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Experimental investigations on the interactions between the process parameters of hot forming and the resulting residual stresses in the component

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Abstract

In metal forming, the arising residual stresses influence the material behaviour during manufacturing as well as the performance of the final component. In the past, the focus of forming process design was on minimising or eliminating residual stresses. However, residual stresses can also serve to improve the properties of the components through targeted use, for example with regard to distortions or wear behaviour. For this purpose, knowledge of the interactions between the process parameters of the hot forming process and the resulting residual stresses in the final component is required. In this work, the influences of the process parameters are analysed by means of a reference process of hot forming. In this process, cylindrical specimens with eccentric holes are hot-formed, which leads to an inhomogeneous stress distribution in the material as it occurs in an industrial hot forming process. In the reference process, forming temperature, cooling strategy, forming speed, degree of deformation and steel alloys are varied. It is observed that both, process parameters and material properties, have a significant influence on the resulting residual stresses. Mainly responsible for these phenomena are microstructural effects in the material. As a result of forming at temperatures between 1000 °C and 1200 °C, static and dynamic recrystallisation processes occur, which affect the austenite grain size. The austenite grain size as well as the cooling strategy have a significant influence on the microstructure transformation behaviour, which has a decisive effect on the resulting residual stresses. In addition, the cooling strategy determines whether a diffusion-free phase transformation or a diffusion-controlled phase transformation occurs. At high cooling rates, diffusion-free transformation of the austenitic into the martensitic phase takes place, which leads to severe stresses in the crystal lattice. During diffusion-controlled phase transformation, which occurs during air cooling, comparatively lower residual stresses in the range of zero can be observed.

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Keywords: hot forming process; forming parameters; residual stresses; thermo mechanical process; X-ray diffraction

1. Introduction

Residual stresses are an important issue as they affect both, the manufacturing process as well as the performance of the final parts. During the manufacturing of components, various residual stress states may occur in the material as an effect of the process route. In the past, there have been several investigations of the relationship between forming parameters such as deformation state or temperature profile and resulting residual stresses by experiments and simulations [1, 2, 3]. It is noteworthy that the residual stresses resulting from metal-forming processes are generally known to have negative effects, regarding for example lifetime. Hence, avoidance or minimisation during the manufacturing process are usually targeted instead of specifically influencing component properties [4]. For example, the surface treatment process by shot peening applied as an additional process step has already

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achieved positive effects on the fatigue life of components due to residual compressive stresses [5].

However, such an additional step in the process chain is inevitably associated with increased needs of time, costs and energy expenditure. Consequently, the motivation is to create a favourable residual stress condition in the component within the hot-forming process chain by means of intelligent process management. In the scientific work [6, 7, 8], it was shown that tailor-made cooling strategies using spray-field cooling systems are promising in order to adapt component properties such as strength, hardness or microstructure to the respective application. In [6], spray cooling is used to generate a graded microstructure and hardness profile in a gear wheel. In the work of [8], a tempering effect was created by adjusting the spray duration and pressure in different cooling phases of a pinion shaft, using the core heat is to temper the previously hardened surface layer. In addition, the influence of forming temperature and material parameters on the dimensional accuracy of components in the context of precision forging was for instance investigated in [9]. It was found that the final process result shows a clear sensitivity of the forming and material parameters. An investigation of the interactions between the parameters of the hot forming process and the resulting residual stresses in the final component has not yet been carried out. However, this knowledge is indispensable for the intelligent design of process parameters to induce advantageous residual stresses directly in the component to shorten the process chain and save time, costs and resources.

In order to achieve this goal, a reference process of hot forming was developed, which is presented in section 2. In this reference process, the parameters forming temperature, cooling strategy, forming speed, forming degree and the material of the workpiece are varied. For each type of the mentioned process parameters, different variations are experimentally performed followed by determination of the resulting residual stresses by means of X-ray diffraction. The results of the different process variations are reviewed and discussed in section 3.

