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STABILITY OF FORMING INDUCED RESIDUAL STRESSES IN STAINLESS STEEL PARTS AT ELEVATED TEMPERATURE

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ABSTRACT

The performance characteristics of technical components are influenced by residual stresses. Depending on their sign and magnitude, they may decrease or enhance the products' fatigue strength, corrosion resistance and its achievable lifetime. While compressive stresses in the part surface usually increase the fatigue strength, tensile stresses promote crack initiation and growth. In many cases, the forming induced residual stress state is either unknown or tensile, which is why stress-relief annealing is performed to avoid unexpected effects. This time- and energy-intensive process step may be avoided with an enhanced understanding of residual stresses.

For the prediction of their influences, not only the sign and magnitude, but also the stability during operation is to be taken into account. The aim followed in this paper is to qualify the stability of forming induced residual stresses under typical thermal operation loads. For this purpose, stainless steel specimens are forward rod extruded with different dies, in order to generate varying residual stress states. The formed parts are heat-treated at temperatures between 100 °C and 550 °C to reproduce typical operating conditions. Residual stress measurements based on X-ray diffraction are performed after specific time intervals. From the results, a time and temperature dependent residual stress behavior is derived.

Keywords: Residual Stress Stability; Stainless Steel; Forward Rod Extrusion.

1. Motivation

Inhomogeneous plastic deformations lead to residual stresses remaining in the produced components in bulk forming processes [1]. Due to high material strengths and a limited possibility of recrystallization, these stresses may be particularly pronounced in cold forming. Through superimposition with load stresses, residual stresses have the potential to influence the achievable service life of the parts both in a positive and in a negative way [2]. Compressive stresses usually enhance properties like fatigue strength [3] and corrosion resistance [4]. Tensile stresses, on the other hand are favoring crack initiation and growth [5]. However, in order to be capable of influencing the operating properties under given operating conditions, a sufficient stability of the residual stresses is necessary [6].

During the use of the components, both mechanical and thermal loads may occur and interact with internal stresses. For a selective relaxation of residual stress states in components,

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mechanical loads are used for example in the mechanical stress relief (MSR) process [7]. With this method, specific areas of the workpiece are subjected to overelastic strain in order to achieve local plastic deformation, which results in a new stress state after unloading and elastic springback [8].

A focused reduction of residual stresses by thermal mechanisms is also possible. The application of a thermal load reduces the yield strength of the material. This allows sufficiently high residual stresses to induce plastic deformation and thus be relieved. This mechanism is used in particular in stress-relief annealing [9]. In industrial practice, this is usually performed between 550 °C and 650 °C with soaking times of one to two hours. Another thermally induced mechanism is the dissolution of dislocation accumulations, which is also effective at lower temperatures [10].

From an operational point of view, however, residual stress stability is to be considered, as soon as products are exposed to elevated temperatures. This may be the case in the production process, where temperatures of up to 200 °C occur during paint baking [11]. In the product lifecycle, thermal loads need to be taken into account both during the intended operation and in critical regions of the application range.

2. Objectives and Approach

The objective followed in this paper therefore is the qualification of the stability of forming induced residual stresses under thermal loads. One aspect of this is the identification of the temperature influence during one-time heating. In this context, information is to be obtained on which operating temperatures can be tolerated with regard to residual stress stability. Another aspect is the influence of the soaking time. For this purpose, correlations between the annealing temperature level, the soaking time and the response of the residual stress state are to be identified. The approach is abstracted in Fig. 1.

