JMEPEG (2010) 19:282–286
DOI: 10.1007/s11665-009-9445-3

Effects of Ultrasonic Nanocrystal Surface Modification (UNSM) on Residual Stress State and Fatigue Strength of AISI 304

A. Cherif, Y. Pyoun, and B. Scholtes

(Submitted January 22, 2008; in revised form June 2, 2008)

The effects of a new mechanical surface treatment method, called ultrasonic nanocrystal surface modification (UNSM), on near-surface microstructures and residual stress states as well as on the fatigue behavior of an austenitic steel AISI 304 are investigated and discussed. The results are compared with consequences of other mechanical surface treatment methods such as deep rolling or shot peening.

Keywords AISI 304, deep rolling, fatigue, residual stress, shot peening, ultrasonic nanocrystal surface modification (UNSM), work hardening

1. Introduction

It is well established that the fatigue behavior of metallic materials can be significantly improved by appropriate mechanical surface treatments. This is due to the formation of macroscopic compressive residual stresses and work hardening at the surface and in near-surface regions contributing to inhibit or retard the damage process of fatigue crack initiation as well as of fatigue crack growth (Ref 1-5). Different methods such as deep rolling, shot peening, and laser-shock peening have been developed. Their consequences on near-surface materials properties as well as on strength and lifetime under specific loading conditions have intensively been studied (Ref 6, 7).

Ultrasonic nanocrystal surface modification (UNSM) technology is a new kind of mechanical surface treatment technology (Fig. 1). The main concept and mechanism of UNSM is as follows: A tungsten carbide ball attached to an ultrasonic device strikes the surface of a workpiece 20,000 or more times per second with 1000 to 10,000 shots per square millimeter. These strikes, which can be described as micro cold forging, cause severe plastic deformation to surface layers and, therefore, induce nanocrystal microstructures. However, no information about residual stress distributions compared with conventional methods is available (Ref 8). The nano microstructure modification of surface layers can improve strength (hardness) and ductility (toughness) of the workpiece simultaneously according to the Hall-Petch relationship. This process also improves surface roughness and induces compressive residual stress in surface layers, which will in turn increase fatigue resistance of the workpiece. In this article, near-surface properties of UNSM-treated AISI 304 are compared with the results of analogous investigations of shot-peened and deep-rolled specimens and the stability of the proprieties during fatigue loading is studied.

2. Materials and Experimental Procedures

The investigated material was austenitic stainless steel AISI 304 with the chemical composition: 0.03% C, 0.58% Si, 1.14% Mn, 0.03% P, 0.03% S, 18.3% Cr, 8.8% Ni, and 0.06% N. The material was solution treated, quenched, and warm rolled to cylindrical bars (diameter of 14 mm). The microstructure was fully austenitic with an average grain size of 70 μm.

Cylindrical fatigue samples (Fig. 2) with a diameter of 7 mm and a gage length of 15 mm were used for fatigue tests to obtain S/N-curves. All tests were carried out under stress-controlled tension-compression loading at a stress ratio of $R = -1$ and at room temperature. Residual stress depth profiles were determined by x-ray diffraction (XRD) technique using the classical $\sin^2\psi$-method with CrKα radiation at the {220}-planes and $(1/2)\ s_2 = 6.05 \times 10^{-6}$ mm^2/N as elastic constant. The x-ray beam had a diameter of 1 mm. Near-surface work hardening was characterized by the FWHM values of the x-ray diffraction peaks. All residual stress and FWHM values were measured in longitudinal direction of the specimens. Residual stress and FWHM-depth profiles were determined by successive electrochemical removal of material without carrying out a stress correction. It is well known that in the case investigated here only negligible errors occur when measuring in near-surface areas (Ref 10).

Vickers hardness measurements were carried out on polished cross sections of the specimens.

Surface roughness was analyzed using a Perthometer S8P (Mahr).

Martensite content was determined by a standard procedure using x-ray diffraction technique. Two interference peaks of austenite and martensite, respectively, were taken into account.

