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NON-LINEAR MODEL-PREDICTIVE-CONTROL FOR THERMOMECHANICAL RING ROLLING

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Abstract. The authors present a new ring rolling variant that combines a semi-warm forming process of a bearing ring with controlled cooling directly followed by a cold forming process. The aim is to produce near net shape rings with a selected microstructure and high strength without additional consecutive heat treatment. To achieve this, a new and fast control strategy is necessary that not only controls the geometrical forming of the ring, but also considers temperature development and microstructure formation. The proposed control strategy is based on the application of a fast semi-analytical simulation model with a very short response time in combination with a FE-analysis of the thermomechanical ring rolling process. The semi-analytical model is used as a predictor and a parallel FEA or experimental results as a corrector for the control model. The aim is to correctly identify transient process parameters needed to achieve defined product properties as a basis for a later implementation in a non-linear model-predictive-control of thermomechanical ring rolling. The new approach will be described in detail and demonstrated numerically and experimentally.

1 INTRODUCTION

A new process variant of the well-established ring rolling process with a new approach to apply closed-loop control in order to produce rings with selected specific product properties is presented in the following. A short introduction both into the process itself with current control strategies as well as into thermomechanical processes in general will be given in the following.

1.1 Ring rolling

Ring rolling is an incremental process for bulk metal forming for the production of seamless rings which includes a wide range of process variants that can be classified according to the resulting geometry, process route, machine layout, and process temperature [1]. Cold ring rolling is generally suitable to form near net shape metal rings, e.g. for bearings, that have an advantageous microstructure, desired surface hardness and high strength. Ring rolling also offers the possibility of producing hybrid ring-shaped components [2]. The production of hybrid rings has been proven both numerically and experimentally at the RWTH Aachen within the framework of a hot forming process [3]. In contrast, Küsters et al. have demonstrated the feasibility of producing force-locked brass-steel composite rings by cold ring rolling [4]. Within the scope of these investigations, a radial ring rolling machine, based on the machine concept of PROFIROLL TECHNOLOGIES GMBH, is used originally designed to manufacture outer roller bearing rings. The principle of radial ring rolling is shown in Figure 1. Here, the ring is formed between a main roll and a mandrel in radial direction while two calibration rolls are used to control the ring growth and shaping.

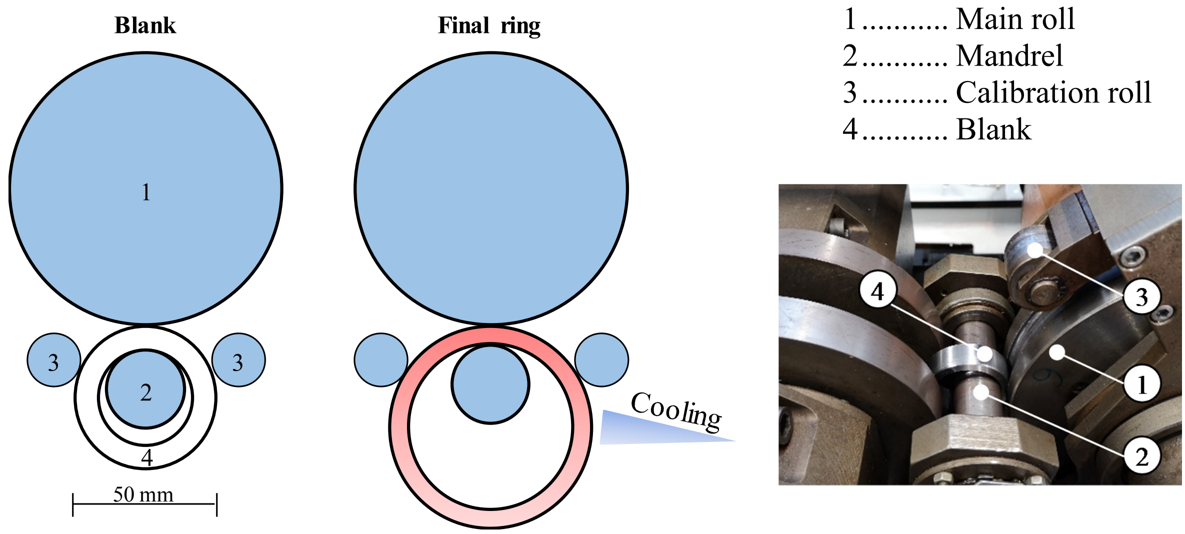

Figure 1: Principle test setup (left) and experimental ring rolling machine (right)