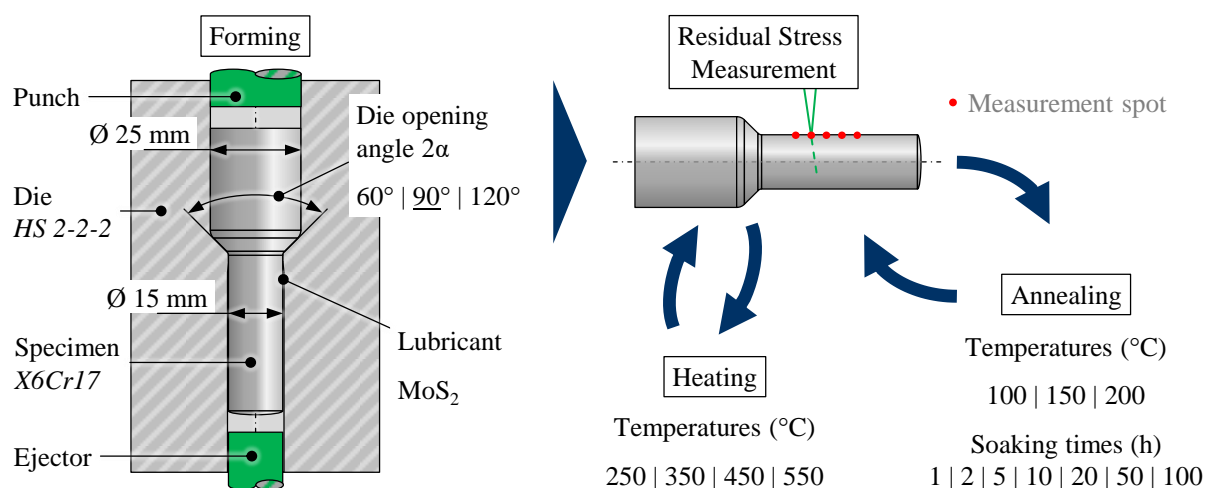


Fig. 1. Approach for the investigation of the influences of heating and annealing on near-surface residual stresses

The basic forming method used for the investigations is forward rod extrusion of the stainless steel X6Cr17 (DIN 1.4016). The influence of simple heating is first investigated on the basis of a reference variant. For this purpose, $n = 3$ components each are heated once to 4 temperature levels ranging from 250 °C to 550 °C. The lower limit thereby corresponds to the maximum temperature to be expected during paint baking, the upper limit represents the stress-relief annealing temperature. After cooling, the near-surface residual stress states in the formed shaft are determined and compared to the states before heat treatment.

In the investigation of the influence of the soaking time, the focus is on typical operating temperatures during component use. Therefore, 100 °C, 150 °C and 200 °C are used as

temperature settings. For each temperature level, $n = 3$ components are heated and retained for time intervals in the range from 1 h to 50 h. After each soaking period, the near-surface residual stresses in the formed shaft are determined. In parallel, the influence of the initial residual stress state is investigated. For this purpose, components are formed with two more die opening angles in addition to the reference variant. They differ in their hardening and residual stress distribution as a result of the process characteristics. The parts are subjected to the heat treatments and residual stress measurements in the same way as the reference variant.

3. Experimental Setup

The components used for the investigations are produced by forward rod extrusion. They are made from cylindrical billets of ferritic stainless steel X6Cr17 (DIN 1.4016) with an initial diameter of 50 mm. To ensure formability, they are coated with a two-part lubrication system commonly used in bulk metal forming. Due to the corrosion resistance of the raw material, phosphating - which is standard practice in bulk metal forming - is not applicable. Iron-III-oxalate is thus used as the lubricant carrier layer. Due to the high surface pressure, the molybdenum disulfide-based *ZWEZ-Lube MD-230* is used as lubricant. The coated billets are formed with the tool setup shown in [12]. The forming die is made of high speed steel *HS 2-2-2* and pressed into a shrink ring made of hot-working tool steel X38CrMoV5. The die bore is extruder honed to provide a smooth surface with consistent tribological properties. The die opening angle is $2\alpha = 90^\circ$ for the reference variant. The influence of different residual stress and hardening states is investigated with parts formed with die opening angles of 60° and 120° . After cleaning, the formed components are used in the thermal experiments.

