Effect of Short-Time Annealing on Fatigue Strength of Shot Peened AISI 4140 in a Quenched and Tempered Material State

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1 Abstract

Increases of residual stress stability and alternating bending strength of shot peened AISI 4140 are obtained by subsequent annealing treatments. This is caused by static strain aging effects, which lead to pinning of dislocations by carbon atoms and finest carbides. It will be shown that by well directed annealing of a quenched and tempered AISI 4140 it is possible to maximize the positive effects of static strain aging without causing extended thermal residual stress relaxation. The amount of flow stress increases caused by static strain aging is quantified and correlated with the gain in alternating bending strength.

2 Introduction

It is known that shot peening at elevated temperatures, so-called warm peening, can significantly increase fatigue strength and life of quenched and tempered steels [1-2]. This is caused by dynamic and static strain aging effects [3]. For a quenched and tempered AISI 4140 an optimized peening temperature of about 310 °C was found [2,4]. When steel is thermally treated at elevated temperatures after being plastically deformed, an increase in yield stress due to static strain aging is observed. This could also be obtained by shot peening as a plastic deformation process with subsequent annealing, though this is hardly investigated yet [5]. Such static strain aging effects may be used to increase the fatigue limit and life of peened steels without the sumptuous experimental set-up of warm peening. However, at the same time thermal activated residual stress relaxation must be considered [6]. This paper explains the benefits of static strain aging on residual stress stability and on alternating bending strength of samples conventionally shot peened and subsequently annealed for relatively short times (1 – 60 min) at different temperatures. It will be shown that it is possible to separate the positive influence of static strain aging from the detrimental effects of thermal residual stress relaxation.

3 Material and Experimental Approach

The investigations were carried out using samples of the steel AISI 4140 (German grade 42 CrMo 4) with the chemical composition 0.42 C, 1.04 Cr, 0.14 Mo, 0.21 Si, 0.71 Mn, 0.01 P, 0.02 Al and balance Fe (all in wt. - %). The 110 mm long hourglass shaped samples with a minimal width of 18 mm were machined from flat material and ground to a thickness of 2.2 mm. Then they were austenitized for 20 min at 850 °C, martensitically hardened in oil (25 °C), tempered at 450 °C for 2 hours and cooled down in a vacuum furnace. After the heat treatment, the samples were ground to a thickness of 2.0 mm in order to eliminate distortions in their flatness. The final geometry of the samples can be seen in [1,2]. The shot peening treatments were performed using an air blast machine. The samples were peened from both sides simultaneously in order to avoid distortions. Cast iron shot S 170 with a hardness of 56 HRC was used at a peening pressure of 1.2 bar with a media flow rate of 1.0 kg/min. The Almen intensity was 0.24 mmA. The subsequent annealing was conducted in a salt bath furnace at defined temperature/time combinations. Residual stresses of the specimens were determined using X-ray technique. The {211}-interference lines of the ferritic phase were determined at 9 ψ-angles between –60° and +60° using CrKα-radiation and analyzed according to the $\sin^2\psi$-method [7]. Neglecting the elastic anisotropy, a Young's modulus E = 210 GPa and a Poisson's ratio ν = 0.28 were used. Mechanical testing was carried out on alternating bending machines at a frequency of 25 Hz. Between 25 and 30 specimens were used for each S-N-curve. The results were evaluated using the arcsin $\sqrt{P}$-method [8].

4 Results and Discussion

After shot peening compressive residual stresses σ_0^{FS} at the surface of about –660 MPa were measured. These samples were then annealed for 1, 5 or 60 min at different temperatures. The annealing caused corresponding residual stress relaxation, which can be described using a Zener-Wert-Avrami function

$$\frac{\sigma^{rs}(T_a,t_a)}{\sigma_0^{rs}} = \exp\{-[C \cdot \exp(-\Delta H / kT_a] \cdot t_a{}^m\} \tag{1}$$