Nomenclature

d_{211}	Spacing of the crystal plane 211
F	Experimentally measured force
FWHM	Full width at half maximum
Mf	Martensite finish temperature
MP1	Measuring point 1 on the thick-walled side of specimen
MP2	Measuring point 2 on the thin-walled side of specimen
Ms	Martensite start temperature
s_2	X-ray elasticity constant
u	Experimentally measured displacement
θ_{Cr}	Bragg angle
σ_t	Tangential residual stress

2. Experimental setup

The residual stress development in hot forming is investigated by means of a reference process. In this process, cylindrical specimens with eccentric holes, as shown in Fig. 1a, are used. Due to the eccentric hole, an inhomogeneous stress profile is created in the material, as it may occur in industrially manufactured components. The specimens are provided with thermocouples to control the experimental temperature boundary conditions. A quasi-isothermal upsetting test is enabled by the use of a thermobox (Fig. 1b). The specimen is heated in an oven to the forming temperature inside the thermobox and soaked for 10 minutes afterwards. Subsequently, the thermobox including the specimen is transferred to the servo-hydraulic forming simulator VHS8800 (Instron GmbH) and the specimen is upset inside the thermobox. Finally, the specimen is removed from the thermobox and quenched in water.

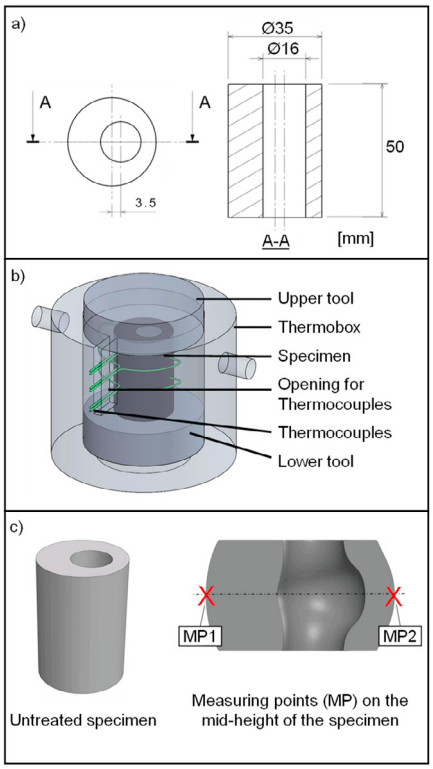

Fig. 1. (a) Shape of the investigated specimen with dimensions in mm, (b) schematic representation of the specimen prepared with thermocouples in a thermobox as well as (c) illustration of the untreated and the hot-formed specimen with the measuring points MP1 and MP2 at the mid height.

Hot forming is carried out for a variety of process parameter combinations shown in Table 1. The basic test is performed with the process parameters according to the work in [4] and also listed in Table 1. Starting from the basic parameter setup, a change in forming temperature, cooling strategy, forming speed, degree of deformation and workpiece material is considered for each process parameter individually. Three repetitions are performed for each parameter combination to ensure statistical validation.

X-ray diffraction is used for residual stress analysis on the final components. The respective measuring points were initially polished electrolytically in order to prevent the layer of scale occurring in the hot forming process from influencing the analyses. Subsequently, tangential residual stresses were determined with the X-ray diffractometer X3000G2 (Stresstech

GmbH) employing Cr-Kα radiation according to the corresponding DIN standard [10]. The measuring point was defined by a collimator with a diameter of 2 mm. Nine tilting positions of the measuring device were used per measuring point for stress evaluation. Afterwards, the measurements were evaluated with the software XTronic (Stresstech GmbH) by means of the sin² method. The values for the X-ray elasticity constant $\frac{1}{2}s_2 = 5.81*10\text{-}6\ mm^2N^{-1}$ and the reference values for the unstressed material ($d_{211} = 1.1703$ Å, $2\theta_{Cr} = 156.084$ °) were taken from the tabular data collection of [11]. These data of X-ray elasticity constants were calculated as mean values from the so-called Voigt [12] and Reuß [13] approaches for the pure alpha iron lattice. The measurements were conducted at the measuring points on the mid-height of the specimen (cf. Fig. 1c).

Table 1. Variation of the process parameter combinations with respect to the basic process.

Parameter	Variants	Basic	Variants
Temperature		1000 °C	1200°C
Cooling strategy		Water	Atmospheric air
Forming speed	1 mm/s	200 mm/s	500 mm/s
Degree of deformation	0 mm	22 mm	30 mm
Material		AISI 4140	AISI 52100

3. Results and discussion

3.1. Thermal-mechanical-metallurgical phenomena in the considered reference process of hot forming.

The development of residual stresses in a component manufactured by hot forming occurs during the cooling phase after the actual forming of the material. Nevertheless, this development of residual stresses during the cooling phase is closely linked to the forming parameters that the material has experienced previously. There are complex thermal-mechanical-metallurgical interrelationships taking place within the material. For example, the forming temperature, forming rate and degree of deformation influence the microstructure, especially the grain size. Thus, the kinematics of the microstructure transformation from the cubic face-centered austenitic microstructure to the cubic body-centered microstructure of the phases ferrite, pearlite, bainite and martensite are modified by a change in process parameters.

