# The Effects of Ultrasound-Aided Deep Rolling Process On Fatigue Enhancement of 30CrMnSiNi2A Steel

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## Abstract

The effect of ultrasound-aided deep rolling (UADR) treatment on the fatigue resistance of 30CrMnSiNi2A steel was studied through fatigue experiments. Residual stress and full width at half maximum (FWHM) were measured by XRD, In-depth hardness profile of the treated specimen was measured with a Vickers micro-hardness tester. Surface finishing and roughness were observed and measured by optical micrograph and a Talysurf roughness tester, respectively. Fractography of the fatigue fractured specimens was evaluated via scanning electron microscope(SEM). It was shown that the UADR process obviously enhanced the fatigue resistance of 30CrMnSiNi2A steel as a results of induced deeper layer of compressive stress, improved surface integrity and refined microstructure. Meanwhile, it was interesting to note that the FWHM value of the top surface layer was decreased due to UADR treatment, which implies that the FWHM value may not be used as the character parameter representing the degree of work hardening of the 30CrMnSiNi2A steel.

**Keywords:** UADR process, residual stress, fatigue resistance, 30CrMnSiNi2A Steel

## Introduction

30CrMnSiNi2A steel is a kind of low-alloyed steel that is widely used in Chinese aviation industry due to its ultra-high strength and favorable fatigue performance. In the past decades, many surface mechanical enhancement techniques such shot peening and roller burnishing, etc., were used to further increase its fatigue resistance for longer service life and better mechanical reliability. Among the various mechanical surface treatments techniques, laser shock peening, low plasticity burnishing, cold deep-rolling and ultrasonic shot peening[1~4] are recognized as alternative methods that expanded research and applications in combat against fatigue failures. Worthy of note are those, such as ultrasonic shot peening, ultrasonic impact treatment[5], ultrasonic burnishing[6] and ultrasonic aided deep rolling(UADR)[7] that uses ultrasonic vibration as driving energy for some special applications are attracting more attention of the shot peening society.

The present research investigated the effects of ultrasound-aided deep rolling process on fatigue enhancement of 30CrMnSiNi2A steel. 30CrMnSiNi2A specimens were treated by UADR process followed by fatigue test for fatigue performance evaluation. Residual stress profile and full width at half maximum (FWHM) were measured by XRD. Vickers micro-hardness tester was used to check the hardness profile of the surface layer of the treated specimen. Surface finishing and roughness were observed and measured by optical micrograph and a Talysurf roughness tester, respectively. Fractography of the fatigue fractured specimens was observed via scanning electron microscope(SEM).

## Experimental Methods

In the UADR device, a free rolling metallic ball is impulsively energized by ultrasonic vibration and simultaneously applied flexible ‘static pressure’, Fig.1. The ultrasonically accelerated ball of heavy mass impulsively impinges and rolls the surface of the part, so that roughness are flattened and residual plastic deformation is produced leading to improved surface finishing, compressive residual stress and work hardened surface layer. Free rolling with dynamic contact and ultrasonic suspension enables friction free rolling contact, so that deeper layer of compression can be exerted without nicking.

Two groups of ground planar fatigue specimens were prepared in the present works, of which, one was treated by the UADR process on a CNC machine center and the other left untreated for comparisons. The material of the specimens is quenched and tempered ultra-high strength 30CrMnSiNi2A steel with chemical compositions in wt% as: 0.3C, 1.1Mn, 1.0Si, 1.05Cr, 1.7Ni, 0.009S, 0.010P, balance:Fe. The tensile mechanical properties of the materials are, UTS=1627MPa, 0.2% yield strength=1375MPa. Fig.2 schematically illustrates the moving route of the ball on the surface of the specimen being treated. Surface profile and roughness in both the longitudinal and the transverse directions of the treated and the untreated specimens were measured on a TR-204 Talysurf Roughness Tester. Surface finishing observations were carried out via an Olympus optical microscope.

