THERMOMECHANICAL SURFACE TREATMENT OF QUENCHED AND TEMPERED SAE 1045: A METHOD TO IMPROVE FATIGUE LIFE AND STRENGTH

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ABSTRACT
Thermomechanical surface treatments such as high-temperature deep rolling and deep rolling with consecutive annealing were developed from conventional surface treatment (deep rolling). The fatigue behaviour of thermomechanically treated quenched and tempered SAE 1045 was investigated using stress-controlled fatigue tests and compared with conventionally deep-rolled conditions (deep rolled at room temperature). Residual stress and work-hardening effects in the modified surface layer before and after the fatigue tests were investigated using X-ray diffraction methods.

KEY WORDS
Fatigue, thermomechanical surface treatment, deep rolling, residual stress

INTODUCTION
It is well established that conventional mechanical surface treatments such as shot peening or deep rolling can considerably improve the fatigue performance of metallic materials and, hence, are of great importance in the field of light weight constructions (Wohlfahrt, 2000, Schulze, 2005, Scholtes, 1990, Altenberger, 2000). The outstanding fatigue properties of the components treated are mainly attributed to the formation of strain hardened layers with compressive residual stresses as a consequence of near surface plastic deformations. Recently, thermomechanical methods have been developed, combining thermal and mechanical treatments, which have the potential to further increase fatigue strength or fatigue life resp. of the components processed (Nikitin, 2006, Wick, 2000, Mening, 2002). One distinguishes between simultaneous methods, i e. mechanical surface treatments at elevated temperatures, and consecutive treatments, where the mechanical process is followed by a thermal annealing process. In this paper, results of consecutive and simultaneous thermomechanical surface treatment processes applied to quenched as well as quenched and tempered plain carbon steel SAE 1045 are outlined and discussed.

MATERIAL AND EXPERIMENTAL DETAILS
The material investigated was the plain carbon steel SAE 1045. Cylindrical specimens with a diameter of 7 mm and a gage length of 15 mm were manufactured from rolled bars. Specimens were austenitized at 850 °C for 15 min and then quenched in water of room temperature. Subsequently, two batches were tempered at 400 °C or 530 °C resp. and cooled in air. The resulting hardness was 690 HV0.1 (hardened), 494 HV0.1 (T_A= 400 °C) and 371 HV 0.1 (T_A= 530 °C). For the deep rolling process, a pneumatic device was used. Rolling force was 1 kN with a feed of 0.11 mm/r and 80 rotations per minute. Specimen were heated by induction during the process and subsequently cooled in air.

Residual stresses were measured using the classical $\sin^2 \psi$-method. Depth profiles of residual stresses and FWHM-values were determined by successive electrolytical surface removal. Measurement were carried out with CrKα radiation at the {211}-planes and $(1/2)\ s_2 = 6{,}05 \times 10^{-6} mm^2/N$ as elastic constant. Near-surface work hardening was characterised by FWHM-values of the X-ray diffraction peaks. All residual stresses and FWHM-values were measured in longitudinal direction of the specimens. No stress correction was carried out after electrolytical material removal of surface layers.

Fatigue tests were carried out with servohydraulic testing machines under stress control without mean stress (R = -1) and a test frequency of 5 Hz.

RESULTS AND DISCUSSION

1. SIMULTANEOUS TREATMENTS

To limit the number of experiments, preliminary tests were made to identify optimum deep rolling temperatures. For this purpose, fatigue tests were carried out leading to appr. 10^4 cycles to failure. In Figs. 1a and b, results are shown. Increasing temperatures lead to clearly increased fatigue lifetimes. After reaching maximum values, however, the numbers of cycles to failure decrease for both heat treating conditions. Optimum temperature for the hardened state is 300 °C and for the quenched and tempered (T_A= 530 °C) state 350°C. Using these process parameters, near surface properties of the specimens treated were investigated more in detail. In Fig. 2, near surface hardness-depth distributions of differently treated specimens are shown. For the hardened materials state, no clear difference can be observed between the starting condition and the condition deep rolled at room temperature. However after deep rolling at 300 °C, hardness decreases by about 150 HV0.1. Quenched and tempered specimens (T_A= 530 °C), too, have identical hardness before and after deep rolling at room temperature. In contrast to the hardened state, after deep rolling at 350 °C a remarkable hardness increase is detected, especially very close to the surface.

In Fig. 3, the corresponding depth distributions of residual stresses and FWHM-values are given. After tempering at T_A= 530 °C, specimens are residual stress free. Deep rolling at room temperature, as expected, produces compressive residual stresses with maximum values of more than -700 MPa below the surface. A similar depth distribution is found after deep rolling at 350 °C, however with 100 MPa lower amounts. In both cases, FWHM-values increase after deep rolling, which is more pronounced for the deep rolling treatment at elevated temperature. Also in the case of the quenched materials state, deep rolling at elevated temperature produces compressive residual stresses. Near the surface, maximum values of -900 MPa are measured. FWHM-values however are diminished and are nearly constant within the probed surface layer.

