Thermal Stability of Residual Stresses in Ti-6Al-4V components

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Abstract. The need for light weight design while maintaining a high safety is essential for many components, especially in the aircraft industry. Therefore, it's important to consider every aspect to reduce weight, improve fatigue life and maintain safety of crucial components. Residual stresses are a major factor which can positively influence components and fulfil all three requirements. However, due to the inconstancy of the behaviour of residual stresses during the life time of a component, residual stresses are often neglected. If the behaviour of residual stresses could be described reliably over the entire life time of a component, residual stresses could be taken into account and components could be optimized even further. Mechanical and thermal loads are the main reason for relaxation of residual stresses. This work covers the thermal stability of residual stresses in Ti-6Al-4V components. Therefore, exposure tests at raised temperatures were performed on specimens with different surface conditions. Residual stresses were measured by x-ray diffraction before and after testing. Creep tests were also carried out to describe the creep behaviour and thereby the ability for residual stress relaxation. A correlation between the creep rate and amount of relaxed stress was found. The creep behaviour of the material was described by using a combination of the Norton Power law and the Arrhenius equation. The Zener-Wert-Avrami model was used to describe the residual stress relaxation. With these models a satisfying correlation between measured and calculated data was found. Hence, the relaxation of residual stresses due to thermal load was described reliably.

1. Introduction

The importance of light weight design is constantly increasing and the ambition to optimize components forces materials to their limits. Optimal materials should offer low density while maintaining high static and cyclic mechanical behavior at elevated temperatures. To meet the demanding safety requirements and to achieve a high service life of components, certain finishing techniques become necessary.

The main reason for material fatigue can be described by crack nucleation and propagation. Cracks initiate mainly on the surface of components and continue to propagate inside the component. The process of crack nucleation and especially the subsequent short crack propagation can be greatly decelerated by a suitable surface treatment. Mechanical surface treatments (e.g., shot peening, rolling, hammering) or manufacturing processes (e.g., machining, low stress grinding) induce residual compressive stresses in near-surface areas of Ti-6Al-4V and cause hardening due to cold working

(Figure 1). While residual compressive stresses are responsible for crack closure effects, local hardening causes a shift of the local yield stress and therefore a modified local plastic deformation behavior. Both effects are responsible for higher fatigue life.

However, the positive effects of residual stresses can't be expected throughout the whole service life of components. There are numerous processes causing a relaxation of residual stresses. For example, high temperatures cause a relaxation of residual stresses through creep, while high stress or strain amplitudes cause a relaxation through local plastic deformation.

Residual stresses are often neglected in the design process of components, mostly because of the insufficient description of their stability over time, mechanical load and temperature. To improve the comprehension of residual stresses in fatigue lifetime estimation, the effects causing a relaxation of residual stresses have to be studied and precisely described.

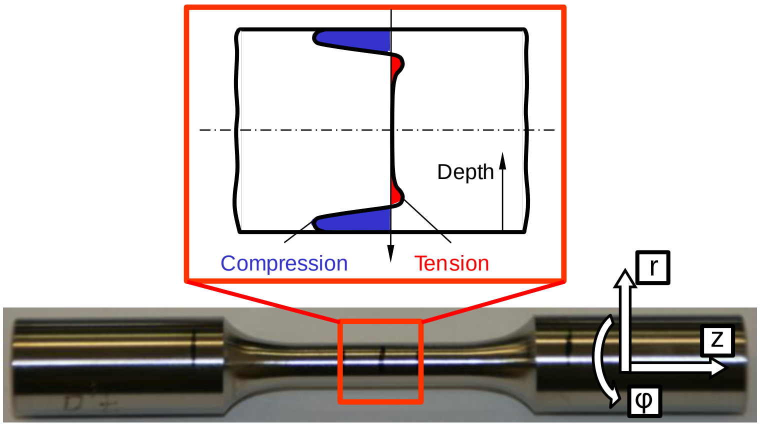

Figure 1. Used specimen with a qualitative residual stress distribution (blue: compression; red: tension)

