Chapter 5

Effects of Deep Rolling and Its Modification on Fatigue Performance of Aluminium Alloy AA6110

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1. Introduction

Recently, low-weight components are particularly required for environmental, ecological and economical aspects. Therefore, light-weight metals are frequently mentioned and selected for many applications where low density and high strength to weight ratios are an important consideration. Consequently, development and improvement in the field of light-weight metals can be seen continuously for advanced applications in automotive as well as aerospace industries. One of the most important light-weight metals is aluminium and its alloys which possess many attractive characteristics including excellent corrosion resistance in most environments, reflectivity, high strength and stiffness to weight ratio, good formability, weldability and recycling potential [1,2]. Certainly, these advantageous properties make them ideal candidates to replace heavier materials (steel or copper) for several industries. Therefore, mechanical behavior of aluminium alloys becomes more and more important, especially under cyclic loading due to failures occurring in machinery components are almost entirely fatigue failures. Accordingly, fatigue performance of aluminium alloys was investigated and also improved by mechanical surface treatments, e.g. shot peening, deep rolling and laser shock peening. Deep rolling is one of the most well-known mechanical surface treatment methods and exhibits a great depth of near-surface work hardening state and compressive residual stresses serving to inhibit or retard fatigue crack initiation as well as crack growth [3-5].

Ageing treatments combined with e.g. shot peening or deep rolling are methods to enhance the effects of conventional mechanical surface treatments for steels or materials having interstitial solute atoms. The fatigue performance of deep rolled steels SAE 1045, AISI 4140 and stainless steel AISI 304 can be considerably improved after annealing due to static/dynamic strain ageing. The formation of carbon atom clouds and very small carbide precipitates are the significant phenomena to impede dislocation movement and thus determine the mechanical properties. Normally, for precipitation-hardenable materials such as aluminium- and titanium alloys, mechanical surface treatment is performed after ageing treatments for fatigue lifetime enhancement. However, in some cases, mechanical surface treatment is performed on solution-heat-treated conditions with subsequent ageing treatments to produce increased hardness by precipitates especially in near-surface regions. The fine precipitates can be reasonably produced by prior plastic deformation due to preferential heterogeneous nucleation in the vicinity of dislocations in near-surface regions thus improving the cyclic deformation behavior [6,7]. On the other hand, the near-surface compressive residual stresses and work hardening induced by mechanical surface treatments decrease during annealing as well as ageing treatments. By the reduction of compressive residual stresses and near-surface work hardening, a detrimental effect for the fatigue lifetime is expected. The effects of decreased residual stress as well as work hardening together with the increased hardness by the ageing treatment on the fatigue performance are of particular interest, especially in smooth, soft and mechanically surface treated aluminium alloys because their fatigue lifetime depends significantly on the stability of near-surface work hardening as well as compressive residual stresses which can inhibit or retard surface fatigue crack initiation as well as fatigue crack growth. The purpose of this work is therefore to investigate systematically how optimized fatigue lifetimes by ageing treatments of deep rolled as-quenched AA6110 can be obtained. It should be noted that the optimize ageing treatment for the solution-heat-treated aluminium alloy AA6110 producing a maximum hardness value and also maximum yield stress is at a temperature of 160 °C for about 12 hr. Moreover, modern mechanical surface treatments have been developed from shot peening and deep rolling to give an optimized surface condition. At elevated temperatures, static/dynamic strain ageing is applied to shot peening and deep rolling. Consequently, warm shot peening and high-temperature deep rolling have become established techniques, particularly for materials that have interstitial solute atoms, e.g. steels containing carbon or nitrogen atoms [7]. Superior stability of macroscopic compressive residual stresses as well as work-hardening states during cyclic loading are observed due to dislocation pinning by interstitial solute atoms (so-called Cottrell clouds) or very fine carbides. Accordingly, superior fatigue performance was observed as compared to conventional mechanical surface treatments. It is very challenging when a modern mechanical surface treatment such as high temperature deep rolling is performed on precipitation-hardenable materials such as aluminium alloys that have mainly substitutional solute atoms where the full beneficial effects of static/dynamic strain ageing cannot be expected. Nevertheless, static/dynamic precipitation occurring during mechanical surface treatment at elevated temperatures may contribute to mechanical properties of the surface as well as the bulk, particularly for the solution-heat-treated condition. Thus, a newly developed mechanical surface treatment, high-temperature deep rolling, was performed on the solution-heat-treated aluminium alloy AA6110 for different deep-rolling temperatures up to 250 °C.