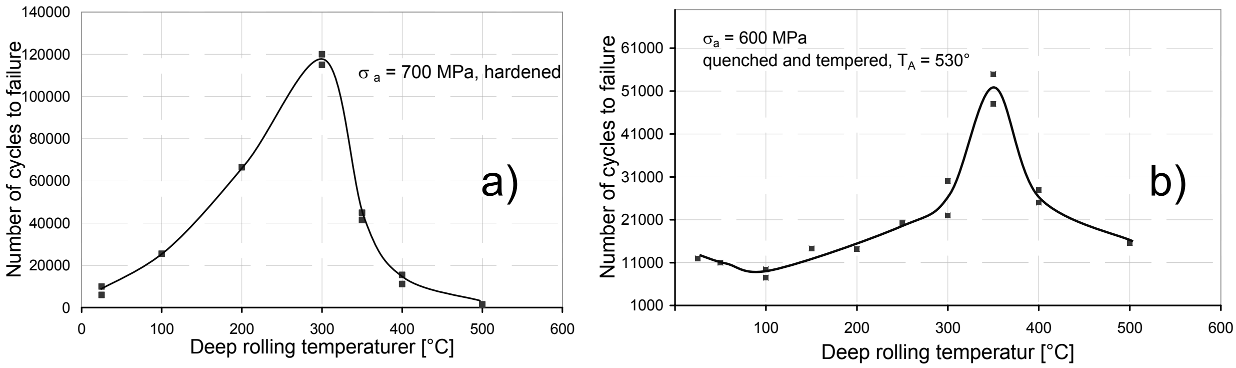

Figure 1: Number of cycles to failure as a function of deep rolling temperature (a: hardened, b: quenched and tempered [5])

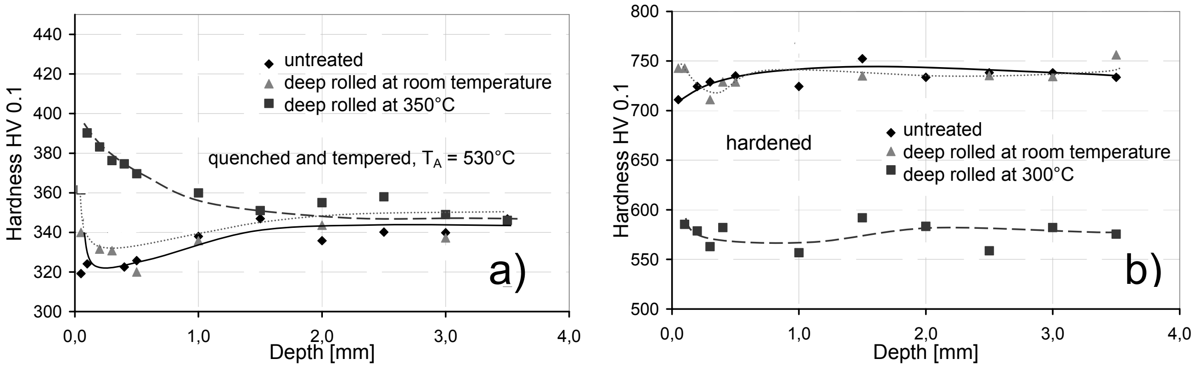

Figure 2: Hardness depth profiles (a: quenched and tempered, b: hardened)

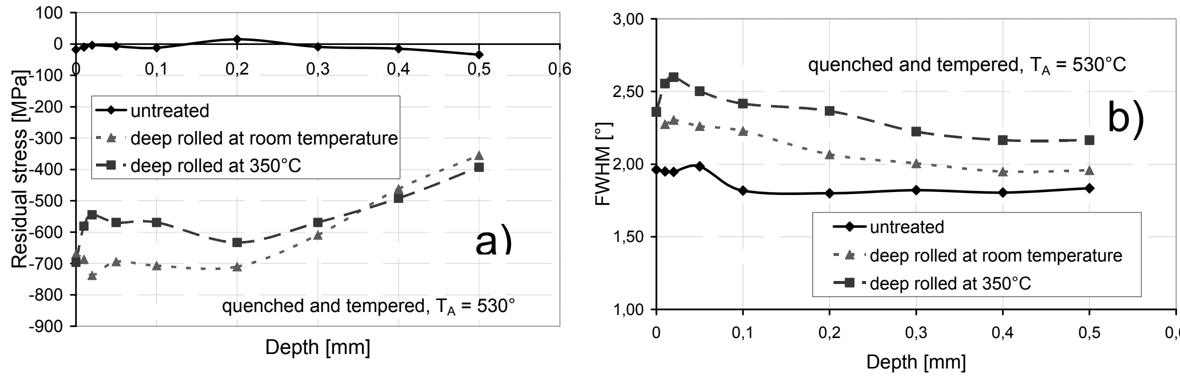

Figure 3: Residual stress (a) and FWHM (b) -depth profiles of the quenched and tempered steel after different treatments