For the thermal loading experiments, the furnace *Nabertherm N 120/65 HA* is used with air as atmosphere. The specimens are positioned in the preheated furnace, held for the defined soaking time after reaching the specified temperature and then cooled in still air outside the furnace. The temperature is controlled with a thermocouple in the core of an additional specimen, which ensures heating of the complete sample. Before and after each thermal loading cycle, the residual stresses are measured in the formed shaft of the specimens.

The residual stresses are determined by X-ray diffraction, as it allows a fast and non-destructive measurement. The 8-axis X-ray diffractometer *Seifert XRD 3003* is used for the determination of the near-surface residual stresses. The measurement is performed in axial direction at the $\{211\}$ lattice plane of the ferritic steel using a Cr anode with a V K β filter. The radiation is guided by glass capillary optics and an aperture with a diameter of 1.5 mm, which results in a spot diameter of approximately 0.8 mm. The diffracted beam intensity is recorded with a line detector *Meteor ID*. The $\sin^2\psi$ method is used with six tilts each in the negative and the positive ψ direction, leading to a total of 13 ψ positions. The line positions are identified in the recorded intensity peaks with a Pseudo-Voigt function. The stress calculation is performed using the software *Rayflex Analyze*, using a fix Bragg angle of $2\theta_0 = 156.09^\circ$. The used elasticity constants are $-s_1 = 1.27 \times 10^{-6} \text{ MPa}^{-1}$ and $\frac{1}{2}s_2 = 5.81001 \times 10^{-6} \text{ MPa}^{-1}$. A detailed description of the measurement setup is shown in [13]. The assumed uncertainty of the measured stresses is about $\pm 40 \text{ MPa}$, of which $\pm 20 \text{ MPa}$ are attributed to general inaccuracy of the x-ray diffraction method [14].

4. Results and Discussion

4.1. Influence of annealing temperature

In order to identify the influence of the annealing temperature on the near-surface residual stresses, components were heated to defined temperature levels below the usual stress relief annealing temperature and cooled at still air. By not including a soaking time, only the influence of heating to a defined temperature is investigated. The results are shown in Fig. 2.