A. Cherif and **B. Scholtes**, Institute of Material Engineering, University of Kassel, Kassel, Germany; and **Y. Pyoun**, DesignMecha/Mechanical Engineering Department, Sun Moon University, Asan City 336-708, Korea. Contact e-mail: echerif@uni-kassel.de.

3. Experimental Results and Discussion

Figure 3 shows the surface topography profile of the specimens before and after UNSM treatment (measured in longitudinal direction in two different positions). It can be seen from the figure that the tooling marks due to the turning process have partially been flattened. As a consequence, surface roughness R_z improved from 1.7 to 1.3 µm. Figure 4 shows the micrograph of the surface.

Residual stress and FWHM-depth distributions were determined at three different locations in the gage length of the specimen (Positions 1-3, center, and ±5 mm).

The results are presented in Fig. 5 and 6. Compressive residual stresses as well as increased FWHM-values of x-ray diffraction peaks were observed at the surface and in near-surface region in all cases.

The stress values immediately at the surface vary between −1100 MPa (Position 3) and −635 MPa (Position 1). With increasing distance from surface, residual stress amounts decrease as well as their range of variation. Measurements along the circumference of the specimen showed only a small residual stress variation.

The thickness of the surface layer exhibiting compressive residual stress is approximately 0.4 mm.

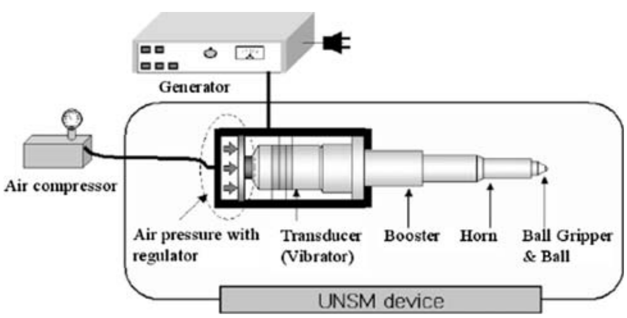

Fig. 1 UNSM system (Ref 8, 9)

