STATIC AND DYNAMIC STRAIN AGEING OF DEEP ROLLED PLAIN CARBON STEEL SAE 1045 FOR OPTIMIZED FATIGUE STRENGTH

I. Altenberger, I. Nikitin, B. Scholtes

University of Kassel, Institute of Materials Engineering,
Mönchebergstrasse 3, 34125 Kassel, Germany

2005094

Combined mechanical and thermal surface treatments offer a great potential for fatigue life enhancement. In literature, shot peening at elevated temperature („warm peening") is already established. In this study, we investigate the effect of high temperature deep rolling as well as of consecutive deep rolling and annealing on the fatigue behaviour and residual stress state of normalized plain carbon steel SAE 1045. For this purpose hysteresis measurements are performed. The results indicate that deep rolling at elevated temperatures may significantly enhance fatigue life and strength. Maximum fatigue lives and smallest plastic strain amplitudes in fully reversed push-pull cycling occurs at rolling temperatures of 350°C where dynamic strain ageing is prevalent. Exemplary residual stress measurements show that thermomechanically treated (either high temperature deep rolled or deep rolled plus annealed) samples exhibit more stable residual macro and microstresses during fatigue loading.

SUBJECT INDEX

High temperature deep rolling, ferritic steel, fatigue, strain ageing

INTRODUCTION

Deep rolling is one of the most effective commercially available mechanical surface treatment for the enhancement of the fatigue behaviour of metallic materials [1]. The outstanding fatigue properties of deep rolled components are generally attributed to surface smoothening and the formation of deep strain hardened layers, exhibiting compressive residual stresses. Only a few studies have been devoted to the effects of high temperatures on the workpiece during the mechanical surface treatment itsself [2,3], indicating that high temperatures may contribute to further strengthening effects, especially in the dynamic strain ageing regime. In this study we therefore investigate the effect of high temperature deep rolling on the isothermal fatigue behaviour of plain carbon steel SAE 1045 in normalized heat treatment state. Details about the material in this heat treatment state can be found in [6]. All specimens (diameter 7 mm) were deep rolled with a mechanical deep rolling device using a rolling force of 1 kN.

RESULTS AND DISCUSSION

Fig. 1 exhibits residual stress depth profiles of deep rolled SAE 1045 for different rolling temperatures between 25°C and 400°C. In all cases pronounced compressive residual stresses directly at and beneath the surface were formed. At the surface the amount of residual stress is almost independent of the rolling temperature and lies in the range 300-350 MPa. A slight subsurface maximum of residual stress is detected in a depth of 0.2 mm. Rolling temperatures of 320 °C and 350°C led to highest compressive residual stresses of about 450 MPa in 0.2 mm depth. For all investigated rolling temperatures the affected layer extends roughly 1.2-1.5 mm into depth as can be seen easily by the depth profile of **f**ull **w**ith at **h**alf **m**aximum

(FWHM)values of X-ray diffraction peaks (Fig. 2). In the case investigated, high temperature deep rolling leads to increased FWHM-values. This effect is generally more pronounced in subsurface layers than directly at the surface.

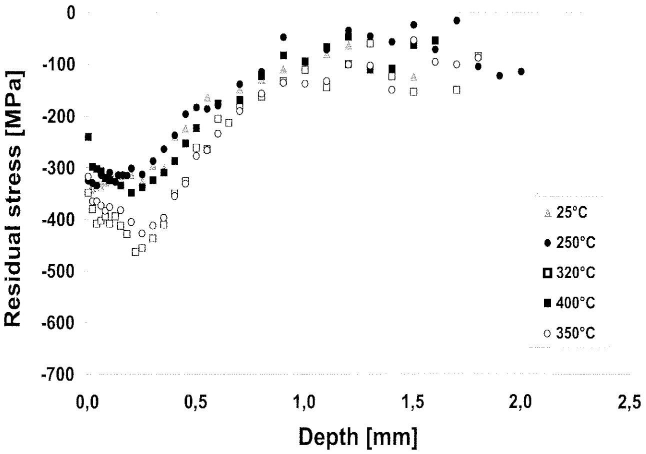

Fig. 1: Residual stress depth profiles of high temperature deep rolled SAE 1045 for different rolling temperatures (rolling force 2 kN)

