

Application of UNSM (Ultrasonic Nanocrystal Surface Modification) Technology for Prolonging the Service life of AISI 1045 Shear Pin in the Flange Yoke Assembly of Stainless Hot Rolling Mill

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Abstract

Due to increasing productivity and fluctuation of roll torque, premature failure of shear pin of flange yoke assembly of stainless hot rolling mill occur and cause significant production loss. UNSM treatment was applied to the neck groove of the shear pin as an alternative to existing solutions to prevent premature failure and increase service life.

Proper process variables of UNSM technology are determined which can give the strongest fatigue strength by the comparison of S-N curve of rotary bending test result. The surface roughness, hardness and compressive residual stress of three kinds of test specimens are analyzed together with SEM analysis of fracture surface. Real shear pins had been produced by the highest fatigue strength condition and installed to the hot mill stand for validation. They had been passed 270 days of operation.

Introduction

The flange yoke assembly of stainless hot mill stand includes a special safety device which is called shear pin. It is designed to transmit the torque from electric motor to the roll. However, it should break in the case of a mechanical overload to prevent electric motor damage. As a sacrificial part, it is a mechanical analogue of a fuse in the electric circuit. The pin is made from AISI 1045; the diameter of the rod is calculated to withstand a normal working load, but allow the shear break when predetermined torque is reached. This built-in controversy makes it hard to ensure high fatigue properties for shear pin. Moreover, increasing productivity and fluctuation of the torque make service life even shorter. To achieve at least 120 days (average for the industry) of service life manufacturer used a shear pin treated with shot peening. Nevertheless, premature failures took place causing significant production losses.

Ultrasonic nanocrystal surface modification (UNSM) [1] is a patented technology in South Korea which can be described as ultrasonic cold forging technology (UCFT) [2]. UNSM produces harder surface hardness and smoother surface roughness comparing with other mechanical surface nanocrystal treatments. It is therefore worth investigating the mechanicals properties of materials subjected to UNSM. Li et al. [3], Roland et al. [4], Dai et al. [5], and Tian et al. [6] respectively reported the effects of surface nanocrystallization on fatigue behavior. In the present work, a nanostructured surface layer was prepared by means of UNSM in a medium carbon steel S45C, an AISI 1045 analogue, which is also normally used in axes, gears, and splines of compressors, pumps, and steam turbines. The micro hardness, surface roughness and residual stress were measured. The effect of the UNSM technique on the fatigue behavior of S45C was investigated.

Experimental procedures

The test specimens were made of a medium carbon steel S45C. It is a Japanese equivalent to AISI1045, which is easy to obtain for the purpose of doing research in South Korea. Table 1 shows chemical composition (in wt %) and some mechanical properties for both steels. The power output of the ultrasonic generator is about 1 kW; the ball diameter was 2.38 mm; the ball was made of tungsten carbide (WC). Kerosene was a lubricant. The static load was 30 N, and the vibration amplitude was 30 μm . The total load acting on the specimen was the sum of the static load and the sinusoidal function of the dynamic load. Table 2 shows the UNSM treatment parameters.

Table 1. Chemical Composition and Mechanical Properties for AISI1045 and S45C.

Mass %	C	Si	Mn	P	S	Cu	Ni	Cr	σ_y , MPa	σ_{uts} , MPa	%
AISI1045	0.45	-	0.72	≤ 0.04	≤ 0.05	-	-	-	505	585	12
S45C	0.45	0.21	0.71	≤ 0.030	≤ 0.035	≤ 0.3	≤ 0.2	≤ 0.2	490	690	17

Table 2. UNSM Treatment Condition.

Type of specimen	UNSM C1	UNSM C2	UNSM C3
Number of strike (times/ mm^2)	34,000	45,000	68,000

Before UNSM, all specimens were polished using sandpaper from grade 120 to grade 2000. To investigate the effect of the nanostructured surface layer on the fatigue behavior of S45C, rotating bending fatigue tests on the four groups of samples (untreated, C1, C2, and C3) were conducted at ambient temperature using a dual-spindle rotating bending fatigue test machine. The frequency of fatigue testing was 52.5 Hz, and the stress ratio was $R = -1$. The fracture surfaces were examined using scanning electron microscopy (SEM). The crack length was measured using the laminated film method. Finally, the actual shear pins were manufactured and field tested based on these results.

Results and Discussion

Investigation of Nanostructured Layer

Fig. 1a shows the microstructure of the untreated S45C specimen (pearlite and ferrite, with the grain size of about 30 μm). The nanostructured surface layer after UNSM C3 is shown in Fig. 1b. Fig 1c of UNSM C3 shows the 30 μm thickness for nanocrystalline surface layers at their fatigue fracture surface. Nanocrystalline surface layers with the thickness of 2 μm , 12 μm and 30 μm were produced by UNSM C1, C2 and C3 respectively, as shown in Table 2.

