Cyclic deformation behaviour of deep rolled and laser-shock peened AISI 304 stainless steel at elevated temperature

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Abstract
Deep rolling and laser-shock peening can significantly improve the fatigue behaviour of metallic materials. These surface treatments induce beneficial residual stress states and lead to characteristic microstructural alterations. Compressive residual stresses as well as work hardening are known to reduce fatigue crack initiation and propagation. The cyclic deformation behaviour of mechanically surface treated metallic materials depends on the nature and stability of these near-surface regions during servive load. For instance, in power plants or gas turbines, the thus treated regions are exposed to elevated temperatures as well as mechanical loading, leading to severe alterations of the residual stress state during service. In this study, we compare the state and stability of near-surface residual stresses and microstructures of fatigued austenitic stainless steel under stress-control in the temperature range 25°C to 600°C in three different surface states, namely milled (untreated), deep rolled and laser-shock peened.

1. Introduction

It is well known, that localized elastic-plastic deformations in near-surface regions of metallic surfaces induce several beneficial effects such as compressive residual stresses and strain hardening thus enabling the strengthened near-surface regions to exhibit higher resistance against fatigue crack initiation and propagation [1,2,3]. For AISI 304, laser-shock peening and deep rolling lead to completely different near-surface microstructures associated with different mechanical and thermal stability. During high temperature fatigue of mechanically surface treated AISI 304 the relaxation of compressive residual stresses is more than 50 % in the LCF-regime (σ_a = 280 MPa, duration of the test 7 min) [4]. In this temperature region, the amount of lifetime enhancement is predominantly influenced by near-surface microstructures rather than by macro residual stresses. Therefore, the analysis of the stability of near-surface microstructures is a necessary prerequisite for utilising such materials under elevated temperature loading conditions.

2. Experimental procedures

The material investigated was hot-rolled AISI 304 stainless steel. Uniaxial tensile testing at 25 °C gave a yield strength of 345 MPa and 52 % elongation. For the deep rolling treatment, a pressure of 150 bar (0.5 kN rolling force) and a spherical rolling element (diameter 6.6 mm) was applied. Laser-shock peening was carried out with a coverage of 200 %, a power density of 10 GW/cm², a pulse time of 18 ns and a spot size of 1,5 x 2,5 mm². Residual stress measurements were performed by X-ray diffraction techniques with CrKa-radiation using the (220)-Bragg peak of the austenite. Isothermal fatigue experiments were performed under load control on a servohydraulical testing machine with a load ratio of R = -1, a frequency of 5 Hz and temperatures of 25-600°C.

The cylindrical samples (diameter 7 mm) were heated with a halogenic radiant heating. Transmission electron microscopy (TEM) was performed using a 200 kV microscope on plan-view samples under two-beam conditions. Local crack growth rates were determined by measuring striation spacings on fracture surfaces. The data represent mean values of 5 single measurements.

3. Results

Deep rolling induced a nanocrystalline layer directly at the surface, containing deformation-induced martensite and high dislocation densities in the austenite phase (Figure 1) as well as high compressive residual stress. Residual stresses are about –670 MPa at the surface and –750 MPa in the subsurface maximum in a depth of 50 µm [4]. The highest martensite content is at the surface and then declines continuously to zero until a depth of approximately 200 µm. Laser-shock peening (LSP) induced a layer with high dislocations densities (Figure 1) and a lower compressive residual stress as compared to deep rolling. Here, the highest residual stresses are about –300 MPa directly at the surface. In comparison to deep rolled samples neither any nanocrystalline layers nor pronounced martensitic transformations were detected. In regard to near-surface work hardening, which can be measured indirectly by half-width values of X-ray diffraction peaks, it was observed that for all treatments work hardening is highest directly at the surface and slowly decays to a constant level in deeper regions [4].