Considering the basic process described in section 2, four stages of residual stress development during the cooling process can be defined. At *stage I*, first the specimen sheath is cooled on the thick-walled as well as on the thin-walled side, and then the specimen core is cooled as well. This means that due to the thermal shrinkage the sheath will contract while the core of the specimen remains thermally expanded. At this stage, tensile stresses in the specimens sheath and compressive stresses in the core occur. According to the dynamic recrystallization processes occurring due to the combination of forming temperature and forming rate, a corresponding microstructure is developed. This influences the parameters martensite start and finish temperature. At *stage II* martensite start temperature Ms is reached and the phase transformation begins in the area of the specimen sheath. Since the martensitic lattice takes up about 2% more volume than the austenitic lattice, this process is accompanied by a volume jump [14, 15]. This volume expansion is also amplified by the superimposed positive elastic stresses due to thermal shrinkage in the specimen sheath, which is also referred to as the transformation plasticity effect [16]. While the specimen sheath has already cooled down until martensite transformation begins, the temperature of the core is still above Ms. The volume expansion due to the martensite transformation therefore only occurs in the specimen sheath at this stage. This leads to a strain gradient, which causes negative stresses in the specimen sheath and positive stresses in the specimen core.

As cooling progresses at *stage III*, martensite transformation also occurs in the specimen core accompanied by volume expansion, which in turn causes positive stresses in the sheath and negative stresses in the core. At *stage IV*, further cooling of the almost completely martensitic specimen to room temperature leads, as described in *stage I* to a further increase in the positive stresses in the sheath due to thermal shrinkage and to an increase in the negative stresses in the specimen core.

The temperature drop between the specimen core and the specimen sheath depends on the heat capacity of the material. In the specimens with eccentric hole used in this study, there is a thick-walled side where MP1 is located and a thin-walled side where MP2 is provided (cf. Fig. 1). Due to the higher mass on the thick-walled side, the specimen core will cool down more slowly than on the thin-walled side. Therefore, the phase transformations between core and sheath are more delayed on the thick-walled side than on the thin-walled side. As a result, the residual stresses at MP1 are higher than at MP2 in each case considered.

The procedure of residual stress development in the four stages described applies only to the hot forming process mentioned in section 2 with the subsequent rapid cooling in water to room temperature. If the cooling strategy is modified or if the martensite transformation is not complete, significantly deviating residual stress profiles will develop. These will be investigated by the authors in a later work. In this paper, the focus is set on the analysis of the influences of the forming parameters on the residual stresses in the final component, which are discussed in the following.

3.2. Forming temperature

Figure 2 shows the results of the residual stresses at the two measuring points MP1 and MP2 on the specimens for the different forming temperatures 1000°C as well as 1200°C.

It was found that a higher forming temperature of 1200°C compared to the lower forming temperature of 1000°C leads to higher residual positive stress values at MP1 (cf. Fig. 2). The stresses at MP1 increase from 212 MPa after forming at 1000°C to 242 MPa after forming at 1200°C. However, similar stresses were measured at MP2 for the forming temperatures

1000°C and 1200°C of 192 MPa and 194 MPa. The higher stresses at MP1 as a result of an increase in the forming temperature can primarily be attributed to a change in the austenite grain size. Due to the higher austenitising temperature, increased grain growth occurs in the material, resulting in larger austenite grains [17, 18, 19]. The increased grain size in turn, leads to several effects.

The enlarged grains cause an increase in the martensite start temperature Ms and in the martensite finish temperature Mf. Due to the coarser structure of the austenite grains, diffusion of the interstitial atoms at the long grain boundaries of the austenitic crystal lattice is hindered and diffusion-free, martensitic phase transformation is facilitated. Since martensite transformation is favoured in the process with 1200 °C forming temperature, in this case less retained austenite is present in the material. Accordingly, in X-ray diffractometric measurements at MP1, for example, an average retained austenite content of 15.9 % was determined for the specimen formed at 1000°C and an average retained austenite content of 8.4 % for the specimen formed at 1200°C.

As a result of a higher martensitic phase fraction in the core of the specimen, the volume shift increases due to the phase transformation in these areas. Consequently, higher strain gradients between the sheath and the core and thus higher residual stresses occur on the surface of the specimen.