This work focuses on the residual stress relaxation due to thermal loads. In order to describe the relaxation behavior reliably, a continuum mechanical approach was necessary. The main driving force behind thermal residual stress (RS) relaxation was identified by occurring creep in the specimen. Therefore it was important to specify the creep behavior of the material through creep tests at all necessary temperature and stress levels. Furthermore temperature exposure tests were performed and the resulting residual stress was measured by x-ray diffraction. The measured residual stress was used to verify the thermal stability of residual stress through creep. Also the Zener-Wert-Avrami parameters were determined and the results were compared.

2. Experimental procedure

In order to obtain all necessary data for the model, creep tests and time exposure tests with residual stress measurement through x-ray diffraction were carried out. The creep tests were performed at 100°C, 250°C, 370°C as well as at room temperature at loads between 550MPa and 800MPa.

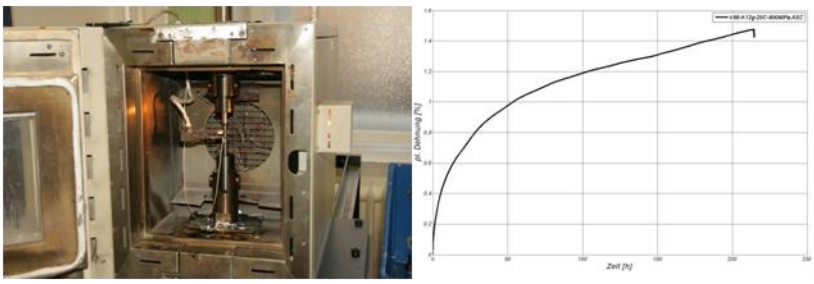

Figure 2. Creep test rig and a measured creep curve

Temperature exposure tests at 100°C, 250°C and 370°C were also performed. At defined time increments the specimens were measured through x-ray diffraction (XRD).

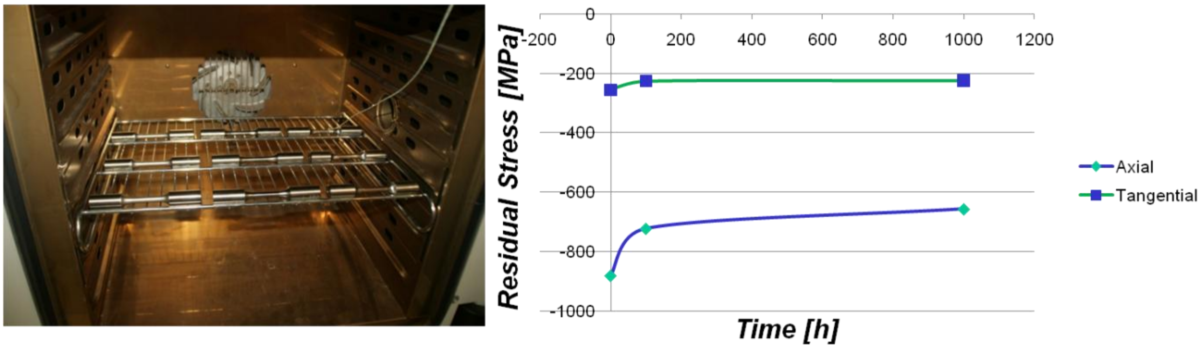

Figure 3. Temperature exposure chamber and measured RS after a certain time period

After XRD measurements, residual stresses and the Full Width at Half Maximum (FWHM) are obtained. The FWHM is proportional to the hardening. The hardening of the specimen can be observed through increased FWHM in the surface layer (Figure 4).

