The concepts and properties of nanoskin materials and components created by ultrasonic nanocrystal surface modification

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Abstract

Material surface and immediate subsurface layers can be called “skin”. A novel Ultrasonic Nanocrystal Surface Modification (UNSM) technology produces uniformed micro dimples on the top surface and nanometer grain in the subsurface, increases surface hardness and induces compressive residual stress. This way mechanical characteristics related to fatigue, wear, friction, etc. can be improved. The concepts and properties of nanoskin materials and components are proposed with their potential application.

Keywords: Nano grain materials; Nano skin materials; Ultrasonic Nanocrystal Surface Modification.

1. Introduction.
Concept of Nanoskin Materals and Components

Friction and wear, low, high and very high cycle fatigue, rolling contact fatigue and some other characteristics of machine components are influenced by the surface characteristics of material. The top surface and immediate subsurface layers can be called “skin”. When subsurface grain dimensions reach nanometer range and top surface acquire micro or nano scale roughness and texture, these properties are much different from those of the ordinary structure. The hardness, compressive residual stress and grain size of subsurface are major factors that determine fatigue, friction, wear and fatigue characteristics. Therefore, nanoskin materials and components can be defined as *top surface of material consisting of nano scale roughness and nano and/or micro scale texture, and subsurface nanoscale grain size with improved hardness and compressive residual stress*.

Lowest roughness of 10 - 200 nm is usually achieved through various forms of abrasive surface finish [1]. However, manufacturing costs rise exponentially with decreasing of the surface roughness. Surface texturing can reduce friction and wear characteristics, but there is no general rule yet to explain its effects on wear and friction. Besides, the size of the pattern is usually bigger than several dozen micro millimeters [2, 3, 4].

Grain size refinement is usually achieved through conventional heat treatment and deformation processes like forging, rolling, drawing and extrusion. However, 1µm (for steels) is a limit for the grain size refinement [5]. The severe plastic deformation process such as ECAP (Equal Channel Angular Process) is a novel technology which refines the grain size of bulk rod into nano scale [6]. But from the view point of nano skin of materials and components, there is still a lot more research to do.

2. The UNSM Technology

Ultrasonic Nanocrystal Surface Modification (UNSM) stands out for ability to generate specifically nanoskin on the surface of material. The main concept and mechanism of UNSM shown in Figure 1 are as following [7, 8, 9]. A tungsten carbide ball attached to an ultrasonic device strikes the surface of a work piece 1.2 ~2.4 x 10^6 times per minute with 1,000 to 100,000 shots per mm^2 and under contact pressure range from 3 to 100 GPa. These strikes bring severe plastic-elastic deformation to surface and subsurface. Thus *uniformed micro dimple pattern* on the surface and *nanocrystalline structure* and *compressive residual* stress in subsurface layer are induced. This change has potential to simultaneously improve static and fatigue strength, as well as surface hardness and surface roughness of the work piece.

Figure 1. UNSM Mechanism and UNSM Device with CNC Lathe for Hub Bearings

2.1 Top surface properties: roughness and micro dimples texture

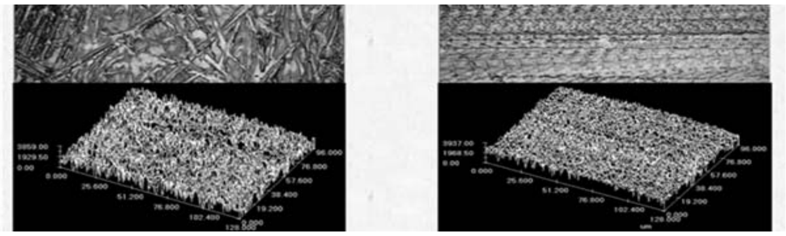


Figure 2. Micrograph images and 3-D topology of AISI52100

The uniform micro dimple pattern of the surface is the *signature mark* of the UNSM treatment. Figure 2 shows modification of the surface pattern of SAE52100 bearing steel ground specimen treated with UNSM. Ra roughness is improved from 0.19 µm to 0.11 µm and uniform micro dimple structure improved entrapped oil volume [9, 10, 11]. Table 1 shows that dimensions of micro-dimples measured by AFM are rather in nano order.