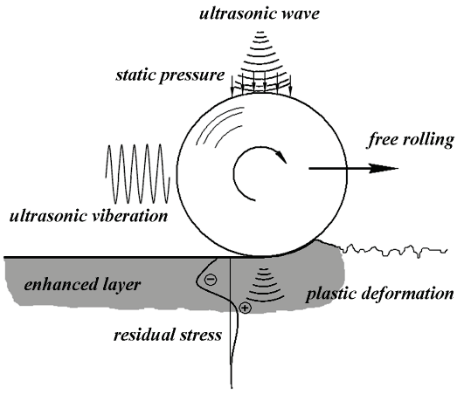

Fig. 1 Schematics of the UADR process

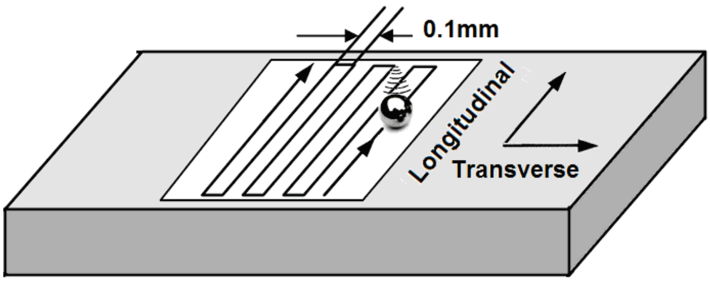

Fig.2 Schematics of the ball moving routine

Residual stresses at the surface and subsurface region of the parts were obtained using Stresstech X-3000 X-ray diffraction tester with the $\sin^2\psi$-method with Cu K$\alpha$ radiation at the {211} plane of the samples. The FWHM (full width at half maximum) distributions at the surface and subsurface layer of samples were measured as well. In-depth profile of residual stress and FWHM were determined by successively removing materials with electro polishing while attention was paid to minimize alteration of residual stress distribution.

The hardness profile in the subsurface of treated sample after polishing and etching (in solution of 5% $HNO_3$ and 95% $CH_2CH_3OH$) was examined with a Vickers micro-hardness tester with a load of 0.1 N and loading duration of 15s. The surface hardness of the untreated sample was also tested with the same method.

For both groups of specimens, tension-compression fatigue tests were performed with stress ratio R=-0.976, maximum stress=670MPa, minimum stress=-653.92MPa, and loading frequency of 10Hz at ambient temperature. The fractured fatigue specimens were ultrasonically cleaned in acetone solution for 5 min. followed by fractographic observation with scanning electron microscope (SEM).

## Results and discussions

### *Fatigue performance*

Table. 1 shows the fatigue test results. It indicates that all the 5 specimens UADR treated were not failed until $5\times10^5$ cycles, while the average cycles to failure for the untreated specimens is about $1.29\times10^5$, which means that the fatigue improvement of the UADR treatment is evident.

Table. 1 Fatigue test results

| *Group* | *Surface Treatment* | | *Cycles* | *Fatigue Failure* |
|---|---|---|---|---|
| *1* | *UADR* | *1* | 500000 | *No* |
| | | *2* | 500000 | *No* |
| | | *3* | 500000 | *No* |
| | | *4* | 500000 | *No* |
| | | *5* | 500000 | *No* |
| *2* | *Untreated* | *1* | 43585 | *Yes* |
| | | *2* | 120189 | *Yes* |
| | | *3* | 225448 | *Yes* |
| | | *4* | 102759 | *Yes* |
| | | *5* | 154861 | *Yes* |

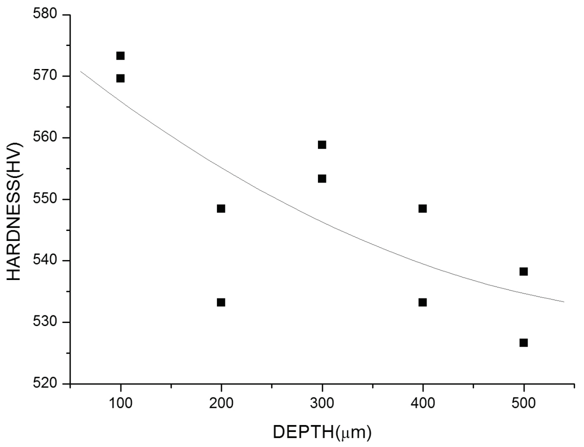

Fig.3 In-depth hardness profile after UADR

### *Hardness distribution*

The hardness distribution along the depth from the surface of the treated specimens is shown in Fig.3. It is shown that the hardness value decrease with increasing depth from the surface to 500 μm, while the hardness of the untreated surface is about 530 HV, which implies that the UADR treatment resulted in work hardening of the surface layer of the 30CrMnSiNi2A steel.