where σ_0^{FS} is the initial residual stress state and σ_{FS} (T_a, t_a) the remaining amount of residual stresses after annealing at temperature T_a and time t_a. ΔH is the activation enthalpy, k the Boltzmann constant, and C and m are material related constants [6]. The thermal residual stress relaxation, which is increasing with increasing annealing temperature T_a can be seen in Fig. 1a-c (N = 0). For longer annealing times t_a the residual stress decline is stronger. With Eq.1 it is possible to determine the activation enthalpy ΔH as well as the constants C and m by using an iterative mathematical procedure based on a least squares algorithm [9]. The results for C, m and ΔH found are $4.96 \cdot 10^{13}$ 1/min, 0.138 and 2.23 eV, respectively. The calculated activation enthalpy of 2.23 eV is close to the value of the activation enthalpy for self-diffusion of α-iron (.2.6 eV). This implies that the main microstructural process responsible for the residual stress relaxation is controlled by volume diffusion controlled creep, which is determined mainly by climb of edge dislocations. Using Eq. 1 and the values found for C, m and ΔH the thermal residual stress relaxation is calculated and is spread in Fig. 1a - c (N = 0). It is in good accordance with the values measured. The ratios of the surface compressive residual stresses remaining after annealing plus defined loading amplitudes at alternating bending are also shown in Fig. 1. The applied alternating bending stress amplitude was $\sigma^*_{a,s}$ = 1000 MPa. The samples aged only at ambient temperature face a strong compressive residual stress relaxation of almost 50 % after the first bending cycle. Subsequent bending cycles (N = 10, 10^2, 10^3) provoke further stress relaxation down to a value of about 20 % of the initial compressive residual stress value. Increasing annealing temperatures lead to an increasing amount of remaining residual stresses, after quasi static (N = 1), and cyclic (N = 10, 10^2, 10^3) loading. Above a certain annealing temperature, a maximum of remaining residual stresses is found, depending on the annealing time. This is caused by static strain aging with the formation of carbon atom clouds mainly around edge dislocations and the associated stabilization of the dislocation structure. At further elevated temperatures the remaining residual stresses decrease again. The optimum annealing temperatures for AISI 4140 decrease with increasing annealing time from about 300 °C–350 °C for t_a = 1 min to 230 °C–260 °C for t_a = 60 min.

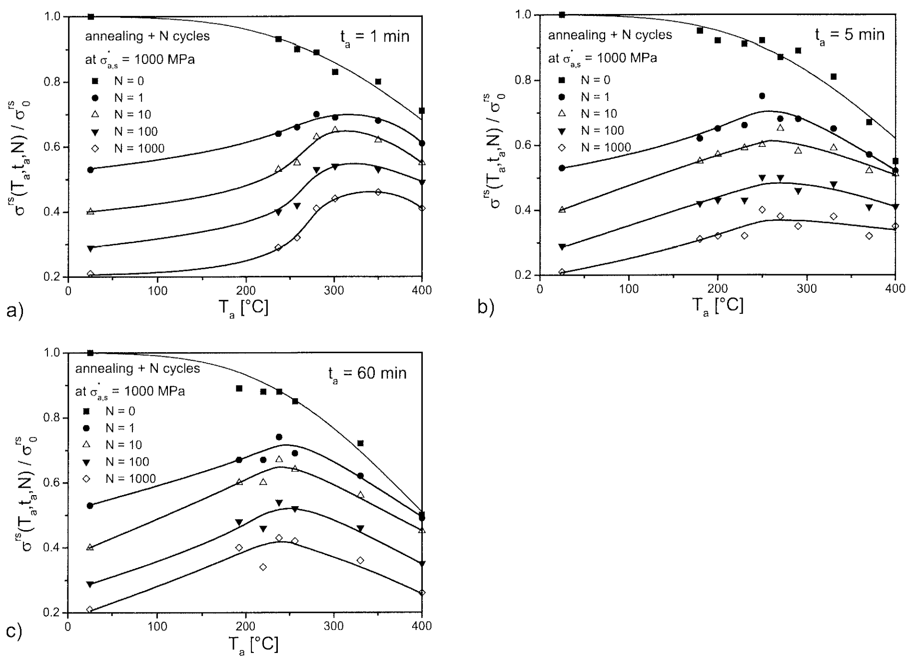

Figure 1: Ratios of the surface compressive residual stresses after annealing and defined alternating bending cycles

Static strain aging tests were conducted over a wide range of annealing temperatures and times to determine the yield stress increases $\Delta\sigma_{ssa}$ caused by static strain aging. After tensile loading to a total strain of 2 % the tensile samples specimen in a salt bath in the same way as the bending specimen. Afterwards they were reloaded until failure occurred. The yield stress increase caused by static strain aging was measured and is spread in Fig. 2 versus the annealing temperature T_a. There is a maximum in yield stress increase in the temperature range 250 °C $\leq T_a \leq$ 325 °C for the times investigated. This temperature range corresponds with the range in Fig. 1 for which the combined thermal and mechanical residual stress re-laxation decreases. For higher annealing temperatures over-aging with coarsening of carbides which is combined with dislocation rearrangements occurs and the values of $\Delta\sigma_{ssa}$ decrease again. This is more pronounced the higher the annealing times and temperatures are. The kinetics for coarsening of carbides are governed by the slowest participating partner, which is self-diffusion of α-iron instead of diffusion of carbon atoms during the formation of carbon clouds.