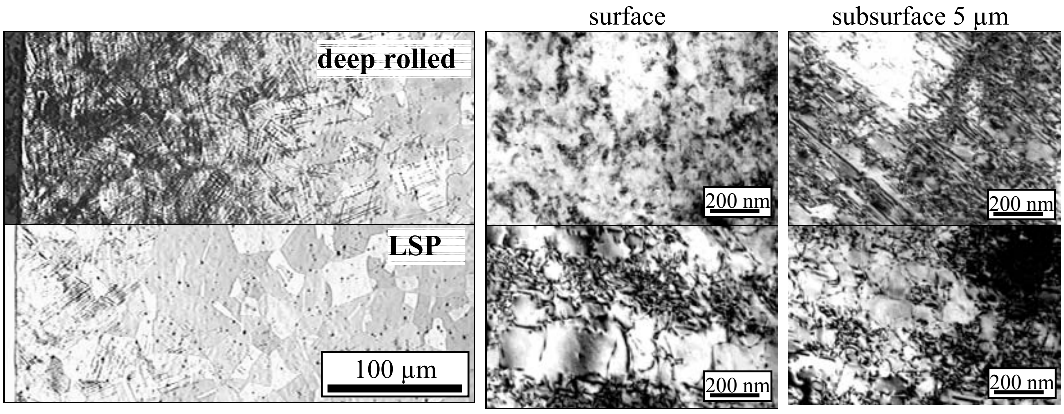

Figure 1: Microstructure of deep rolled and laser-shock peened (LSP) AISI 304

Deep rolling and laser-shock peening improves the fatigue behaviour of AISI 304 at all investigated amplitudes and temperatures from 25 °C to 600 °C. The cyclic deformation curves of deep rolled and laser-shock peened samples for a stress amplitude of 280 MPa and different test temperatures are shown Figure 2. Both surface treatments decrease the plastic strain amplitude as compared to the untreated material state (Figure 3).

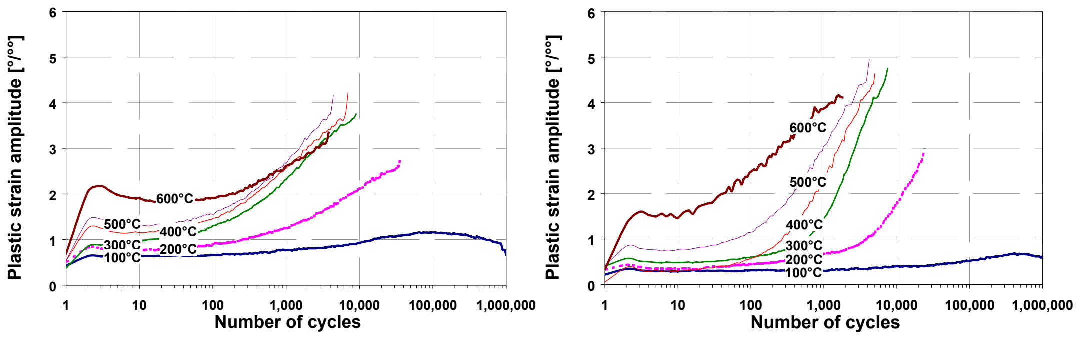

Figure 2: Cyclic deformation curves of deep rolled (left) and laser-shock peened (right) AISI 304 (σ_a = 280 MPa)

Moreover, both surface treatment states exhibit pronounced cyclic softening above 100-200 °C. With rising temperature increased plastic strain amplitudes occurred. A comparison of the cyclic deformation curves of the deep rolled and laser-shock peened condition reveals that at high test temperatures the plastic strain amplitude of the deep rolled condition is higher as compared to the laser-shock peened condition during the initial stages of fatigue. However, at higher number of cycles this behaviour is reversed. With increasing temperature the intercept point between the cyclic deformation curve of the laser-shock peened condition and the deep rolled condition shifts to lower number of cycles (Figure 3).

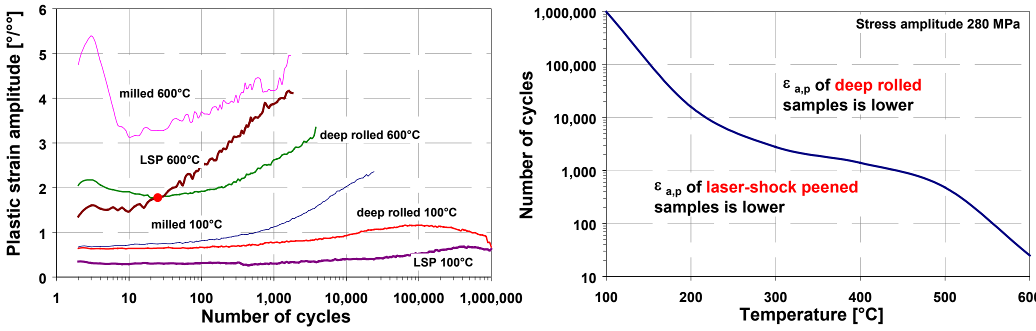

Figure 3: Cyclic deformation curves of milled, deep rolled and laser-shock peened (LSP) AISI 304 (σ_a = 280 MPa)

Since the extent of residual stress relaxation is governed by the amount of cyclic plastic strain [5], as characterised by the plastic strain amplitude, for instance, the kinetics of residual stress relaxation are expected to be different for the two investigated surface conditions.

If the stress amplitude is decreased from 280 MPa to 240 MPa the intercept point of the two cyclic deformation curves moves to higher number of cycles. For a stress amplitude of 240 MPa, the laser-shock peened condition exhibits almost up to fracture a lower plastic strain amplitude than the deep rolled condition (Figure 4, left).

Apart from lowering the plastic strain amplitude during the crack initiation phase, fatigue crack propagation is also decreased by deep rolling and laser-shock peening (Figure 4, right).

