Deep Rolling at Lower and Elevated Temperatures – Effects and Consequences on Fatigue Behavior

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Abstract

Mechanical surface treatments, e. g. deep rolling or shot peening, are widely used in industrial practice to increase fatigue life and strength of complexly loaded components like axles or shafts in drive systems. Their effectiveness is based on near surface plastic deformation resulting in strain hardening effects as well as compressive residual stress fields, alterations of surface topography and possibly phase transformations. Due to the influence of process temperature or subsequent annealing processes on the resulting materials microstructures, in addition to conventional processes, various simultaneous or consecutive combinations of heat input and plastic deformation are used to produce favorable near surface microstructures. In this paper, selected examples are presented and discussed.

Keywords: Deep rolling, residual stress, combined process, consecutive process, integrated process, fatigue

Introduction

Today it is well known that all individual process steps along the process chain, starting from the formation of the solid body, contribute to characteristic microstructures and residual stress states in the produced components. As a consequence, strength and lifetime are determined in this way. Especially near surface properties are crucial, because in most cases, damage processes start in this region and, additionally, near surface layers are highest loaded regions. Typical examples are components under fatigue loading conditions with or without a corrosive environment. Therefore specific processes were developed and manufacturing steps were worked out in such a way that beneficial near surface materials microstructures and residual stress fields are created. As a result components with optimized properties are produced. In this context, mechanical surface treatments play a key role and have been continuously developed over the years to produce safe and reliable damage tolerant materials states.

In some cases, mechanical surface treatments were consecutively combined with thermal treatments. A well known and established example is case hardening followed by shot peening, which leads to highest fatigue strengths and, hence, considerably contributes to light weight constructions in power transmission and drive engineering. Also other combinations of thermal treatments with mechanical processes have proved to be very efficient making use of the arising diffusion and/ or recrystallization processes. A distinction is made between consecutively or simultaneously coupled processes depending on the sequence of the process steps. In this context, processes combining heat input with plastic deformation, e. g. shot peening or deep rolling at elevated temperature lead to enhanced near surface materials states compared with conventional processes [1 - 4]. It could be demonstrated that residual stress fields with improved stability during cyclic loading are created. The same is valid for consecutive processes, i. e. mechanical surface treatments followed by a thermal annealing with an appropriate temperature/time combination [5]. Integrated processes, using thermal energy of preceding process steps, e. g. deep rolling during the cooling-down period from annealing processes are especially promising from an economic point of view [6]. In addition, it was demonstrated that fine-grained near surface microstructures can be produced with improved mechanical properties [7]. There is also evidence suggesting enhanced diffusion processes after near surface plastic deformation which opens new perspectives for chemo-thermal surface treatments [8]. Applying combined surface treatments, the challenge is the integration of the procedural steps in the process chain in such a way that complex and time-consuming processes are avoided and robust as well as efficient treatments result allowing economic manufacturing conditions.

In the following section, characteristic examples are presented of combined surface treatment processes and the resulting near surface materials properties with a special focus on residual stress states and their stability under fatigue loading conditions.

Experimental Methods and Results

Combined and integrated warm deep rolling at elevated temperature

The material investigated was steel SAE 1045 quenched from 850°C in water and tempered at 400°C for 2h. In this state a hardness of 35 HRC and a yield strength of 1200 MPa were measured. Three different variants of rolling processes were applied: conventional deep rolling at room temperature, deep rolling at 320°C (warm deep rolling) and deep rolling during the cooling-down process from annealing temperature at 320°C (integrated process). Deep rolling was carried out with a specifically developed device with three cemented carbide tools. Warm deep rolling was achieved by a heat gun and temperatures were controlled by thermocouples. Residual stresses and integral widths IW were measured by X-ray diffraction.

Fig. 1 shows depth distributions of residual stresses (σ^{RS}) and integral widths (IW) for the three different deep rolling treatments. Similar depth distributions are observed with maximum values immediately at the surface. Integral width depth distributions are also identical for the three deep rolling processes applied. Obviously, due to the relatively small effect of temperature on strength and strain hardening in the relevant temperature range, residual stress formation during deep rolling is hardly influenced by the deep rolling temperature.