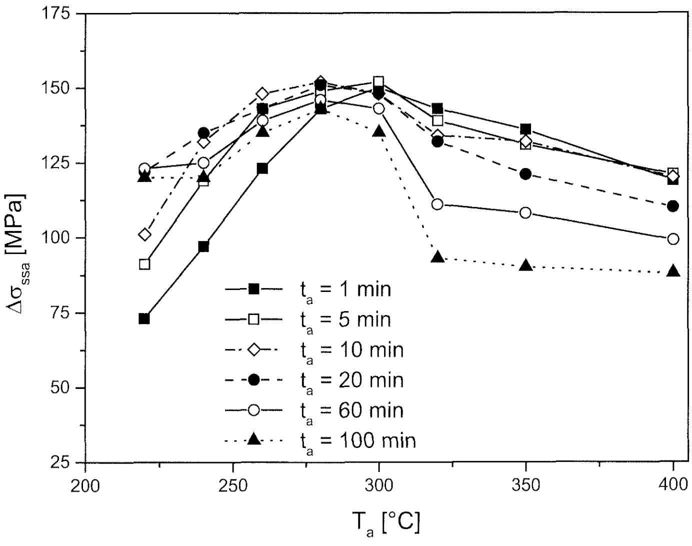

Figure 2: Yield stress increases in static strain aging tests vs. annealing temperature

It is unknown to which scale the alternating bending strength R_{ab} of the as shot peened state is improved by different annealing treatments, because not only the aging effects have to be taken into account, but also the detrimental effects of thermal residual stress relaxation. Therefore, the alternating bending strengths of shot peened samples were determined after annealing at different temperature/time pairs. For the annealing time t_a = 1 min temperatures of 235 °C, 280 °C and 300 °C were chosen to determine the respective alternating bending strengths. According to Fig. 1a those temperatures are equivalent to increasing residual stress stabilization, which was found after mechanical loading of specimens annealed for 1 min. The yield strength increases $\Delta\sigma_{ssa}$ shown in Fig. 2 are also increasing at t_a = 1 min with increasing annealing temperature up to a maximum of $\Delta\sigma_{ssa}$ = 150 MPa at 300 °C. Additionally, alternating bending strengths were determined for t_a = 60 min at 220 °C and 255 °C. According to Fig. 1c both variants are taken from the range of highest residual stress stabilization when annealed at t_a = 60 min. However, in Fig. 2 at t_a = 60 min the maximum of $\Delta\sigma_{ssa}$ is not yet reached at these temperatures. In [1] no increase of R_{ab} was found after the same shot peened steel was annealed at 300 °C / 20 min. However, Fig. 2 shows that for this annealing treatment there is an obvious increase of $\Delta\sigma_{ssa}$, which should improve the alternating bending strength. For clarification, R_{ab} was determined additionally for 300 °C / 20 min.

All results of the alternating bending strengths are shown in an extended residual stress Haigh - diagram in Fig. 3 where the alternating bending strengths R_{ab} are spread versus the residual stresses before cyclic loading. The solid Goodman line connects the R_{ab} of the nearly residual stress free ground state [1] (on the ordinate) with the UTS (1375 MPa) at the tensile side of the residual stress axis (not plotted in Fig. 3). The slope yields a residual stress sensitivity of 0.32, which is a value expected for quenched and tempered AISI 4140. The Goodman line is extended to the compressive side of the Haigh – diagram. This describes the expected increase of R_{ab} caused by the induced or remaining compressive residual stresses. However, as soon as the sum of loading stresses and assumed uniaxial residual stresses trespasses the cyclic yield strength $R_{e,s}^{cycl}$ residual stress relaxation occurs and no further increase of R_{ab} is possible. This is indicated by the dotted lines ($\sigma = R_{e,s}^{cycl} - \sigma^{FS}$). The one for the as shot peened state is originating at $R_{e,s}^{cycl}$ = 895 MPa [1] and the one for the shot peened plus annealed state originates at $R_{e,s}^{cycl}$ = 1052 MPa [10] (note, that in Fig. 3 only the range 300 MPa ≤ R_{ab} ≤ 900 MPa is shown). The increases of R_{ab} compared with the as shot peened state are between about 60 MPa and 150 MPa despite thermal residual stress relaxation caused by the annealing treatments. This indicates, that the increases of R_{ab} are caused by static strain aging. The extended Goodman line found for 300 °C / 1 min does not describe the respective alternating bending strength satisfactorily, though the tendency to increasing alternating bending strengths is clearly given. It is conceivable, that R_{ab} of a shot peened and annealed state, which would be assumed to be free of residual stresses could also be raised by short time annealing and that therefore it is not appropriate to use the regular Goodman line to describe the alternating bending strengths found after shot peening plus annealing.

