

Enhanced Mechanical Characteristics of Metal Alloys by the Ultrasonic Nanocrystal Surface Modification

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Abstract

Ultrasonic nanocrystal surface modification (UNSM) technology is a surface enhancement technology analogous to shot peening, laser shot peening (LSP), ultrasonic peening (UP), deep rolling (DR) and low plasticity burnishing (LPB). The UNSM utilizes ultrasonic vibration energy to maximize coverage and stress-field density. In this process, a tool-steel, tungsten carbide or ceramic ball is attached to an ultrasonic device and strikes the surface of a workpiece 20,000 to 40,000 times per second and 1,000 to 100,000 shots per square millimeter. The UNSM treatment induces deep compressive residual stress comparable to LSP and DR, but improves surface roughness not like other technologies and also produces a uniformly distributed micro dimples on the surface. Steel alloys, Cu alloys, Ti alloys and Al alloys are treated by UNSM and their mechanical properties are analyzed and compared before and after UNSM treatment.

Keywords: UNSM (Ultrasonic Nanocrystal Surface Modification) technology, Surface technology, Fatigue, Wear, Friction

1. Introduction

UNSM technology is patented and developed in South Korea [1]. The main concept and mechanism of UNSM shown in Figure 1 are as following [2,3,4]. 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 nanocrystalline structure. This 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 [5,6]. This process also improves surface integrity and surface hardness, makes micro dimples, and induces compressive residual stress in surface layers. The UNSM effects and their anticipated benefits as well as comparison of surface texturing technologies are summarized in Table 1 and 2, respectively [7,8,9]. In this paper, the changes in mechanical characteristics generated by UNSM treatment and their effects on fatigue, wear, friction and rolling contact fatigue strength are summarized. Possible applications of this UNSM technology for the innovative design and manufacturing of machine systems are suggested.

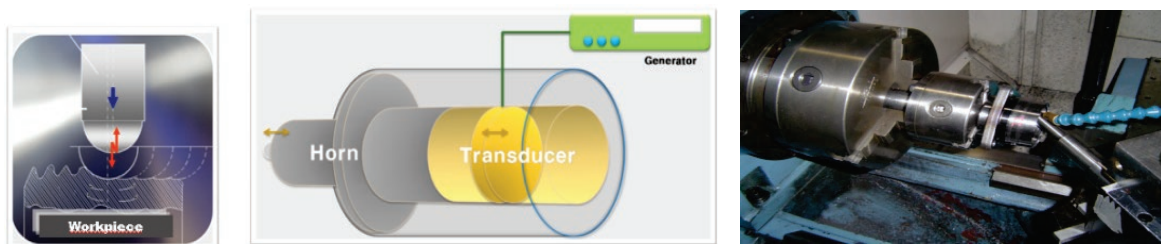


Fig.1. UNSM Mechanism and UNSM Device along with CNC Turning Machine.

Table 1. The Effects of UNSM Treatment and Their Anticipated Benefits.

Effects of UNSM treatment	Anticipated benefits
Deep compressive residual stresses (Greater than 1000MPa into depths of more than 2000 μm)	1) Improved LCF and HCF endurance limit 2) Improved rolling contact fatigue strength 3) Improved stress corrosion cracking resistance
Micro dimples surface (Area: 1-2 μm^2 , Depth: sub micron, Pattern pitch: few μm)	1) Reduced surface roughness 2) Decreased friction coefficient 3) Reduced wear rate
Increased hardness (into depths of more than 1500 μm)	1) Reduced wear rate 2) Improved LCF and HCF endurance limit
Nanocrystalline structure (Grain Sizes of 50-200nm into depths of 100 μm)	1) Increased tensile strength and hardness 2) Increased fatigue strength 3) Increased wear resistance

Table 2. The Effects of UNSM Treatment and Their Anticipated Benefits

Tech.	MSP	LSP	LPB, DR	USP	UNSM
Energy or load	Fluid power	Laser heat	Static load	Ultrasonic dynamic load	Static load + Ultrasonic dynamic load
Compressive Residual Stress/Depth	3	5	4	2	4
Hardness & Depth	2	4	3	2	5
Nano Structure	2	1	3	4	5
Surface Topology	4	5	1	3	4
Surface Roughness	2	1	4	3	5

(5: excellent - 1: poor)

2. Improvement of Mechanical Properties

2-1. Compressive Residual Stress by UNSM Treatment

Many kinds of steel alloys and non-ferrous metals have been treated by UNSM technology. Compressive residual stress of a typical tool steel SKD 61 (equivalent H13) treated by UNSM is shown in Figure 2A, a typical bearing steel SUJ2 (equivalent H13) is shown in Figure 2B, a Ti-6Al-4V for medical and aircraft design is shown in Figure 2C and a SUS 304 for power plant parts is shown Figure 2D. Comparison between deep rolling and UNSM is shown also in Figure 2D [4, 10, 11, 12, 13].