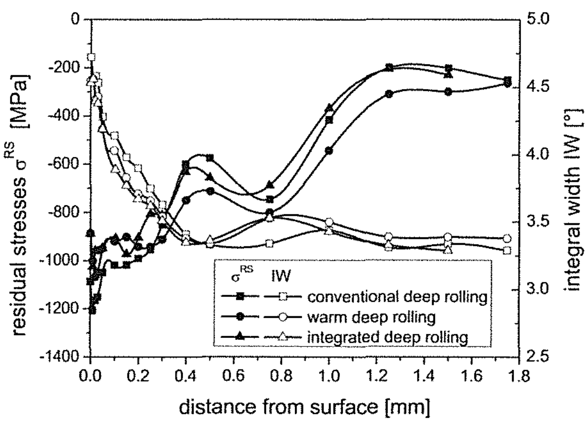

Fig. 1: Depth distributions of residual stresses and integral width at different peeing conditions

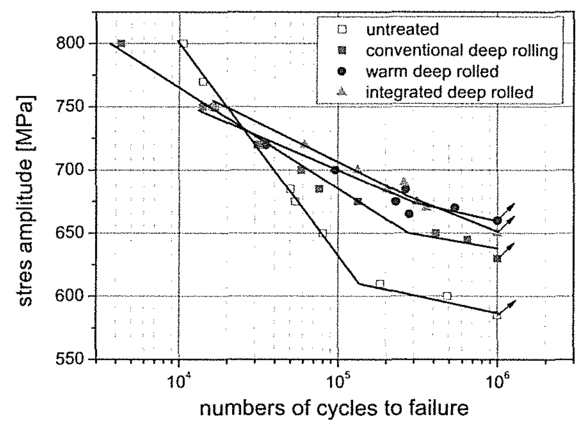

Fig. 2: S,N- curves after different deep rolling procedures

S,N-curves of the different materials states are shown in Fig. 2. Although only a limited number of specimens were tested in each case, one can clearly notice separate curves for the different surface treatment processes. Compared to the untreated starting condition, in all cases deep rolling increases fatigue strength or lifetime of the specimens. Of particular relevance is the observation, that both warm deep rolled states increase the fatigue strength considerably compared with the conventional room temperature deep rolling and that the integrated process reaches identical values as the combined process. An interesting observation is the fact, that for small numbers of cycles to failure, i. e. for higher loading amplitudes, a crossing of the curves and a tendency for lower fatigue strengths of deep rolled specimens compared to untreated ones occurs. Obviously in this case the deep rolling process introduces a mechanical damage. For a better understanding and assessment of the results, experiments were carried out to analyze the stability of the near surface materials states during fatigue loading. Characteristic observations are presented in Fig. 3. The diagrams show depth distributions of the percentage of relaxation of residual stresses (above) and of integral widths (below) after $8 \cdot 10^4$ loading cycles under stress control with a stress amplitude of 660 MPa. One can clearly see that residual stress relaxation is most pronounced immediately below the surface and is higher for the room temperature treatment than for both warm deep rolling processes. It is interesting to note that the combined and the integrated deep rolling processes lead to a comparable residual stress stability. The same is valid for the relaxation if integral width IW. One can conclude that the better stability of residual stresses after warm deep rolling is responsible for the resulting higher fatigue strength. This effect can be attributed to static or dynamic strain aging processes together with the precipitation of small carbides during the warm deep rolling process achieving a pinning effect of dislocations. As a consequence cyclic plasticity during fatigue loading is hindered which is necessary for residual stress relaxation.