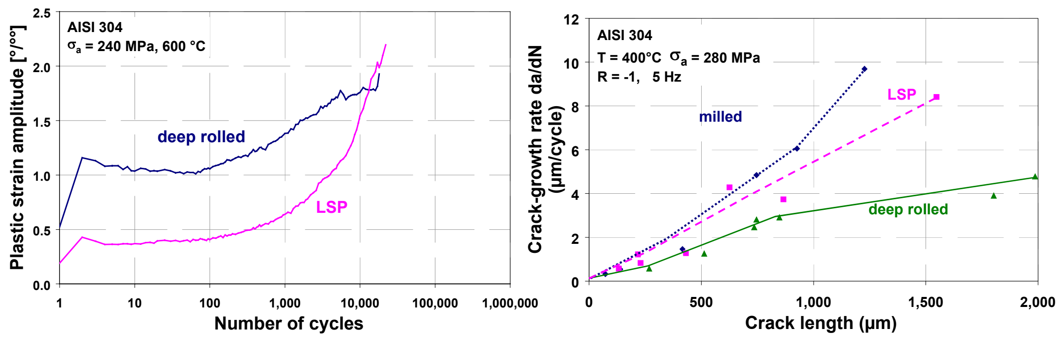

Figure 4: Cyclic deformation curves of deep rolled and laser-shock peened (LSP) AISI 304 (σ_a = 240 MPa) (left) and crack growth rates from striation spacing measurements on fracture surfaces milled, laser-shock peened and deep rolled AISI 304 (400°C σ_a = 280 MPa) (right)

For all crack growth stages, both investigated surface treatments reduced the crack growth rate significantly, even in regions deeper than the surface treatment induced „case“. Deep rolling reduced the crack growth rate more effectively than laser-shock peening.

The work hardening state can be characterised by measuring half-width values of X-ray diffraction peaks. The half-width values contain valuable information about the microstructural state of mechanically surface treated materials. The higher the half-width value, the higher the inhomogeneous microstresses, as e.g. produces by work hardening. Therefore, we can characterise alterations of near-surface microstructures during fatigue loading. Figure 5 (left) depicts the evolution of the half-width value of the surface as a function of fatigue test temperature for a given stress amplitude at σ_a = 280 MPa and a constant number of cycles of 2000. One can see, that the work-hardening decreases linearly for both surface conditions with increasing temperature, in spite of completely different initial near-surface microstructures. The kinetics of microstress reduction are almost the same for both conditions, since the slope of both linear fits are very similar. In the material states fatigued at 600 °C the near-surface work hardening decreased by 67 % in the laser shock-peened condition as compared to 40 % in the deep rolled condition.

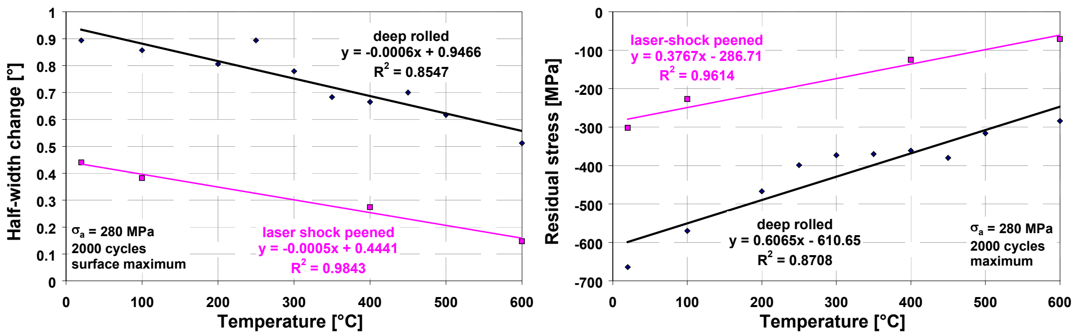

Figure 5: Half-width value change and residual stress state of surface regions for deep rolled and laser-shock peened AISI 304 as a function of test of temperature (σ_a = 280 MPa, 2,000 cycles)

Figure 5 (right) shows the macro residual stress relaxation as a function of test temperature during fatigue for both surface conditions. Obviously, the kinetics of residual stress relaxation during isothermal fatigue are different for both surface treatments. In both cases residual stress relaxation increases linearly with temperature, however, the slope of the curve for deep rolled samples is higher than for the laser shock peened condition (0.6 as compared to 0.4). The residual stress relaxation at the surface is about 58 % for the deep rolled and about 76 % for the laser-shock peened state after 2000 cycles at 600°C.