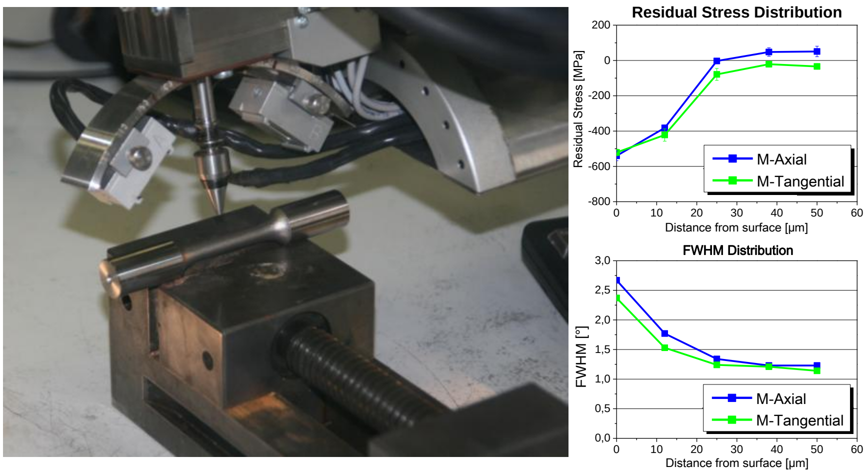

Figure 4. X-ray diffraction with measured Residual Stress and FWHM depth profiles through incremental surface layer erosion

3. Analysis and Simulation

To describe the residual stress relaxation behavior through creep it is necessary to identify all present load cases depending on the distance from the surface. A compressive residual stress with initial hardening can be found in the surface layer of the specimen. The subsurface layer beneath that contains tensile residual stresses without any initial hardening. The crucial part for the stability of residual stress due to thermal loads is the compressive residual stress, which is higher than the tensile part. The increased level of dislocation in the surface layer through cold working leads to a shift of the starting point along the creep curve [1]. This means that creep won't occur until the initial amount of dislocations due to cold working is reached (Figure 5). Only after that the creep will continue along the measured creep curve. Therefore as an approximation primary creep was neglected and thermal residual stress relaxation due to thermal loads was calculated based on only secondary creep.