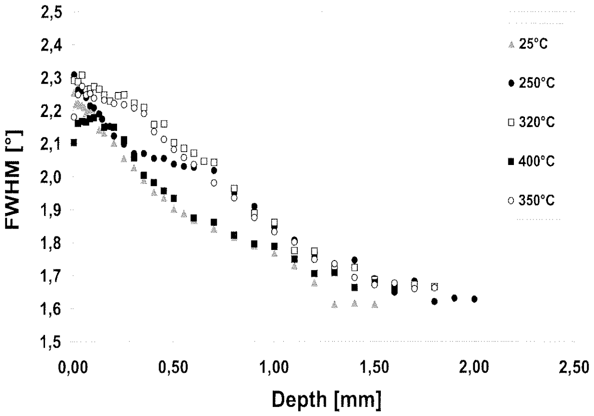

Fig. 2: FWHM depth profiles of high temperature deep rolled SAE 1045 for different rolling temperatures (rolling force 2 kN)

Temperatures of 320-400°C during deep rolling also lead to significantly increased hardness in the affected surface layer. An example is presented in Fig. 3, showing the hardness depth profile of the untreated, conventionally deep rolled (T = 25°C) and high temperature deep rolled (T = 350°C) condition. Obviously, the surface hardness increase by rolling at 350°C is twice as high as by room temperature deep rolling.

The cyclic deformation behaviour of normalized deep rolled SAE 1045 at room temperature and a stress amplitude of 340 MPa is depicted in Fig. 4 for different rolling temperatures. All conditions exhibit pronounced cyclic softening after a quasielastic incubation period. Deep rolling at room temperature already leads to a pronounced lifetime increase by significantly reduced plastic strain amplitudes over the majority of the fatigue life. This reduction of plastic strain amplitude is further enhanced by high temperature deep rolling. Especially rolling temperatures of

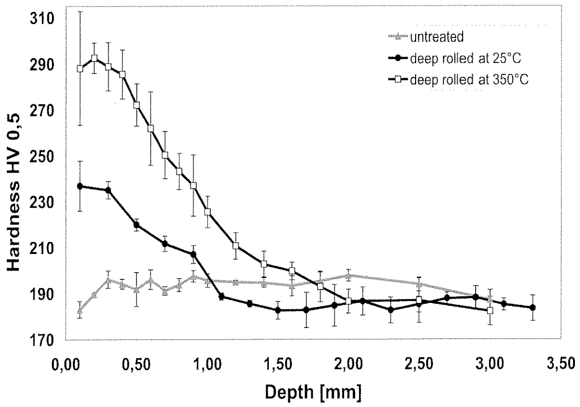

Fig. 3: Hardness depth profiles of untreated and deep rolled SAE 1045 for rolling temperatures of 25°C and 350°C