Table 1. Micro dimple size for AISI52100 treated with UNSM

Conditions	Feedrate, mm/rev	Amplitude, µm	Lathe Spindle Speed, rpm	Static Load, N	Tip diameter, mm	Micro dimple diameter/depth, µm
UNSM I	0.07	30	50	60	2.38	0.8/0.07
UNSM II			100			0.56/0.05
UNSM III			150			0.42/0.04

2.2 Subsurface properties

2.2.1. Nano crystallization

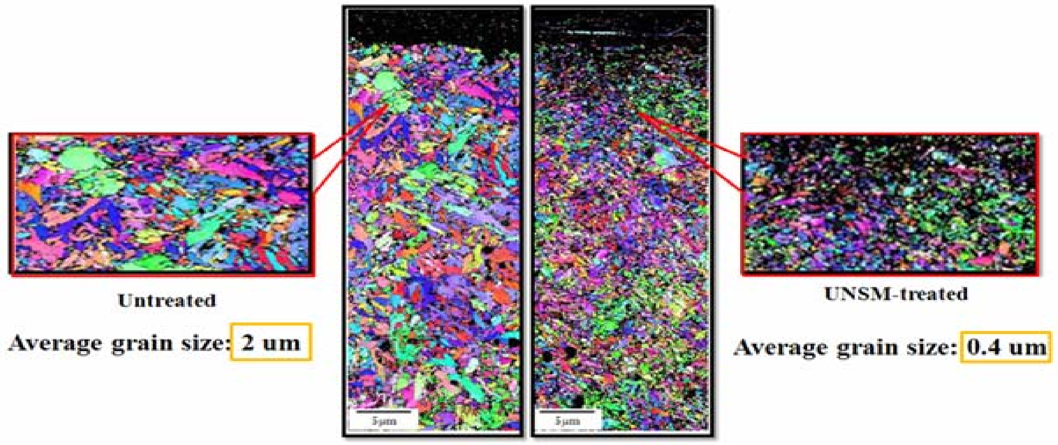
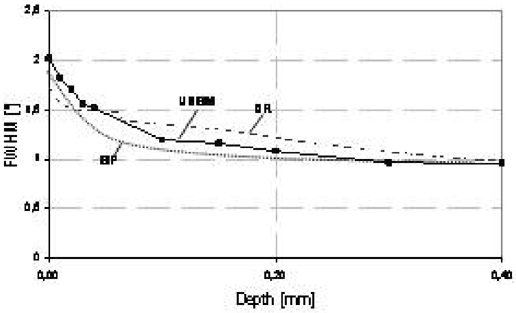


Figure 3. Comparison of grain size before and after UNSM treatment for SAE52100 bearing steel specimen.

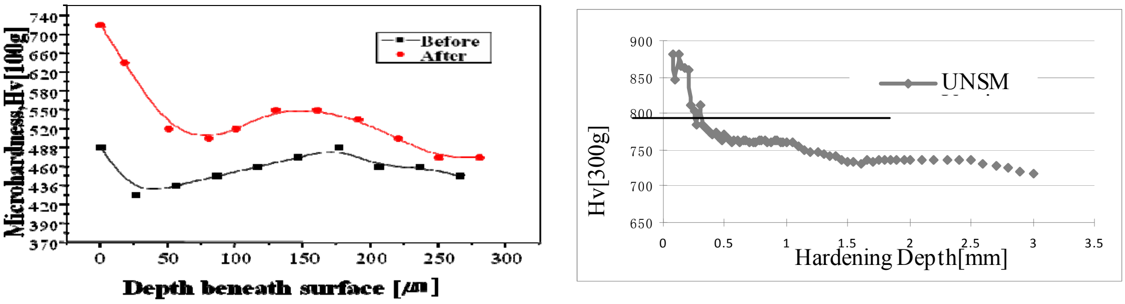
Figure 3 shows modification of the grain structure in the subsurface of specimen made of SAE52100 bearing steel. It can be seen that strikes induced grain size refinement from 2 µm to 0.4 µm. Figure 4 shows grain size in the subsurface of UNSM generated nanoskin of SUS 304 steel. The grain was refined almost 1/1000 [8, 13].



Depth, µm	Grain size, nm
5	30
10	36
20	42
30	45

Figure 4. TEM and XRD analysis and calculation of SUS 304 steel grain size of after UNSM

2.2.2. Increase of top surface and subsurface hardness



SKD61 SAE52110

Figure 5. Microhardness depth profile of SKD61 and SAE52110 steels treated with UNSM

Table 2. Top surface hardness

	Ti–6Al-4V	Inconel738	Inconel690	Cu-Zn alloy	Al6061-T6
Untreated/UNSM Hardness(HV)	380/424	405/448	164/280	130/210	100/141

Hardness at the top surface increased by 33% and 17% for SKD61 and SAE52110, respectively. Table 2 shows improvement of top surface hardness of some other materials nanoskin-treated by UNSM technology.

