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Influence of transformation plasticity on residual stresses and distortions due to the heat treatment of steels with different carbon content

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Abstract. The field of heat treatment of steels offers a large variety of applications for the use of simulation tools. It always includes the development of residual stresses and distortions. The geometry of the part, the composition of the material, the heat treatment process as well as the initial state of the part interact with each other in complex ways and have an influence on the distortion of the part. Using simulation the temporal development of temperature, phases, stresses and distortions while quenching as well as the residual stress distribution and distortion after quenching can be calculated. Transformation plasticity has been proved to be very important for heat treatment simulation. Three steels with identical contents of alloying elements but different carbon contents of 0.2, 0.5 and 0.8 wt. % were analysed. The influence of transformation plasticity during the martensitic transformation on the distortions and residual stresses after quenching of cylinders made out of the three steels was analyzed in simulations and compared to experimental results.

Introduction

Hardening of steels always leads to residual stresses and distortions after quenching. They affect the following manufacturing steps as well as the service properties of the component and therefore play an important role in the manufacturing process. Detrimental residual stresses and distortions require expensive stress relieve treatments and re-machining of the parts, respectively. It is aimed to produce residual stress states enhancing the fatigue properties and to minimise distortions. With experiments only the final state of distortions and residual stresses after heat treatment processes can be investigated. To understand their origin it is necessary to know their temporal development in the whole part. This can only be achieved by numerical methods, such as the finite element method (FEM) [1-7]. The effects of important process parameters, which usually cannot be separated experimentally, on the development of stresses and distortions can be studied by variations of their quantities. With these results appropriate measures can be taken to optimise the heat treatment process. To set up suitable models for heat treatment process simulation it is important to study and to understand the different processes and effects, e.g. transformation plasticity, that occur in the component while quenching. However, this requires the availability of an enormous number of temperature-, phase- and carbon content-dependent input data.

The prediction of residual stresses and distortions after the heat treatment process is difficult for quenching processes with phase transformation. Due to the increase of volume during phase transformation the stresses due to cooling are superimposed by stresses due to phase transformation. As shown in Fig. 1, the temporal development of temperature and phase transformation and their influence on deformations and stresses are relevant for the formation of distortions and residual stress states. The cooling behaviour is mainly determined by the heat transfer coefficient between the part and the quenchant. Phase transformations can occur with and without diffusion. The development of strains and stresses is determined by the deformation behaviour which can be considered elastic-plastic as well as visco-plastic and which can show isotropic or kinematic hardening. The interactions between temperatures, phase transformations and strains as well as stresses which are also shown in Fig. 1 have additional important influences. The phase transformations of austenite due to quenching are triggered by the temperature which in turn is influenced by the heat that which evolves due to the phase transformations. Additionally the development of the temperature may be affected by heat caused by mechanical work. Stresses and strains are composed of temperature and phase transformation induced components. Phase transformations due to strains and stresses as well as additional strains due to transformation plasticity also occur. For the calculation of materials states containing a carbon gradient after diffusion processes, e.g. at case hardening, the influence of the varying carbon content must be considered.

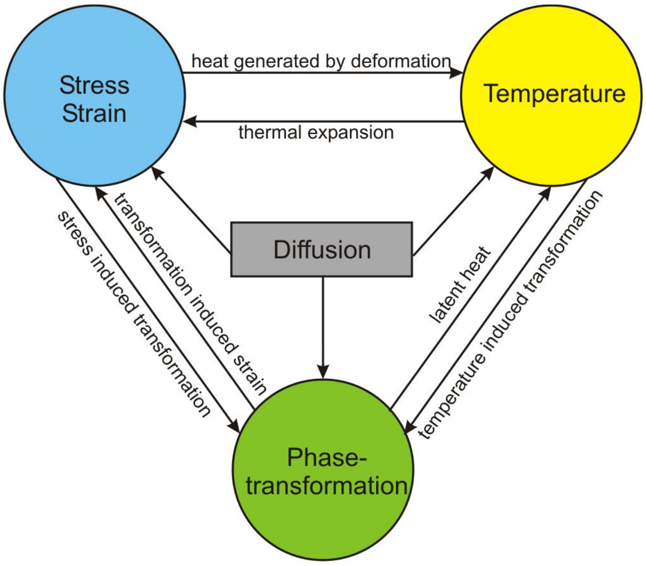


Figure 1: Interactions during the heat treatment of steel.

