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Fatigue Performance of High-Temperature Deep-Rolled Metallic Materials

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Abstract

High-temperature deep rolling was developed from conventional deep rolling (deep rolling at room temperature) and performed on various metallic materials, such as austenitic stainless steel AISI 304, normalized plain carbon steel SAE 1045, aluminium alloys (non-precipitation-hardenable AA5083 and precipitation-hardenable AA6110). The fatigue performance of high-temperature deep-rolled specimens was investigated using stress-controlled fatigue tests and compared with the conventionally deep-rolled condition. It was found that high-temperature deep rolling effectively enhances the fatigue performance of steels. However, for aluminium alloys, the beneficial effects of high-temperature deep rolling are not pronounced due to the different strengthening mechanisms in aluminium alloys.

Key words : Aluminium alloy, Fatigue, High-temperature deep rolling, Plain carbon steel, Stainless steel

Introduction

Mechanical surface treatments, such as shot peening, laser shock peening and deep rolling efficiently enhance the fatigue performance of various metallic materials, such as magnesium.(1-3) titanium(3,4) aluminium alloys(3,5-7) and different steels.(8,9) This enhance-ment results from induced macroscopic compressive residual stresses and work hardening at the surface and in near-surface regions inhibiting or retarding crack initiation and propagation resulting in fatigue performance enhancement.(3,10) Nowadays, conven-tional mechanical surface treatments are modified using a static/ dynamic strain ageing concept. Therefore, thermo-mechanical surface treatments, such as warm shot peening were finally established. Superior fatigue performance and stability of residual stresses of warm shot peened AISI 4140 were observed due to pinning dislocation movements by interstitial solute atoms of carbon and nitrogen (so-called Cottrell-clouds) as well as very fine carbides.(11,12) Deep rolling is an alternative method of mechanical surface treatment which offers many advantages, e.g. greater depth of near-surface macro-scopic compressive residual stresses, work hardening and surface smoothening.(5-7,13) Therefore, an advanced deep rolling process, namely high-temperature deep rolling is of particular interest. However, for materials having mainly substitutional solute atoms (such as non-precipitation-hardenable aluminium alloys), the full beneficial effects of static/dynamic strain ageing cannot be expected. Nevertheless, for precipitation-hardenable materials, static/dynamic precipitation during mechanical surface treatment at elevated temperature may contribute to enhanced mechanical properties of the surface and the bulk particularly for the solution-heat-treated (as-quenched) condition. In this paper, therefore, fatigue performance of high-temperature deep-rolled various metallic materials, e.g. normalized plain carbon steel SAE 1045, austenitic stainless steel AISI 304, aluminium alloys AA5083 and as-quenched AA6110 were investigated.

Experimental Procedures

Cylindrical specimens with a diameter of 7 mm and a gauge length of 15 mm of austenitic stainless steel AISI 304, normalized plain carbon steel SAE 1045, aluminium alloys AA5083 and as-quenched AA6110 were prepared from the delivered sheets/bars. The loading direction during fatigue test corresponds to the rolling/extrusion direction of the sheet/bar. The plain carbon steel SAE 1045 was delivered in the normalized condition. The aluminium alloy AA6110 was solution heat treated at a temperature of 525°C for about 30 min followed by water quenching. Austenitic stainless steel AISI 304 and aluminium alloy AA5083 were

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investigated without any further heat treatment. For deep rolling, a pneumatic rolling device with a 40 mm diameter roller and a rolling force in the range of 0.27−1 kN was applied at room and elevated temperatures using inductive heating.

Tension-compression fatigue tests were conducted using a servohydraulic testing machine under stress control without mean stress ($R = -1$) and with a test frequency of 5 Hz. Strain was measured using capacitative extensometers. Residual stresses were measured using the classical $\sin^2\Psi$-method. Residual stress-depth profiles were determined by successive electrolytical material removal. Near-surface hardening was characterized by the full width at half maximum (FWHM) value of the X-ray diffraction peaks and by microhardness measurements.

Results and Discussion

Fatigue tests were carried out to find the optimized temperature for deep rolling for each investigated materials. Specimens deep rolled at different temperatures were cyclically deformed at room temperature at a constant selected stress amplitude. For example, Figure 1 shows a diagram exhibiting the effect of deep rolling temperature on the fatigue lifetime of normalized SAE 1045. A maximum fatigue lifetime of about 135,000 was observed at an applied stress amplitude of 340 MPa after deep rolling at a temperature of 350°C. Other investigated materials show also a similar manner. The optimized deep rolling temperatures for all investigated materials were summarized in Table 1. However, it should be noted that the degree of improvement is different for each material due to the different strengthening mechanism which will be shown and described in the following discussion.