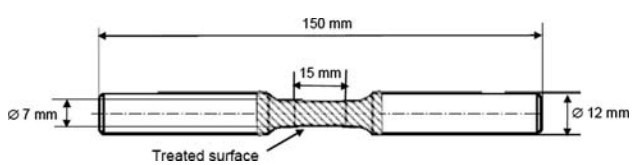

Fig. 2 AISI 304 specimen

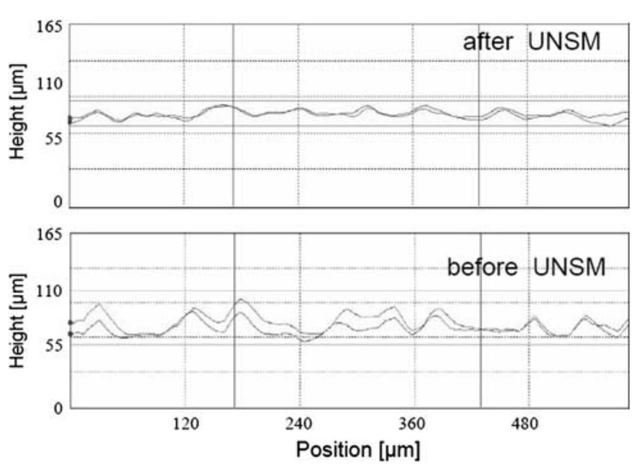

Fig. 3 Surface topography profile before and after UNSM-treated AISI 304

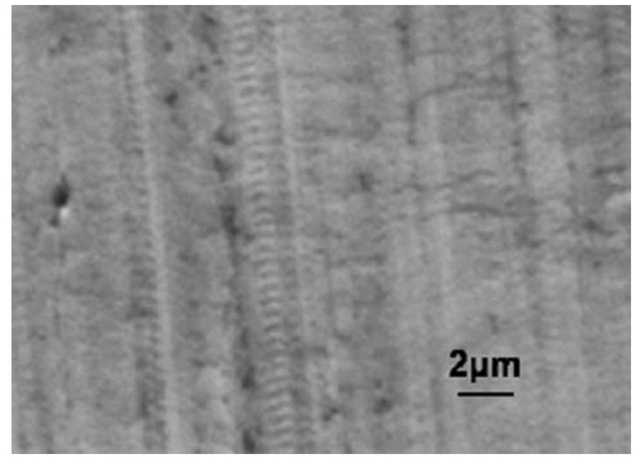

Fig. 4 SEM micrograph of UNSM-treated AISI 304 at the surface

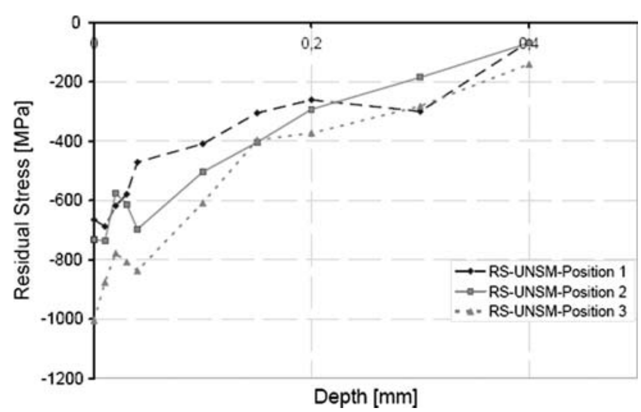

Fig. 5 Residual stress depth profiles of UNSM-treated AISI 304 at different surface positions

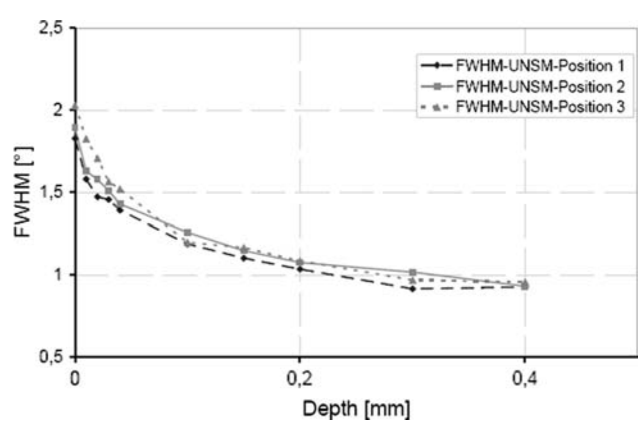

Fig. 6 FWHM depth profiles of UNSM-treated AISI 304 at different surface positions

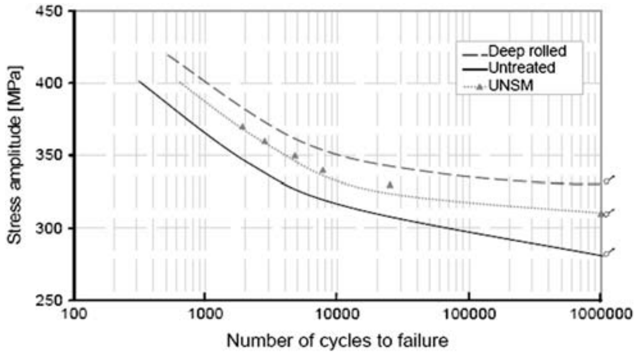

Fig. 7 S/N plot of room temperature-fatigued AISI 304 specimens in different surface treatment conditions (UNSM, deep rolled (Ref 11), untreated)

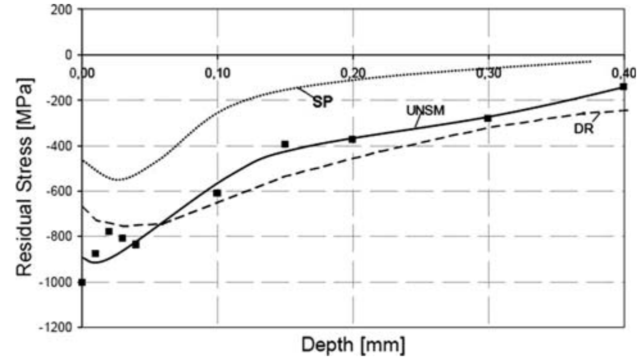

Fig. 9 Residual stress depth profiles of AISI 304 after different mechanical surface treatment [DR: deep rolled (Ref 11), SP: shot peened (Ref 7)]