2. Methodology

The aluminium wrought alloy AA6110 was delivered from Alcoa Extrusions, Hannover, Germany as extruded bars with a diameter of 34 mm. The chemical composition of this alloy is 0.86 Si, 0.19 Fe, 0.45 Cu, 0.46 Mn, 0.78 Mg, 0.17 Cr, 0.02 Zn, 0.01 Ti and Al balance (all values in wt%). The alloy is a precipitation-hardenable Al–Mg–Si–Cu alloy, forming ′′ as well as Q ′ precipitates. Cylindrical specimens with a diameter of 7 mm and a gauge length of 15 mm were prepared. The loading direction during fatigue investigations corresponds to the extrusion direction of the bar. The specimens were solution heat treated in a furnace with argon atmosphere at a temperature of 525 °C for 30 min followed by water quenching to room temperature. The specimens were deep rolled at room temperature immediately after quenching. A hydraulic rolling device with a 6.6 mm spherical rolling element and a rolling pressure of 80 bar was used. The deep rolled as-quenched specimens were aged in the temperature range 50–300 °C with different ageing times up to approximately 28 and 148 h. For a high-temperature deep rolling, a pneumatic rolling device with a 40 mm diameter roller and a rolling force of 0.27 kN was applied at room temperature and at elevated temperatures up to 250 °C using inductive heating. On all specimens fatigue tests as well as thermal relaxation investigations were carried out. The non-mechanically surface treated specimens were electrolytically polished in the gauge length leading to a material removal of 100 μm before testing to avoid any influence of machining. Tension-compression fatigue tests were conducted with a servohydraulical testing device at stress control without mean stress (R = -1) and with a test frequency of 5 Hz. Strain was measured using capacitative extensometers. Residual stress- and FWHM-value-depth-profiles were determined by successive electrolytical material removal using the classical $\sin^2\Psi$-method with CuKα-radiation and the {333}-planes and $1/2\ s_2 = 19.77 \times 10^5$ mm^2/N as elastic constant. 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.

3. Results and discussion

3.1. Deep rolling followed by ageing treatment

Normally, for precipitation-hardenable materials, such as aluminium- and titanium alloys, mechanical surface treatment is performed after ageing treatments for fatigue lifetime enhancement as reported in [5,8-11]. However, in some cases, mechanical surface treatment is performed on solution heat treated (as-quenched) conditions with subsequent ageing treatments to produce increased hardness by precipitates especially in near-surface regions [12-15]. However, on the other hand, at the same time, near-surface macroscopic compressive residual stresses and work hardening states induced by mechanical surface treatments decrease during ageing treatments due to thermal residual stress relaxation. By the reduction of near-surface macroscopic compressive residual stresses and work hardening states, a detrimental effect for the fatigue lifetime can be expected. The effects of decreased residual stresses as well as work hardening states together with increased hardness values by the ageing treatment on the fatigue behavior of aluminium alloy AA6110 will therefore be thoroughly investigated and closely monitored in this section. Fig. 1 shows the hardness values at the surface of the deep rolled as-quenched condition after ageing treatments as a function of ageing times and temperatures. After ageing treatments in the temperature range 160-250 °C, the hardness values at the surface increased continuously with increasing ageing time until reaching a maximum value. Maximum hardness values of approximately 140, 133 and 123 HV were measured after ageing at temperatures of 160

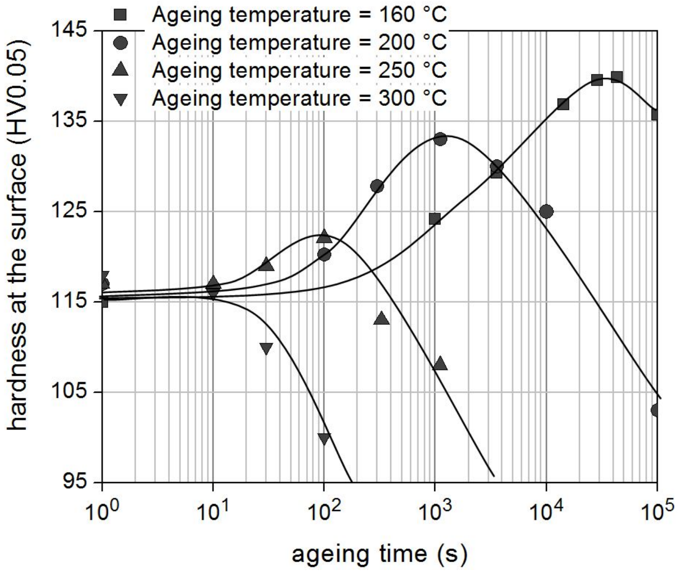

Figure 1. The hardness values at the surface of deep rolled as-quenched AA6110 during different ageing treatments.