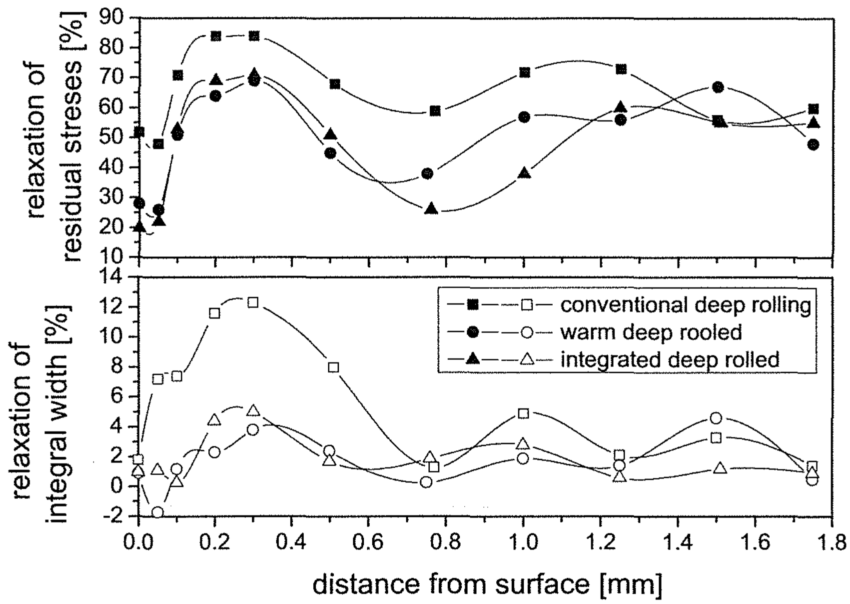

Fig. 3: Relative stability of residual stresses and integral width for different deep rolling procedures

<u>Consecutive deep rolling and annealing of aluminium alloy AA 6110</u>

Consecutive deep rolling with subsequent aging processes have extensively been studied in [9]. In the following section, for the precipitation hardenable Al-alloy AA 6110, characteristic examples are presented. As-quenched deep rolled specimens were aged for different temperatures between 50-300°C up to approximately one week and then tested in tension-compression fatigue tests. Fig. 4 shows the relation between aging time and numbers of cycles to failure for a stress amplitude of 250 MPa and the aging temperatures indicated. Aging treatments between 160 and 250 °C lead to continuously increasing lifetimes until reaching a maximum for characteristic aging times. Highest fatigue lifetime was observed for the temperature/time combination of 160 °C / 12h [10]. The cyclic deformation behavior of characteristic materials states is shown in Fig. 5. Cyclic hardening occurred for the as quenched deep rolled condition. The same behavior was observed for specimens aged at 160 °C for 100 s, but plastic strain amplitudes were smaller. For specimens aged at 160 °C for 12 h, which revealed highest fatigue lifetimes, only very small plastic strain amplitudes were observed. Fig. 6 shows depth distributions of residual stress (above) and full width at half maximum (FWHM, below) for the as-quenched and deep rolled condition as well as for specimens subsequently age-hardened at 160 °C for 12 h. In both cases, compressive residual stresses are observed in the surface layer, which, however, were reduced considerably by the aging treatment. This effect can also be seen comparing the FWHM-values, which are clearly smaller in the age hardened state. Finally, Fig. 7 shows (not statistically evaluated) S,N-curves for differently processed materials states. It came out that deep rolling after an optimized aging treatment results in an excellent combination of work hardening and precipitation hardening and, hence, in excellent fatigue properties. The reverse process order – aging after deep rolling the as-quenched condition –

provides smaller fatigue strengths and lifetimes, however is still superior to the as-quenched and then deep rolled condition [10].

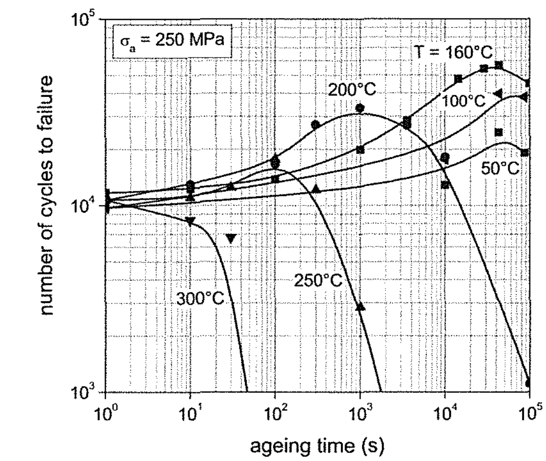

Fig. 4: Fatigue lifetime as a function of aging time and temperature [10]