Transformation plasticity has been proved to be a very important effect occurring during heat treatment and therefore must be taken into account in heat treatment simulation. However, only few works exist about this topic, today. During phase transformations plastic deformations occur due to thermal and/or mechanical stresses even if the locally effective stress is lower than the yield strength of the softer phase at the momentary temperature. Transformation plasticity leads to additional plastic strains in the component acc. Eq. 1 [8],

$$\dot{\varepsilon}_{ij}^{tp} = {}^{3}\!/_{2} \cdot K \cdot \sigma_{ij} \cdot f'(w) \cdot \dot{w} \qquad (1)$$

where $\dot{\varepsilon}_{ij}^{tp}$ is the strain rate due to transformation plasticity, K is the transformation plasticity constant, σ_{ij} is the deviatoric stress tensor and $f'(w)\cdot\dot{w}$ describes the progression of the transformation. Among others [9], the models of Greenwood and Johnson [10] and of Magee [11] are important to describe the effect of transformation plasticity. Greenwood and Johnson presume, that during the transformation the softer austenite deforms plastically near the areas where the transformation is in progress as a result of the volume change due to the transformation. The orientation distribution of the martensite is not influenced by the stress. Volume change and yield strength affect the K-value and increase differently with increasing carbon content and hence decreasing M_S-temperature. As the yield strength increases faster than the volume change this should lead to decreasing K with increasing carbon content. Magee considers the martensitic transformation as a special type of deformation of the austenite. Its local anisotropic deformation leads to a macroscopic anisotropic deformation because of the irregular orientation distribution of the martensitic plates. Growing carbon contents lead to increasing amounts of plate martensite and therefore to a stress dependent change of the orientation distribution of the martensite, which leads to an increase of K.

Material and experimental Details

The experimental quenching investigations were carried out using cylinders made out of the three steels 20NiCrMo4-3-5, 50NiCrMo4-3-5 and 80NiCrMo4-3-5 with carbon contents of 0.2, 0.5 and 0.8 wt.-%. The alloying elements were always 1 wt.-% Ni, 0.7 wt.-% Cr and 0.5 wt.-% Mo. The cylinders had a diameter of 20 mm and a length of 60 mm. Thermocouples were placed inside the cylinders by means of spark-eroded holes. The experiments were run under constant boundary conditions using a self-developed quenching unit [12], where the specimen can be lowered from the furnace directly into a circular nozzle field. The cylinders were heated up to 910 °C, austenitized for 20 minutes under inert atmosphere (nitrogen) and then quenched with helium of 20 °C which was expanded from 10 bar to 1 bar. The heat transfer is the significant parameter which is responsible for the temporal and spatial development of temperature, microstructure, distortions and stresses [13]. To determine the heat transfer coefficient, the cylinders were equipped with two thermocouples, one in the centre and another one below the surface which serves as input for calculation of the temperature dependent heat transfer coefficient using a self-developed FD-program. To determine the radial distortion due to the heat treatment, the shapes of the cylinders were measured using a 3D coordinate measurement system. X-ray diffraction measurements were carried out to obtain information about the residual stress distribution along the surface of the cylinders. Information about the phase composition was obtained metallographically.