Like all processes, hot and cold ring rolling are subject to uncertainties, which are mainly caused by the cooling conditions and heat generation during forming [5]. Coupled with the forming stages over the process time, these uncertainties not only influence the geometric properties of the manufactured rings, but also the formation of the microstructure and the resulting material properties. For the control of the ring rolling processes, there are various approaches, most of which are exclusively concerned with the geometric shape of the rings produced. Industrial plants usually use a controller based on a kinematic model of Koppers [6] as described by [7]. For radial-axial ring rolling, Choi and Cho [8] present an approach to control the ring geometry adaptively by controlling the infeed of the working roll and the conical support rolls to increase the final accuracy. Due to the non-linear behavior and the uncertainty of the input parameters, they design an adaptive control that can map the dynamic changes over the process time. In further work, the approach for force control of the guide rollers is transferred [9]. By default, hot ring rolling mills do not have thermal actuators such as cooling or heating, only the forming speed can be actively influenced by the roll infeed [5]. Process models must take the transient boundary conditions of the forming into account and thus become too slow to be used for control, so that controllers are essentially used to maintain the tool path [10]. In the field of sensor technology, development is moving towards the use of camera-based geometry acquisition and evaluation, as well as the use of thermographic cameras [11]. FE models show that the influences of the adjustable control variables speed, roll infeed and position of the guide rolls show strong interdependence, although the influenced areas in the ring are very different [5]. Therefore, strongly simplified models appear to be unsuitable for an adequate process analysis. Currently, existing control algorithms within FE models are used to investigate the influence of geometric control on temperature distribution and microstructure, as for example presented by

Jenkouk [12]. An extension of the ring rolling mills with thermal actuators opens up possibilities for setting a desired microstructure, even under interference [5].

1.2 Thermomechanical processes

Due to a large number of manufacturing processes in which both thermal and mechanical processes are interlinked, it is necessary to define thermomechanical manufacturing processes as applied by the authors. Sometimes they are also summarized under the term Thermomechanical Treatment (TMT) and include those processes which "during the process, by means of a targeted combination of temperature and forming conditions, give the end product material properties which are superior to or at least equivalent to those properties which exist after conventional production" [13]. In [14] thermomechanical rolling is defined as "a rolling process with final forming in a certain temperature range which results in a material condition with certain properties which cannot be achieved by heat treatment alone and which cannot be repeated". For the TMT, "temperature and deformation in their temporal sequence" must be controlled according to Stahl-Eisen-Werkstoffblatt 082 (steel iron material data sheet) [15]. The objective here is to achieve a homogeneous microstructure state with defined properties by a targeted combination of temperature and forming conditions, using certain metallurgical mechanisms and phase transformations in the material [13]. The temperature range, degree of forming and cooling speed between 800 °C and 500 °C are relevant process variables for setting lasting effects by thermo-mechanical forming [16]. Multiphase microstructures of ferrite and martensite or ferrite, bainite and retained austenite can be adjusted by material-adapted cooling. Using this method, very good material properties with high tensile and good impact strength can also be achieved on the basis of low-alloy steels [17]. Due to the low carbon content, the weldability remains completely intact, while tensile strengths of up to 1100 MPa can be reached [18]. Von Hehl [13] has demonstrated this in principle for the ring rolling of large rings at high temperatures with guided cooling. The basis for the increase in strength is a temperature treatment according to the transformation-time-temperature diagram of 100Cr6. Based on the state of the art the authors propose the application of a thermomechanical ring rolling process in order to control and improve selected material properties while also expanding the process window and lowering process forces.

