rpm, Lubrication : Automatic Transmission Oil. RCF crack initiates from surface or subsurface depending on the contact condition, and Lubrication determines where crack initiates from.(Choi, Liu,2002) RCF test was carried out in the oil bath. And the result of 6 ball type RCF test is shown in Table 2

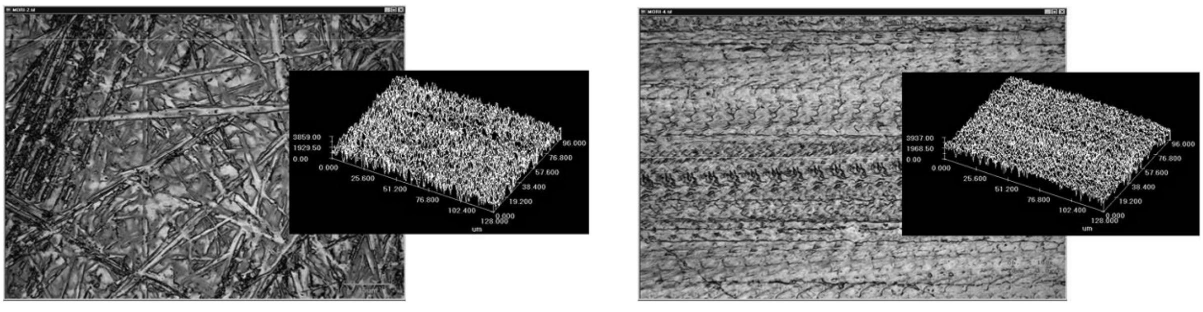


Fig. 8 Variation of surface topography by UNSM before UNSM(left), after UNSM(right)

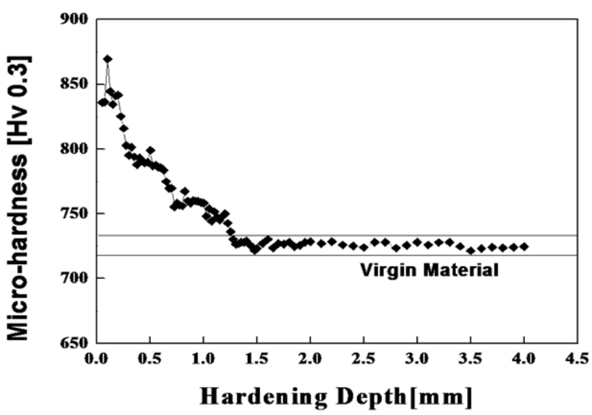


Fig. 9 Variation of Micro hardness by UNSM

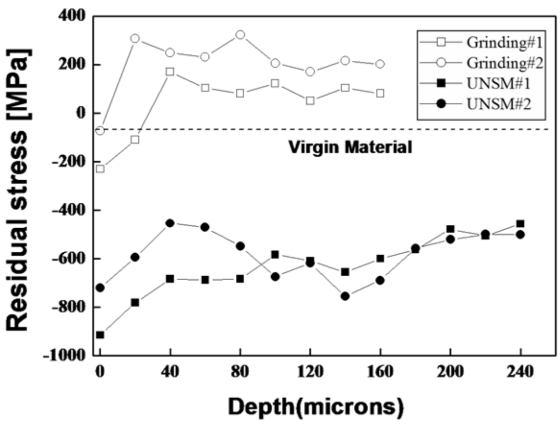
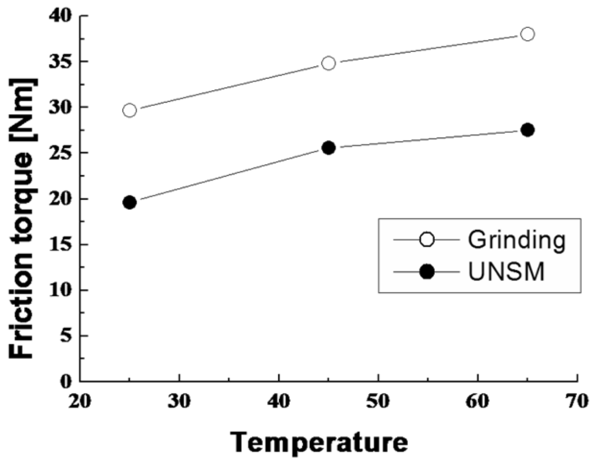


Fig. 10 Variation of compressive residual stress by UNSM

2-2. Friction Characteristics

Stribeck curve which shows the variation of friction coefficient versus the Sommerfeld number are under studying. Due to the limit of volume, two graphs in Fig. 11 are only presented in this paper for showing the UNSM effects on reduction of friction torque and friction coefficients at the taper journal bearing made of bearing steel(SUJ2).



