# EFFECT OF DEEP ROLLING AT ELEVATED AND LOW TEMPERATURES ON THE ISOTHERMAL FATIGUE BEHAVIOR OF AISI 304

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## Abstract
This paper proposes a new method of surface optimisation to enhance the fatigue behaviour of AISI 304 stainless steel at ambient and elevated temperatures. High temperature deep rolling is a combination of classical methods for surface enhancement namely mechanical and thermal treatments. Mechanical surface treatments have been investigated thoroughly and can significantly improve the fatigue behaviour of steels. For AISI 304 stainless steel, which is used among others in nuclear power plants, deep rolling enhances the fatigue behaviour at room temperature as well as at elevated temperatures over a wide temperature range. Annealing after mechanical treatments can also improve the fatigue behaviour of many steels and has been studied already. However the combination of these two factors namely thermal and mechanical treatment is rarely investigated. For this purpose a classical and a novel surface treatment method are compared to each other in terms of their impact on fatigue behaviour. The treatments induce distinctly different near-surface microstructures with different mechanical and thermal stability. The aim of this paper is to clarify the role of the different near-surface microstructures on the fatigue behaviour of stainless steel AISI 304.

## Subject Index
Fatigue, deep rolling, residual stress, microstructure, strain ageing, turbines

## 1. Introduction
It is well known that localized elastic-plastic deformations in near-surface regions of metallic surfaces, produced for example by deep rolling, induce several beneficial effects such as compressive residual stresses and strain hardening thus enabling the strengthened near-surface regions to exhibit higher resistance against fatigue crack initiation and propagation [Sch 91, Alt 99, Wag 99]. Mechanically deformed AISI 304 exhibits transformation induced martensite ($\alpha'$) and micro twins. The volume fraction of the induced martensite and micro twins depends also on the local stress and temperature. By applying different temperatures during deep rolling with constant pressure different volume fractions of martensite and twins as well as different residual stress states can be produced in the surface region. Moreover, high temperature deep rolling produces very stable microstructures with high dislocations densities and fine carbides in the austenitic grains. Fine carbides affect the dislocation movement significantly. These strain ageing effects during deep rolling in combination with deep rolling effects, like e.g. relatively high compressive residual stress, decrease of roughness, can be exploited for fatigue improvements of many metallic materials such as metastable austenitic stainless steel AISI 304 investigated here.

## 2. Methods

The investigated material was hot-rolled AISI 304 stainless steel. Uniaxial tensile testing at 25 °C gave a yield strength of 345 MPa and 52 % elongation. Deep rolling treatments with 0.5 kN rolling force at different temperatures from –192 °C to 800 °C were applied. Heating and cooling for high and low temperature deep rolling was achieved by induction heating and with fluid nitrogen, respectively. Residual stress measurements and determination of the martensite content were performed by X-ray diffraction techniques. Isothermal fatigue experiments were performed under load control on a servohydraulical testing machine with a load ratio of R = -1, a frequency of 5 Hz and temperatures of 25-600°C. The cylindrical samples (diameter 7 mm) were heated with a halogenic radiant heating. Transmission electron microscopy (TEM) was performed using a 200 kV microscope on plan-view samples under two-beam conditions.

## 3. Results

The microstructures produced by deep rolling at different temperatures are presented in Figure 1. The initial state, exhibiting a grain size of 70 µm, is heavily deformed in near surface layers after deep rolling at room temperature. The deformed layer consist of slip lines, martensite and twins. Deep rolling at low temperatures produces significantly more martensite. It is assumed that the pronounced sub-surface maximum of the martensite content is caused by the water cooled / warmed rolling-element, thereby decreasing the temperature at the immediate contact area between workpiece and rolling tool. This maximum can be found in a depth of approximately 60 µm. At a rolling temperature of –192 °C the martensite content reaches a peak value of 68 %, in contrast to the room temperature condition, where only 6 % martensite is formed. Below a depth of 400 µm no martensite could be detected by X-ray methods. Above a deep rolling temperature of 100 °C the detectable martensite formation is suppressed completely. At a rolling temperature of 500 °C no visible surface deformation (twins, slip lines) can be found in micrographs obtained by light microscopy.