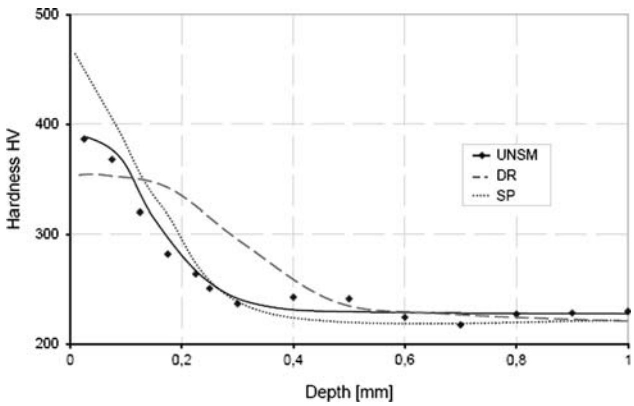

Fig. 8 Vickers hardness depth profile of AISI 304 after different mechanical surface treatment [DR: deep rolled (Ref 11), SP: shot peened (Ref 12)]

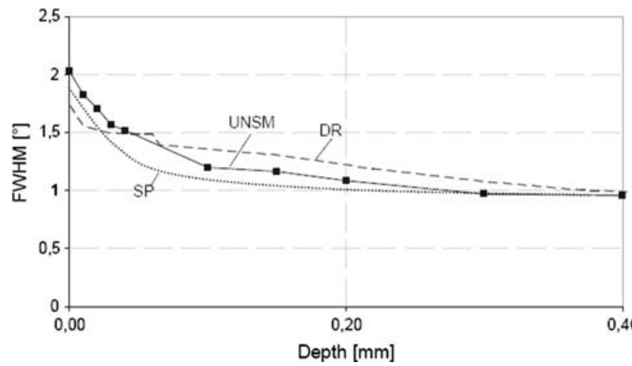

Fig. 10 FWHM depth profiles of AISI 304 after different mechanical surface treatment [DR: deep rolled (Ref 11), SP: shot peened (Ref 7)]

The FWHM values in the near-surface regions increase from approximately 0.9° in the bulk to 2° at the surface.

Similar depth distributions were measured at all three measuring positions. However, position 3, with maximum compressive residual stress, shows slightly higher FWHM values near the surface than in the other cases. Corresponding to the residual stress depth distribution, the thickness of the affected surface layer is about 0.4 mm.

A limited number of specimens were available for fatigue tests. Consequently, the S/N-curves shown in Fig. 7 allow only a rough estimation of the fatigue strength of UNSM-treated specimens compared to the untreated and the deep-rolled state. From Fig. 7, one can conclude that UNSM treatment clearly improves fatigue strength and lifetime in the high as well as in the low cycle fatigue regime compared to the starting condition with a turned surface, but it is not as effective as deep rolling. One has, however, to take into account that process parameters, although realistically chosen, were not optimized for highest fatigue performance, which limits the validity of Fig. 7.

For a more detailed assessment of the consequences of UNSM treatment in Fig. 8 to 10, characteristic near-surface properties measured in the center of the gage length are compared with the characteristics of shot-peened or deep-rolled specimens (Ref 7, 11, 12). Figure 8 shows that distinct differences exist between the measured hardness depth distributions. Shot peening produces the highest hardness values immediately at the surface, whereas in the case of deep rolling, a thicker surface layer is affected. It is interesting to note that this is in contrast to the residual stress depth distribution (see Fig. 9) and FWHM depth distribution (see Fig. 10), where specimens treated by UNSM technique show the highest values in near-surface regions.

The hardness values increase from approximately 220 HV in the unaffected bulk of the material up to 390 HV at the surface after UNSM treatment.