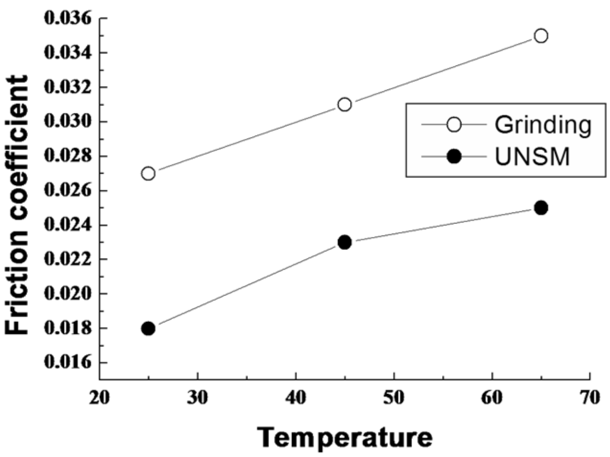


Fig. 11 Friction torque and friction coefficient before and after UNSM

3. Field test of trimming knives

Two field tests were conducted to verify the effect of UNSM on the trimming knives in cold rolling lines of POSCO. The one was for the trimmed strip material "TRIP(Transformation-induced plasticity)80" which was one of high strength steels (HSS) whose tensile strength was 780MPa. The other was for the general steel strips that had many different strength and thickness. As shown in Table 3, the UNSM trimming knives prolonged their service lives by about two times, so the UNSM trimming knives became standard operating tool of those lines and are giving better effects than that of test. The increased hardness, nano-crystal surface structure and the reduced friction coefficient are major effects to prolong wear of trimming knife edge. The compressive residual stress and nano-crystal surface structure are major effects to increase fatigue strength and shock resistance.(Suh, Song, Pyoun, 2007, Pyoun, Kim, Son, et al, 2005)

Table 3. Summary of field test results

Kind of knife	Steel grade	Result	Remarks
UNSM	80 TRIP	16 Coils	2 times improvement
Conventional		8 Coils	
UNSM	General	2004' : 80km, 2007' : 110km	1.6~2.4 times improvement
Conventional		50km	

CONCLUSION AND IMPLICATIONS

UNSM Treatment improves hardness, roughness, and compressive residual stress and makes micro dimples surface and nano crystal structure simultaneously. So UNSM technology is very effective solution for reducing the weight and friction loss and for increasing durability and reliability of rolling bearings and hydrodynamic journal bearings and is very effective solution for the improvement of fatigue strength (Tension/Compression, Bending, and Torsion): Torsion bar, input or out shaft of gear box or motor, crankshaft, etc. It is also very effective solution for the improvement of wear resistance; trimming/shearing knife, forming roll, mechanical seal, etc.

The results show that UNSM technology can be utilized also for weight and friction reduction of power train components and thus become a very efficient technology for reduction of fuel consumption and CO_2 emission of vehicle.

ACKNOWLEDGMENTS

Authors wish to express great thanks to KEPRI for their partial support for this work.

REFERENCES

Cho I.H., Kim C.S., Jin S.G., Moon J.G., Pyoun Y.S., Jeong D.H., Lee K.B.," Nano surface modification of hub bearing race ways for increasing the dynamic load rating and decreasing the friction loss" Proceeding of APAC 2007, 07-APAC-280, SAE.

Choi Y.S., Liu C.R., "Rolling contact fatigue life of finish hard machined surfaces Part 1. Model development", Wear, Vol.261, pp485~491, 2002

Eckersley J.S., Meister T.J., "Three innovations advance the science of shot peening", Proceedings of ICS 1997

Grebe, Dr. Uwe Dieter, "Future Powertrain Technologies to meet global requirements", Proceedings of FISITA 2006, Japan.

Hall E.O., Proceedings of Physical Society of London, B64, 747, 1951

Han C.H., Pyoun Y.S., Kim C.S., "Ultrasonic micro-burnishing in view of eco-materials processing," ATM, Vol.4[1], pp.25-28, 2002.

Hoyashita S., Hashimoto M., Seto K., "Basic studies on fatigue strength of case hardened steel gear-Effects of shot peening and/or barreling processes", Proceedings of ICS 1998

Matsuyama Hiroki, Toda Kazutoshi, Kouda Kanichi, Kawaguchi Kouji, Uemura Atsuji, "Development of super-low friction torque tapered roller bearing for high efficiency axle differential", Proceedings of FISITA 2006, Japan

Petch N.J., Journal of Iron and Steel Institute, 174, 1953, 25.

Pyoun, Y.S., An application of micro cold forging technololgy using ultrasonic energy for the nano level surface texture and the improved mechanical properties, Korea-Japan international nano-symposium, Nov. 2003.

Pyoun Y.S., Kim H.S., Son K.G., Song G.H., Kim M.K., Kang J.H., Choi B.U., Park J., Cho I.H., Kim C.S., Park J.H., Kinney J., "Development of D2 Tool Steel Trimming Knives with Nanoscale Microstructure" Proceeding of AIST 2005, 2005

Suh C.M., Song G.H., Pyoun Y.S., "Fatigue and mechanical characteristics of nano-structured tool steel by ultrasonic cold forging technology", J. Mat. Sci. Eng. A, Vol. 443, 2007