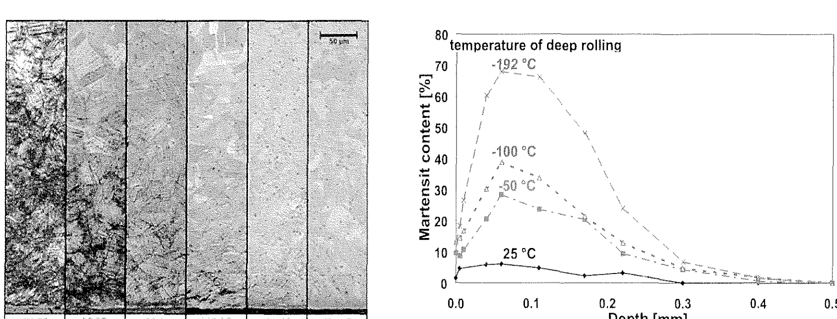


**Figure 1** Microstructure (left) and martensite content (right) of deep rolled AISI 304 at different temperatures

At room temperature, deep rolling induces a 2 µm thick nanocrystalline layer directly at the surface with a grain size of about 20 nm. The size of the nanocrystals increases with increasing temperature. After deep rolling at 500 °C the nanocrystal size is about 40 nm (Figure 2, left). At a rolling temperature of 800 °C microcrystals with relatively high dislocations densities were formed and the grain size increased to several hundred nanometers (Figure 2, right). We can see micro twins and relatively big carbides homogeneously distributed in an austenitic matrix. The size of the carbides is about 20 nm.

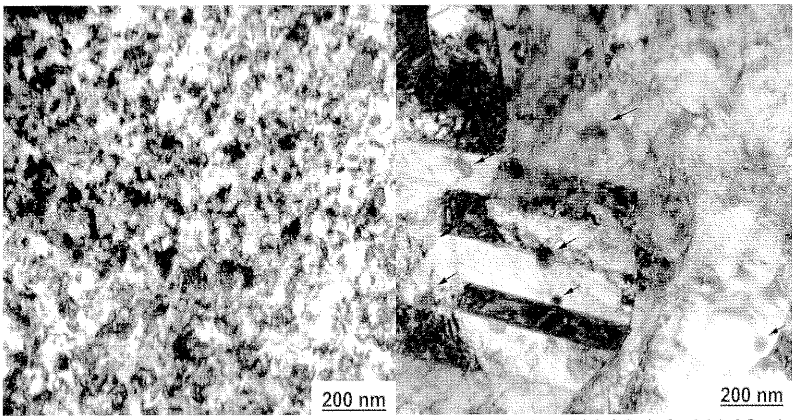


**Figure 2** TEM micrographs of the surface (deep rolled at 500 °C, left, 800 °C, right)

The subsurface in a depth of about 5µm of the deep rolled state shows a very high density of dislocations and relatively finely distributed carbides after high temperature deep rolling (Figure 3). Interestingly, the carbides in the subsurface region at 800 °C of the deep rolled state are smaller than at the surface.

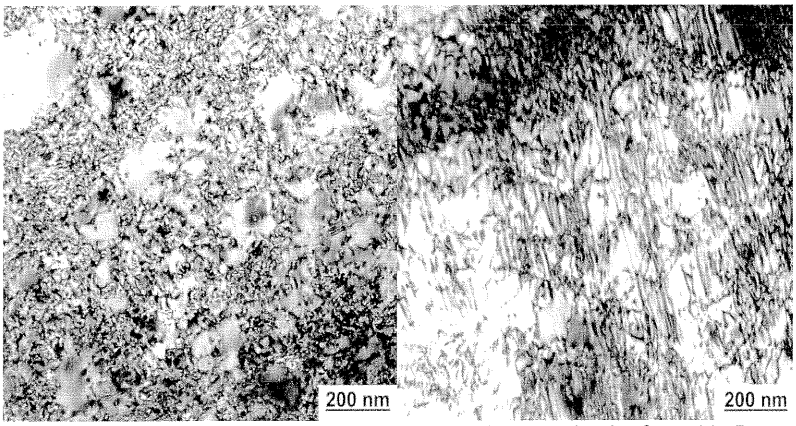


**Figure 3** TEM micrographs of the subsurface region at a depth of roughly 5 µm (deep rolled at 500 °C, left, 800 °C, right)

The size of the carbides in the subsurface region is almost identical for deep rolling at 500 °C and 800 °C, but the dislocations arrangements are significantly different. Deep rolling at 500 °C leads to high dislocations densities with a tangled structure. In contrast, deep rolling at 800 °C leads to mostly aligned and rather planar dislocations arrangements. Moreover, the deep rolled state at 500 °C exhibits small regions free of dislocations and exhibiting small precipitates.