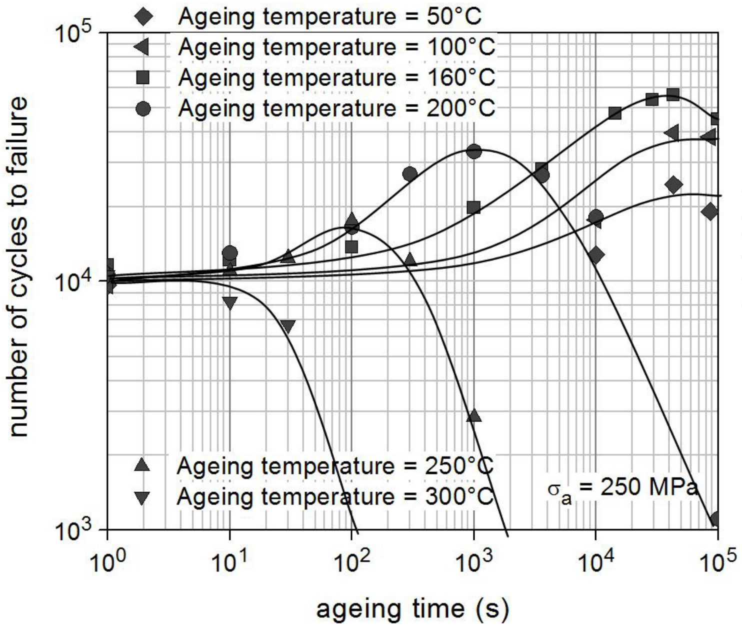

Figure 2. Fatigue lifetime as a function of ageing time and –temperature for an applied stress amplitude of 250 MPa

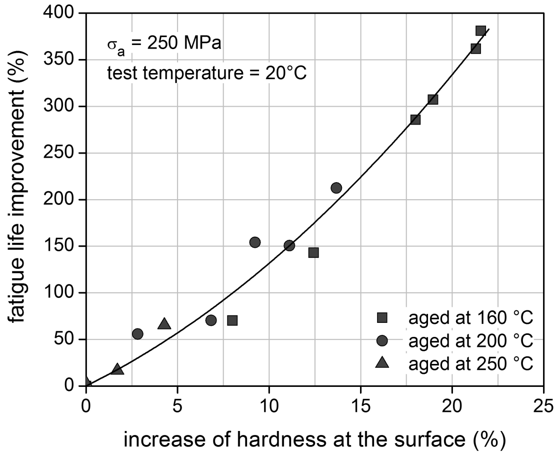

Figure 3. Fatigue life improvement as a function of hardness increase at the surface of deep rolled as-quenched AA6110 after ageing treatments at 160-250 °C.

200 and 250 °C for ageing times of approximately 12 hr, 1,000 and 100 seconds, respectively. For an ageing temperature of 300 °C, increased hardness values at the surface were not observed. The precipitated phases, '' as well as Q' lead to the increased hardness of copper-containing Al-Mg-Si aluminium alloys [1,2]. The maximum hardness of the deep rolled as-quenched AA6110 can be found after an ageing treatment at a temperature of 160 °C and an ageing time of 12 hr. For prolonged ageing treatments in the temperature range of 160-250 °C, the hardness values at the surface of deep rolled as-quenched specimens declined after having reached the peak hardness. The formation of coarse, semi-coherent, ' and/or Q' as well as incoherent precipitates, and/or Q at the surface as well as in near-surface regions is the reason for this observation. Conversely, for an ageing treatment at a temperature of 300 °C with a short ageing time, an increase of hardness was not observed. It might be due to the dominant recrystallization process taking place before occurring precipitation process [16].

Fatigue tests were also performed to evaluate the optimized fatigue lifetime. For this purpose, the relation between ageing time, temperature and fatigue lifetime was established at an applied stress amplitude of 250 MPa as shown in Fig. 2. After ageing treatments in the temperature range 160-250 °C, the fatigue lifetimes increased continuously with increasing ageing time until reaching a maximum lifetime. The optimized fatigue lifetime of the deep rolled as-quenched AA6110 was found after an ageing treatment at a temperature of 160 °C for about 12 hr. As expected, the increase of near-surface hardness after the ageing treatments resulted in an enhancement of the fatigue lifetime. Fig. 1 and Fig. 2 show that there is a clear correlation between hardness values and fatigue lifetimes of the deep rolled as-quenched AA6110 after ageing treatments. To clarify this correlation, a diagram of fatigue life improvement versus increase of hardness at the surface was constructed as shown in Fig. 3 using experimental data from Fig. 1 and Fig. 2. The residual stresses and FWHM-values decreased due to the relaxation as well as recovery processes. Residual stress and FWHM-values at the surface were reduced from -265 to -100 MPa and from 2.3° to 2.0°, respectively.

Because residual stress relaxation immediately at the surface is stronger than in subsurface layers, after ageing, a subsurface compressive residual stress maximum is formed as shown in Fig. 4. Non-statistically evaluated s/n-curves of the deep rolled as-quenched state after the optimized ageing treatment are shown as compared to the deep rolled as-quenched conditions in Fig. 5. At room temperature, the ageing treatment after mechanical surface treatment can enhance the fatigue lifetime especially in low cycle fatigue regime. However, in the high cycle fatigue regime, the difference in fatigue lifetimes was almost negligible. For elevated test temperature, the optimized-aged deep rolled condition exhibits also greater fatigue lifetimes as compared to the deep rolled as-quenched condition. Fatigue lifetimes of the deep rolled as-quenched condition were improved especially in the low cycle fatigue regime after the optimized ageing treatment (see Fig. 5) due to increased hardness values at the surface and in near-surface regions as well as in the bulk. However, the induced macroscopic compressive residual stresses as well as work hardening states seem to be essential in the high cycle fatigue regime, where relatively low stress amplitudes were applied and mechanical relaxation was not significant during cyclic loading at room temperature.