Shot peening leads to the highest surface hardness of about 450 HV. The influence of deep rolling on hardness achieves a depth of about 0.55 mm compared to 0.3 mm after UNSM treatment as well as of shot peening; however, hardness values immediately at the surface are lower than in the other cases.

From Fig. 9 it is evident that residual stress depth distributions of UNSM-treated and deep-rolled specimens are very similar with higher amounts after UNSM treatment at the surface and somewhat lower amounts at greater distances from the surface. The residual stress values of shot-peened specimens are clearly smaller, and the affected surface layer is thinner.

Similar observations can be made regarding the depth distributions of FWHM values. Again, UNSM treatment leads to higher values at the surface, and the deep-rolled specimens show the thickest affected surface layer. Immediately at the

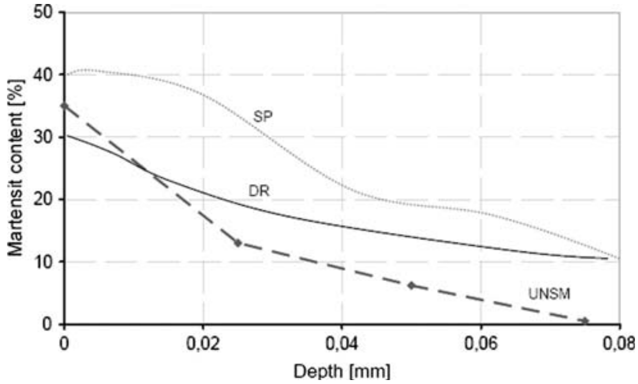

Fig. 11 Martensite content depth profile after different kinds of surface treatment [DR: deep rolled (Ref 7), SP: shot peened (Ref 7)]

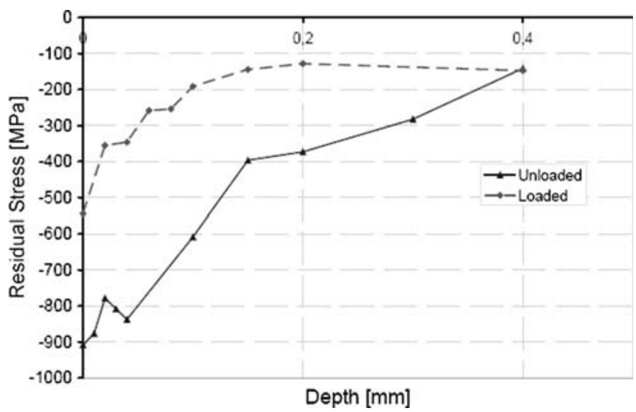

Fig. 12 Residual stress depth profiles of UNSM-treated AISI 304 unloaded and fatigued to half the number of cycles to failure (stress amplitude σ_a = 340 MPa)

surface, shot peening leads to higher FWHM values than deep rolling (Ref 7; Fig. 11).

As a consequence of the surface treatments applied, mechanically induced martensite is formed in the surface layer of AISI 304. The measured martensite content strongly depends on the type of the process applied. Shot peening leads to the highest transformation effects at and below the surface. UNSM treatment leads to a martensite content of approximately 35% immediately at the surface. This value continuously decreases with increasing distance from the surface; except for layers very close to the surface, the value is always smaller than for shot peening or deep rolling.

Figures 12 and 13 show the relaxation behavior of macroscopic compressive residual stresses as well as of FWHM values of UNSM-treated specimens fatigued to half the number of cycles to failure. One observes that cyclic loading at a stress amplitude of 340 MPa (N_f = 8000 cycles) leads to a reduction of surface compressive residual stresses by approximately 60%. A similar residual stress relaxation was also observed below the specimen's surface.

FWHM values relax too, indicating that microstructural alterations occur in near-surface layers due to the cyclic loading process. However, the work hardening effect of UNSM treatment is still visible after half the number of cycles to failure.