2.2.3. Increase of compressive residual stress

A:SKD61 (H13)

B: Ti-6Al-4V

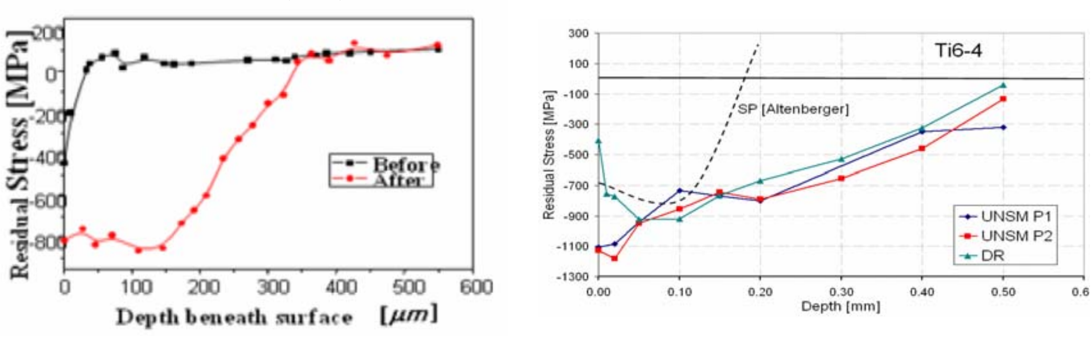


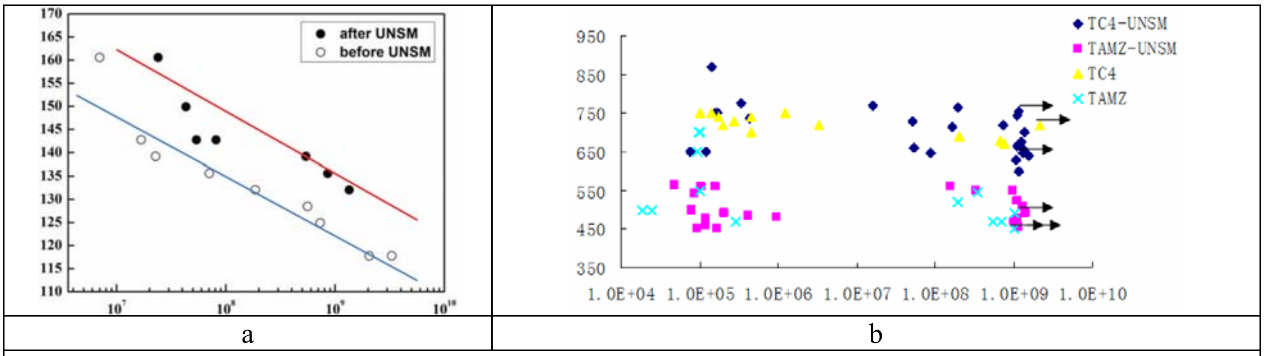
Figure 6. Compressive residual stress treated by UNSM technology

Compressive residual stress within a nanoskin created by UNSM of SKD61 (equivalent of H13) is shown in Figure 6A, and of a Ti-6Al-4V for medical and aircraft application is shown in Figure 6B. Comparison between deep rolling (DR) and UNSM is also shown in Figure 6B [9, 12, 14].

2.3. Mechanical performance of nanoskin: fatigue, wear, friction and rolling contact fatigue

2.3.1. Improvement of HCF and VHCF strength

In order to evaluate the effects of UNSM generated nanoskin on fatigue performance of some automotive, aircraft and medical alloys, ultrasonic fatigue tests (UFT) were carried out on Al6061-T6, Ti-6Al-4V (TC4) and Ti-3Al-2Mo-2Zr (TAMZ) specimens. Using UFT device reduced test time and better simulated extremely high frequency loading and influence of strain rate on fatigue behavior of tested material. The test frequency was 20 kHz and stress ratio R=-1. The specimens were hourglass shape with neck diameter 6 mm and notch radius 60 mm for Al-alloy and 3 mm/31 mm for Ti-alloys. Figure 7 shows S-N curves acquired through UFT for UNSM treated and untreated specimens.