3.2. Comparison of conventional and modified deep rolling

The most important and interesting issue of the modified mechanical surface treatment (deep rolling followed by optimized ageing treatment) is the comparison with the conventional mechanical surface treatment (optimized ageing followed by deep rolling). First of all, important information of surface properties of the optimized-aged deep rolled as-quenched and deep rolled optimized condition is shown in Fig. 6 illustrating residual stress- and FWHM-depth-profiles of deep rolled as-quenched AA6110 after the optimized ageing treatment as compared to deep rolled optimized-aged AA6110. Hardness values of 137 and 161 HV are measured at the surface of deep rolled as-quenched AA6110 after the optimized ageing treatment and deep rolled optimized-aged AA6110, respectively. Noticeably, all important properties which are beneficial effects for fatigue lifetime enhancement, such as hardness, macroscopic compressive residual stress as well as the work hardening state of the optimized-aged deep rolled as-quenched condition are significantly less than of the deep rolled optimized/peak-aged condition. The greater near-surface macroscopic compressive residual stresses, FWHM-values as well as hardness values of the deep rolled optimized condition indicate that the deep rolling after an optimized ageing treatment results in an excellent combination of work- and precipitation hardening and thus excellent fatigue lifetime could be expected for the deep rolled optimized/peak-aged AA6110. To confirm this assumption, s/n-curves of the optimized-aged deep rolled as-quenched condition were plotted and compared to the deep rolled optimized/peak-aged condition in one diagram in Fig. 7. Obviously, fatigue lifetimes as well as -strength of the deep rolled optimized/peak-aged condition are superior to the optimized-aged deep rolled as-quenched condition. It can be concluded that both hardening effects, work- and precipitation hardening are required to yield the best fatigue lifetimes of AA6110. As known, the deep rolling treatment serves principally to induce near-surface work hardening and macroscopic compressive residual stress. For the ageing treatment after deep rolling, unfortunately, the work hardening and macroscopic compressive residual stresses were partially annealed out rapidly during the ageing treatment due to the relaxation process (mainly self diffusion). Therefore it can reasonably be assumed that fatigue lifetimes of the optimized-aged deep rolled as-quenched AA6110 were governed by the precipitation hardening and residually effective work hardening as well as compressive residual stresses at the surface and in near-surface regions. Therefore, the fatigue lifetime of the deep rolled as-quenched AA6110 followed by the optimized ageing treatment is better than of the deep rolled as-quenched AA6110 in the low cycle fatigue regime (see Fig. 5). However, the deep rolling after a suitable/optimized ageing treatment can completely combine the work- and precipitation hardening in near-surface regions of AA6110 into an optimized microstructure and thus result in the best surface properties and fatigue lifetime of the investigated AA6110 (see Fig. 7).

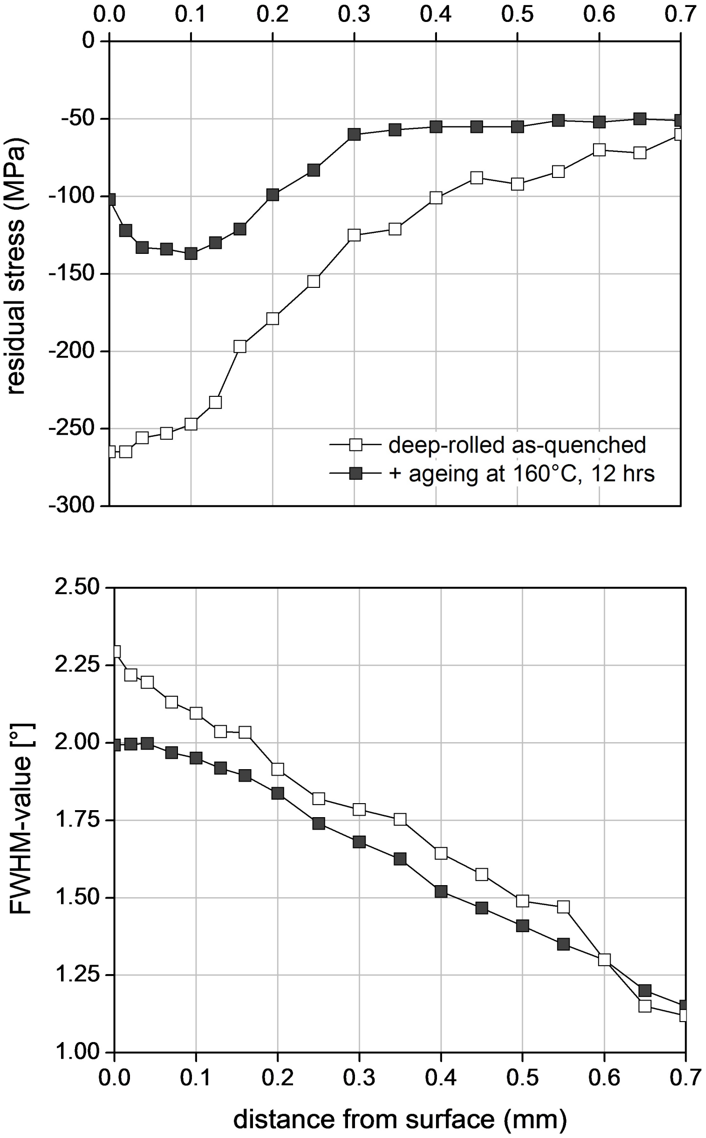

Figure 4. Residual stress- and FWHM-depth-profiles of deep rolled as-quenched AA6110 before and after the optimized ageing treatment.