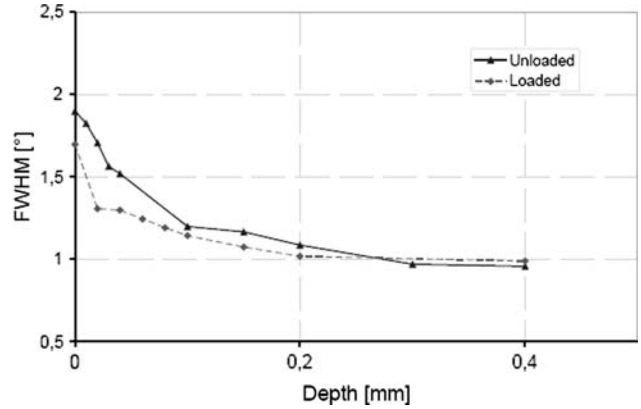

Fig. 13 FWHM depth profiles of UNSM-treated AISI 304 unloaded and fatigued to half the number of cycles to failure (stress amplitude σ_a = 340 MPa)

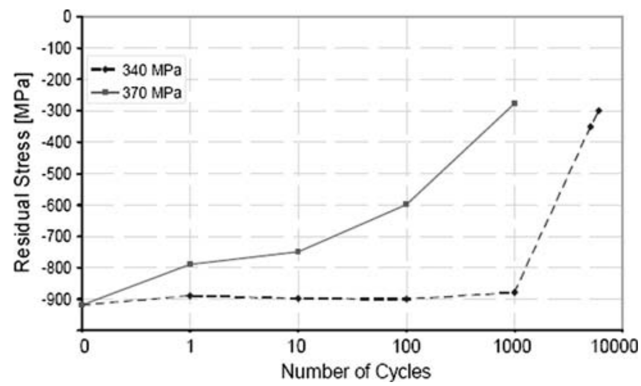

Fig. 14 Residual stress relaxation at the surface of UNSM-treated AISI 304 during stress-controlled fatigue at room temperature for different stress amplitudes

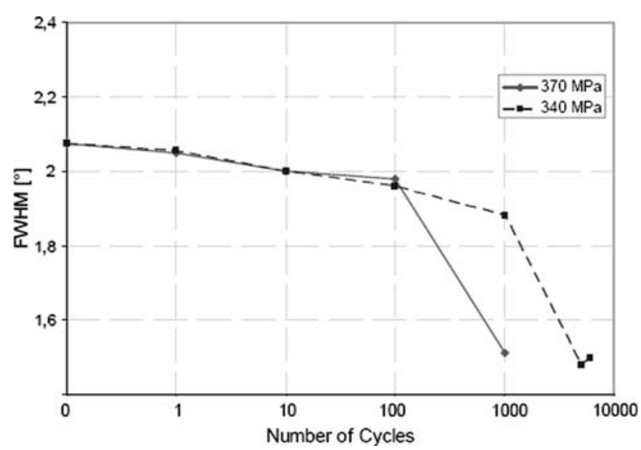

Fig. 15 FWHM value relaxation at the surface of UNSM-treated AISI 304 during stress-controlled fatigue at room temperature for different stress amplitudes

Figures 14 and 15 show the relaxation of macroscopic compressive residual stresses as well as of FWHM values at the surface of UNSM-treated specimens as a function of the number of loading cycles for two different stress amplitudes. For the lower stress amplitude of 340 MPa, residual stress remains stable during the first 1000 loading cycles and then decrease until fracture occurs. On the other hand, for a stress amplitude of 370 MPa, leading to fracture already after approximately 1000 cycles, a continuous residual stress relaxation is observed. For both loading amplitudes, FWHM values decrease with increasing number of cycles, indicating a continuous alteration of UNSM-induced microstructures during fatigue loading.