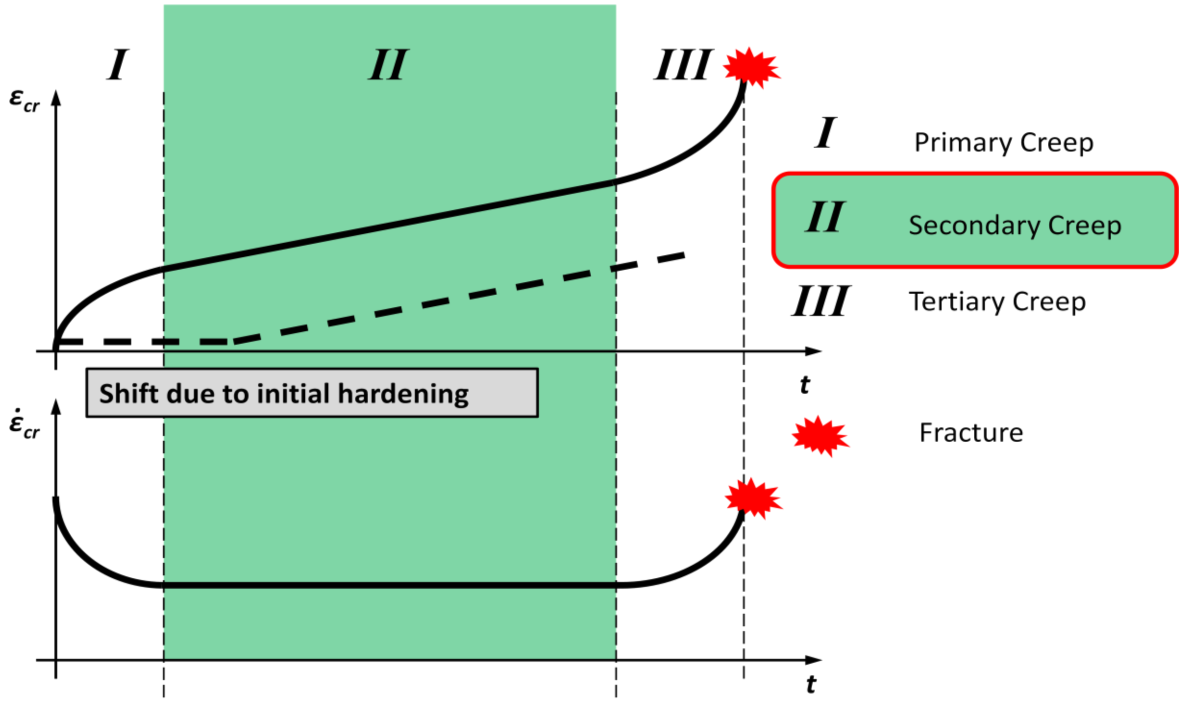

Figure 5. Creep curve with a shift of the initiation of creep due to initial hardening in the surface layer

The amount of relaxed residual stress is calculated by the local occurring creep strain in the surface layer of the specimen. With increasing temperatures and the same surface condition (in this case only machined specimen were examined) the creep strain also increases. Every portion of creep strain causes a reduction of the elastic strain leading to a reduction of the remaining residual stress (Figure 6). The steadily decreasing residual stress will also cause lower strain rates. This iterative process of interaction between strain rate and residual stress will end at a saturated level of residual stress where the creep strain is low enough to not cause any further relaxation.

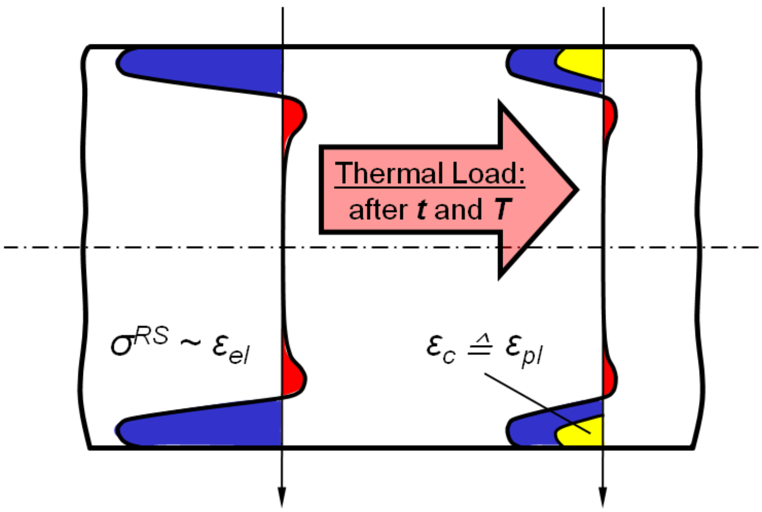

Figure 6. Schematic mechanism behind residual stress relaxation through creep

3.1. Determination of the Creep Parameters

The description of creep was achieved through the definition of the stationary (secondary) creep rate due to temperature and stress. A combination of the Norton Power law and the Arrhenius equation was used [2]:

$$\dot{\varepsilon}_c = C\left(\frac{\sigma}{E(T)}\right)^n e^{-\frac{Q_C}{RT}} \tag{1}$$

Equation (1) shows the dependence of the stationary creep rate due to temperature T and stress σ. The necessary parameters for this equation are the velocity constant C, the power law exponent n and the activation energy Q_c. They can be determined using the secondary creep rates from creep tests. It was observed that the power law exponent is almost independent from temperature (Figure 7) but the activation energy is strongly affected by the temperature. For low temperatures the activation energy is nearly zero up to 240°C. Beyond that the activation energy increases with increasing temperature (Figure 8).