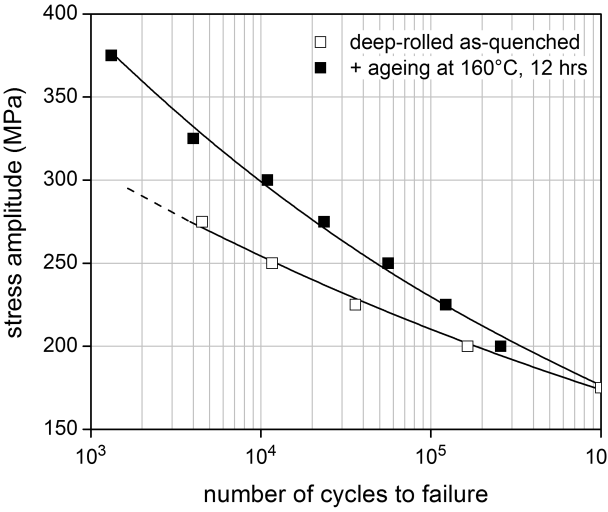

Figure 5. Non-statistically evaluated s/n curves of deep rolled as-quenched specimens before and after the optimized ageing treatment.

3.3. Deep rolling at elevated temperature

Thermomechanical surface treatment, the high-temperature deep rolling, has been successfully investigated for SAE 1045 as well as AISI 304 [20-24]. The fatigue behavior of these steels can be enhanced considerably due to static/dynamic strain ageing and together with very fine carbides at the surface and in near-surface regions [20-24]. Nevertheless, for aluminium alloys, it is still doubtful whether thermomechanical surface treatments can enhance the fatigue behavior more significantly than conventional mechanical surface treatments because aluminium alloys have mainly substitutional solute atoms. Thus, the fully beneficial effects of static/dynamic strain ageing can not be expected. However, static/dynamic precipitation during mechanical surface treatment at elevated temperature may contribute to mechanical properties of the surface as well as the bulk particularly for the as-quenched condition. Therefore, high-temperature deep rolling on the as-quenched aluminium alloy AA6110 was investigated. As-quenched specimens were deep rolled at different elevated temperatures of 160, 200 and 250 °C. Afterwards, near-surface properties and fatigue behavior were investigated and presented in this section. After deep rolling at elevated temperatures, near-surface residual stress, work hardening state and hardness-depth-profiles were measured as compared to the room-temperature deep rolled state as shown in Fig. 8 and Fig. 9. Obviously, macroscopic compressive residual stresses tend to decrease with increasing deep rolling temperature. Maximum macroscopic compressive residual stresses of -181, -152 and -59 MPa were measured at a depth of 20 μm after deep rolling at temperatures of 160, 200 and 250 °C, respectively. In contrast, after deep rolling at room temperature, a maximum macroscopic compressive residual stress value of -286 MPa was measured directly at the surface (see Fig. 6). After deep rolling at a temperature of 160 °C an approximately FWHM-value of 2.3° was measured which was to identical to the one observed after room-temperature deep rolling. However, FWHM-values tend to decrease at high temperature with increasing deep rolling temperature. The

FWHM-values about 2.1 and 1.6° were detected after deep rolling at temperatures of 200 and 250 °C, respectively. In addition, the case depth of work hardening after deep rolling at elevated temperatures seem to be greater than after room-temperature deep rolling. Near-surface hardness values, however, increased with increasing deep rolling temperature up to 200 °C as compared to deep rolling at room temperature. Hardness values in a depth of 25 μm of about 125 and 134.5 HV were measured after deep rolling at temperatures of 160 and 200 °C, respectively, whereas after deep rolling at room temperature, the hardness in a depth of 25 μm was approximately 113 HV. Conversely, after deep rolling at a temperature of 250 °C, a hardness in a depth of 25 μm of only about 104 HV was observed. As expected, due to occurring static/dynamic precipitation during deep rolling at elevated temperatures, near-surface hardness values after high-temperature deep rolling (160-200 °C) increased as compared to the room-temperature deep rolled as-quenched AA6110 (see Fig. 9). On the other hand, lower macroscopic compressive residual stresses and work hardening states