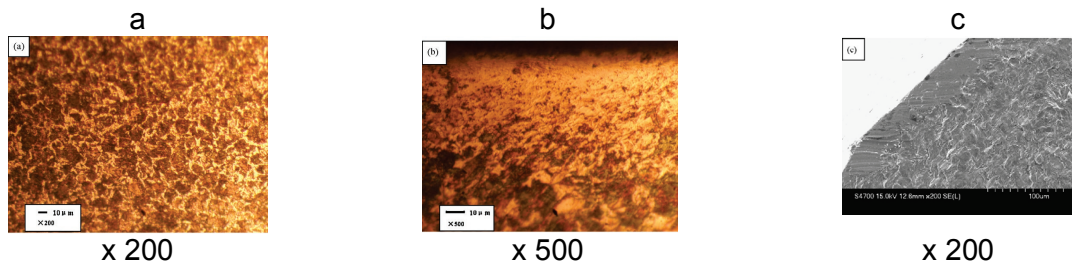


Figure. 1. Microstructures and Features of S45C: (a) Before UNSM; (b) UNSM C3; (c) Nanostructured Layer on Fatigue Fracture Surface Observed by SEM, UNSM C3.

Micro-Vickers Hardness Distribution

The micro-Vickers hardness along the depth from the UNSM treated surface layer was measured for cross-sectional samples. The microhardness of the untreated S45C specimen

was about 220 Hv, as shown in Figure 2. The values of microhardness of UNSM C1, C2, and C3 were 324 Hv, 407 Hv, and 436Hv respectively. The microhardness of UNSM treated specimens rapidly decreases at about 60µm and then decreases more gradually down to 235Hv at a depth of 400µm.

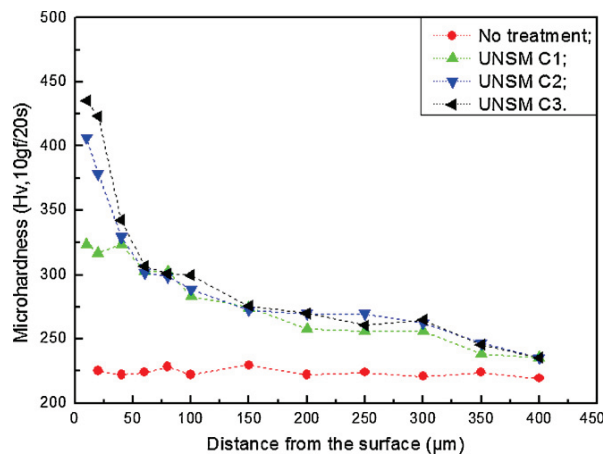


Figure 2. Distribution of micro-Vickers Hardness Before and After UNSM.

Residual Stress of Fatigue Specimens

There are many reports on the residual stress variation by depth [1, 2, 3, 4, 7]. Table 3 shows the residual stress measurement results at about 20µm below the surface acquired by X-ray scattering technique using diffraction pattern of the Fe (2 1 1) crystal plane obtained by Cu K α radiation. Residual stress increased 8, 12 and 18 times for UNSM C1, C2 and C3 respectively.

Table 3. Residual Stress on Fatigue Specimens.

Processing method	Last polished by grade 2000 sandpaper	UNSM C1	UNSM C2	UNSM C3
Residual stress, MPa	-20.5	-162.8	-244.1	-366.7

Observation of Surface Roughness and Surface Features

Table 4 shows the observation of surface roughness before and after UNSM treatment.

Table 4. Surface Roughness Before and After UNSM.

Group	No treatment	UNSM C1	UNSM C2	UNSM C3
Roughness (Ra), µm	0.225	0.149	0.146	0.10

Fatigue Characteristics

Rotary bending test was performed to investigate the fatigue characteristics of S45C after UNSM, which are shown in Figure 3. From S–N curves, it can be concluded that as the vibration strike number increases, the 10^7 cycles fatigue limit gradually increased. The slope of the S–N curve is also reduced. UNSM C3 improves the fatigue strength by as much as 33% for S45C. Figure 4 shows the SEM micrograph of the fatigue fracture surface of S45C after UNSM.

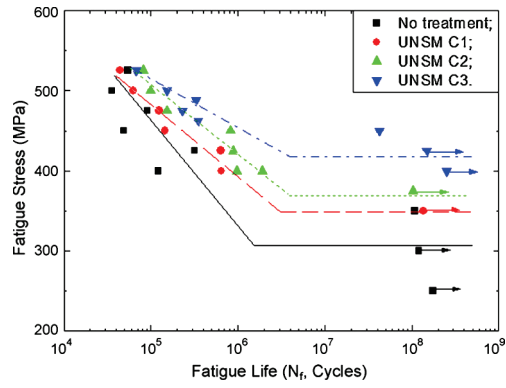


Figure 3. S–N curves of S45C after UNSM.

