Integration of a Deep Rolling Process in the Heat Treatment of SAE1045 Steel: a Way to Reduce and Optimize the Production Chain

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Abstract
Simultaneous surface treatment such as deep rolling at elevated temperature are further developments of conventional mechanical surface treatment processes. They combine the positive effects of low temperature annealing with the beneficial consequences of mechanical surface treatments. In this paper, a special process is described where the residual heat from a quenching and tempering heat treatment process is exploited for deep rolling of cylindrical specimens at elevated temperature. Results of this process will be compared with conventional deep rolling operations at room temperature and at elevated temperature. The fatigue behaviour of quenched and tempered steel SAE 1045, deep rolled under three different process conditions was investigated using stress-controlled fatigue tests. Residual-stress and work-hardening effects in the modified surface layers were investigated using X-ray diffraction methods. Special attention was paid to the stability of the induced near surface microstructures and residual stresses.

Keywords Residual stress, deep rolling, fatigue

Introduction
Mechanical surface treatments are widely used in industry to produce high strength light weight components such as axles and shafts in vehicles or drive systems with increased fatigue strength and lifetime. The positive effects of the treatments, which are based on local plastic deformations and the associated formation of strain hardened surface layers with compressive residual stresses, are well understood as it is demonstrated in many scientific papers and textbooks [1,2]. To further improve the efficiency of the methods, processes at elevated temperature have been developed. Here, under supply of additional thermal energy, special effects such as static and dynamic strain aging or formation of small precipitations are exploited to produce additional strengthening effects in the components under investigation [3,4] One has, however, to bear in mind that this leads to more complex processes due to heating of the components because an additional process step is necessary. Consequently, in this paper the possibility to integrate this process in the production chain during heat treatment, avoiding an additional heating of the components under investigation is analyzed.

Experimental Methods
The material investigated was steel SAE 1045 with the chemical composition 0.46 C, 0.4 Mn, 0.21Si, rest Fe (wt.-%). Specimens were quenched from 850 °C in water and tempered for 2 h at 400°C. After heat treatment, a hardness of 340 HV 0.2, a yield strength of 1200 MPa and an ultimate tensile strength of about 1400 MPa were measured. Notched specimens as shown in Fig. 1 were produced by turning. Three different variants of the mechanical surface treatment process were applied: conventional deep rolling at room temperature, deep rolling at 250°C and integrated deep rolling at the end of the annealing process. The treatments were carried out using a conventional milling machine. In all cases, a deep rolling tool “ecoroll-EF90” with a diameter of 25 mm and a radius of 1.5 mm was used. This deep rolling tool is typically applied for the treatment of screw thread radiuses. A rolling force F_G = 3 kN and a rotational speed of 63 rpm were used and an overlap of 1000% was realized. It has to be pointed out that these process parameters are not optimized to produce highest fatigue

strengths. Moreover, they are typical in case of deep rolling processes of e. g. crank shafts or axles. For deep rolling at 250°C a heat gun was used and temperature was measured by thermocouples. In the case of integrated deep rolling specimens were taken out of the annealing furnace, cooled down to 300°C and then deep rolled. In this way in the gage length, a mean temperature of 250°C was achieved which was also controlled by thermocouples.