2 CONCEPT

The presented approach, similar to [13], is a combination of semi-warm ring rolling with guided cooling with a directly subsequent cold rolling process in order to produce near-net-shape rolling bearing rings with advantageous microstructural properties at high strength without additional heat treatment steps. Due to the relatively low component volume of the rings, active cooling ensures sufficiently rapid cooling for the formation of a martensitic microstructure. Compared to a pure cold rolling process, the advantages lie in the achievement of higher degrees of forming and reduced process forces. The prerequisite for this combined process route is the use of a suitable material and the development of a control system in order to achieve the set microstructure and the resulting work hardening by means of the forming process and cooling curve. The resulting combined process of a first stage of semi-warm rolling directly followed by a cold rolling calibration is significantly shorter than a conventional process chain to achieve the same combination of microstructure and geometry, see Figure 2.

a) Conventional process

Heating → Rolling → Cooling Forming process	→ (Storage) →	Heating → Quenching → Tempering Heat treatment

b) Thermomechanical Treatment

Heating → Rolling → Quenching → Tempering Thermomechanical Treatment

c) Modified Thermomechanical Treatment

Heating → Rolling → In-process quenching → Calibration (cold) Thermomechanical Treatment

Figure 2: Different manufacturing strategies for rolled rings according to [13]

A prerequisite to fully implement a thermomechanical ring rolling process to specifically choose microstructure and corresponding part properties is a fast process model as a basis for the integration of a closed-loop predictive control. This closed-loop control is necessary for a robust process, because of the numerous interdependent thermal and mechanical parameters. The approach proposed by the authors is a combination of suitable soft-sensors and semi-analytical models to achieve a closed-loop control, depicted in Figure 3. Soft-sensors are aimed at deriving current material properties and process states from secondary measurements. For example, the temperature development in the ring core cannot be measured during the process and therefore has to be modelled via soft sensors from the surface temperature and amount of forming energy induced into the workpiece. Eddy-current sensors can be used to observe microstructure development during the process. This sensor information is then fed into the fast analytical process model which in turn is used for the closed-loop control of the thermal and mechanical process actuators.

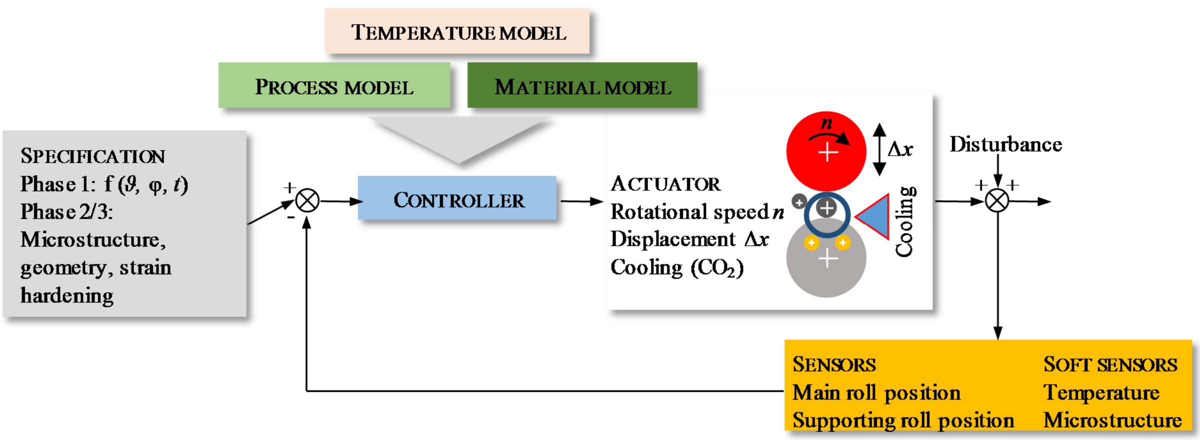

Figure 3: Principle scheme of the control loop with analytical models

The process model to be implemented will consist of the semi-analytical model based on the theory of plasticity for ring rolling as developed by Küsters et al. [4] for hybrid ring rolling.

Specifically, it will be adapted to consider additionally the temperature dependency of the current flow stress as provided by the advanced material and temperature models. In combination with all necessary semi-analytical models for the soft-sensors and control-loop, parameter identification and functional integration, it will serve as the central model for the control-loop. The microstructure model delivers the necessary input for an adaptive material model, the soft-sensor models for temperature and microstructure in the ring core, as well as a model to describe temperature development during forming will feed into the process model. The connection between these models is schematically summarized in Figure 4.