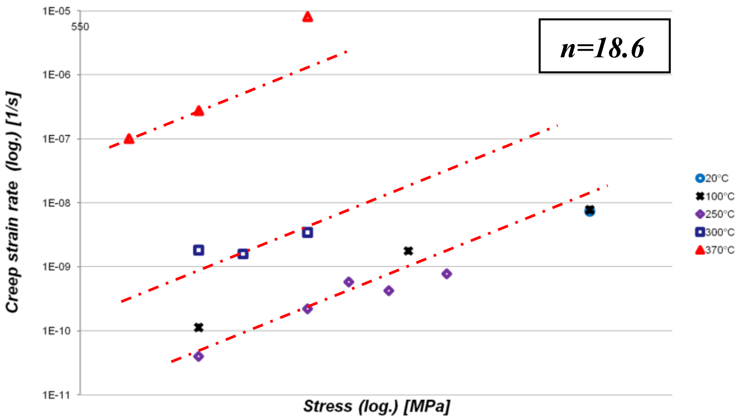

Figure 7. Dependence of the stationary creep rate on stress at different temperature levels (Assumption: constant Power Law Exponent (red dashed line))

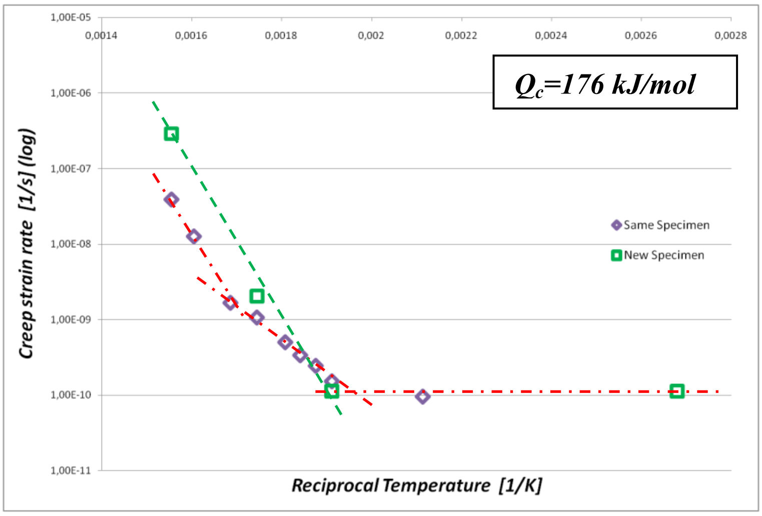

Figure 8. Dependence of the stationary creep rate on temperature at 600MPa (Possible change of activation energies due to varying active creep mechanisms (red dot and dashed line);Simplification: constant activation energy (green dashed line))

Figure 8 shows a comparison between two different investigations of the creep rate. On the one hand the creep curves were measured on new unloaded specimens (green squares) and on the other hand one specimen was used increasing the temperature after every creep test on the same specimen consecutively (purple diamonds). Experiments prove that the secondary creep rate is not affected by the temperature until 240°C but also show that the secondary creep rate at room temperature is just as high. Beyond 240°C a slight increase of the temperature sensitivity of the secondary creep rate was observed, increasing again after 320°C. This matter can be observed as an increased slope in Figure 8 (red dot and dashed line).

However, due to the fact that literature mentions only one slope (constant activation energy) at higher temperatures (above 600°C) and the insufficient existence of detailed creep investigations at the required temperature range (between 20°C and 370°C) the mentioned behavior has to be proved at more stress levels. Therefore as a simplification, constant activation energy for creep was chosen between 250°C and 370°C (green dashed line). For lower temperatures the temperature sensibility was set to zero.

3.2. Verification of creep rates in a FE-simulation model

The determined creep parameters were implemented into Abaqus (Dassault Systems). When a unified cube (one element) with precisely set material parameters is loaded with a constant force adequately to the performed creep tests, the simulated results match the measured data.