Furthermore, it is assumed that the larger grains prevent stress relief during the cooling process and thus accumulate more stress inside the material. The increased number of grain surfaces in the material within the process at 1000 °C forming temperature causes a better transfer of distortions, which leads to lower residual stresses (cf. [20]).

In addition, since the maximum possible residual stresses are limited by the yield stress, increasing the proportion of the harder martensitic phase and reducing the softer austenitic phase can lead to an increase in residual stresses. These effects obviously conceal the fundamental reduction in yield stress that occurs according to the Hall-Petch law [21, 22] as a result of grain enlargement.

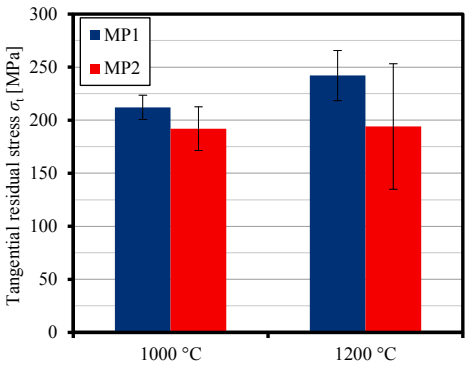

Fig. 2. Comparison of the resulting residual stresses in the reference process of hot forming at varying forming temperatures.

As the similar values of MP2 for both forming temperatures show, the above-mentioned effects have less influence on the stresses of the thin-walled side. The thin-walled side of the specimen thus obviously shows a low sensitivity of the residual stresses to forming temperature due to the shorter time delay between the phase transformation in the core and in the sheath discussed in section 3.1.

3.3. Cooling strategy

At high cooling rates, a diffusion-free phase transformation of the austenitic into the martensitic phase takes place, which leads to severe stresses ranging from 192 MPa at MP2 to 212 MPa at MP1 (cf. Fig. 3a). During diffusion-controlled phase transformation, which occurs during air cooling, comparatively lower residual stresses around zero can be observed.

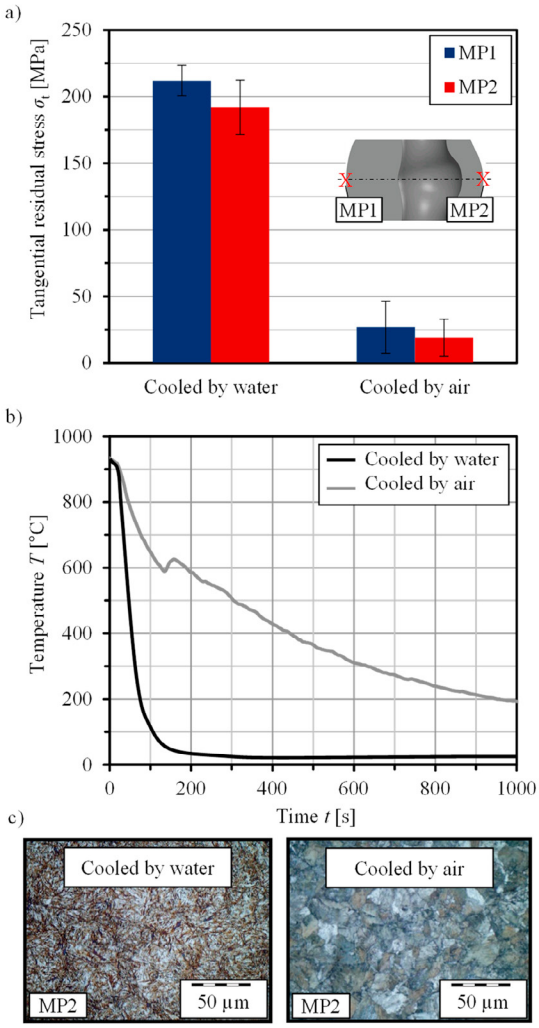

Fig. 3. Comparison of the resulting residual stresses (a) in the reference process of hot forming at varying cooling profiles (b) as well as the resulting microstructure depending on the cooling profile (c).

Due to the different cooling media water and air, different temperature-time profiles as shown in Fig. 3b and different transformation kinematics occur in the steel alloy. During rapid cooling in water, a diffusionless transformation occurs, where austenite is transformed to the martensitic body-centered

tetragonal (bct) lattice structure (cf. Fig. 3c, left). When cooled by air, a body-centered cubic (bcc) lattice with a bainitic microstructure is formed for AISI 4140 (cf. Fig. 3c, right), because of diffusion-controlled transformation.