Experimental results

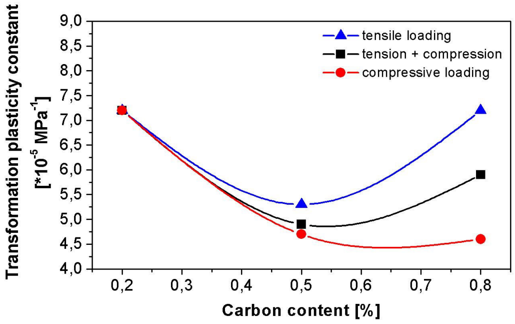


Figure 2: Transformation plasticity constant vs. carbon content [15].

The transformation plasticity constants used in these investigations were determined using a special dilatometer described in [9,14] and were published in [15]. If the transformation plasticity constant is regarded vs. the carbon content as shown in Fig. 2 one observes that it initially decreases and that there is only a small difference for tensile and compressive stresses up to a carbon content of 0.5 wt.-%. For lower carbon contents it is proved from these results that the Greenwood-Johnson effect is dominant. For carbon contents larger than 0.5 wt.-% additionally the Magee-effect becomes relevant and increases K. The plate-orientation is different for uniaxial tensile and compressive stresses but it is largely independent from the absolute value of the stress. Therefore K varies significantly between tensile and compressive stresses. With a carbon content increasing from 0.5 to 0.8 wt.-% the Magee-effect about compensates the Greenwood-Johnson-effect for compressive stresses, i.e. K remains nearly constant. For tensile stress the Magee-effect over-compensates the decreasing tendency of K due to the Greenwood-Johnson-effect which leads to an increase of K from 0.5 to 0.8 wt.-% carbon.

In Fig. 3 the measured axial residual stress distributions along the surface of the cylinders are presented. The residual stress levels of the cylinders vary strongly. Fig. 4 shows the radial distortion of the cylinders. The cylinders with 0.5 and 0.8 wt.-% carbon have a similar radial distortion of about 0.02 mm whereas the cylinders with 0.2 wt.-% carbon show almost no radial distortion. The metallographic investigations showed that the microstructure of the cylinders with 0.2 wt.-% carbon is a mixture of martensite and bainite, the cylinders with 0.5 wt.-% carbon transform completely martensitically and the cylinders with 0.8 wt.-% carbon consist of martensite and retained austenite after quenching [16].

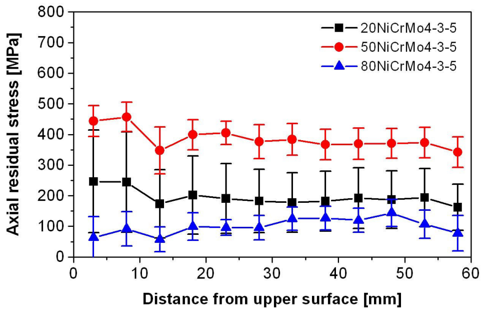


Figure 3: Axial residual stress along the surface of the cylinders.