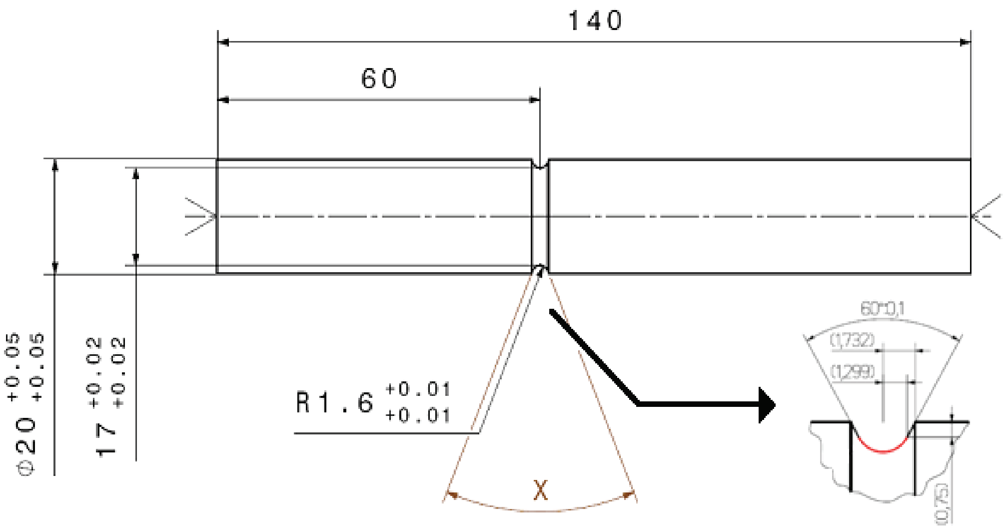

Fig. 1 Specimen geometry

Fatigue tests were carried out at room temperature under stress controlled alternating bending at a stress ratio of R= -1. Stress amplitudes given have been calculated as maximum bending stresses assuming elastic behavior and neglecting notch effects. Residual stress depth profiles were determined by X-ray diffraction (XRD) using the classical $\sin^2 \psi$-method with CrKα radiation at the {211}-planes and (1/2) s_2 = 6.05 x 10^{-6}mm^2/N as elastic constant. The X-ray beam had a diameter of 0.5 mm. Near-surface work hardening was characterised by integral width (IW) values of the X-ray diffraction peaks. Residual stress and IW values were measured in longitudinal as well as in tangential direction of the specimens. In the following figures, only longitudinal components are shown. Depth profiles were determined by successive electrochemical removal of material without carrying out a stress correction. Vickers micro hardness measurements HV 0.2 were carried out on polished cross sections of the specimens.

Experimental Results

Fig. 2 shows residual stress depth distributions of the specimens after being processed with different types of deep rolling treatment. In all cases compressive residual stresses were produced with similar shapes of the distributions. Close to the surface, residual stress amounts at first decrease slightly and then increase. Maximum amounts of compressive residual stress occur at surface distances between 0.4 – 0.6 mm. They vary between -600 MPa and -700 MPa. Even at a surface distance of 1 mm, compressive residual stresses are still present.

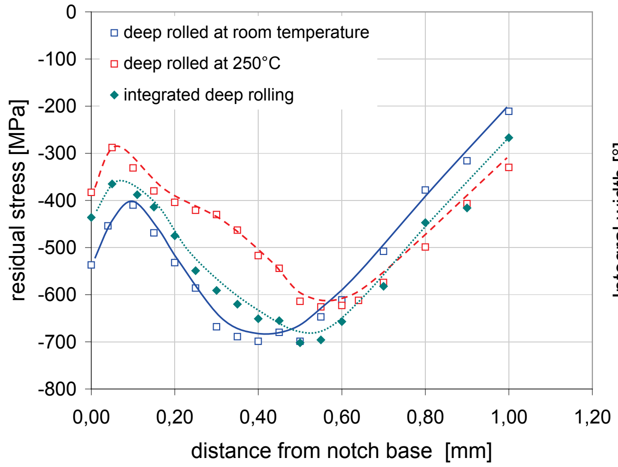

Fig. 2 Residual stress depth distributions after different deep rolling processes