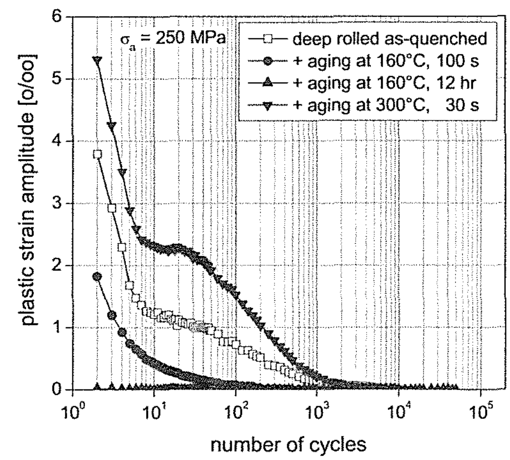

Fig. 5: Cyclic deformation curves of differently treated materials states

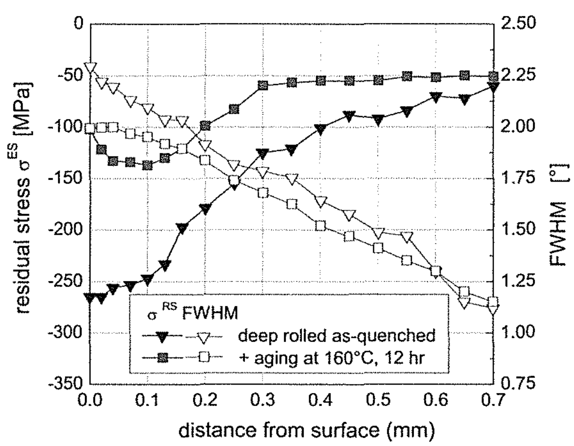

Fig.6: Residual stress an FWHM value depth profiles of differently treated materials states

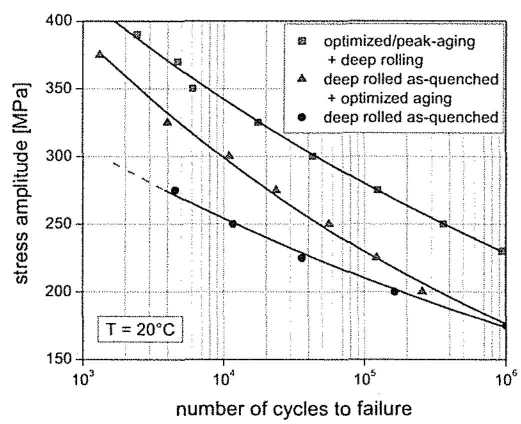

Fig. 7: S,N- curves of differently treated materials states

<u>Deep rolling of metastable austenitic steel AISI 304 at different temperatures</u>

In the case of metastable austenitic steels, mechanical surface treatments give rise to the formation of deformation induced near surface martensite. In the case of deep rolling, the amount of phase transformation can be controlled in a wide range by the process temperature. In addition, depending on the process parameters applied, different residual stress fields as well as strain hardening effects are produced. Hence, characteristic consequences in the case of fatigue loaded components have to be expected [11].

For steel AISI 304, deep rolled at different temperatures between room temperature and -192°C, the resulting depth distributions of near surface martensite content measured by X-ray diffraction are plotted in Fig. 8. Cryogenic deep rolling was realized by a specially designed equipment using liquid nitrogen allowing a temperature controlled process down to -192°C. With decreasing temperature, considerable amounts of martensite are produced with maximum values below the surface. This can be explained by the special loading condition, characterized by a Hertz'ian pressure between tool and workpiece, but also heat production during the deep rolling process in the contact zone between specimen and rolling tool may play a role. The influence of the deep rolling temperature on surface residual stresses is shown in

Fig. 9. One can see that materials states with highest amounts of martensite content. i. e. deep rolled at cryogenic temperatures, have only small amounts of compressive residual stresses in the austenite phase. With increasing deep rolling temperature, compressive residual stresses increase and reach maximum values for a deep rolling temperature of approximately 300°C. Axial stress components have considerably higher amounts than tangential components. Residual stress depth distributions, as exemplarily presented in Fig. 10 show, as expected, compressive residual stress maxima below the surface. Maximum residual stress amounts are highest for deep rolling at room temperature and smaller for high temperature as well as for cryogenic deep rolling.