The stability of near surface microstructures and residual stresses is crucial with respect to their effectiveness to influence fatigue strength of the component treated. In Fig. 4, a result characteristic for the quenched and tempered materials state is shown. In addition to the residual stress distribution after deep rolling at room temperature or at 350 °C, the corresponding depth distributions of specimens fatigued to half the number of cycles to failure with a stress amplitude of 600 MPa are shown. Whereas in case of conventional deep rolling residual stresses are considerably reduced to about -100 MPa, they remain almost stable after deep rolling at 350 °C and up to a depth of 0.3 mm compressive residual stress amounts of more than 500 MPa are still existent. This result clearly indicates, that the higher stability of residual stress after deep rolling at elevated temperature is responsible for the better fatigue behavior.

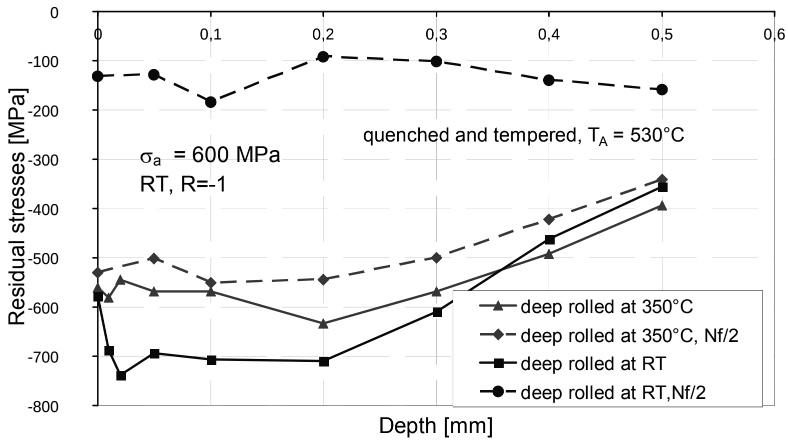

Figure 4: Stability of residual stresses after different mechanical loading states

2. CONSECUTIVE TREATEMTENTS

For a quenched and tempered (T_A= 400 °C) state, the consequences of a deep rolling treatment followed by annealing was studied. As in the above mentioned cases, fatigue tests were carried out to identify optimum annealing temperatures. Fig. 5 shows, that under the test conditions applied, annealing at 250 °C for 20 min after deep rolling leads to highest fatigue lifetimes. Specimens treated in this way were further investigated.

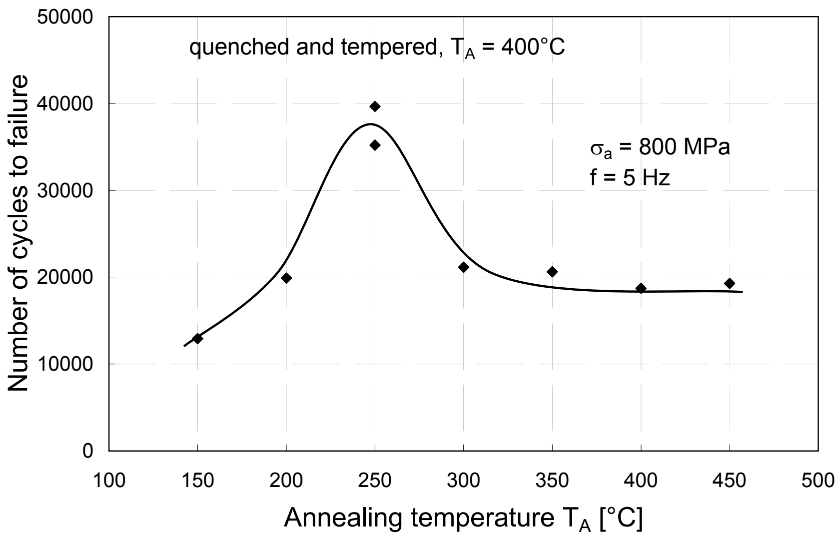

Figure 5: Influence of ageing temperature on fatigue lifetime

The resulting residual stress and FWHM-depth distributions are shown in Fig. 6. One can see that for both characteristics no significant differences are to be observed. Only very near to the surface annealed specimens have lower residual stresses than deep rolled ones. Also in the case of hardness distributions, no significant effect of an additional annealing treatment could be detected.