On the one hand, the phase transformation from austenite to martensite is accompanied by significant volumetric expansion, which leads to a strain gradient in the material. This effect is further enhanced by the highly pronounced transformation plasticity of martensitic transformation.

On the other hand, the growth of the harder martensitic phase in the softer austenitic phase leads to stresses in the crystal lattice structure. The relatively high yield stress of the martensitic phase compared to the phases resulting from diffusion-controlled transformation thus determines the maximum achievable residual stress in the material.

3.4. Forming speed

Varying the deformation speed led to considerable diversity in the residual stresses in the specimens (cf. Fig. 4a). At a forming speed of 1 mm/s, residual stresses of about 265 MPa were measured at both measuring points, at 200 mm/s 212 MPa at MP1 and 192 MPa at MP2 and at 500 mm/s the highest residual stresses of 363 MPa at MP1 and 417 MPa at MP2 were measured. This shows that no general tendencies can be derived from the relationship between forming speed and resulting residual stresses. It is rather necessary to consider each parameter combination individually.

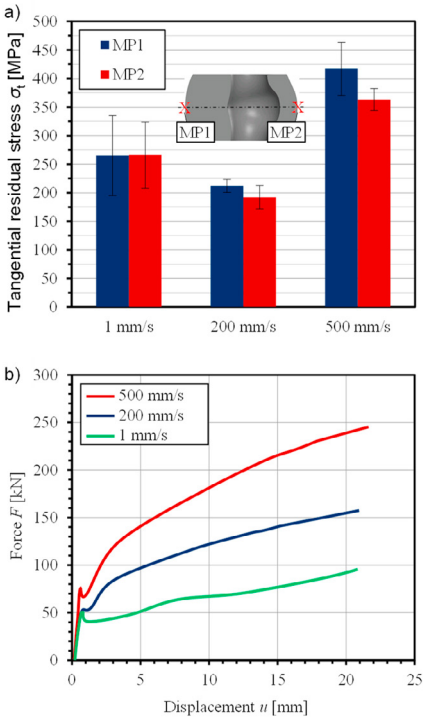

Fig. 4. Comparison of (a) the resulting residual stresses as well as (b) the process forces in the reference process of hot forming at varying forming rates.

In each of the three cases, it is assumed that dynamic recrystallisation occurs in different forms. Dynamic recrystallisation means that starting at a certain level of critical deformation, the dislocations and lattice defects caused by forming are absorbed by grain formation and grain growth. This leads to a decrease in the yield stress reducing the required process forces and increases the maximum plasticity of the material [23].

At first, the results of the processes at 200 mm/s and 1 mm/s are considered. It is obvious that in the slower process the material is kept at forming temperature for a longer period of time and thus the grain growth could progress further than in the faster process with a forming speed of 200 mm/s. As depicted in Fig. 4b concerning process forces, hardening effects occur in the test at 200 mm/s in contrast to the test at 1 mm/s. At a forming speed of 200 mm/s it is therefore assumed that the ratio between the formation of new dislocations due to forming and the formation of new austenitic grains is matched to produce a fairly fine grain. As described in section 3.2, the smaller grains lead to decreased strain gradients and subsequently lower residual stresses. With a further increase in forming speed from 200 mm/s to 500 mm/s, significant hardening effects were determined (cf. Fig. 4b). Forming was completed with a large number of dislocations which could not yet be absorbed by recrystallisation. Since quenching of the specimen takes place immediately after forming, secondary static recrystallisation also hardly takes place.

Evidence that a clearly hardened material is present in the specimen formed at 500 mm/s was also supported by the characteristics of the emission profile from X-ray diffraction. Different values of full width at half maximum (FWHM) were found on the specimens formed at different speeds. At MP1, for example, an FWHM of 4.55 ° in average was found on a specimen formed at 500 mm/s, compared to 3.42 ° on a specimen formed at 1 mm/s. According to [24] this may be an indication of increased dislocation density. As a result, diffusionless phase transformation takes place on the hardened material, which leads to a significantly distorted crystal lattice.

3.5. Degree of deformation

In order to investigate the influence of the degree of deformation on the residual stresses in the hot forming process, the specimens were upset to two different final heights. In addition, a series of tests did not involve forming of the specimens, but only the exposure to the thermal loads of hot forming and quenching.