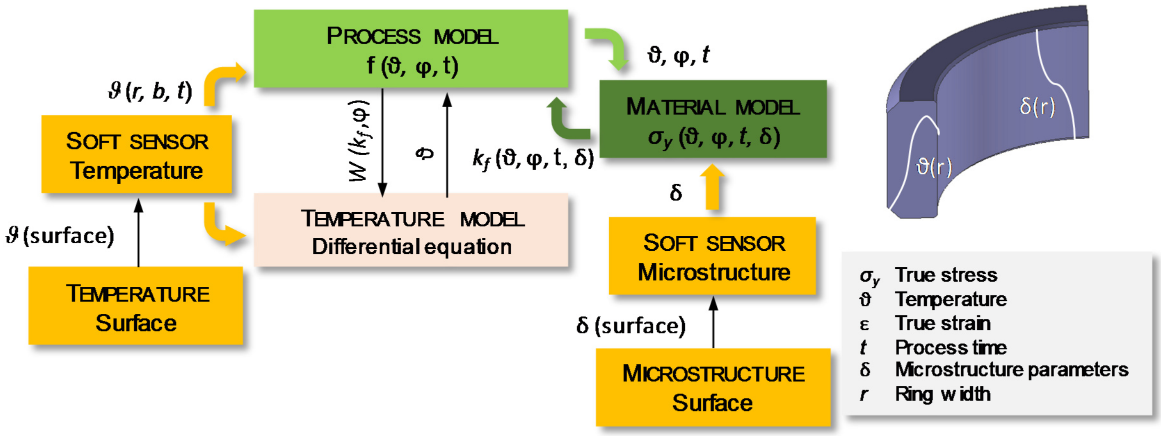

Figure 4: Context of the all interacting models

3 EXPERIMENTAL INVESTIGATION OF THE ROLLING PROCESS

The two main goals of the experimental investigations are to show the feasibility of the proposed process regarding process stability and ability to significantly influence final material properties in the same final near net shape ring geometry via Thermomechanical Treatment. Secondly, the experimental analysis is used to verify the fast process model proposed in the next chapter. As a first step, the influence of the combined forming and cooling on the strength and hardness of the ring will be demonstrated by means of experimental and numerical investigations.

3.1 Experimental set-up

Basic comparative tests are carried out between different process temperature routes. The initial workpiece temperature at the start of the rolling process is varied between room temperature and a semi-warm temperature of about 600 °C. As a second variable, the semi-warm process is carried out with and without additional cooling using liquid nitrogen (LN_2) or compressed air (0.8 MPa) after a certain expired process time. A thermal camera ImageIR® 8340 hp (company INFRATEC GMBH, detector format 640 x 512 pixels, thermal resolution of 20 mK, frame rate up to 1 kHz) is used to visualize the surface temperature of the ring over the process time in order to evaluate the effect of the workpiece cooling, see Figure 9.

The cooling of the workpiece starts after the forming of the ring has begun in order to exploit the reduced flow stress of the material at higher temperatures at the beginning of the process.

The amount of deformation induced during this phase also has an influence on the microstructure evolution during the cooling phase due to the resulting microstructural dislocations and additional heat input from forming energy. Despite the very short process time of five seconds, the heat treatment of the workpieces is expected to result in a change in structure and hardness compared to the ring rolled conventionally at room temperature. Table 1 shows an overview over the selected process parameters for different specimen as well as the final geometry.

Table 1: Process parameters

Specimen	Initial rolling temperature in °C	Cooling	Max. plastic strain φ
0 (Blank)	-	-	-
1	20	None	0.248
2	600	None	0.237
3	600	Compressed air / Liquid N_2	0.250

The roller bearing steel 100Cr6 (1.3505) is used for the thermomechanical ring rolling. The ring geometry is a simple symmetrical ring with a ball track as the inner contour. The geometry of the finished part and the blank are shown in Figure 5. Based on the ttt-diagram, a workpiece temperature of 800 °C is required for austenitization of the workpiece material. In order to achieve the high cooling rate required for martensite formation, cooling with liquid nitrogen (about -200 °C) is used. Due to the experimental conditions, a workpiece temperature of 600 °C can currently be achieved. However, this temperature is sufficient to investigate the cooling strategy with regard to the cooling rate and to influence the microstructure.