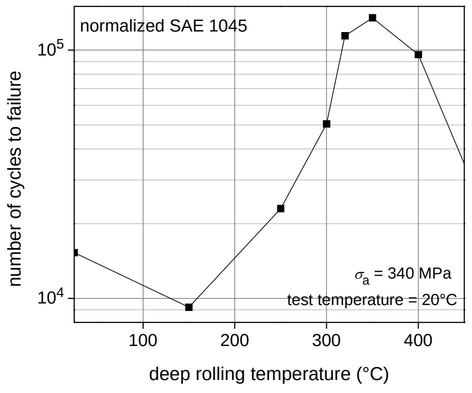

Figure 1. Fatigue lifetimes of normalized SAE 1045 at room temperature for different deep rolling temperatures.

Table 1. Optimized deep rolling temperature for the investigated materials

Materials	Optimized deep rolling temperature (°C)
Normalized SAE 1045	350
AISI 304	550
AA5083	150
as-quenched AA6110	200

Generally, high-temperature deep rolling mostly induced lower macroscopic compressive residual stresses as compared to the room-temperature deep rolled condition due to recovery processes. Nevertheless, in some cases, higher macroscopic compressive residual stresses were measured after high-temperature deep rolling, such as for normalized SAE 1045 as shown in Figure 2

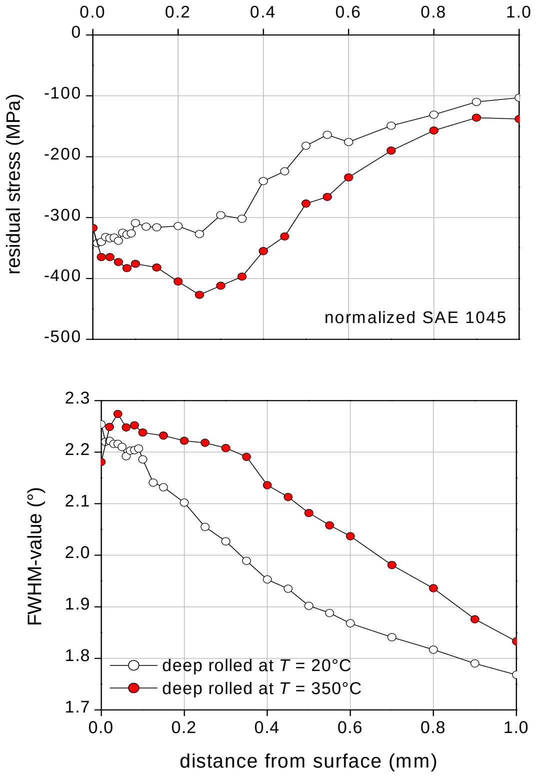

Figure 2. Residual stress- and FWHM-value-depth profiles of normalized plain carbon steel SAE 1045 after deep rolling at room temperature and optimized temperature.

Therefore, it can be mentioned that there are several factors influencing the residual stress state of the high-temperature deep rolled condition, e.g. amount of plastic deformation and recovery (dislocation arrangement) behavior of materials at the selected deep rolling temperature. Inhomogeneous micro residual stresses occurred due to dislocations, second phases as well as precipitates can be characterized using FWHM-values of X-ray diffraction peaks. High-temperature deep rolling altered the near-surface properties and microstructures, such as increased dislocation densities, precipitated carbides as well as other precipitates. Therefore, FWHM values of the high-temperature deep rolled condition can increase or decrease depending on the degree of deformation, phase transformation and recovery behavior of the investigated materials. If the rate of the recovery process is high and its effect dominates during high-temperature deep rolling, lower FWHM-values were detected although precipitates occurred and hardnesses increased (see Figure 3).

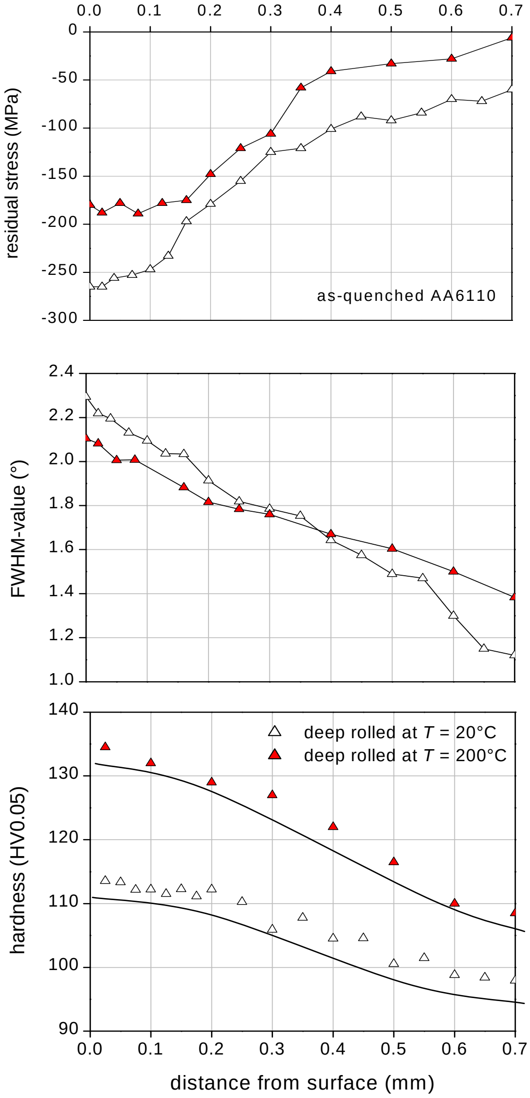

Figure 3. Residual stress-, FWHM-value-and hardness-depth profiles of as-quenched AA6110 after deep rolling at room temperature and optimized temperature