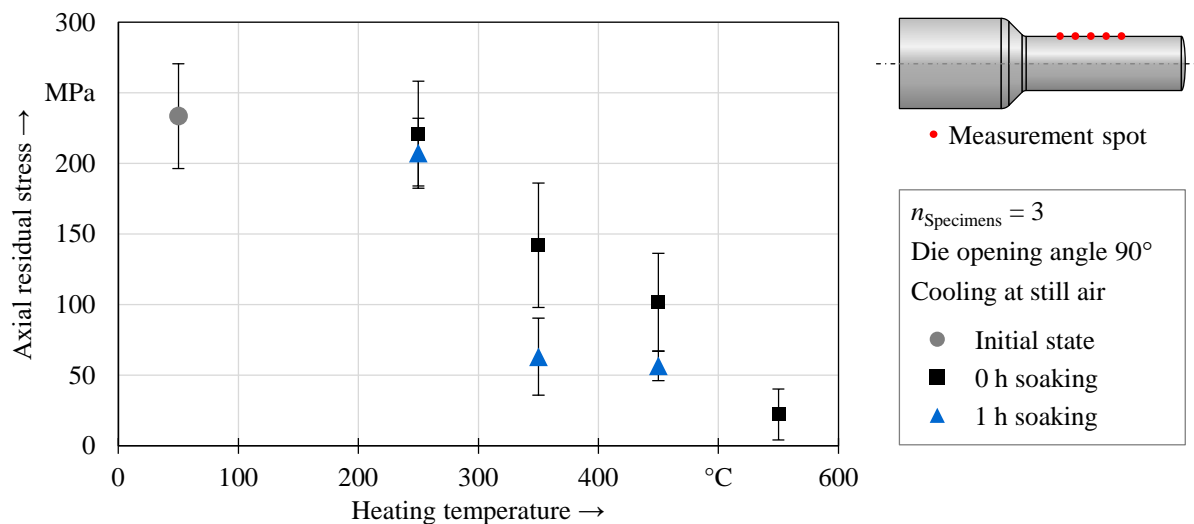


Fig. 2. Influence of single heating on the residual stresses of components

After forming and ejecting, distinct tensile stresses of 234 MPa are present in the specimens. Single heating to a temperature of 250 °C does not lead to a significant reduction. With increasing temperature, however, a distinct reduction of the residual stresses is observed. Heating to 350 °C causes a decrease of the residual stresses by 39% to 142 MPa. With a temperature of 550 °C, 22 MPa are remaining in the measurement area. Since this value is within the measurement uncertainty, this residual stress state is considered stress-free. An additional heating with a soaking time of 1 h leads to a non-significant minor reduction of the residual stresses for a temperature of 250 °C. Temperatures of 350 °C and 450 °C with a soaking time of 1 h are significantly reducing the stresses to 63 MPa and 57 MPa.

This residual stress reduction is attributed to a reduction in material strength at elevated temperature, which leads to a reduction of the highest residual stresses. To substantiate this, compression tests at elevated temperature were performed with the servohydraulic testing machine *Gleeble 3500* by *Dynamic Systems Inc.* to characterize the strength and hardening behavior of the used material. In Fig. 3, the flow curves obtained in the compression tests are shown for room temperature to 400 °C.

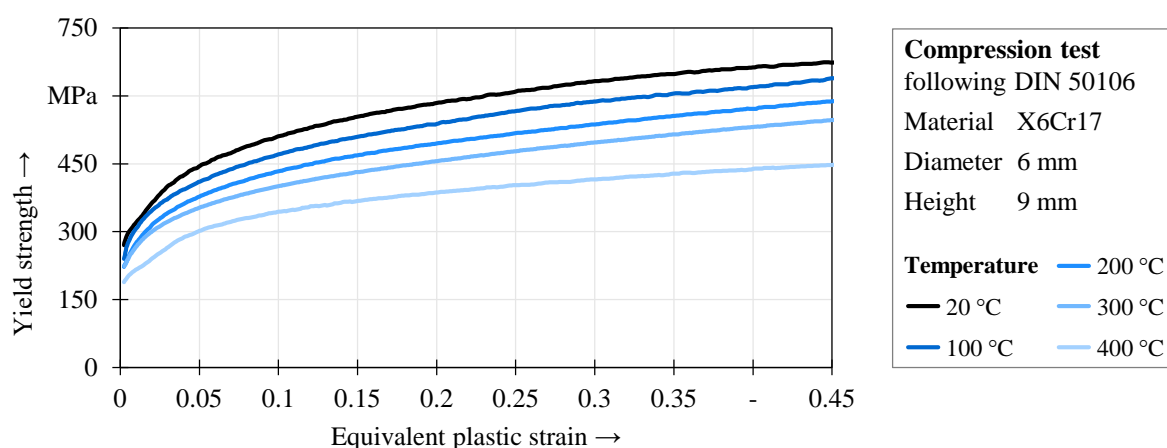


Fig. 3. Flow curves of the used material X6Cr17 (1.4016) for elevated temperatures

At room temperature, the material shows a yield stress of 263 MPa, which is doubled at an equivalent plastic strain of $\bar{\epsilon} = 0.12$ due to work hardening. It is observed that an increase in test temperature by 100 °C leads to a mean reduction of the yield strength of 7% to 10%. In the formed parts, high compressive residual stresses are present in the core, which are in equilibrium

with tensile stresses near the surface [15]. An overall reduction of the material strength by thermal mechanisms leads to a relaxation of the highest stresses due to plasticization. This mechanism is pronounced in macroscopic areas with high stresses like the part core. A second relevant mechanism is the dissolving of high dislocation densities. This effect particularly affects microscopic volumes such as grain boundaries. For temperatures from 300 °C to 550 °C, a reduction of the dislocation densities was shown by [10]. This reduction of the macroscopic and microscopic residual stress maxima results in the formation of a reduced overall residual stress level due to the necessary stress equilibrium within the material.

