Application of UNSM (ultrasonic nanocrystal surface modification) technology for increasing fatigue strength of Ti-6Al-4V ELI spine rod and for decreasing 15% of the spine rod diameter

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Abstract
The spine rod in the spinal fixation system should be tough enough to support the dynamic force and flexible also for flexible movement. 5.5 mm ~ 6 mm diameter spine rods made of Ti-6Al-4V ELI are common products. Two possibilities are studied. The one is that while keeping the flexibility unchanged (using 6mm diameter), how much the fatigue strength can be increased. The other is while the flexibility increased more than two times, how much the diameter of spine rod can be reduced.
UNSM technology has been applied to increase the fatigue strength of Ti-6Al-4V ELI. The surface roughness, hardness and compressive residual stress are compared before and after UNSM treatment. 6 mm and 5 mm gauge diameter of rotary bending test specimens are made. S-N curves of rotary bending test results are compared before and after UNSM and analyzed with their fracture observation.

Keywords: Fatigue, spine, Ti alloy, Ultrasonic Nanocrystal Surface Modification (UNSM).

Introduction
The spine rod in the spinal fixation system should be tough enough to support the dynamic force and flexible enough for flexible movement. 5.5 mm ~ 6mm diameter spine rods made of Ti-6Al-4V ELI are common products. Fatigue failure is not often case, but if happened, it causes big problem to patients and medical doctors. Also patients with the slim physique, especially women, do not like to implant 6mm diameter spine rod because of its protrusive appearance. Two possibilities are studied. The one is that while keeping the flexibility unchanged (using 6mm diameter), how much the fatigue strength can be increased. The other is while the flexibility increased two times, how much the diameter of spine rod can be reduced.
The UNSM is an emerging technology using the hard ball to strike a work piece surface 20,000 or more times per second. These strikes produce micro-dimples on the top surface and severe plastic deformation to the surface layer. Thus big and deep compressive residual stress is induced, surface hardness and roughness are improved, and the grains are refined into nanocrystal [1,2]. The UNSM technology was applied to spine rods to verify these two possibilities.

Experiment
Two kinds of fatigue test (R= -1 tension and compression test and R= -1 rotary bending test) were carried out in order to derive proper UNSM treatment parameters for spine rod specimen.

Tension and Compression Fatigue Test
The process parameter of UNSM treatment on the test specimens and their effective mechanical characteristics are shown in Table 1.

Table 1. UNSM Parameters and Hardness and Roughness Before and After UNSM Treatment.

Tip material of UNSM device	WC
Tip diameter of UNSM device, mm	2.38
Amplitude of UNSM device, fKm	30
Load of UNSM device, N	50
Strikes by UNSM tip, Hz	53,000
Hardness before UNSM, HV	365
Hardness after UNSM, HV	410
Roughness before UNSM (R_a), µm	0.71
Roughness after UNSM (R_a), µm	0,22

Roughness is reduced to 31% and hardness is increased to 112% of that of the untreated specimen after UNSM treatment.
The residual stress before and after UNCM treatment is shown in Figure 1.

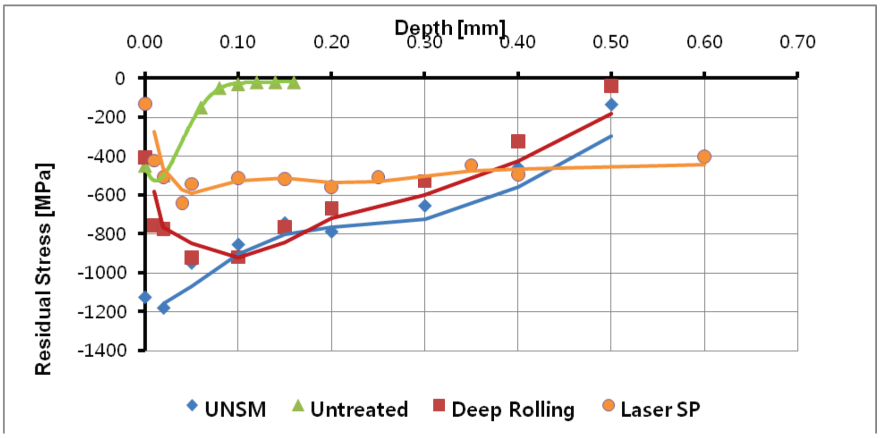

Figure1. Residual Stress Before and After UNSM.