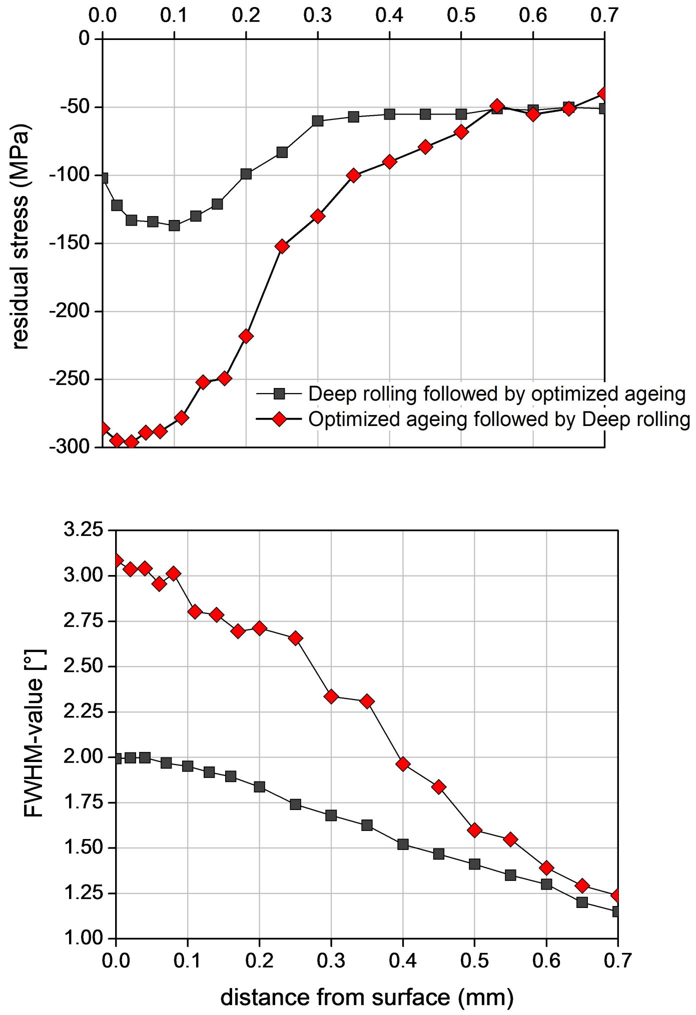

Figure 6. Residual stress- and FWHM-depth-profiles of deep rolled as-quenched AA6110 after the optimized ageing treatment as compared to deep rolled optimized-aged AA6110.

were measured as compared to the room-temperature deep rolled as-quenched condition (see Fig. 8) because static/dynamic recovery processes, which bring about relaxation phenomena, took place during deep rolling at elevated temperatures. The deep rolling treatment at a temperature of 250 °C produced detrimental effects on the near-surface properties, i.e. near-surface macroscopic compressive residual stresses, work hardening states and hardness values are considerably lower than of the room-temperature deep rolled as-quenched condition. That might be due to the fact that this temperature too high for the aluminium alloy AA6110 and leads to serve over-ageing effects and a high-rate static/dynamic recovery for this situation.

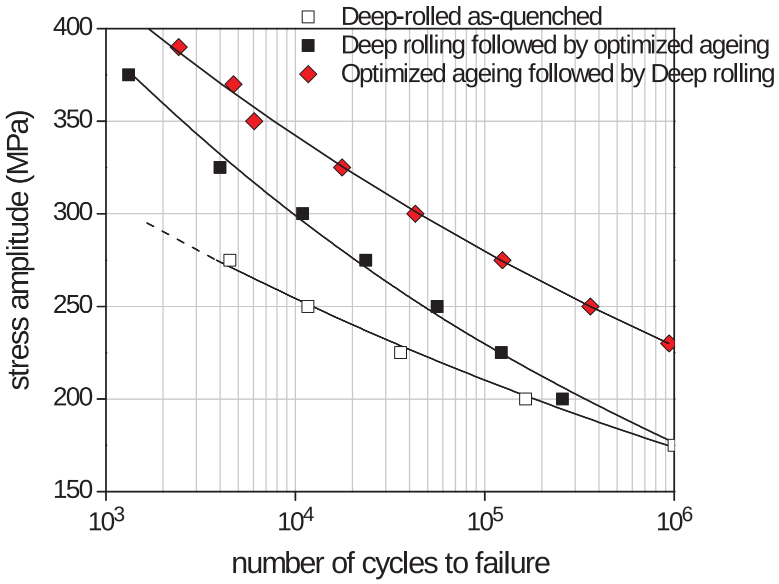

Figure 7. Non-statistically evaluated s/n curves of optimized-aged deep rolled as-quenched AA6110 as compared to deep rolled optimized-aged AA6110 as well as deep rolled as-quenched AA6110.