Residual stress and full width at half maximum (FWHM) depth profiles of the {220}-Bragg peak are presented for different deep rolling temperatures in Figure 4. The residual stress state in the tangential and axial direction relatively to the sample geometry is distinctly different. The residual stress in the axial direction is always larger than in the tangential direction. If we compare the residual stress state for different deep rolling temperatures, we can observe a maximum of compressive residual stress (-834 MPa) at a deep rolling temperature of 300 °C. Cryogenic deep rolling as well as deep rolling above 400 °C leads to relatively small axial and tangential compressive residual stresses. At low temperatures the tangential residual stress is close to zero or even slightly in tension. The surface residual stresses are smallest for rolling temperatures of –192 °C and 800 °C for both the axial and tangential direction. For a rolling temperature of 550 °C residual stress in the axial and tangential direction is about –300 MPa and about –100 MPa respectively. For the cryogenically deep rolled state a residual stress subsurface maximum in a depth of approximately 110 µm was found, whereas for the higher temperatures the residual stress decreases continuously with increasing depth.

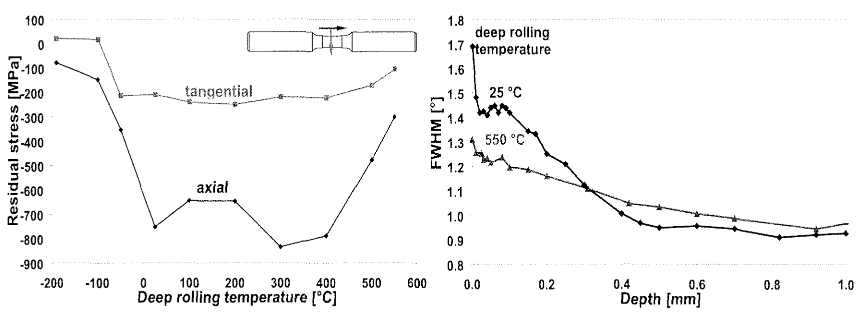


**Figure 4** Residual stress and FWHM-value at different temperatures

The FWHM-values at the surface decrease continuously with increasing rolling temperature. It is assumed that the maximum of the FWHM-value under the conditions investigated is associated with the occurrence of a maximum martensite content and very high density of twins. Deep rolling at room temperature and elevated temperatures leads to high dislocation densities but only a small amount of martensite. Especially interesting is a comparison between the FWHM-values of specimens deep rolled at room temperature and at 550 °C. At the surface, the FWHM value after room temperature deep rolling is considerably higher than after high temperature deep rolling. However, the opposite is observed in greater depths. These results are also essentially consistent with hardness measurements which yielded higher surface hardness values after room temperature deep rolling as compared to high temperature deep rolling at 550 °C.

The highest fatigue lifetime of deep rolled AISI 304 were obtained for a rolling temperature of 550 °C (Figure 5, left). Here, the fatigue life improvement in the LCF-regime is about 600 % (from 8,500 to 48,000) as compared to the condition deep rolled at room temperature. In spite of a very high martensite content at very low temperatures, the fatigue behaviour is not improved or even deteriorated as compared to the conventionally deep rolled state at room temperature. Here, the fatigue life decrease in the LCF-regime is about 40% between deep rolling at –100 °C and room temperature.

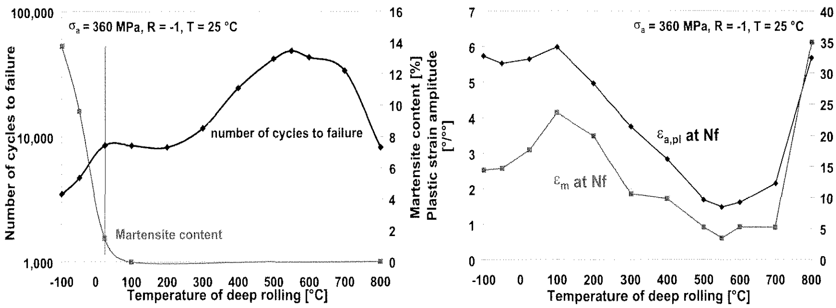


**Figure 5** Fatigue behaviour (left) and cyclic deformation curves (right) of deep rolled AISI 304 ($\sigma_a$ = 360 MPa, T = 25 °C)

Figure 5 (right) depicts the plastic strain amplitude and mean strain as a function of the deep rolling temperature. As predicted by the Manson-Coffin-law the maximum of the cyclic lifetime corresponds to a minimum of the plastic strain amplitude. A similar correlation is observed for the mean strain.