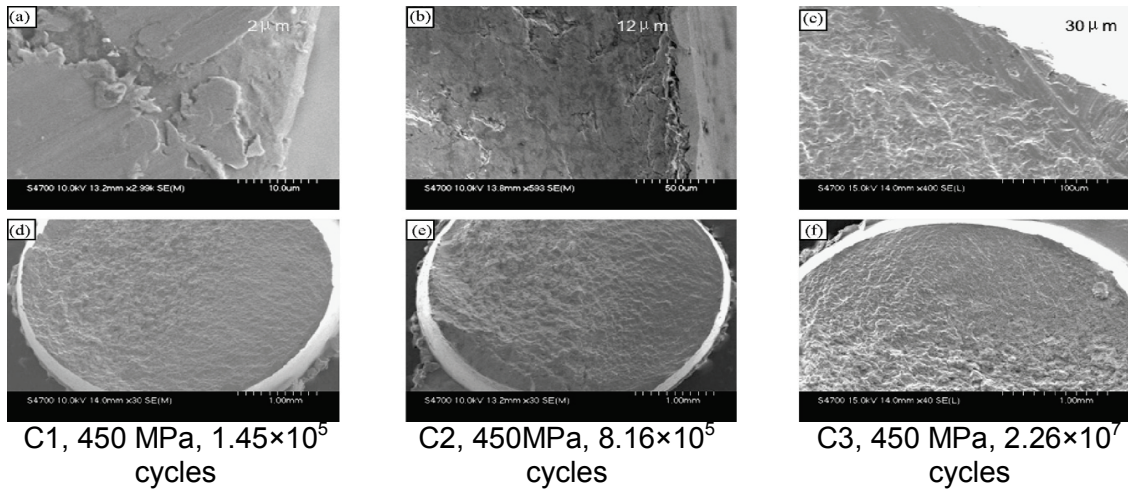


Figure 4. Fracture Surface of S45C after UNSM.

Figure 5 shows the surface crack growth speed for S45C under a fatigue stress of 475 MPa. The surface crack growth speed diagram shows that the nanostructured surface layer does effectively restrain crack initiation. The fatigue endurance limit is typically controlled by the number of fatigue cycles to initiate a dominant crack, which could account for 90% of the total fatigue life [8]. In this test, the same phenomenon has been observed with UNSM as well.

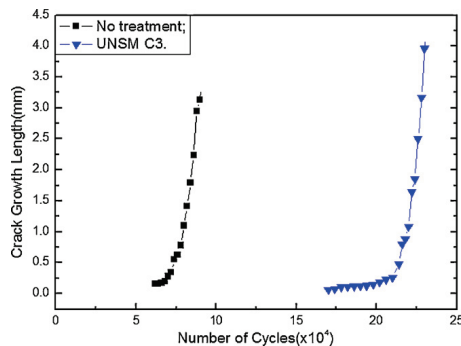


Figure 5. Surface Crack Growth Speed ($\sigma = 475$ MPa).

Field Test

Shearing pins were produced from AISI1045 to manufacturer's specifications as shown in Figure 6. The neck groove of the shear pins were treated by UNSM technology with parameters chosen based on this research (UNSM C3), and were installed into the flange

yoke assembly of stainless hot mill stand to be tested under practical working conditions. Under circumstances of normal production operations they withstood 240 days period.

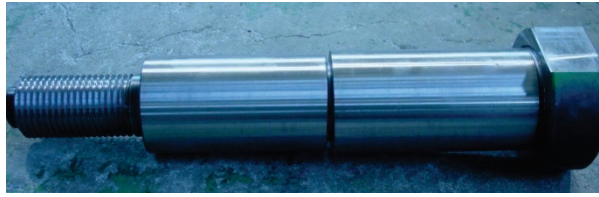


Figure 6. Shear Pin.

Conclusions

(1) The surface microhardness of S45C increased following UNSM and the hardness of UNSMC3 was about twice that of the coarse grained matrix.

(2) Compressive residual stress has been induced by UNSM. As the vibration strike number of UNSM increased, the value of residual stress also increased.

(3) UNSM C3 with the maximum vibration strike number had the lowest surface roughness and intergranular microcracks caused by UNSM have been observed on the surface of S45C after UNSM.

(4) Fatigue endurance was improved by as much as 33% (UNSM C3) for S45C. Cracks initiated at the intergranular microcracks on the surface and then extend along the tip traces of UNSM which are considered as process defects.

(5) The nanocrystal surface layer has the effect of retarding the initiation of fatigue cracks. In S45C, the efficiency of crack resistance is more than 48%.

(6) The results of research on S45C can be easily transmitted to AISI 1045 regarding UNSM treatment and can be applied in the field with 100% fatigue improvement.

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