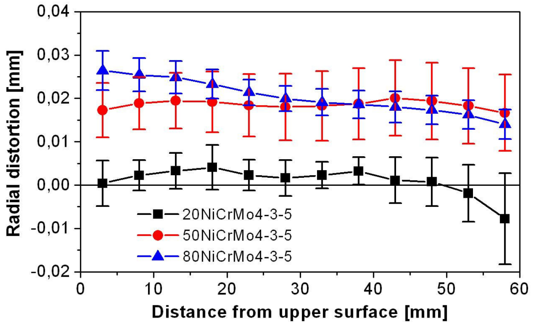
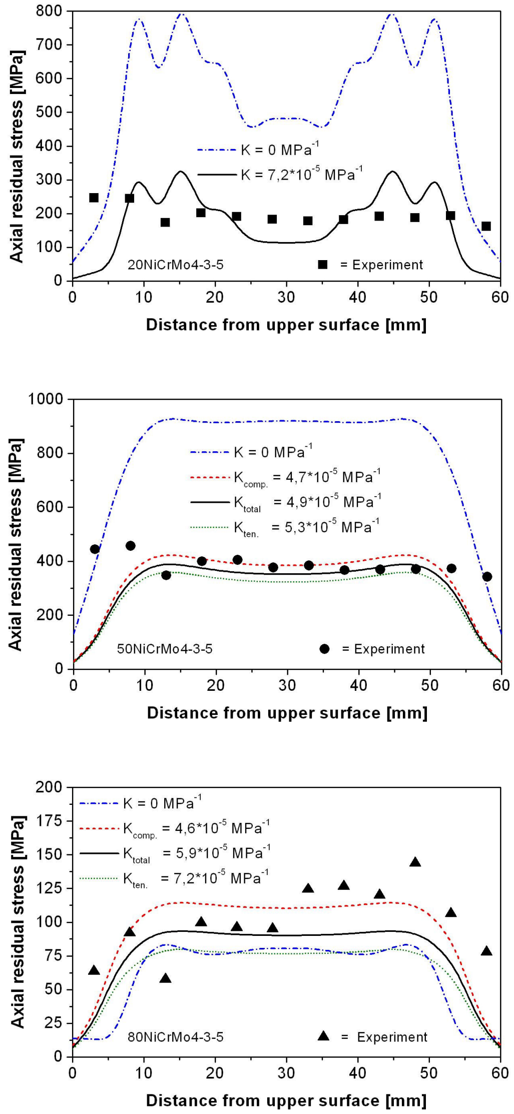


Figure 4: Radial distortion of the cylinders.

Numerical results

For the numerical investigations the Software DEFORM™ HT-2D was used. This Finite Element Method (FEM) based software allows to model heat treatment processes, including quenching and carburizing, which helps to predict hardness, residual stresses, quench deformation and other mechanical characteristics. In the program the couplings described in chapter 2 are implemented. For the simulation temperature dependent input data was used. Isothermal time-temperature-transformation (TTT) diagrams were modelled. The phase transformation kinetics of the diffusional and the martensitic transformation are very different [13]. The volume fraction according to the diffusion controlled ferritic/pearlitic and bainitic transformation was calculated by means of the Avrami equation. The volume fraction of the diffusionless transformed martensite was calculated using the model of Magee. Elasto-plastic behaviour was taken into account in the model. Transformation plasticity was taken into account using the model of Greenwood-Johnson.

The influence of the transformation plasticity constants *K* determined on the residual stress distribution of the cylinders was studied in the simulation. As can be seen in Fig. 5a the disregard of transformation plasticity (K = 0) in the simulation of the 20NiCrMo4-3-5 cylinders leads to a much higher residual stress level and to a pronounced difference between minimum and maximum residual stresses. Fig. 5b shows that the disregard of transformation plasticity in the simulation of the 50NiCrMo4-3-5 also leads to a much higher residual stress level but the fluctuation of the residual stresses besides the regions close to the upper and lower surface is quite lower. There is also a significant influence of the different *K* for tensile and compressive stresses. An increase of *K* results in a decrease of the calculated residual stresses and vice versa. The influence of *K* on the axial residual stresses for tensile and compressive stresses is about ± 9 % compared to the total value. The disregard of transformation plasticity in the simulation of the 80NiCrMo4-3-5 cylinders does not lead to a difference as significant as for the two other steels as proved by Fig. 5c. It leads to residual stresses which are a bit lower than for the total value of *K*. The *K* for tensile stresses leads to a decrease of the residual stress level of about - 15 %, and the *K* for compressive stresses increases the residual stress level of about + 18 %. The comparison of the simulations of the axial residual stress with the experimental results in Fig. 3 show a very good accordance for all three steels. For the steels with 0.5 and 0.8 wt.-% carbon the best accordance is achieved with the total value for *K*. It seems that the faults made by not separating between tensile and compressive stresses are equalled out in these specific cases. However, the investigations of the steel with 0.8 wt.-% carbon prove that the sign of the stresses has be taken into account in the simulations, but the software used for this work does not allow this.