### *Residual stress and FWHM*

Fig.4 shows the residual stress distribution in the depth direction of the surface layer of the UADR treated sample. The residual stress along the depth direction distributes parabolically with a local extreme value of -1418MPa at depth about 150μm, and the residual stress on the immediate surface is -1120.9MPa, while the top surface residual stress of the untreated specimen (ground state) is -91.7MPa. Fig.4 also indicates that the depth of compressive residual stress layer produced by the UADR process is greater than 500 μm. The formation of a deep layer of compressive residual stress is believed to be the primary contribution of the

UADR process in improving the fatigue performance of the 30CrMnSiNi2A steel specimen in view of retarding fatigue crack initiation and propagation. Compared to the conventional shot peening process[8], the compressive residual stress generated by the UADR treatment is higher and the depth of the compressive residual stress layer is greater.

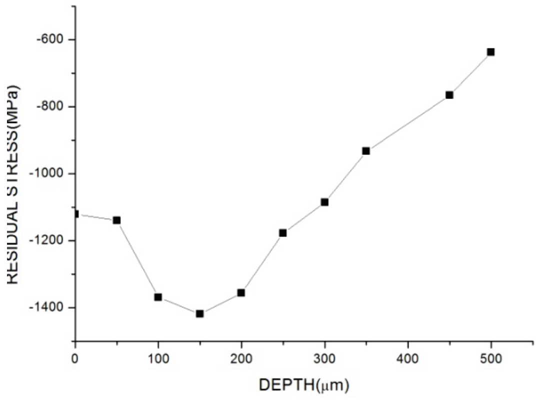

Fig.4 Profile of residual stress after UADR

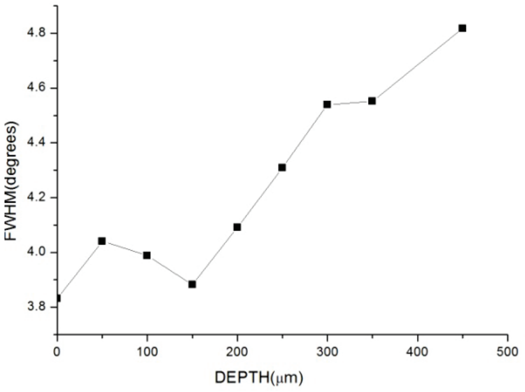

Fig.5Profile of FWHM after UADR

The FWHM value vs. depth profile in the layer of compressive residual stress is depicted in Fig.5. While exists a small fluctuation at about 50 μm, the general distribution tendency of FWHM value is increasing in the depth direction and attained a maximum at about 500 μm which is close to that of the untreated surface of 5.127. This phenomenon is a little bit confusing, as generally the FWHM value is considered to be a character parameter representing the degree of work hardening. The larger the FWHM value the greater the work hardening degree. However, the present FWHM results is in contradiction with the hardness distribution tendency discussed above, which implies that the value of FWHM could not describe the degree of work hardening for the ultra-high strength steel 30CrMnSiNi2A in the current work. In fact, the same phenomenon has been found in a previous research[9].

*Surface roughness and finishing*

After UADR treatment, the surface roughness Rz in the longitudinal direction decreased from 0.56 μm to 0.293 μm, while that in the transverse direction decreased from 0.973 μm to 0.653μm. Fig.6 is the optical micrograph of the surface topography of the specimens with and without UADR treatment. It shows that the surface finishing of treated surface area is much smoother than the untreated area. Besides, the pittings or scars on the untreated surface are diminished after UADR treatment which helps in reducing stress concentration.

The above results show a visible improvement of surface finishing after UADR treatment. Surface roughness and finishing are consider to be detrimental to fatigue crack nucleation due to stress concentration, so that reduction in surface roughness is one of the major contributions of the UADR process in improving the fatigue resistance of the specimens.