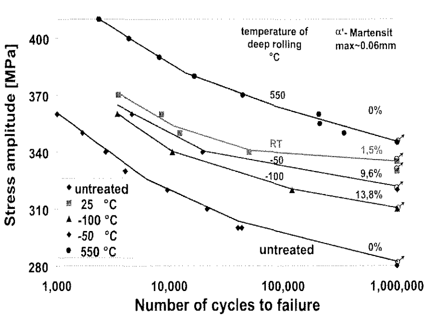


**Figure 6** s/n curves of deep rolled AISI 304 for room temperature fatigue after deep rolling at different temperatures

Deep rolling at all temperatures investigated significantly enhances the fatigue life (Figure 6). A maximum of improvement is obtained by deep rolling at 550 °C. In comparison to the untreated state, deep rolling at 550 °C improves the fatigue life in the LCF-regime by more than factor of 1000. The endurance limit for $10^6$ cycles is increased from 280 MPa to 345 MPa.

## 4. Discussion

Deep rolling improves the fatigue behaviour of AISI 304 [Nik 04]. This improvement depends on the rolling temperature. A maximum of improvement can be found for AISI 304 for a rolling temperature of 550 °C. This temperature is well known as strain ageing temperature for this alloy [Chr 91]. In the case investigated, strain ageing effects are added to classical mechanical surface treatment effects like work hardening or/and high compressive residual stress state. A combination of several effects, the formation of carbides, near surface nanocrystallisation, high dislocation densities, higher surface quality as well as compressive residual stress strongly improves the fatigue life and strength of AISI 304. First studies to combine these

effects for surface treated components have already been performed in [Wic 99, Alt 99].
The investigation of the cryogenically deep rolled state shows that the increased martensite content alone without relatively high compressive residual stresses does not improve the fatigue life as well as for the standard room temperature deep rolling method. This is clearly presented in Figures 1, 4, 5 and 6. It can be seen that relatively small residual stresses and relatively high martensite contents show the smallest fatigue lifetime. The FWHM-value of the compared states are more or less the same. In the present studies, obviously a high martensite content without a favourable residual stress state has little effect.
The comparison of the high temperature deep rolled state with the room temperature deep rolled state indicates that the finely distributed carbide precipitates have a stronger influence on the fatigue strength than the residual stress state or martensite content. The carbide formation starts already for deep rolling at 100 °C, as can be assumed by the decline of plastic strain amplitude with increasing temperature (Figure 5, right). Obviously, at 550 °C deep rolling leads to an optimised carbide size and distribution leading to a maximum fatigue life improvement and smallest plastic strain amplitudes and mean strain in stress-controlled tests. Above a rolling temperature of 550 °C, the carbide precipitates obviously cannot compensate the macro and micro residual stress relaxation. This is reflected in the slight increase of mean strain and plastic strain amplitude and in the decline of the fatigue life respectively. Finally, a rolling temperature of 800 °C leads to a relatively small fatigue life and relatively large mean strain and plastic strain amplitude, respectively. The carbides at this temperature are already too large for the compensation of macro and micro residual stress relaxation.

## 5. Conclusion

In this paper we investigated the effects of deep rolling temperature on the fatigue behaviour of AISI 304 at room temperature. The following conclusions can be made:
1. At all investigated rolling temperatures deep rolling improves the room temperature fatigue behaviour of AISI 304 significantly.
2. The maximum of fatigue life improvement occurs at a deep rolling temperature of 550 °C.
3. A high martensite content without a favourable residual stress state has no large effect on the fatigue life time or is even detrimental.
4. The residual stress state obviously has a smaller effect on the fatigue behaviour than the microstructure. Especially important are the finely distributed carbide precipitates.

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