4.2. Influence of soaking time under low thermal loads

In addition to the magnitude of the thermal load, the loading duration and the initial residual stress state may also have an influence on the stability. In order to investigate different work hardening states, components are produced with die opening angles 2α of 60°, 90° and 120°. Due to the considerably different material deflection in the forming zone of the die, characteristic strength and residual stress distributions are present in the formed parts, depending on the die opening angle. At the surface, different residual stresses are present, which were used for the investigation of the stability under the influence of temperature and time.

The formed and ejected specimens are annealed at temperatures of 100 °C, 150 °C and 200 °C. After defined time intervals, the near-surface residual stresses are measured in the formed shaft after cooling at still air. For a die opening angle of $2\alpha = 60^\circ$, the results are shown in Fig. 4.

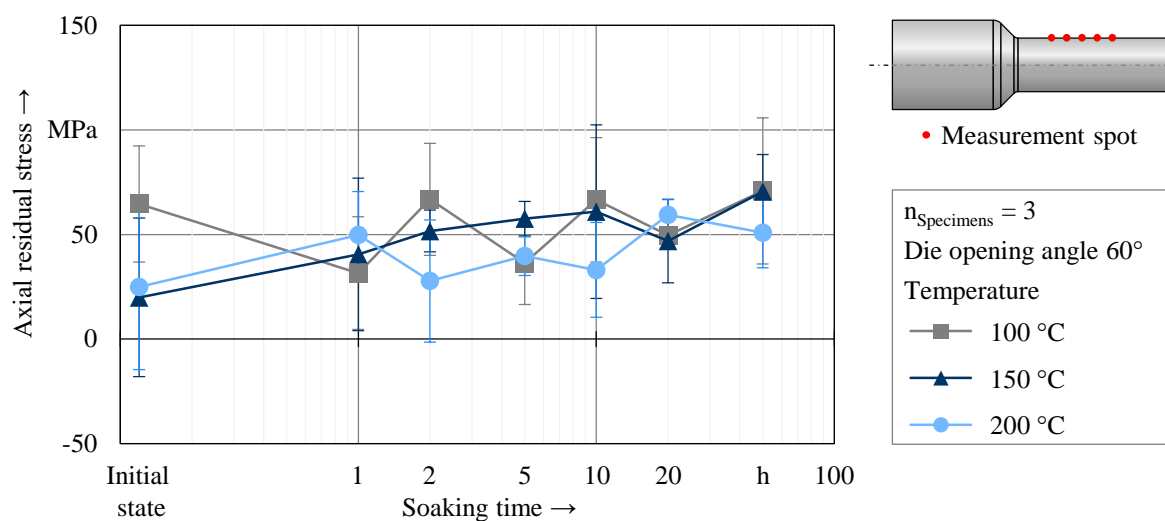


Fig. 4. Influence of soaking time on the residual stresses for a die opening angle of $2\alpha = 60^\circ$

After forming, low tensile residual stresses from 20 MPa to 60 MPa are present in the formed shafts. This state with low tensile residual stresses is due to material deflection during extrusion. Due to the low die opening angle, the material is being deflected gently, resulting in low work hardening differences between core and surface and thus in low residual stresses. Annealing with temperatures from 100 °C to 200 °C for up to 50 h does not have a significant effect on the near-surface residual stresses since they are not very pronounced. With increasing soaking time, however, the scattering of the measured stress values decreases. This may indicate that high micro residual stresses are being relieved, which are increasing the measurement uncertainty.

For a die opening angle of $2\alpha = 90^\circ$, higher tensile stresses are present in the formed parts [15]. In Fig. 5, their stability under thermal load is shown.