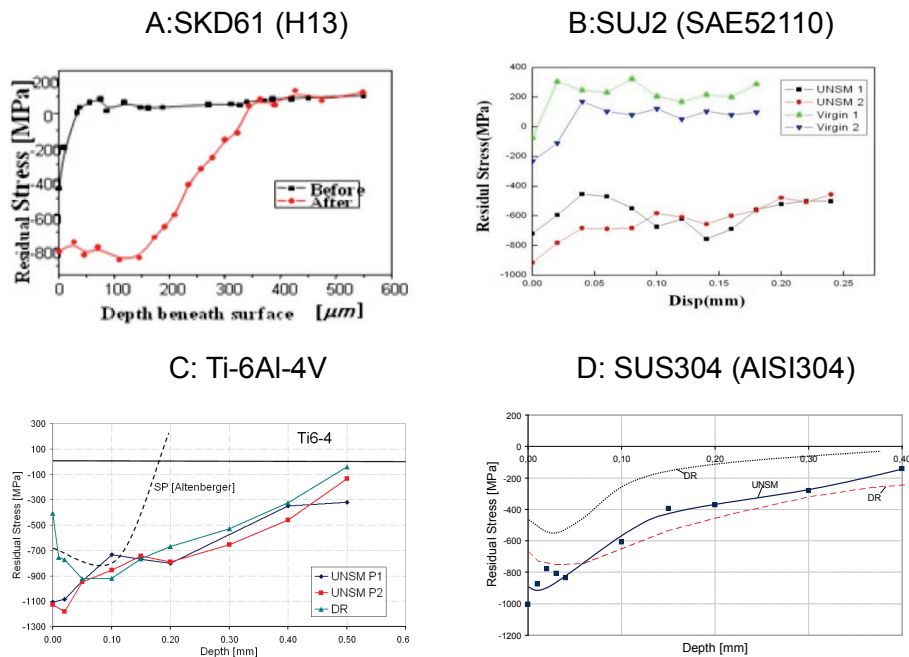


Fig.2. Compressive Residual Stress Treated by UNSM Technology.

2-2. Improvement of Surface Integrity and Micro Dimples on the Surface Treated by UNSM

2D and 3D topography of ground specimen and UNSM treated specimen after grinding made of bearing steel (SUJ2) are shown in Figure 3. The roughness is improved from $R_a=0.19$ to $R_a=0.11$. Not only surface roughness is improved but also relieving micro hair cracks and micro dimples are induced by UNSM treatment. In case of Ti-6Al-4V, the roughness is improved from $R_a=0.7$ to $R_a=0.2$. The micro dimpled structure after UNSM treatment shows that entrapped oil volume is improved significantly [4,8,9].

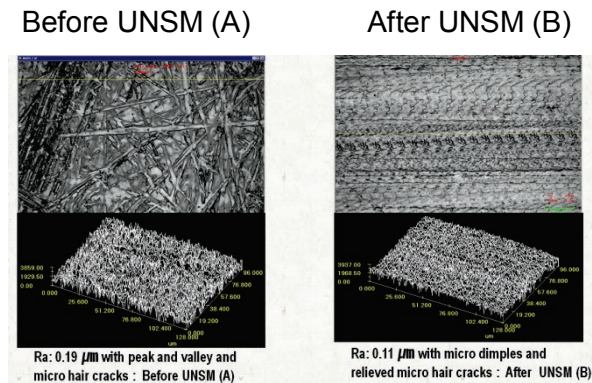


Fig.3. Improvement of Surface Integrity and Micro Dimpled Surface by UNSM.

2-3. Increase of Surface Hardness by UNSM Treatment

Surface hardness of a SKD 61(H13) specimen treated by UNSM increased from Hv480 to Hv720 as shown on Figure 4A, SUJ2 specimen increased from Hv740 to Hv890 as shown on Figure 4B. For Ti alloy, Al alloy, Cu alloy and Super alloys specimens treated by UNSM surface hardness increased as shown on Table 3. [4,7,9].