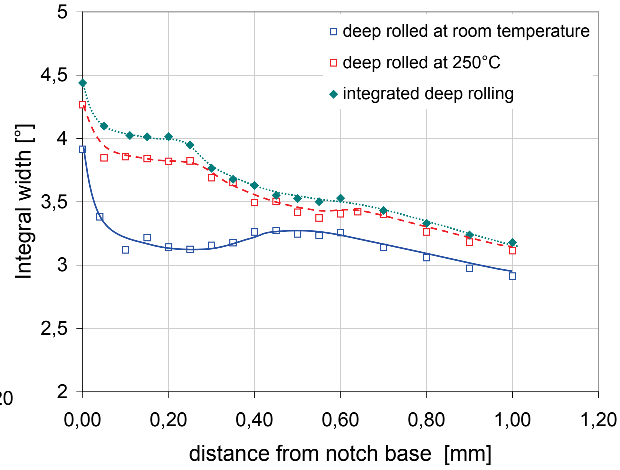

Fig. 3 Integral width depth distributions after different deep rolling processes

Depth distributions of integral widths shown in Fig. 3 exhibit decreasing values close to the surface. For specimens treated at room temperature a minimum at a surface distance of approximately 0.2 mm is found which is not the case for deep rolling treatments at elevated temperature. In general after warm deep rolling higher values are measured than for conventional room temperature deep rolling. Depth distributions of Vickers hardness in all cases show a steep decrease near the surface (see Fig. 4). In greater depths identical and constant values of 340 HV0.2 are reached. It is interesting to note that the hardness increase near the surface is more pronounced for specimens treated at elevated temperature than in the case of a conventional room temperature treatment, which is in agreement with the distributions of integral widths (see Fig. 3).

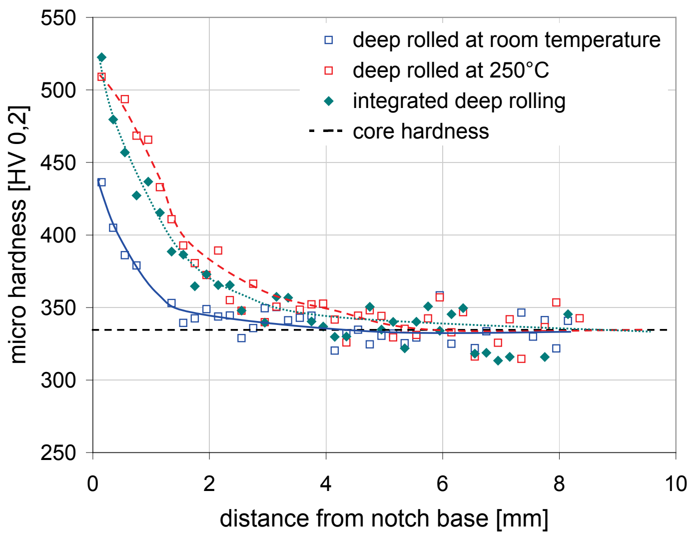

Fig. 4 Depth distributions of Vickers hardness after different deep rolling processes

Altogether, despite of the different types of deep rolling processes applied, with the exception of slightly higher hardness and integral width values close to the surface, no significant differences of the near surface states of the materials can be stated. Therefore it is remarkable that clearly different S,N-curves were measured in fatigue tests. This is shown in Fig. 5. Although only few specimens were available allowing no statistical evaluation of the individual fatigue tests, one can see clearly separated curves for the different treatments applied, if measured data are described by straight lines. Compared with the not deep rolled starting condition, as expected, deep rolling at room temperature leads to a remarkable increase of fatigue strength and fatigue lifetime. Both treatments at elevated temperature cause a distinct increase of fatigue strength and lifetime which is almost identical for both treatment variants. In comparison with the untreated starting condition for 10^6 loading cycles a fatigue strength increase of 190 MPa corresponding to more than 50% was achieved after both simultaneous deep rolling methods.