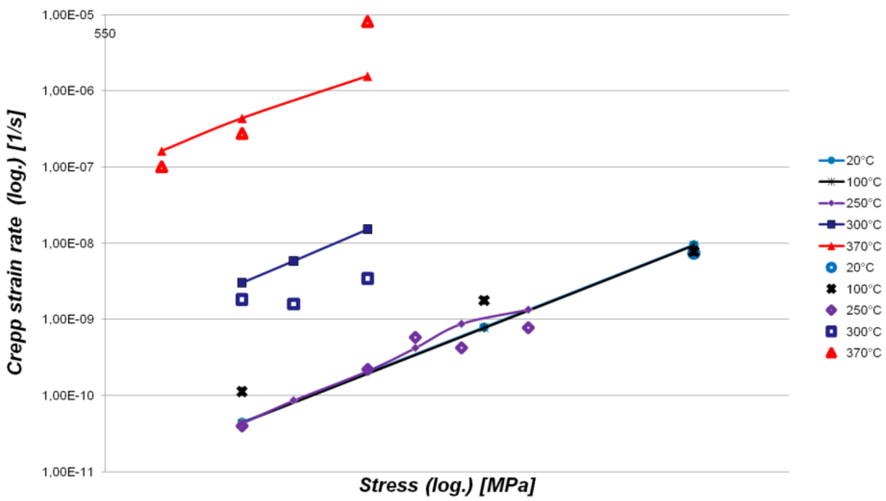

Figure 9. Comparison of measured data (points) and FE-simulated stationary creep strain data (lines) vs. stress at different temperature levels

3.3. Consideration of effects during the heating process

During the heating process of the specimen different effects may occur, which can cause a residual stress relaxation. If the temperature gradient during heating is too high and causes plastic deformation, the residual stress will decrease permanently. The deviation of mechanical properties with increasing temperature has to be considered as well. On the one hand the Young's Modulus decreases causing an elastic, temporary relaxation of the residual stress (initial residual stress recurs after cooling) on the other hand the yield stress decreases and can cause a local plastic deformation due to high compressive residual stresses in the surface layer which leads to a permanent residual stress relaxation. Every other permanent diminishment of the residual stress is caused by creep (in the investigated temperature range).

Table 1. Effective residual stresses at a certain temperature: The decrease is caused by temporary, elastic relaxation

Temperature (°C)	Effective residual stress (MPa)
20	540
100	518
250	473
370	450

3.4. Calculation of the residual stress relaxation

The residual stress relaxation was calculated using a FE-model with a mapped residual stress distribution. The specimen was implemented as an axial symmetric model containing one quarter of the round specimen. The residual stress was mapped on each integration point of every element according to the measured residual stress distribution. For more detailed information about the application of residual stresses see [3].

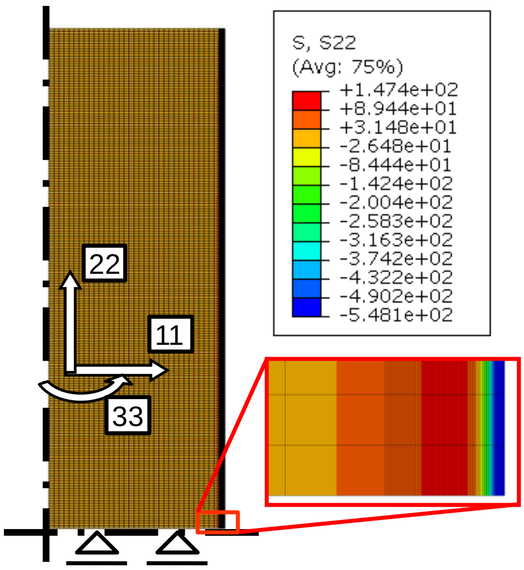

Figure 10. Model of the FE-supported calculation of the residual stress distribution.

The model assigned with a desired residual stress distribution was heated at a defined temperature and remained at that elevated temperature for a defined amount of time. Afterwards the calculated remaining residual stress distribution was compared with the measured data from the iterative exposure test measured by XRD.