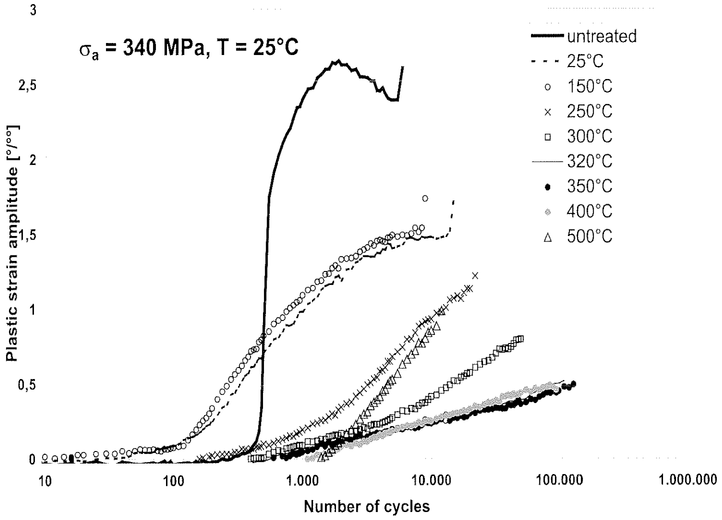

Fig. 4: Cyclic deformation curves of untreated, conventionally deep rolled (T = 25°) and high temperature deep rolled SAE 1045 (σ_a = 340 MPa, test temperature = 25°C).

320-400°C significantly reduce the plastic strain amplitude and increase the fatigue life. Interestingly, most high temperature deep rolled conditions also exhibit delayed softening as compared to the untreated and conventionally deep rolled state. In Fig. 5, the plastic strain amplitude and the number of cycles to failure is plotted versus the rolling temperature. The cyclic lifetime is inversely proportional to the plastic strain amplitude. This finding confirms the applicability of the Manson-Coffin-law for mechanically surface treated materials as already found earlier. Lowest plastic strain amplitudes and highest fatigue lives are found for a rolling temperature of 300-350°C which corresponds to the regime of dynamic strain ageing for that alloy [4].

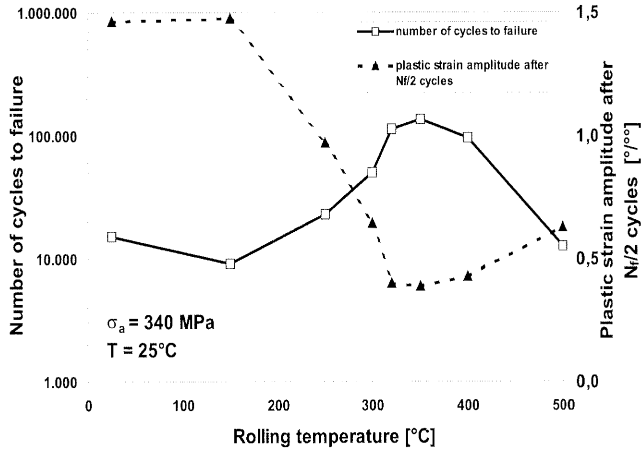

Fig. 5: Cyclic lifetime and plastic strain amplitude after half the number of cycles to failure as a function of rolling temperature for push-pull room temperature fatigue

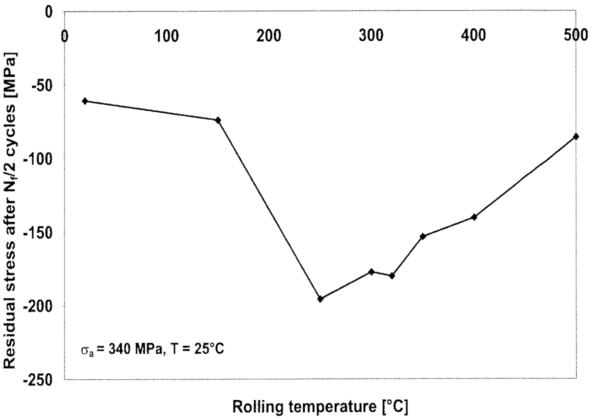

Fig. 6: Surface residual stresses after half the number of cycles to failure as a function of rolling temperature for push-pull room temperature fatigue

Since residual stress relaxation correlates strongly to the amount of the plastic strain amplitude during fatigue loading [5], most stable residual stresses were expected in the temperature regime of dynamin strain ageing. At a stress amplitude of 340 MPa almost complete residual stress relaxation by cyclic plasticity occurs if the material was deep rolled at room temperature. However, at rolling temperatures of 250-320°C residual stress relaxation is diminished and significant amounts of residual stresses prevail even after fatigue loading (Fig. 6).