Non-statistically evaluated s/n-curves of the differently high-temperature deep rolled as-quenched condition at room temperature are presented as compared to the room-temperature deep rolled as-quenched condition in Fig. 10. The difference fatigue lifetimes for deep rolling treatments at temperatures between room temperature and 200 °C were insignificant. In the low cycle fatigue regime, fatigue lifetimes of as-quenched specimens deep rolled at a temperature of 200 °C seem to be slightly better than of the room-temperature deep rolled as-quenched condition, however in the high cycle fatigue regime, a contrary behavior was seen. The improvement of fatigue lifetimes at room temperature of the high-temperature deep rolled as-quenched AA6110 is not obvious as compared to the room-temperature deep rolled as-quenched AA6110. However, increased near-surface hardness values after deep rolling at a temperature of 200 °C slightly enhance fatigue lifetimes at room temperature in the low cycle fatigue regime. On the other hand, in the high cycle fatigue regime, the specimens deep rolled at a temperature of 200 °C show slightly lower fatigue lifetimes as compared to the room-temperature deep rolled as-quenched condition (see Fig. 10). This can be attributed to the lower near-surface macroscopic compressive residual stresses as well as work hardening states after deep rolling at a temperature of 200 °C (see Fig. 8).

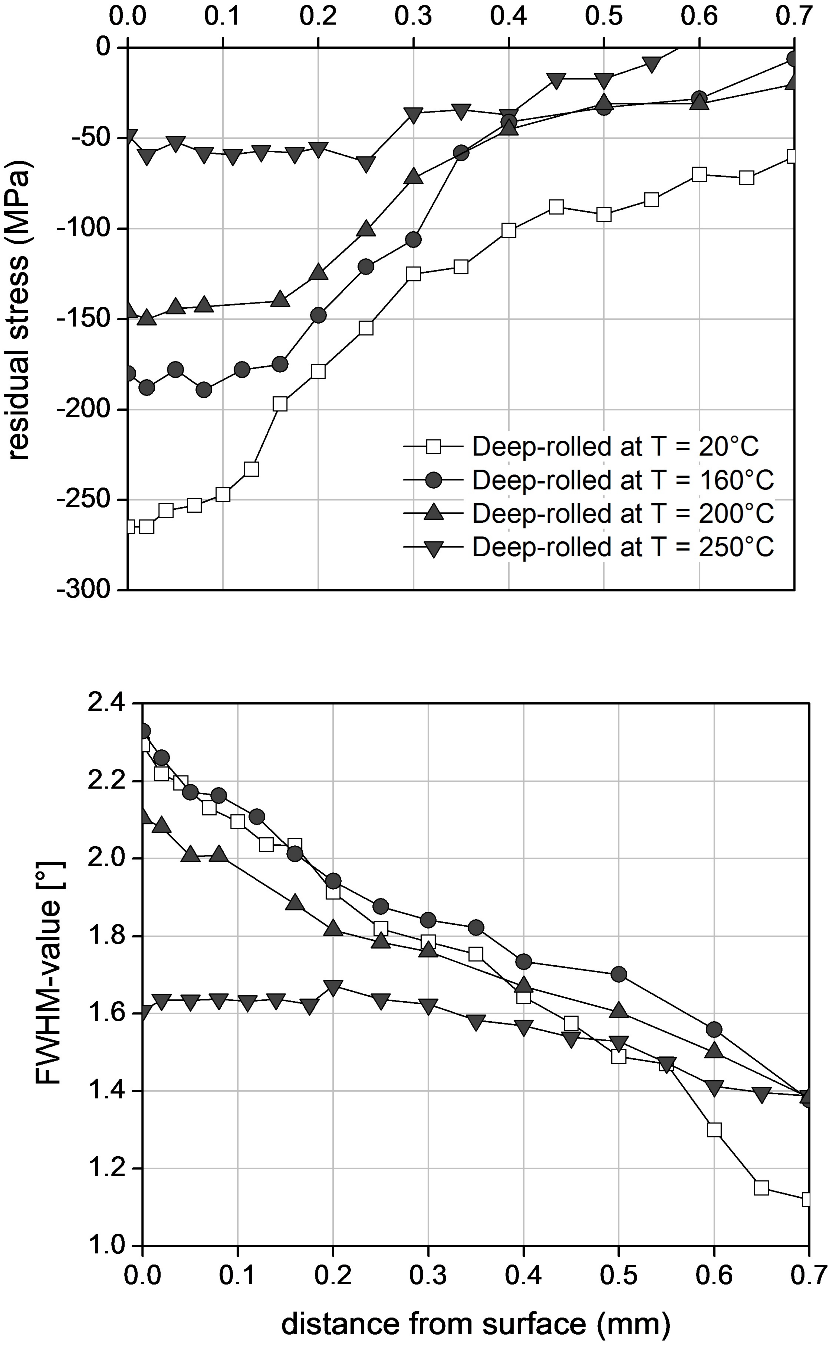

Figure 8. Depth-profiles of near-surface macroscopic compressive residual stresses and FWHM-values of high-temperature deep rolled as-quenched AA6110 for different deep rolling temperatures.