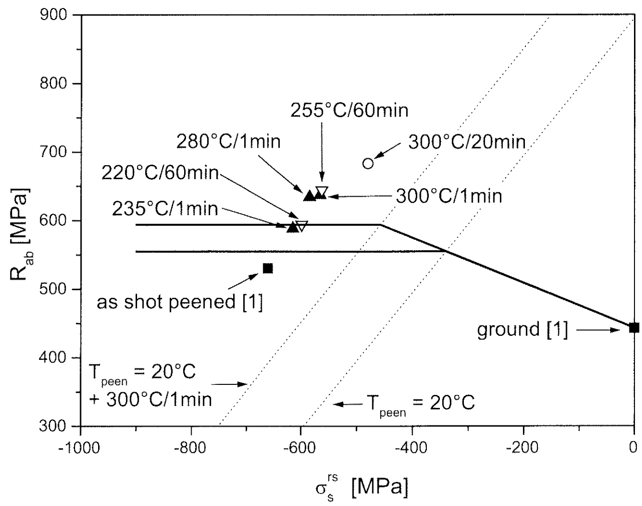

Figure 3: Extended residual stress Haigh – diagram for shot peened as well as shot peened plus annealed samples of AISI 4140

In Fig. 4 the increases of the alternating bending strength ΔR_{ab} compared with the as shot peened state are spread versus the flow stress increases $\Delta\sigma_{ssa}$ introduced in Fig. 2. The increases of the alternating bending strength correlate roughly linearly with the yield stress increases $\Delta\sigma_{ssa}$. After annealing for 1 min the strong increases of $\Delta\sigma_{ssa}$ with increasing annealing temperature cause corresponding ΔR_{ab}-increases. This correlates well with the increased stability of the residual stresses seen in Fig. 1a. While annealing for 60 min at 220 °C and 255 °C leads to similar remaining residual stresses after cyclic loading (Fig. 1c), strong changes in the alternating bending strength can be seen from Fig. 4. This shows that not only the residual stress stability but also the static strain aging itself lead to increases of the alternating bending strength. Finally, it can be stated that in contrast to [1] annealing at 300 °C / 20 min also increases R_{ab} of the as shot peened state.

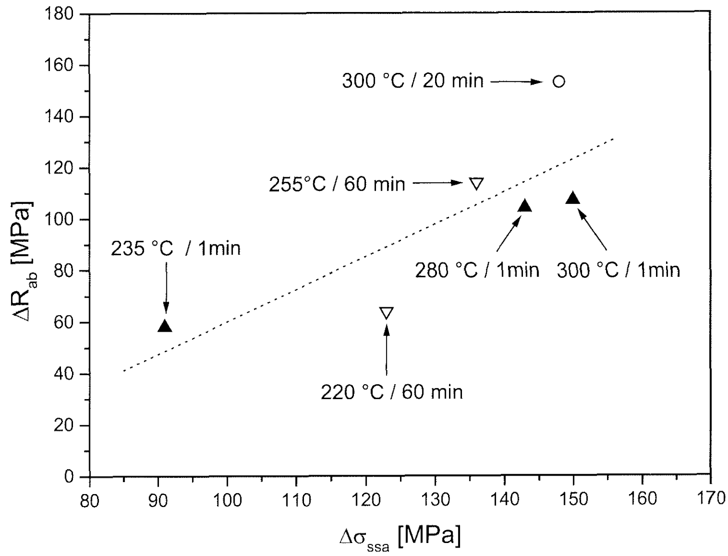

Figure 4: Effect of yield stress increase on the alternating bending strength caused by different annealing treatments

5 Conclusion

Shot peening with subsequent annealing was conducted. The residual stress relaxation behavior caused by the annealing process was modeled using a Zener-Wert-Avrami function. The activation enthalpy for residual stress relaxation was determined to 2.23 eV, which is in the range of the activation enthalpy for self diffusion of α-iron. Therefore, volume diffusion controlled creep is considered to be the main microstructural process that leads to residual stress relaxation. Well directed annealing treatments performed after shot peening clearly decrease the amount of mechanical residual stress relaxation in alternating bending compared to the as shot peened state. This is caused by the formation of carbon atom clouds around dislocations and very small carbides leading to highly stabilized dislocation structures. Tensile tests were conducted to quantify the yield stress increases caused by static strain aging. The results confirmed the temperature/ time ranges for which highest reductions of mechanical residual stress relaxation were found. The alternating bending strengths for selected shot peened and annealed variants were determined and compared with the alternating bending strength of the as shot peened state. Pronounced increases of the alternating bending strength after short-time annealing could be identified. Excessive annealing temperatures lead to over-aging, which is caused by coarsening of carbides and the rearrangement of dislocations. As long as over-aging is prevented it is possible to correlate the alternating bending strength increases with the flow stress increases found in tensile tests.

6 References

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