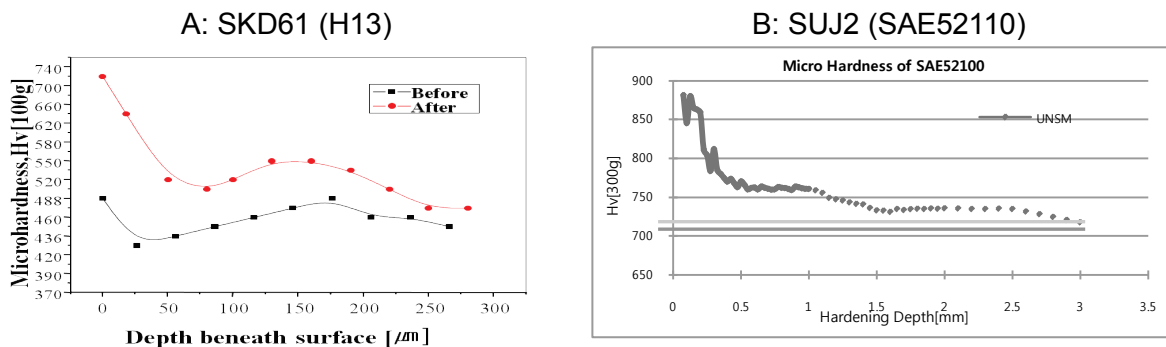


Fig.4. Increase of Surface Hardness by UNSM Treatment.

Table 3. Increase of Surface Hardness by UNSM Treatment.

	Ti-6Al-4V	CP Ti	Inconel 738	Inconel 690	WASPALLOY	Cu-Zn alloy	Al6061-T6
Untreated Hardness (HV)	380	115	405	164	420	130	100
UNSM-treated Hardness (HV)	424	142	448	280	510	210	141

2-4. Refinement and Nanocrystallization by UNSM Treatment

Micro cold forging on the surface by 20,000 or 40,000 strikes per second induces severe plastic deformation, which refines the structure from micrograins into nanocrystal. TEM and XRD analysis after UNSM treatment on SUS 304 show 30-45 nm grain size till depth 30 μm from surface. It is refined almost 1/1,000. as shown in Figure 5 and Table 4, respectively. [3,12]

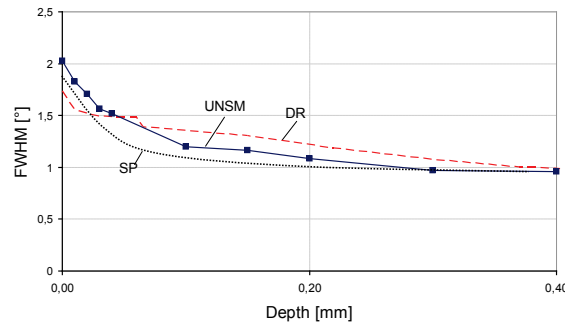
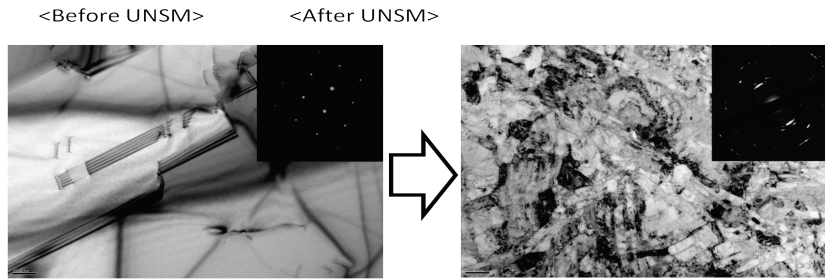


Fig.5. Comparison of FWHM and TEM.

Table 4. Calculation of Grain Size.

Depth from surface(μm)	Grain size (nm)
5	30
10	36
20	42
30	45

3. Test Results of Fatigue, Wear, Friction and Rolling Contact Fatigue

3-1. Improvement of Fatigue Strength by UNSM Treatment

In order to evaluate the effects of the compressive residual stress, the improved surface integrity and hardness, and nanocrystal structure on fatigue strength of UNSM treated SKD 61 specimen, rotary bending test was carried out and its results are shown in the left of Figure.6.