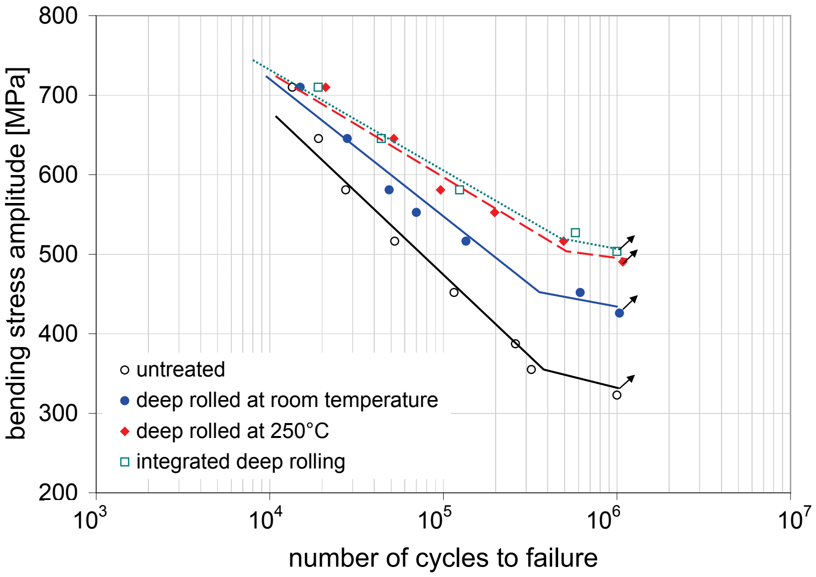

Fig. 5 S, N-curves of the different materials states

To understand and assess these observations further experiments were carried out to analyze the stability of near surface materials states in the course of fatigue loading. For this purpose specimens were loaded for 30000 cycles by a stress amplitude of 580 MPa. Then depth distributions of residual stress and integral width were measured and compared with the starting condition after deep rolling. Results of these investigations are shown in Figs. 6 and 7. In Fig 6a, for specimens conventionally deep rolled at room temperature one can see that after fatigue loading, compressive residual stresses are almost completely relaxed. Only in greater distances from the surface smaller amounts of compressive residual stresses are still present whereas at and near the surface, a complete relaxation and even small tensile residual stresses can be seen. In contrast to that for both types of treatments at elevated temperature a much smaller compressive residual stress relaxation is found (see Figs. 6 b and c). If one takes the scatter of individual residual stress depth distributions into account, for the specimen deep rolled at elevated temperature, almost no relaxation can be stated. Also for the deep rolling treatment integrated in the heat treatment process, relaxation of compressive residual stresses is very small and clearly noticeable only very close to the surface.

In all cases, the depth distributions of integral widths before and after fatigue loading under the loading conditions mentioned above are almost unchanged if the fluctuation range of the data of individual specimens is taken into account (see Figs. 7a-c). No significant relaxation of strain hardening in the surface layers was detected.

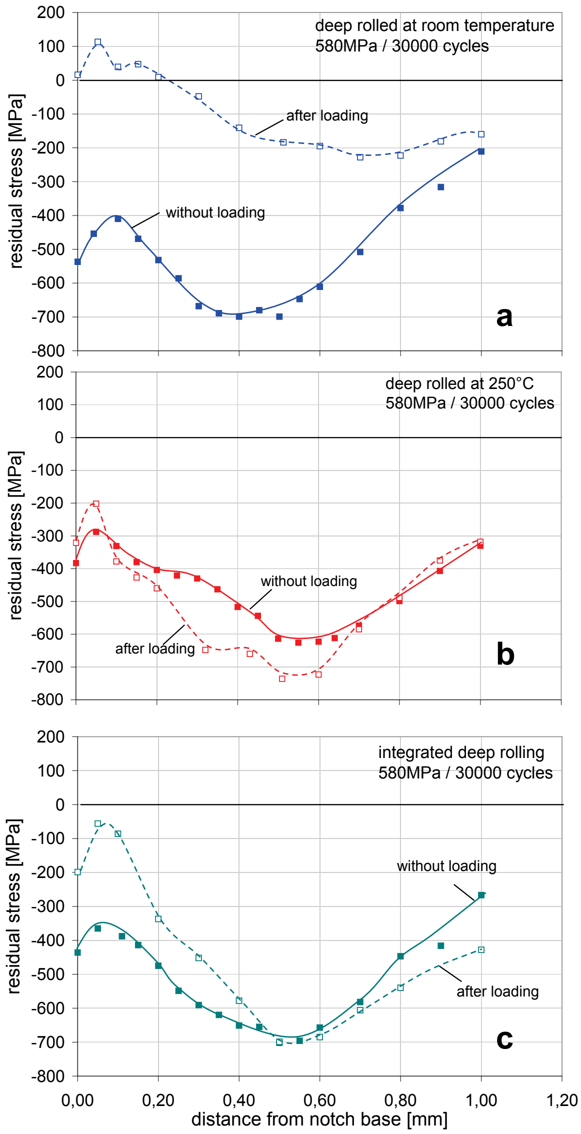

Fig. 6 residual stress stability of different materials states (σ_a = 580MPa, 30000 loadings cycles)