4. Discussion

The cyclic deformation behaviour of laser shock peened and deep rolled AISI 304 is distinctly different: At low stress amplitudes and low temperatures the laser-shock peened condition exhibits lower plastic strain amplitudes and higher lifetime than the deep rolled surface state. This behaviour is completely reversed at elevated temperatures and high stress amplitudes, where the deep rolled condition generally yields superior fatigue properties as compared to the laser-shock peened state.

These findings can be explained by taking into account, firstly, the different initial near- surface microstructures of the two surface treated states, secondly, the different thermomechanical stability during fatigue loading, and thirdly, the different depth of the work hardened layer.

Whereas the deep rolled surface state exhibits partially martensitic regions as well as a nanocrystalline surface layer, none of these features are present in the laser-shock peened condition. Instead, dislocation tangles in high density extend deeper into the material in the laser-shock peened condition than in the deep rolled condition [6].

At low temperatures, all surface treatment induced microstructures are basically stable. Nevertheless, at high stress amplitudes some relaxation of long-ranged macroscopic residual stresses may occur [2,7]. With increasing fatigue test temperatures and increasing stress amplitudes the surface treatment induced work hardening (primarily dislocation tangles in high density) „anneals out" or rearranges into low energy dislocation arrangements.

In contrast to that, the martensitic and nanocrstalline regions remain fairly stable [8], enabling the deep rolled state to withstand higher fatigue loading at elevated temperatures in the Low Cycle Fatigue regime as compared to the laser-shock peened condition. Although the work-hardening (as expressed by the half-width value) exhibits a similar stability in the laser-shock peened condition as compared to the deep rolled surface state, the „relaxation" begins at much lower initial half-width values in the laser-shock peened condition leading to much lower remaining work hardening at high temperatures.

Additionally, surface treatment induced macroscopic residual stresses are smaller and less stable during fatigue in the laser-shock peened surface state as compared to the deep rolled condition.

As a consequence of all these factors, the S/N-behaviour as well as the crack growth resistance (Figure 4) of deep rolled surface states is superior to the laser-shock peened condition at elevated temperatures in the LCF-regime. However, these conclusions are not to be applied to solely thermal exposure or predominantly HCF-fatigue, where the stability of the above mentioned microstructures is different [6,9].

5. Conclusions

The investigations on the high temperature fatigue behaviour of laser-shock peened and deep rolled AISI 304 can be summarised as follows.

(I) At low temperatures (100°C or lower) both surface treatment states exhibit initial cyclic softening followed by cyclic hardening for the stress amplitudes investigated.

(II) At elevated temperatures (above 200°C) this behaviour shifts to monotonous cyclic softening for both surface conditions.

(III) At high temperatures and high stress amplitudes, the deep rolled material condition exhibits lower plastic strain amplitudes and slightly longer lifetimes in stress controlled tests than the laser-shock peened condition. The opposite is true for low stress amplitudes and low temperatures. It appears that this effect can be attributed to the different thermomechanical stability of near-surface microstructures.

(IV) Macroscopic residual stresses as well as the near-surface work hardening (as expressed by half-width-values) decline linearly with increasing fatigue test temperatures.

(V) Exemplary studies on the fatigue crack growth behaviour reveal that the crack growth rate at 400°C is lowest for the deep rolled condition followed by the laser-shock peened condition.

6. Acknowledgement

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1 Scholtes B.: Eigenspannungen in mechanisch randschichtverformten Werkstoffzuständen Ursachen, Ermittlung, Bewertung, DGM Informationsgesellschaft Verlag, 1991
2 Altenberger I., et al.: Cyclic deformation and near surface microstructures of shot peened or deep rolled austenitic stainless steel AISI 304, Materials Science & Engineering A264, pp. 1-16, 1999
3 Wagner L.: Mechanical surface treatment on titanium, alluminium and magnesium alloys, Mater. Sci. Eng. A 1999, A263-210
4 Nikitin I., et al.: Residual stress state and cyclic deformation behaviour of deep rolled and laser-shock peened AISI 304 stainless steel at elevated temperature, ICRS-7, Xian, June 2004
5 Altenberger I., et al.: Analysis and assessment, of residual stress states in mechanically surface treated materials, Mater. Sci. Research Int., Special Technical Publication 1, pp. 275, 2001
6 Altenberger I., et al.: An in situ transmission electron microscope study of the thermallstability of near-surface microstructures induced by deep rolling and laser-shock peening, Scripta Materialia 48, pp. 1593, 2003
7 Holzapfel H., et al.: Residual stress relaxation in AISI 4140 steel due to quasistatic and cyclic loading at higher temperatures, Material Science and Engineering A248, pp. 9-18, 1998
8 Nikitin I., et al.: High temperature fatigue behaviour and residual stress stability of laser-shock peened and deep rolled austenitic steel AISI 304, Scripta Materialia 50, pp.1345, 2004
9 Prevey P.S., Proc.5th National Turbine Engine HCF Conference, 2001