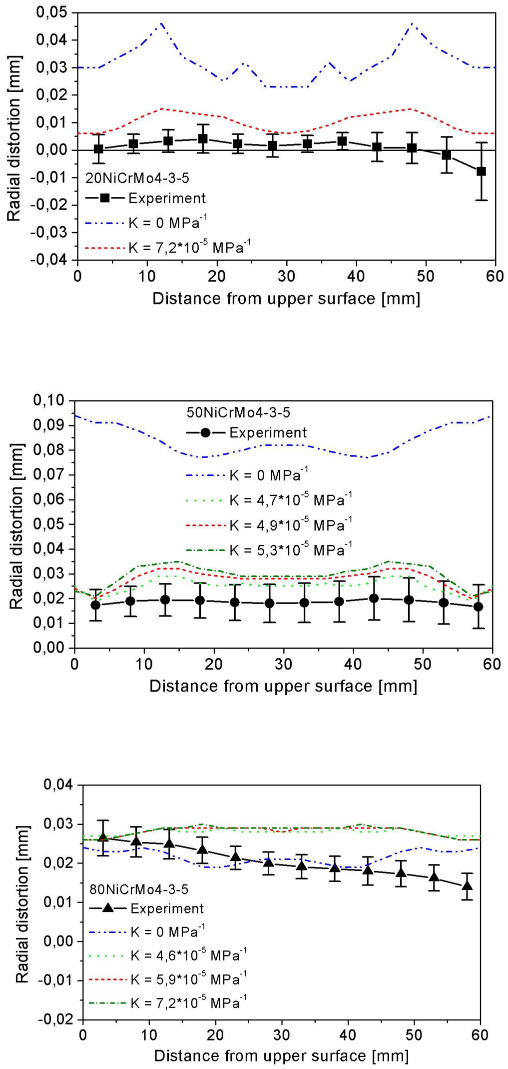


a)

b)

c)

Figure 5a-c: Influence of the transformation plasticity constant on the axial residual stress distribution along the surface of the cylinders.



a)

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Figure 6a-c: Influence of the transformation plasticity constant on the radial distortion along the surface of the cylinders.

Fig. 6. shows analogously the influence of transformation plasticity on the simulated distortions and their comparison with experimental results. As at the residual stresses, at 20NiCrMo4-3-5 and 50NiCrMo4-3-5 the disregard of transformation plasticity leads to a poor estimation in the simulation compared to the experimental results. For all steels the influence of the K-value itself is quite low. The distortions of 80NiCrMo4-3-5 are clearly asymmetric due to the experimental procedure, which leads to quenching effects starting first at the lower surface of the cylinder during lowering it into the gas nozzle field. This effect seems to be dominant in the 0.8 wt.-% carbon steel but is not taken into account in the simulations. Only slight effects of asymmetry can be seen in the experimental distortions of the 0.2 wt.-% carbon steel.

Summary

The transformation plasticity constant *K* was determined for three steels with identical composition but different carbon contents of 0.2, 0.5 and 0.8 wt.-%. The experiments show, that *K* first decreases and then increases again with increasing carbon content. Furthermore, there is a difference of *K* for tensile and compressive stresses which becomes pronounced for carbon contents larger than 0.5 wt.-%. The numerical analysis of the influence of K on the development of residual stresses clearly proves that transformation plasticity is a very important parameter that must not be neglected. The disregard of transformation plasticity leads to much to high residual stress levels and radial distortions for the steels with 0.2 and 0.5 wt.-% carbon. The increasingly varying K for tensile and compressive stresses with increasing carbon content also increasingly affects the residual stress level. However, in this specific case good accordance of the simulation with the experimental results could be achieved using the total values of K for the steels with 0.5 and 0.8 wt.-% carbon.

Acknowledgements

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