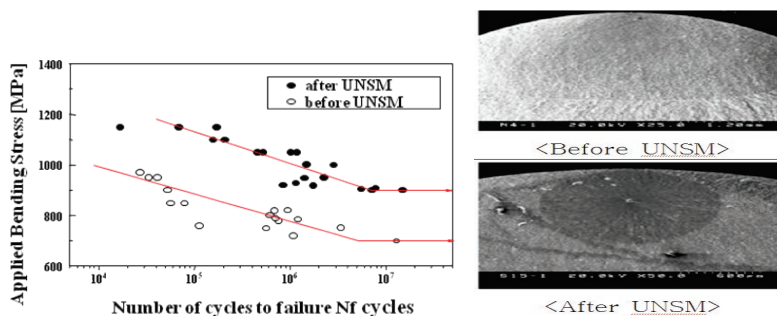
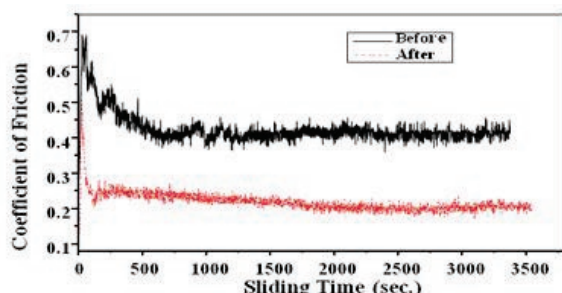


Fig.6 Improvement of Fatigue Strength by UNSM Treatment: SKD 61(H13).

Fatigue strength is increased by more than 25% and fish-eye of fracture surface after UNSM treatment explains the effect of improvement as shown in the right of Figure 6 [11,14]. Tension/compression fatigue test and torsion fatigue test were carried out for several different steel alloys, Ti alloys and Al alloys.

3-2. Reduction of Friction Coefficient and Wear Rate by UNSM Treatment

In order to evaluate the effects of the micro dimpled surface, the improved surface integrity and hardness, and compressive residual stress of SKD 61 specimens, a pin-on-disc test in dry condition was carried out. The wear rate and the friction coefficient of UNSM treated specimens are reduced to 4% and to 52% of untreated specimens respectively, as shown in Figure 7. Industrial tests of real trimming knives had been carried out for several years and summary of test results are shown in Table 5 [4,11,14].



	Average friction coefficient	Average wear amount
UNSM-treated	0.22	0.039
Untreated	0.42	1.179

Fig.7. Reduction of Friction Coefficient and Wear Rate by UNSM Treatment: SKD 61.

Table 5. Summary of Field Test Results on Trimming Knives at POSCO, etc..

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

3-3. Improvement of Rolling Contact Fatigue Strength and Reduction of Friction Torque by UNSM Treatment

In order to evaluate the integrated effects of UNSM treatment on the compressive residual stress, the improved surface roughness and hardness, the micro dimpled surface, and nanocrystal structure of UNSM treated bearings steel (SUJ2), two kinds of rolling contact fatigue strength test were carried out as shown in Figure 9. The life cycle of UNSM treated specimens in 6 balls test is increased from 6.3 million to 25.7 million by more than 4 times. The life cycle of UNSM treated specimens in roller test is increased from 4.9 million to 10.2 million by more than 2 times. Friction torque of UNSM treated specimens is 20~30% lower than that of untreated specimens as shown in Figure 8 [4,8].

	Before UNSM	After UNSM
6-Ball RCF	6,380,000 Cycles	26,000,000 Cycles
Roller RCF	3,000,000 Cycles	10,000,000 Cycles

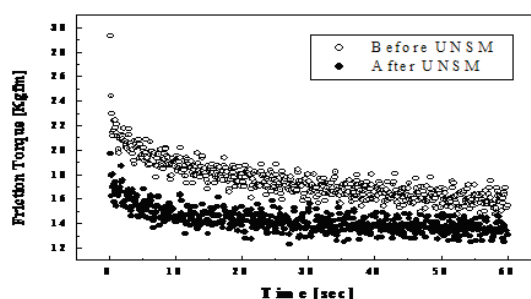


Fig.8. Friction Torque of 6 Balls Test Specimens Before and After UNSM (500rpm, 8,000N)

4. Conclusion and Implications

The most important implication of UNSM technology is that UNSM technology improves surface

integrity and surface hardness, makes micro dimples, and induces compressive residual stress and nanocrystallization in surface layers simultaneously, therefore reducing friction and increasing fatigue life. For rolling bearings, rotating shaft, sliding bearings as critical components of any dynamic systems the UNSM can give integrated effects and benefits as shown in Table 1. A crankshaft in engines, compressors, pumps, and etc. is a typical example of a rotating shaft. By using UNSM treatment designer can chose a smaller journal diameter and length thus the size and the weight of engine can become smaller and lighter without losing durability/reliability, and therefore the fuel efficiency and cost can be improved. Hub bearings of axle system in automobiles are also typical rolling bearings which size can become one size smaller – such that the weight of axle system can become lighter without losing durability/reliability and the fuel efficiency and cost can be improved at the same time. So UNSM technology can be used for innovation of design and manufacturing technology.

5. References

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