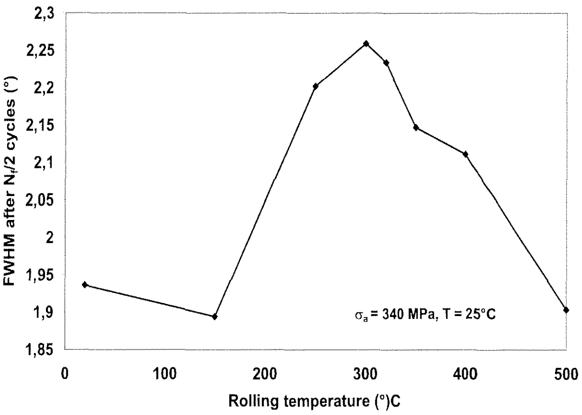

Fig. 7: Surface FWHM-values after half the number of cycles to failure as a function of rolling temperature for push-pull room temperature fatigue

In a similar way, also the stability of work hardening against fatigue loading is affected (Fig. 7). The FWHM-values are most stable for a rolling temperature of 300°C. It is therefore expected that the most stable near-surface microstructures can be found for this condition, since the FWHM-value is an effective tool to assess the stability of near-surface microstructures during fatigue loading [6].

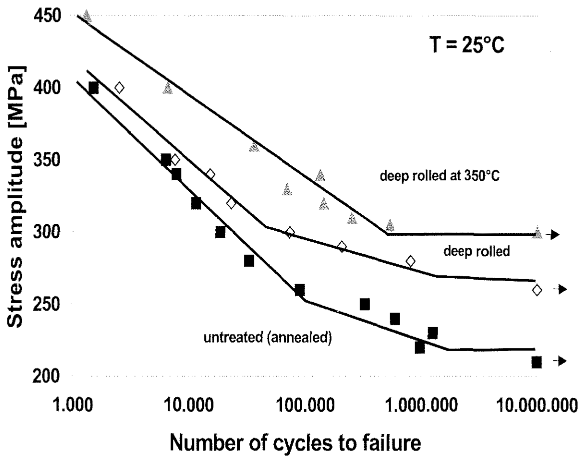

Fig. 8: Stress-Life (S/N) curves of untreated and deep rolled SAE1045 for conventional deep rolling conditions (T= 25°C) and for optimized high temperature deep rolling (T = 350°C)

Alltogether, an optimized rolling temperature of 350°C leads to an improvement of the fatigue life in the finite life regime as well as to an increase of the fatigue endurance strength by 50% for push-pull loading as compared to the untreated state (Fig. 8).

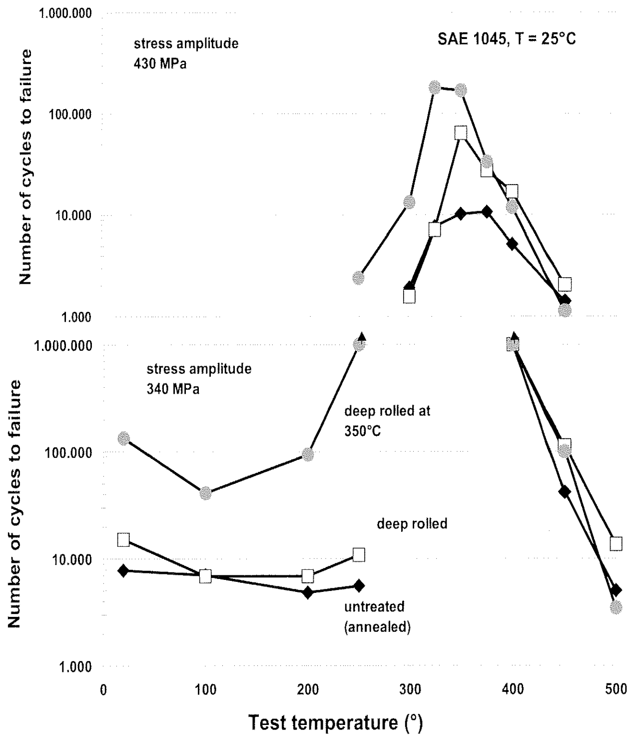

Fig. 9: Influence of test temperature and rolling temperature on the isothermal fatigue life of untreated and deep rolled SAE1045 (σ_a = 340 MPa and 430 MPa, f = 5 Hz)