Figure 1 shows that residual stress at the surface layer of the specimen after UNSM treatment matches other surface treatments [3].
The result of R= -1 tension and compression fatigue test was shown in Figure 2. [4]

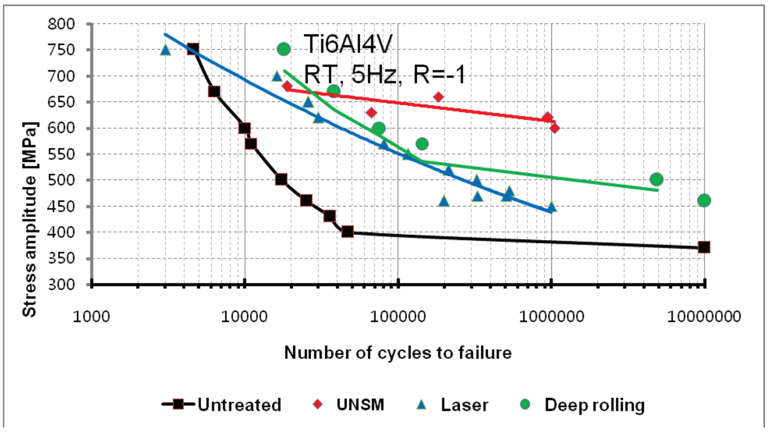

Figure 2. Tension and Compression Fatigue Tests.

This two diagrams show that due to higher compressive residual stress at the surface level UNSM treated specimens perform better in tension and compression fatigue test.

R=-1 Rotating Bending Fatigue Test
The process parameters of UNSM treatment and their effective mechanical characteristics are shown in Table 2.

Table 2. UNSM Parameters and Hardness and Roughness Before and After UNSM Treatment.

Rod diameter, mm	6	5
Tip material	WC	
Tip diameter, mm	2.38	
Amplitude, ƒKm	20	
Load, N	15	
Strikes, Hz	18189	21838
Hardness before, HV	325	
Hardness after, HV	395	
Roughness before (R_a), μm	0.20	
Roughness after (R_a), μm	0.16	

Roughness is reduced to 80% and hardness is increased to 121% of that of the untreated specimen after UNSM treatment. The compressive residual stress before and after UNSM treatment for 6 mm specimen are shown in Figure 3.

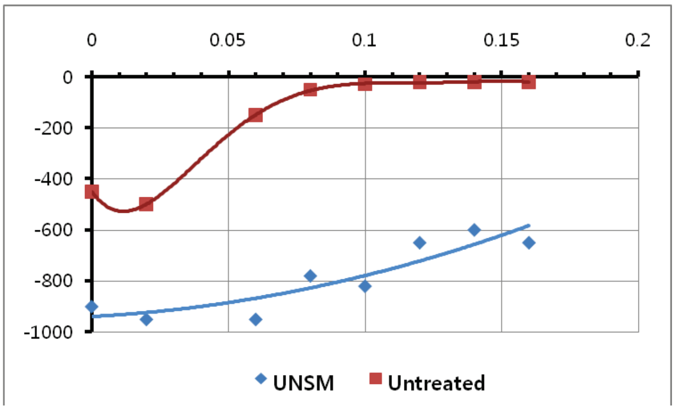

Figure 3. The Compressive Residual Stress Before and After UNSM Treatment.

UNSM treated specimen shows not only about 50% higher compressive residual stress at the surface, but the slope of the curve was also greatly reduced.
The results of R= -1 rotary bending fatigue test are shown in Figure 4. [5]

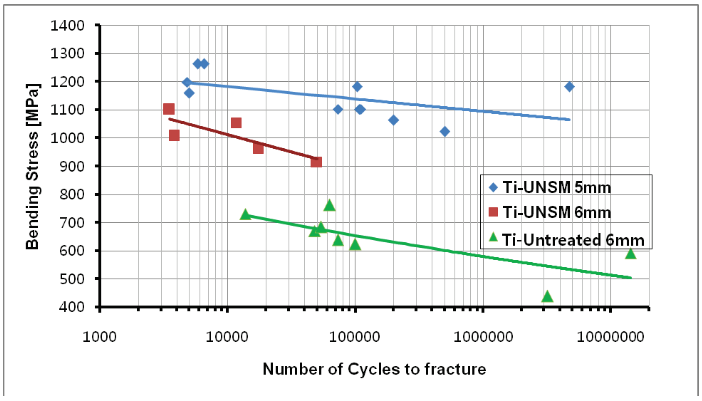

Figure 4. Rotary Bending Fatigue Test.

UNSM treated 6 mm rod shows 30% increase of fatigue life at 10^4 cycles, while due to larger number of strikes 5 mm UNSM treated rod displays 70% increase from untreated at 10^5 cycles and longer.

Conclusion

The UNSM technology was applied to Ti-6Al-4V ELI for spine rod to improve fatigue strength and thus it allowed reducing rod diameter while maintaining same level of fatigue strength. The results of two kinds of fatigue test (R= -1 tension and compression test and R_{-1} rotary bending test) showed that UNSM treatment significantly increases compressive residual stress, which leads to improvement of fatigue strength, more than 30% in cases described above. Thus 10% of rod diameter could be reduced. Therefore, the possibility of replacement of 6mm rod with 5mm rod is established, provided that UNSM treatment is applied.

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