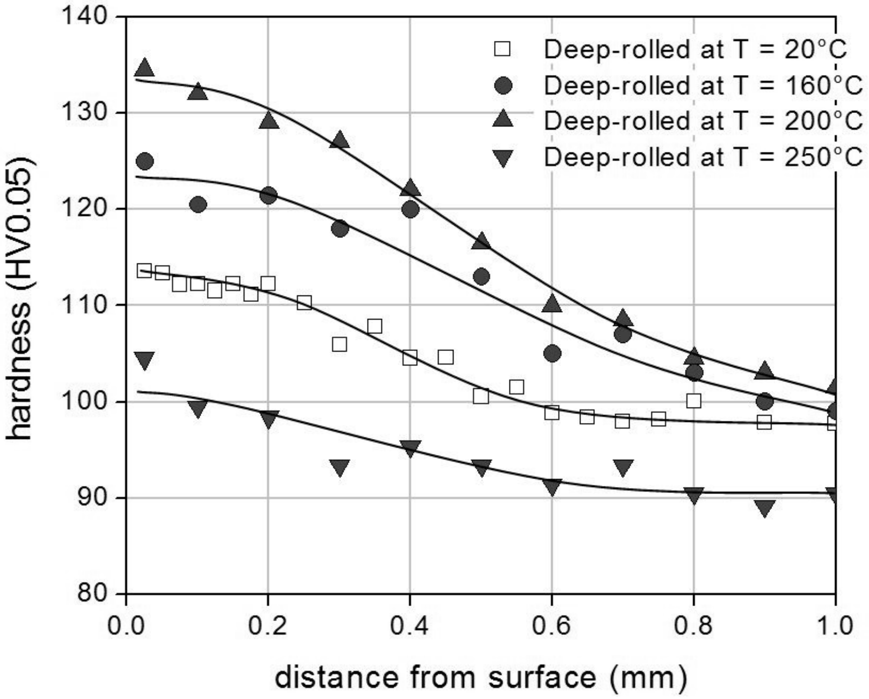

Figure 9. Depth-profiles of near-surface hardness values of high-temperature deep rolled as-quenched AA6110 for different deep rolling temperatures.

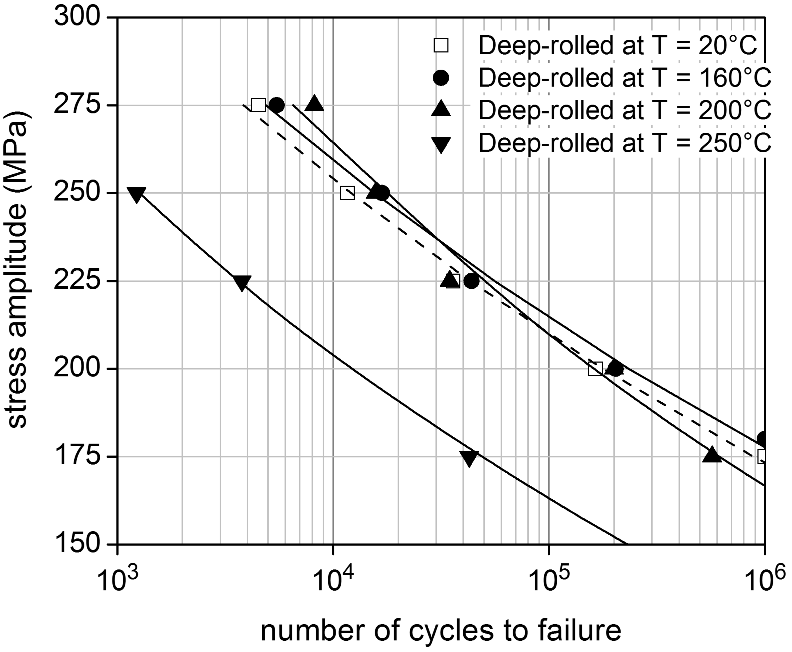

Figure 10. Non-statistically evaluated s/n-curves of high-temperature deep rolled as-quenched AA6110 for different deep rolling temperatures.

4. Conclusions

1. Deep rolling combined with an ageing treatment of as-quenched AA6110 resulted in an increase of near-surface hardness values. At the same time, a reduction of near-surface macroscopic compressive residual stresses and work hardening states takes place. The optimized ageing condition is an ageing temperature of 160 °C for about 12 hr.

2. Increased near-surface hardness values after the optimized ageing treatment seem to be very beneficial for the fatigue lifetimes in low cycle fatigue regime, whereas in the high cycle fatigue regime, macroscopic compressive residual stresses are additionally important.

3. Deep rolling at elevated temperatures up to approximately 200 °C resulted in an increase of near-surface hardness values in the as-quenched condition, whereas lower macroscopic compressive residual stresses and work hardening states were observed because static/dynamic recovery processes occurred. Deep rolling at a temperature of 250 °C exhibits detrimental effects on near-surface properties due to the over-ageing effects and high-rate static/dynamic recovery at this temperature.

4. An optimized ageing treatment followed by a conventional deep rolling treatment, can completely combine precipitation hardening and work hardening in near-surface regions of AA6110 into an optimized microstructure and residual stress state and thus result in the best surface properties and fatigue lifetime of the investigated AA6110.

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