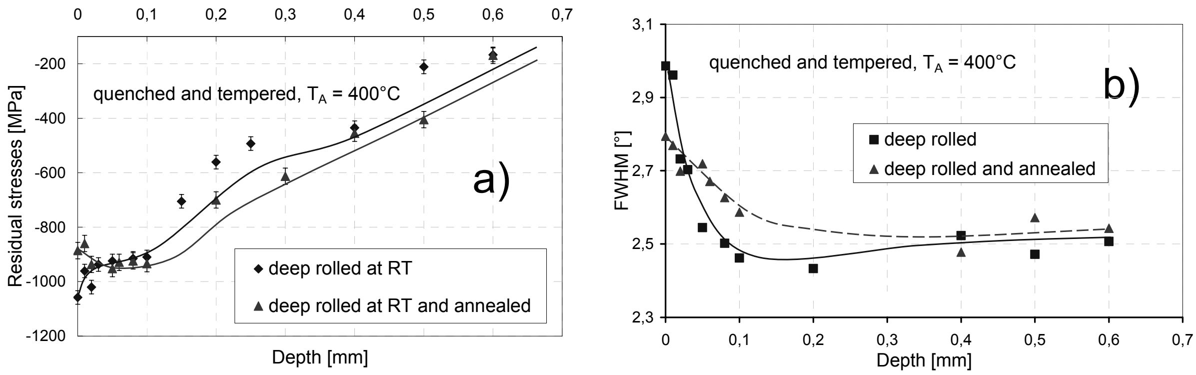

Figure 6: Influence of ageing process on residual stress depth profile (a) and FWHM-depth profile (b)

Also after fatigue loading (800 MPa) to half the number of cycles to fracture no clear differences between the depth distributions of the remaining residual stresses and FWHM-values of both surface treatment states could be detected. On has, however, to take into account that different specimens have to be investigated during such tests and, hence, small effects are difficult to be discovered. It is conspicuous that FWHM-values after annealing are somewhat lower than immediately after deep rolling. Another indication proving the effect of annealing after deep rolling is given in Fig. 7. It shows plastic strain amplitudes as a function of the number of cycles for differently processed specimens. In all cases, after an incubation period, strain softening is observed. Conventional deep rolling at room temperature lowers the plastic strain amplitude considerably. Additionally annealed specimens clearly show a further decrease of plastic strain amplitudes during the whole lifetime, which is in agreement with the longer fatigue lifetimes observed.

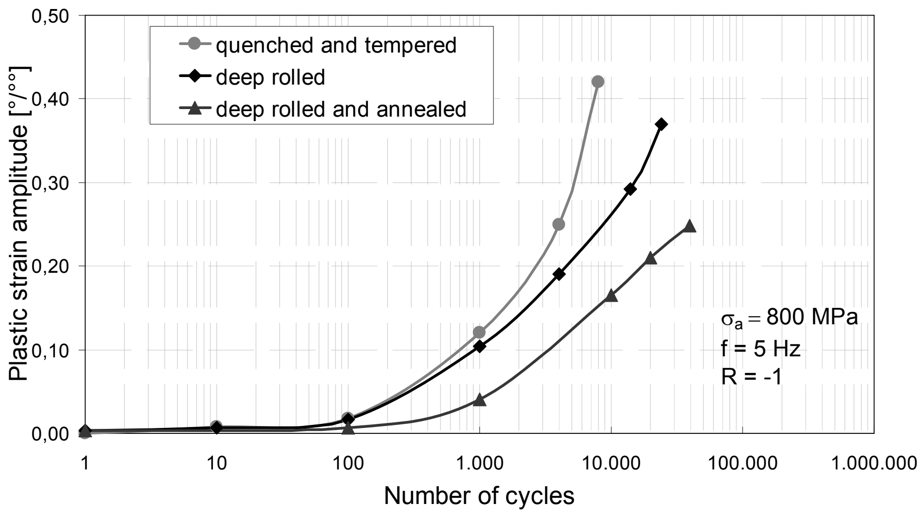

Figure 7: Cyclic deformation curves of different material states for a stress amplitude of 800 MPa

CONCLUSION

The aim of the investigations presented was to gain basic information about the effectiveness of simultaneous and consecutive thermomechanical surface treatments in the case of hardened and of quenched and tempered steel SAE 1045. The results clearly show that compared to conventional deep rolling treatments a further potential for fatigue strength increase exists both for simultaneous as well as for consecutive processes. However a more detailed investigation and assessment of the underlying basic processes is necessary.

ACKNOWLEDGMENTS

The authors would like to express sincere thanks to Mr. S. Schönborn for experimental work and to Mr. Dr. I. Altenberger for technical assistance and fruitful discussions.

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