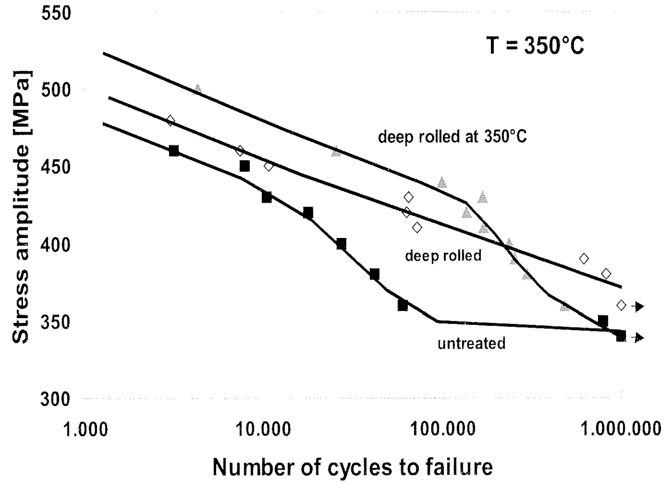

Fig. 10: Stress-Life (S/N) curves of untreated and deep rolled SAE1045 for conventional deep rolling conditions (T= 25°C) and for optimized high temperature deep rolling (T = 350°C) for a test temperature of 350°C

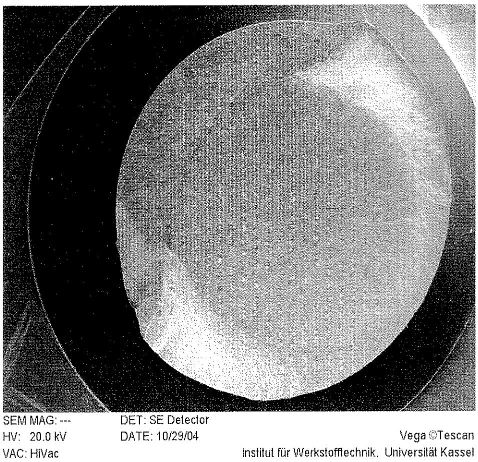

Fig. 11: Subsurface crack initiation in high temperature deep rolled SAE 1045 (rolling temperature = 350°C) in isothermal high cycle fatigue tests (test temperature = 350°C, σ_a = 430 MPa)

High temperature deep rolling is also a very effective tool to enhance the isothermal high temperature fatigue behaviour of SAE 1045 up to roughly 400°C (Fig. 9). A typical maximum of fatigue life is observed at 350°C due to dynamic strain ageing for all three investigated conditions, with highest lifetimes for the high temperature deep rolled condition. However, even though the fatigue life is enhanced by high temperature deep rolling in the LCF- as well as partially in the HCF-regime, the fatigue limit (in contrast to room temperature fatigue) is not improved as compared to the untreated state (Fig. 10). This is due to subsurface crack initiation (Fig. 11) near the fatigue limit at this temperature, rendering the surface treatment ineffective.

CONCLUSIONS

High temperature deep rolling is a very effective means of enhancing the fatigue properties of plain carbon steels if the rolling temperature is appropriately chosen. The resulting fatige lives and limits are superior to those generated by conventional deep rolling at room temperature. The superior fatigue properties are due to dynamic strain aging, which stabilizes micro and macro residual stresses in near-surface regions and leads to enhanced surface hardness thus preventing or delaying crack initiation.

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