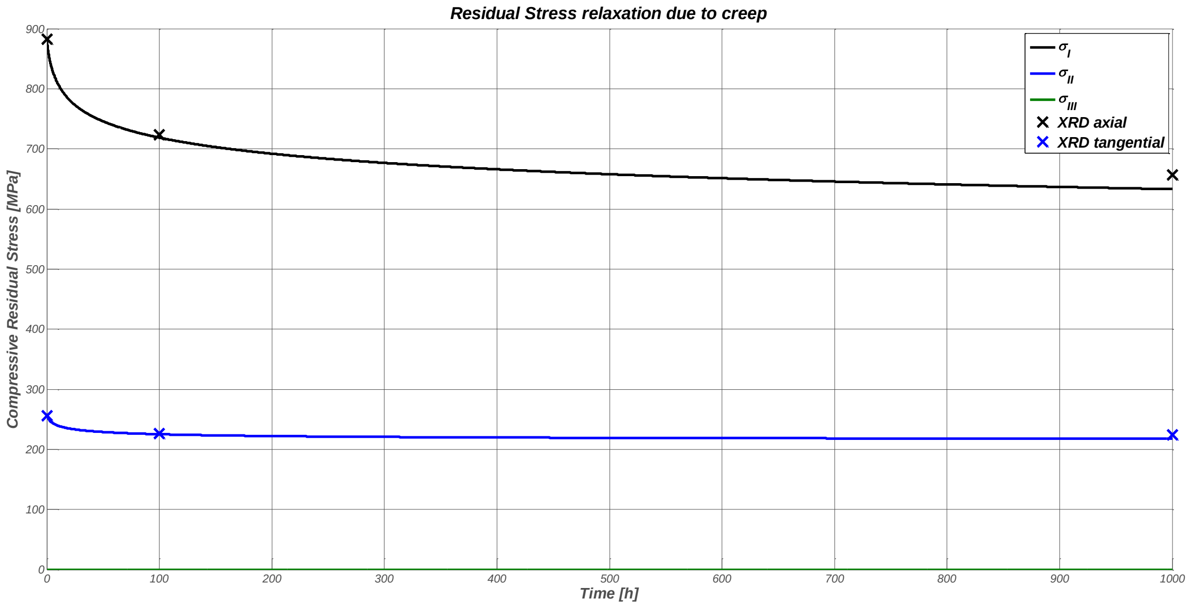

Figure 11. Comparison of the measured and calculated remaining residual stresses over temperature and time

Figure 11 shows an example of the evolution of the residual stress on the surface of a machined specimen exposed to a defined temperature for a certain amount of time. It can be observed, that the higher axial residual stress shows a high relaxation, especially in the beginning. The tangential residual stress doesn't show any relaxation due to creep. The residual stress decreases foremost due to the transversal strain of the axial direction.

Furthermore the parameters for the Zener-Wert-Avrami model were determined [4]. Therefore equation 2 was approximated to measured values of residual stress in axial and tangential direction respectively (Figure 12).

$$\frac{\sigma^{RS}(t,T)}{\sigma^{RS}(t=0)} = e^{-\left(C\,t\,e^{-\frac{\Delta H_A}{k_B T}}\right)^m} \qquad (2)$$

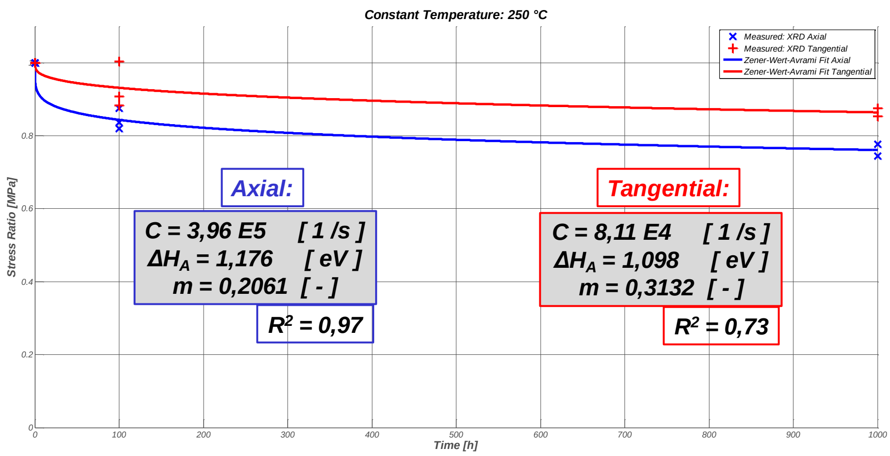

Figure 12. Fit of the Zener-Wert-Avrami parameters for axial (blue) and tangential (red) direction