a

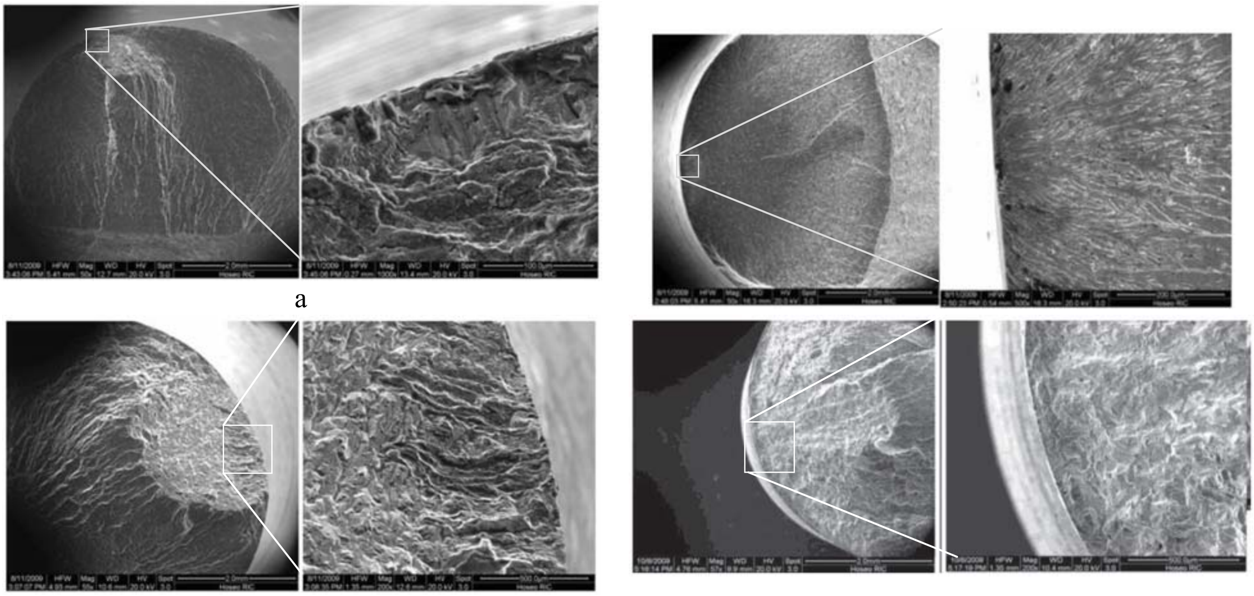
b

Figure 7. S-N curves for UNSM treated and untreated Al6061-T6 specimens (a) and TC4 and TAMZ (b)

It is shown that UNSM induced nanoskin prolongs fatigue life of all three alloys. In many instances UNSM treated specimens lasted well beyond 10^9 cycles or run out. S-N curve of UNSM treated Al6061-T6 is shifted approximately 25 – 30 % towards higher stress level compared with untreated specimens. Meanwhile, UNSM induced nanoskin improved fatigue strength of TC4 and TAMZ by 11 % and 13 % respectively.

Untreated Al6061-T6 specimens show various fracture surfaces. At high stresses (Figure 8a) cracks are initiated at inclusions or other defects and rapidly spread, forming a “canyon” shaped damage. At medium stresses (Figure 8b) fatigue failure occurs at the surface followed by propagation into the interior, as indicated by cross-section lines. At lower stresses (Figure 8c) slip bands occur at crack starting point.

Figure 8d shows a typical high cycle fatigue fracture of UNSM treated specimens.



a

c

d

Figure 8. Untreated (a-c) and UNSM treated (d) Al6061-T6 specimens fracture surfaces

Although fatigue strength of TC4 is higher than that of TAMZ alloy, their fracture behavior is very similar. Fractographic analysis of typical untreated Ti-alloy gigacycle (> 10^8 cycles) specimens displays that cracks always initiate at the surface, as shown on Figure 9. The fracture surface can be divided in to four areas: (I) an initial relatively flat area; (II) a distinctly rough area with propagation traces like radiate wave lines; (III) a wider fracture surface with radial streaks along propagation direction and (IV) overload fracture area.

For specimens with UNSM induced nanoskin, the fracture surface can be divided in four areas, much the same way as untreated specimens. The important difference, however, is that the crack initiation always occurs in the subsurface, about 50 µm below, at the internal inclusion and form a fish-eye, as shown on Figure 10.