An increase in upsetting distance led to a reduction in residual stresses (cf. Fig. 5). Stresses between 291 and 306 MPa were measured on the specimens without deformation, 192 to 212 MPa on the specimens upset by 22 mm and 84 to 165 MPa on the specimens upset by 30 mm.

As the final height of the specimen decreases, the degree of deformation in the material increases and thus also the number of dislocations. As mentioned above, at a critical degree of deformation, dynamic recrystallization occurs. Nucleation forms in the deformed areas, resulting in the growth of new

austenite grains. The greater the deformation, the higher the number of dislocations and the finer the newly formed grain. In the non-deformed specimen, grain growth can proceed unhindered by static recrystallisation during the holding time at 1000°C. Accordingly, depending on the resulting grain size, the same effects were found with a decrease in the forming parameter "deformation degree" as with an increase in the forming temperature discussed in section 3.2.

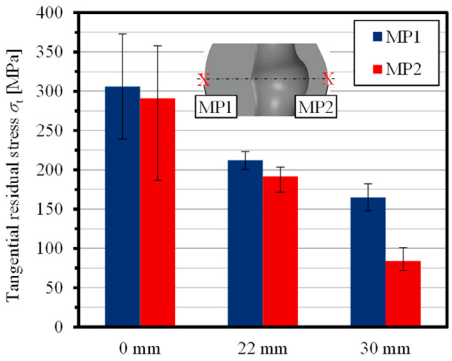

Fig. 5. Comparison of the resulting residual stresses in the reference process of hot forming at varying degree of deformation.

3.6. Material properties

To investigate the influence of material properties on the resulting residual stresses, material AISI 52100 was investigated in comparison to material AISI 4140. As it can be seen in Fig. 6 at MP1, almost the same residual stress states of about 212 MPa have been observed in both materials. At MP2, in contrast, significantly different residual stresses of 192 MPa in material AISI 4140 and 138 MPa in material AISI 52100 were determined.

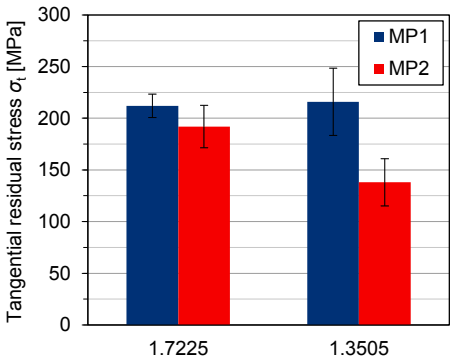

Fig. 6. Comparison of the resulting residual stresses in the reference process of hot forming at varying materials.

The comprehensive material characterisation of the authors in [4, 25, 26] has shown that the plastic behaviour, the transformation-related and transformation-plastic parameters of the two materials are different. Of particular importance is the material-specific martensitic transformation behaviour, which starts much later in material AISI 52100 with Ms = 184 °C compared to AISI 4140 with Ms = 334 °C. This phase transformation is superimposed by the differing transformation plastic behaviour of AISI 52100. As stated in section 3.1, the phase transformation effects in turn are subject to the flow behaviour and the kinematics of grain growth as a result of dynamic and static recrystallisation.

In conclusion, not only the process parameters but also the material properties are closely linked to the thermal-mechanical-metallurgical phenomena involved in the hot forming process, resulting in complex interrelations with the residual stresses generated in the final component.

4. Conclusion and outlook

In this work, the interactions between the process parameters of hot forming and the resulting residual stresses were investigated. For this purpose, an experimental reference process of hot forming was performed using specimens with an eccentric hole. The parameters forming temperature, cooling medium, forming speed, degree of deformation and the workpiece material were varied. As described in section 3.1, the residual stresses arise during the cooling phase after hot forming. The main factor influencing the residual stresses is phase transformation kinematic. As shown in sections 3.2 to 3.6, this significantly depends on process parameters as well as material properties.

It is important to note that the relationships between forming parameters and residual stresses shown here are only valid for the reference process of hot forming presented in section 2. However, the work provides a knowledge base for a better understanding of the interactions between process parameters and the material-specific thermal-mechanical-metallurgical phenomena occurring in the hot forming process.

The complete phase transformation with continuous cooling from forming temperature to room temperature was considered in each case. If there is a deviation from this process sequence, significantly changed stress states are expected. Accordingly, the authors plan to identify further control parameters for adjusting the residual stresses by means of non-continuous cooling and tailored phase transformation in the material in a next step.

Acknowledgements

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