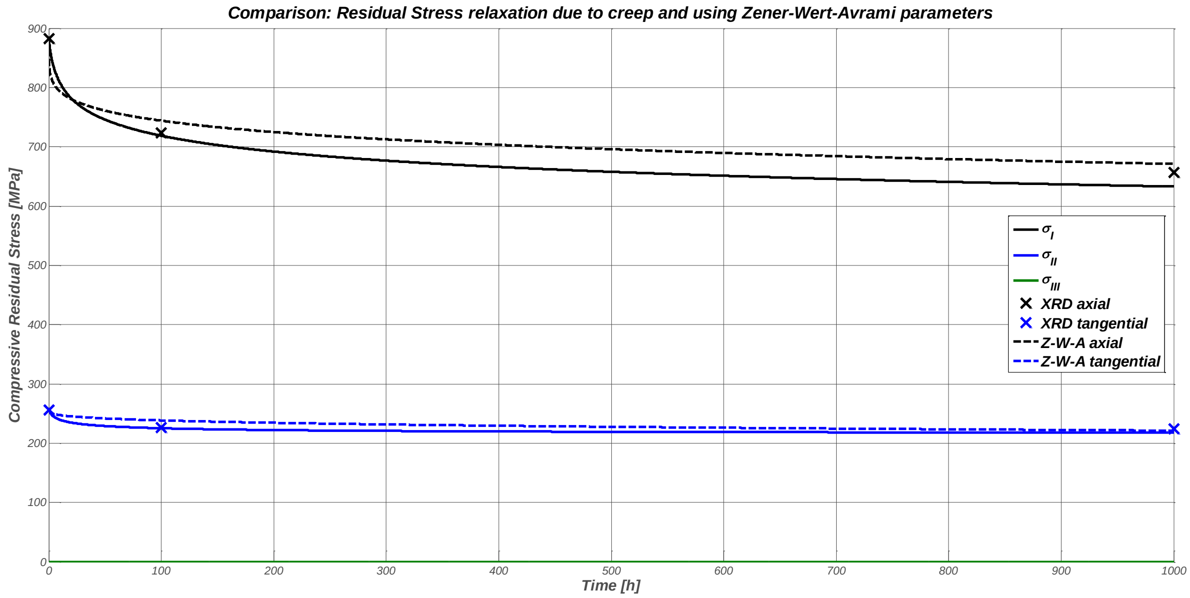

Figure 13. Comparison of the measured and FE-simulated remaining residual stresses over temperature and time with the Zener-Wert-Avrami Fit (dashed Lines)

Figure 13 shows a comparison between the calculated residual stress relaxation through creep and the characterization of the residual stress relaxation by the Zener-Wert-Avrami equation. It can be observed that both approaches lead to satisfying and accurate results. Considering the scatter of the XRD measurement of 50MPa, both approaches for calculation of the residual stress relaxation fit the scatter band adequately.

4. Summary and Outlook

In this work, a basic overview about the description of thermal stability of residual stresses through creep was given. The determination of creep material properties was explained as well as the influence of the heating process on the residual stress distribution. Also the amount of relaxed stress was matched using the approach based on creep. Finally the results were compared with the Zener-Wert-Avrami approach and discussed.

Further studies and investigations will cover following topics:

- Accurate evaluation of the effect of hardening due to cold work on the creep behavior [1]
- Description of the stability of residual stresses due to the combined thermal and cyclically mechanical load
- Calculation of different surface conditions (Shot peened, Low Stress Grinded)
- Identification of local creep behavior including primary creep

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