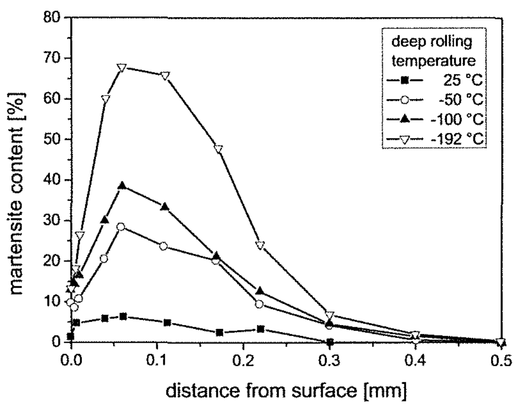

Fig. 8: Depth distribution of martensite content after different deep rolling treatments [11]

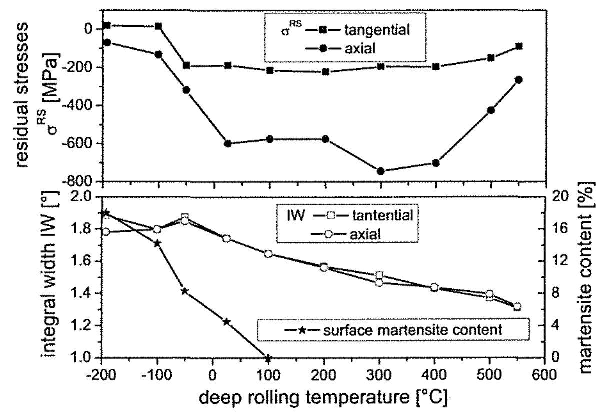

Fig. 9: Surface residual stresses (above) and integral width and martensite content (below) after deep rolling at different temperatures

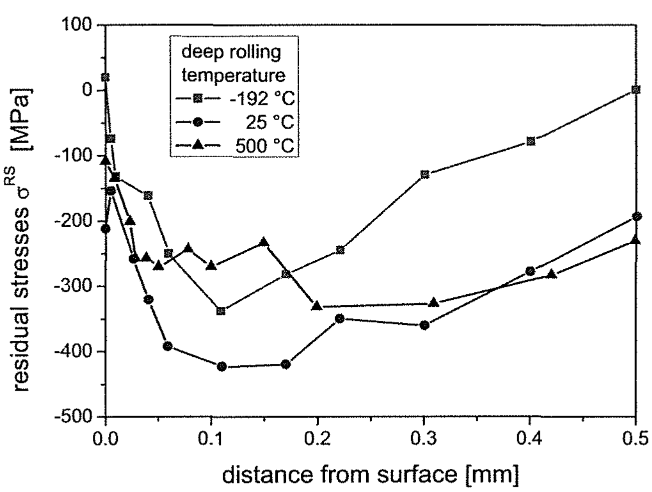

Fig. 10: Residual stress depth distributions (tangential direction) at different deep rolling temperatures

Fatigue tests clearly indicated, that the amount of strain induced martensite in the surface layers produced by the deep rolling process is not the decisive parameter for fatigue strength or lifetime. Moreover, the stability of induced compressive residual stress fields in the strain hardened surface layers is crucial, which is better for high temperature deep rolling as already explained in the previous section [11].

Conclusions

Mechanical surface treatments combined with selected high temperature effects are promising methods to achieve excellent near surface mechanical properties especially for components intended for fatigue loading. It is, however, necessary to clearly understand the underlying physical processes of the individual process steps to realize optimum materials states.

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