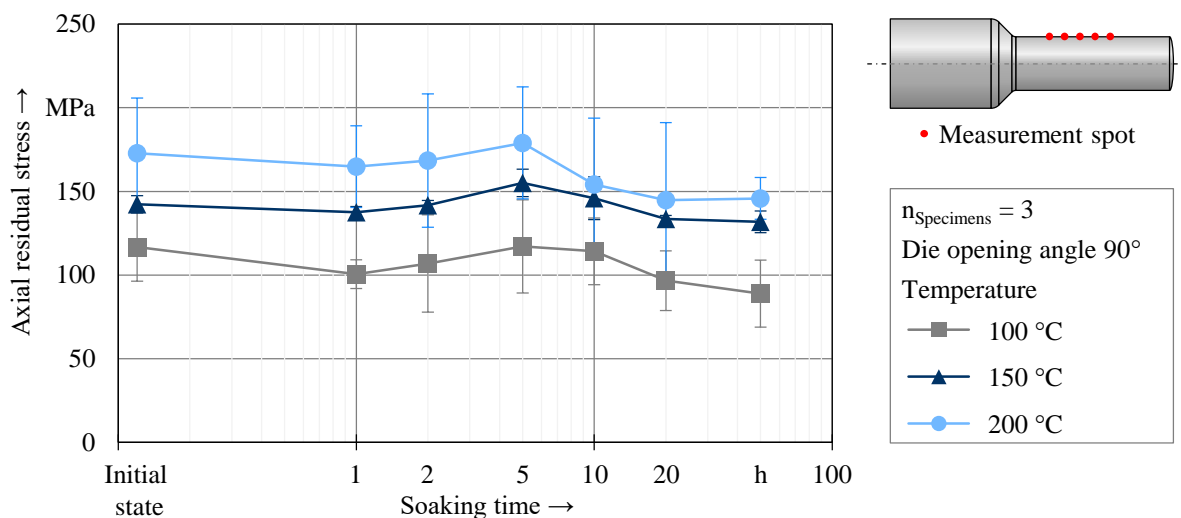


Fig. 5. Influence of soaking time on the residual stresses for a die opening angle of $2\alpha = 90^\circ$

Distinct tensile residual stresses from 117 MPa to 173 MPa are present in the formed specimens. Despite the different initial residual stress levels, a similar pattern is observed with increasing soaking time for all annealing temperatures. The first annealing procedure for 1 h leads to a slight decrease of the near-surface residual stresses, followed by a slight increase and a slight reduction from a soaking time of 5 h. One explanation for this pattern is the reduction of high residual stresses in material volumes other than the surface. The initial decrease may be a result of the reduction of the compressive stress maximum in the core and a necessary redistribution of the residual stress state. Similar to the experiment with a temperature of 250 °C and a soaking time of 1 h, this has the effect of a reduction of the tensile near-surface stresses. A reduction of the tensile stress maximum below the surface with increasing soaking time may be the reason for the observed increase at the surface between 1 h and 5 h soaking time. The absolute influence of the heat treatment, however, is low for the analyzed variants. With a soaking time of 50 h, the residual stresses are reduced by 11 MPa to 28 MPa, which still is in the range of measurement uncertainty.

In the parts formed with a die opening angle of $2\alpha = 120^\circ$, different residual stress states are present in the surfaces. This offers the possibility of investigating the residual stress stability for different initial states. The results are shown in Fig. 6.