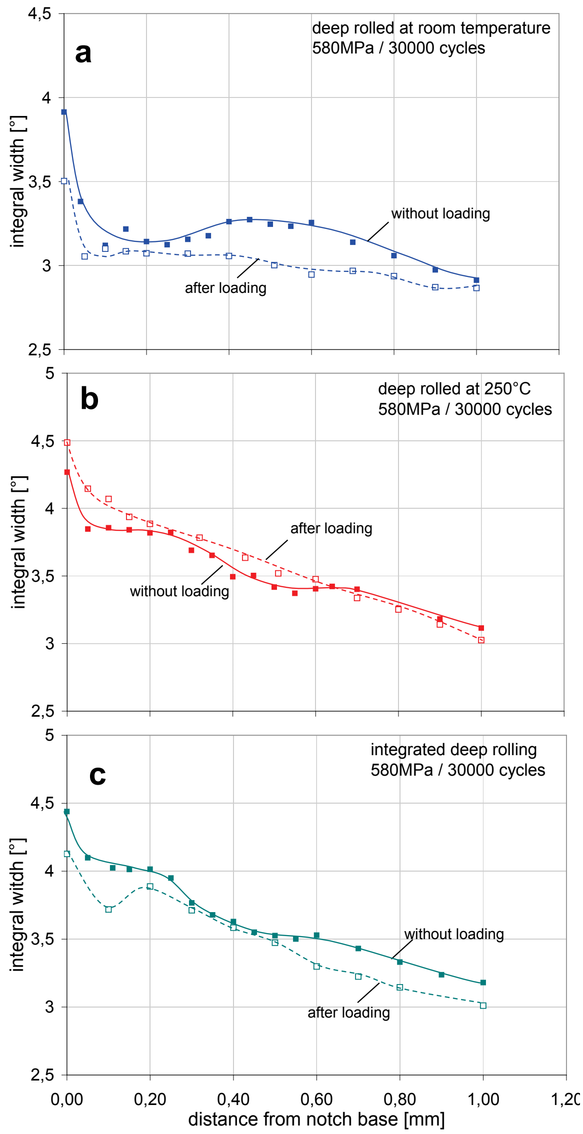

Fig. 7 integral width stability of different materials states (σ_a = 580MPa, 30000 loadings cycles)

Discussion and Conclusions

Residual stress depth distributions as shown in Fig. 2 are characteristic for deep rolling processes. They are often observed and are the consequences of the Hertzian pressure between workpiece and tool leading to a compressive residual stress maximum below the surface. Immediately at and close to the surface special effects occur as a consequence of local geometrical conditions and friction effects.

Obviously, in comparison with conventional room temperature treatments, the effect of elevated temperature on the formation of residual stress and on strain hardening is negligible, because very similar residual stress distributions with nearly the same amounts of maximum compressive residual stresses are measured. This can be explained by the relative small effect of temperature on strength and strain hardening of the steel investigated in the relevant temperature range.

It is interesting to note that a deep rolling process integrated in the heat treatment process chain as explained above leads to the same residual stress depth distribution and strain hardened layer as in the case of a separate process added after the heat treatment. Here, a great potential is demonstrated to avoid individual process steps i. e. a renewed heating up

of the component for warm deep rolling operations. Instead, the heat of the heat treatment operation is exploited in an economical and ecological way.
A very important observation is that residual stress states produced by warm deep rolling either by separately heating the specimens or by integrating the process in the annealing procedure are much more stable compared to conventional deep rolling at room temperature. This can be attributed to static or dynamic strain aging processes occurring during the warm deep rolling operation, leading to pinning effects of dislocations [3]. In addition, it can be assumed that the formation of small carbides also contributes to impediment of dislocation motion. Relaxation of residual stress states in the course of fatigue loading is based on local plastic deformations, replacing elastic strains connected to the individual residual stress states. Thus dislocation pinning by the above mentioned processes impedes or even prevents local plasticity and, hence, residual stress relaxation [5]. Due to the well known influence of compressive residual stress states on initiation and propagation of cracks, this explains the observed increase in fatigue strength or lifetime after warm deep rolling for both process variants compared to conventional processes.
The fact that close to the surface in case of the integrated process a relaxation of compressive residual stresses is found has no negative consequences. Actually small cracks were observed in the notch root of the specimens, even for fatigue tests applying the smallest stress amplitudes. However, these cracks were stopped by existing compressive residual stresses at greater distances from the surface and did not propagate furthermore.

Acknowledgement: The work presented here was carried out in the frame of the Transregional Collaboration Centre TR 30 funded by German Research Foundation DFG.

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