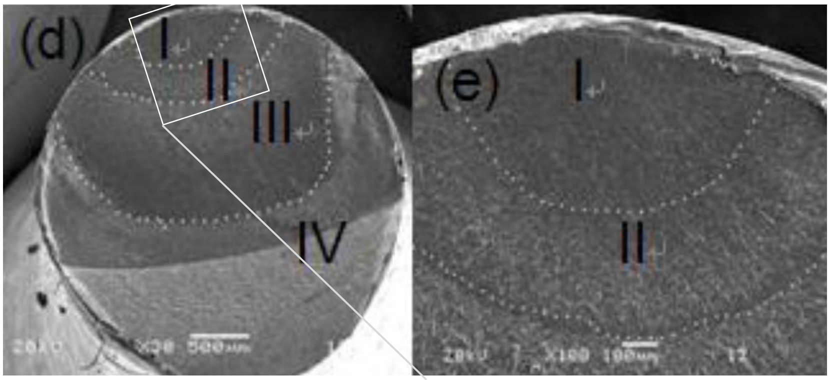


Figure 9. Fracture surface of untreated Ti-alloys, gigacycles

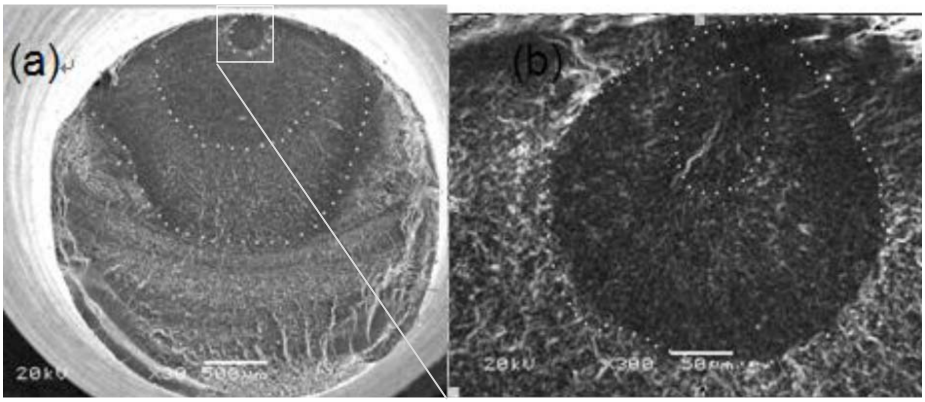


Figure 10. UNSM treated Ti-alloys' fracture surface, gigacycles

The crack initiation area appears as a white dot in the middle of dark spot (also known as "optically dark area", or ODA). This dark zone is relatively flat and circular, and relates to short crack propagation, where no crack closure is present. Typically, specimen with larger ODA has longer fatigue life [15, 16]. Outside of ODA there is wide fracture surface with large radial patter. There are some ridge patterns and striation.

2.3.2. Improvement of RCF strength and reduction of friction torque

In order to evaluate the effects of nanoskin on rolling contact fatigue strength of bearings steel SAE52100 (SUJ2), two kinds of tests were carried out: 6 balls test and roller test. The life cycle in 6 balls test is increased from 6.3 x 10^6 to 25.7 x 10^6 and in roller test increased from 4.9 x 10^6 to 10.2 x 10^6. Friction torque is 20~30% lower than that of untreated specimens as shown in Figure 8 [9, 10].

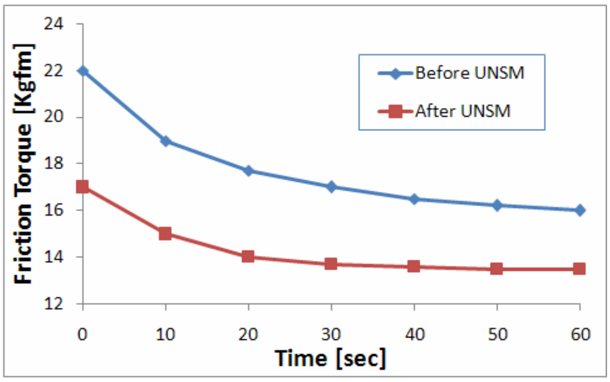


Figure 8. Friction Torque of 6 Balls Test Specimens Before and After UNSM (500rpm, 8000N)

2.3.3. Reduction of friction coefficient and wear rate

In order to evaluate the effects of nanoskin on tribological properties of SKD61 specimens, a dry pin-on-disc test was carried out. The friction coefficient and wear rate of UNSM treated specimens are reduced by 48% and 96%, respectively. Industrial tests of UNSM trimming knives for hot and cold rolling mills of high strength steel manufacturing had been carried out for several years. Results showed that UNSM generated nanoskin doubled production intervals between knives replacements, therefore increasing productivity and reducing production cost [9, 12, 14].

3. Conclusions

Due to effects of surface nano and/or micro scale roughness and texture, and subsurface nanoscale grain size with improved hardness and compressive residual stress of UNSM created nanoskin the limits of fatigue strength and rolling contact fatigue strength of conventional materials can be extended by nanoskin materials and components. Coincidental size and weight reduction of mechanical components can be obtained also by nano skin components as well. High cycle and very high cycle fatigue improvements are supported by changes in fracture mechanism as illustrated by fractographic analysis.

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