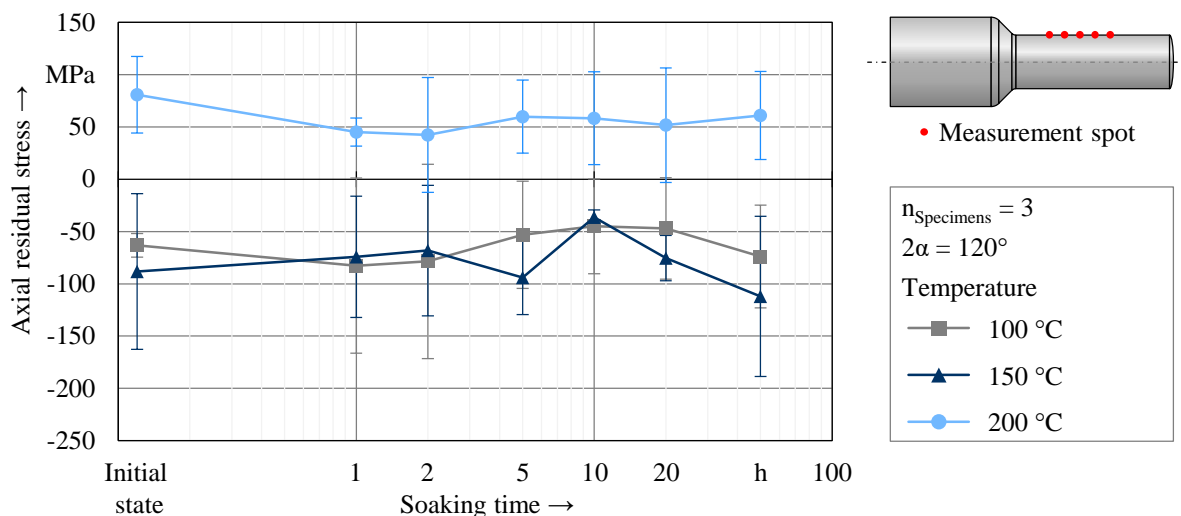


Fig. 6. Influence of soaking time on the residual stresses for a die opening angle of $2\alpha = 120^\circ$

One possible reason for these differences is the tribology. In [15] it was shown, that the friction influences the surface residual stress state in forward rod extruded components. A die opening angle of $2\alpha = 120^\circ$ leads to a strong deflection of the material in the forming zone of the die, resulting in high surface pressures at the die shoulder. With high surface pressures, variations in the lubricant application quantity are influencing the tribological conditions in the interface layer between part and tool, which then influences the residual stresses. For this reason, some of the formed parts show compressive residual stresses at the surface, while others show tensile stresses. An annealing with temperatures from 100 °C to 200 °C and soaking times up to 50 h does not lead to distinct changes, since there are low residual stresses. This is consistent with the results shown for a die opening angle of $2\alpha = 60^\circ$.

5. Conclusions

From the presented results, the following conclusions are drawn.

- Single heating does not significantly influence the near-surface residual stresses for a temperature of 250 °C.
- With temperatures above 250 °C, the residual stresses are already affected by a single heating operation.
- Single heating to 550 °C eliminates the near-surface residual stresses in the examined components.
- Temperatures up to 200 °C can be tolerated for at least 50 h in the parts extruded with the presented setup.

When stable residual stresses are required within the components, they should therefore not be subjected to high thermal loads during use. If the components are exposed once to a temperature above 250°C, a critical evaluation of the residual stress state should be considered. Regarding the long-term stability at temperatures up to 200 °C, components with a high residual stress level should be observed.

6. Summary and Outlook

In the present paper, the influence of thermal loading on forming induced residual stresses was investigated. For this purpose, parts were produced from stainless steel X6Cr17 (DIN 1.4016) by forward rod extrusion with different die opening angles and subjected to single heating and annealing with defined soaking times from 1 h to 50 h. It was shown, that a single heating operation may be tolerated for temperatures below 250 °C. With higher temperature levels, single heating affected the component residual stresses, leading to an elimination at 550 °C. For temperatures of 100 °C to 200 °C, a slight change in near-surface residual stresses was found for pronounced residual stress states. In variants with lower stresses, no significant influence of the annealing temperature was observed for soaking times up to 50 h. In future work, the influence of high soaking times above 100 h will be investigated.

7. Acknowledgement

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