The beneficial effects of conventional (room-temperature) deep rolling, e.g. induced near-surface compressive residual stresses, work hardening, increased hardnesses and surface smoothening result in fatigue performance enhancement of metallic materials as compared to the non-surface-treated as well as polished condition.(3,5-7) After deep rolling at optimized temperature (see Table 1), superior fatigue performance was observed as compared to the conventionally deep-rolled condition as shown in Figure 4 presenting an example of non-statistically evaluated S/N curves of differently deep rolled SAE 1045 as compared to the non-surface-treated condition. Figure 5 illustrates also some examples of fatigue lifetimes of the investigated materials, deep rolled at room temperature and optimized elevated temperature. The results are always compared to the non-surface treated/ polished condition. The strong increase in fatigue lifetime and strength by high-temperature deep rolling can be attributed to the static/dynamic strain ageing in steels. Dislocations are impeded by Cottrell-clouds and very fine carbides(14) occurring during high-temperature deep rolling. Consequently, macroscopic compressive residual stresses and work hardening at the surface and in near-surface regions of the high-temperature deep rolled condition are more stable than that of the conventional deep rolled condition.(14) These significant effects as mentioned above including increased hardnesses result in a superior fatigue performance of steels. However, in some cases, the full beneficial effects of static/dynamic strain ageing cannot be expected, such as in aluminium alloys. Aluminium alloy AA5083 has mainly subs-titutional solute atoms which cannot impede efficiently dislocation movements as compared to the interstitial solute atoms in steels. As a consequence, fatigue performance of AA5083 is enhanced only slightly after high-temperature deep rolling (see Figure 5). For the as-quenched AA6110, precipitation occurred during high-temperature deep rolling resulting in increased near-surface hardnesses. Nevertheless, an increase of near-surface hardnesses was not fully optimized due to the short period of the high-temperature deep rolling process (2-3 min). For that reason, only a slight fatigue lifetime enhancement was observed (see Figure 5). Normally, as-quenched AA6110 has to be aged at a temperature of 160°C for 12 h to obtain a maximum hardness (peak-aged condition).(6)

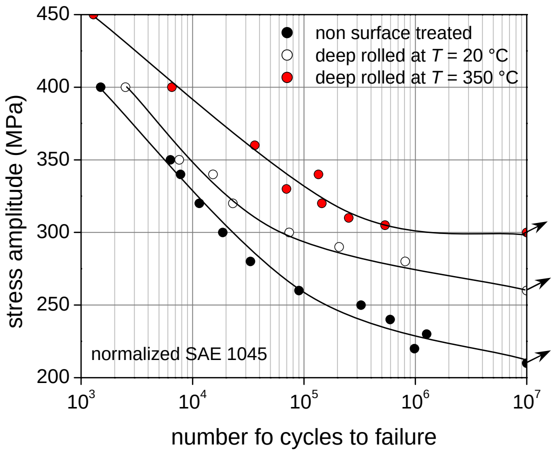

Figure 4. Non-statistically evaluated S/N curves of room temperature and optimized temperature deep rolled SAE 1045 as compared to the non-surface- treated condition.

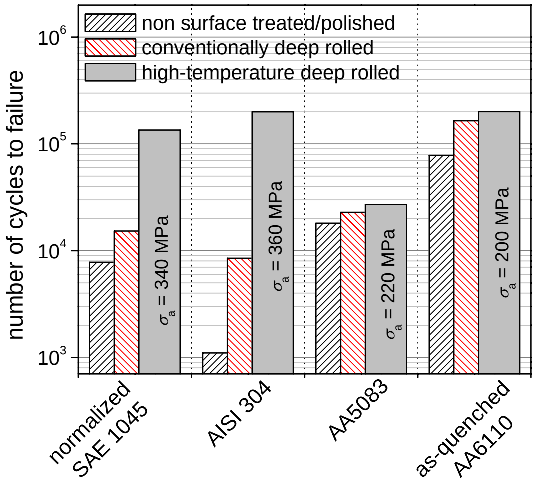

Figure 5. Exemplary fatigue lifetimes of various investigated materials deep rolled at room temperature and optimized elevated temperature as compared to the non-surface treated/ polished condition.

Conclusion

High-temperature deep rolling enhances effectively the fatigue performance of various steels. Here, static/dynamic strain ageing and very fine carbides are the most important mechanisms. High-temperature deep rolling is not entirely effective for aluminium alloy AA5083 where the beneficial effects of static/dynamic strain ageing cannot be fully expected. Due to a short period of the high-temperature deep rolling process, a slight fatigue performance enhancement was also observed for the as-quenched aluminium alloy AA6110 where appropriate ageing temperatures and times are necessary to obtain a peak-aged condition.

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