4. Conclusions

The experiments presented in this article were oriented toward gaining basic information about the effects of UNSM treatment in comparison with more traditional and well-established mechanical surface treatment methods of austenitic steel AISI 304, i.e., shot peening and deep rolling. As a result of the tests, it is evident that the near-surface microstructures achieved during the UNSM process are comparable with properties of shot-peened, deep-rolled, or laser shock-peened layers. First of all, it has to be mentioned that a surface layer with high compressive residual stresses is formed together with a remarkable strain-hardening effect. For the material investigated in this work also a mechanically induced phase transformation from austenite to martensite could be detected. The differences of the depth distributions of the properties measured have to be attributed not only to the characteristic features of the processes compared but also to the individual process parameters applied. Consequently, no general conclusions should be drawn about the effectiveness of individual processes to create compressive residual stresses, strain hardening, or other beneficial effects in near-surface layers. It is rather a question of choosing the right method together with appropriate process parameters to achieve optimum conditions in individual cases. It is therefore not surprising that the consequences of cyclic loading on near-surface properties of UNSM-treated AISI 304 are in agreement with observations made for other mechanical surface treatments as well. For the stress amplitudes applied, a partial relaxation of strain hardening as well as of macroscopic residual stress could be detected.

Altogether, it can be concluded that UNSM treatment gives rise to excellent near-surface materials microstructures. Because of the outstanding importance of the properties of near-surface layers for strength and lifetime of components, it can therefore be a very powerful tool to produce high-strength, light-weight structures.

References

1. A. Niku-Lari, Ed., *Advances in Surface Treatments*, Pergamon Press, Oxford, 1987
2. B. Scholtes, Assessment of Residual Stresses, *Structural and Residual Stress Analyses by Nondestructive Methods*, V. Hauk, Ed., Elsevier, Amsterdam, 1997, p 590–632
3. L. Wagner, Mechanical Surface Treatments on Titanium, Aluminum and Magnesium Alloys, *Mater. Sci. Eng. A*, 1999, **263**, p 210–216
4. B. Scholtes and E. Macherauch, Auswirkung mechanischer Randschichtverformungen auf das Festigkeitsverhalten metallischer Werkstoffe, *Z. Metallkd.*, 1986, **77**(5), S. 322
5. V. Schultze, *Modern Mechanical Surface Treatment*, Wiley-VCH, Weinheim, 2005
6. R.K. Nalla, I. Altenberger, I. Noster, G.Y. Lui, B. Scholtes, and R.O. Ritchie, On the Influence of Mechanical Surface Treatments—Deep Rolling and Laser Shock Peening—on the Fatigue Behaviour of Ti-6Al-4V at Ambient and Elevated Temperatures, *Mater. Sci. Eng. A*, 2003, **355**, p 216–230
7. I. Altenberger, B. Scholtes, U. Martin, and H. Oettel, Cycle Deformation and Near Surface Microstructures of Shot Peened or Deep Rolled Austenitic Steel AISI 304, *Mater. Sci. Eng. A*, 1999, **264**, p 1–16
8. Y.-S. Pyun, H.S. Kim, K.G. Son, G.H. Song, M.K. Kim, J.H. Kang B.U. Choi, J. Park, I.H. Cho, C.S. Kim, J.H. Park, and J. Kinney, Development of D2 Tool Steel Trimming Knives with Nanoscale Microstructure, *Proceedings of the AISTech Conference*, Vol. 2, 2005, p 465–474
9. C.-M. Suh, G.-H. Song, and Y.-S. Pyoun, Fatigue and Mechanical Characteristics of Nano-Structured Tool Steel by Ultrasonic Cold Forging Technology, *Mater. Sci. Eng. A*, 2007, **443**, p 101–106
10. B. Scholtes and E. Macherauch, *Eigenspannungsanalysen unter partieller Probenzerstörung mit Hilfe von Röntgenographischer Methoden*, Deutscher Verband für Materialprüfung E.V., Berlin, 1987, p 301–312
11. I. Nikitin and I. Altenberger, Comparison of the Fatigue Behavior and Residual Stress Stability of Laser-Shock Peened and Deep Rolled Austenitic Stainless Steel AISI 304 in the Temperature Range 25–600 °C, *Mater. Sci. Eng. A*, 2007, **465**, p 176–182
12. I. Altenberger, Mikrostrukturelle Untersuchungen mechanisch randschichtverfestigter Bereiche schwingend beanspruchter metallischer Werkstoffe, Forschungsberichte aus dem Institut für Werkstofftechnik, Metallische Werkstoffe, 1999