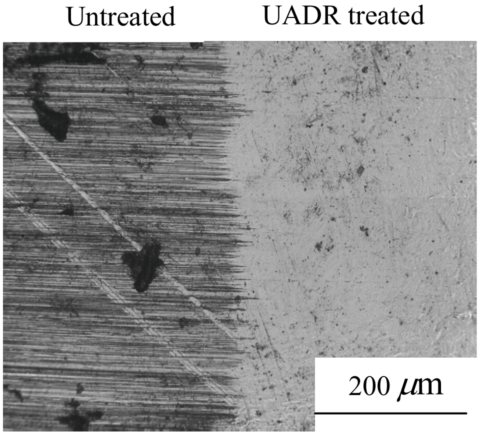

Fig.6 Surface topography

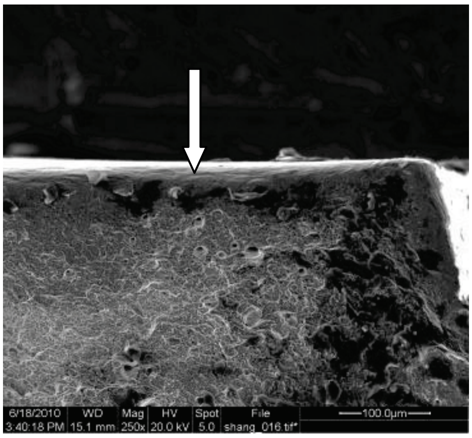

Fig.7 SEM fracture topography of the treated specimen

*Fractography of the fractured specimens*

The fatigue fractures of the specimens s are shown in Fig.7. A white layer(refer to the arrow) with the thickness of about 10 μm was generated in the top surface of the UADR treated specimen, while for the untreated specimens, no such feature can be observed. Previous researches explained that the white layer is composed of high density dislocations and ultra-refine grains due to severe plastic deformation and exhibits intense work hardening and this layer play the role of inhibiting crack initiation[10].

Fig.8 shows that the fatigue crack initiated from a pitting like defect on the surface of the untreated specimen, while the fatigue crack of the treated specimen initiated due to a metallurgical inclusion near the surface (refer to the arrow).

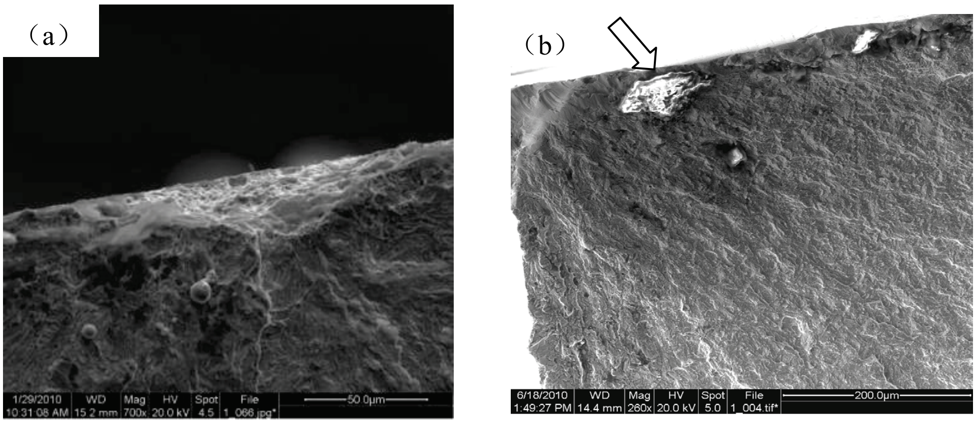

Fig.8 Crack initiation site of the specimens (a) untreated (b) UADR treated

## Conclusions

(1) The UADR treatment improved the fatigue resistance of the 30CrMnSiNi2A steel substantially.

(2) The UADR treatment produced deeper layer of compressive residual stress with maximum value of about -1418MPa and 150μm in depth.

(3) After UADR treatment, the surface roughness Rz in the longitudinal direction decreased from 0.56 μm to 0.293 μm, while that in the transverse direction decreased from 0.973 μm to 0.653μm, which means that the UADR treatment can improve the surface finishing of the 30CrMnSiNi2A steel.

(4) UADR treatment resulted in surface work hardening and a thin layer of ultra-refined microstructure.

(5) The current research results indicated that the FWHM value cannot correctly character the degree of work hardening of the 30CrMnSiNi2A steel.

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