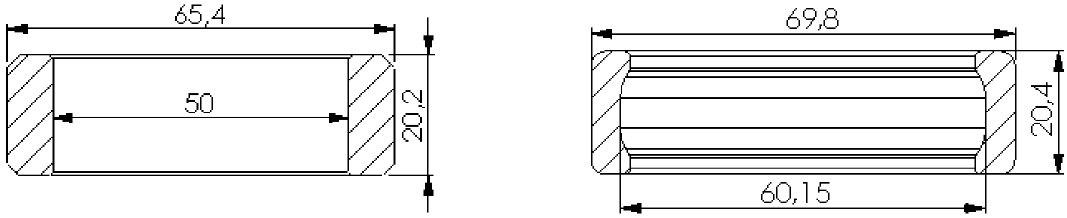

Figure 5: Blank (left) and final ring (right)

3.2 Evaluation

In the following, the results of the thermomechanical investigations compared to conventional cold and semi-hot rolled rings are presented and discussed. Figure 6 shows the different rolling strategies, cold formed, semi-warm formed and thermomechanical formed (semi-warm forming and cooling). On average, the rings have an outside diameter of 69.80 mm and an inside diameter of 56.7 mm for the ball track. In comparison, cold and thermomechanical rolled rings show no significant differences in the geometric dimensions, compare Figure 6. In addition to the geometric dimensions, the surface roughness over the width of the rings is measured. Differences are shown with regard to the average roughness R_a achieved, see Figure 6 (right). In general, the roughness of the blank is reduced by the forming process. The smallest measured roughness, however, is with the cold-rolled ring at approx. 0.6 µm. The hot-rolled ring, on the other hand, has a roughness value of 1.0 µm, which is still significantly lower than that of the blank (specimen 0). The increase compared to the cold rolled rings is at least partially due to some scaling occurring during the heating process. Thermomechanical rolled rings have a mean roughness of 0.8 µm. These results show that the rolling process improves surface roughness and the effects of scaling can be limited. Additionally, these results give a first indications that the process is suitable for influencing the material properties.

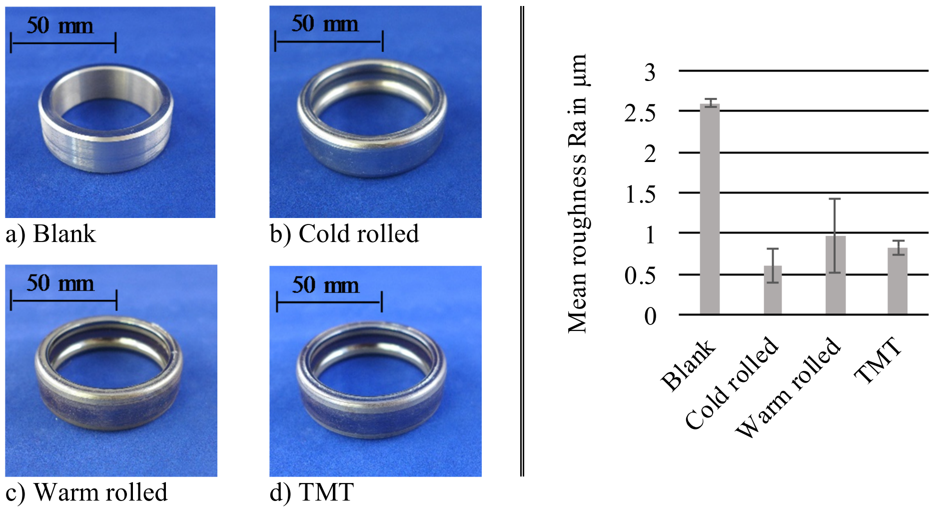

Figure 6: Final ring geometrie (left) and mean surface roughness (right)

The decisive criterion for the approach presented is the development of the microstructure and the hardness of the ring material as a result of thermomechanical ring rolling in contrast to conventional cold ring rolling. In general, it can be said that an increase in hardness occurs just as a result of forming. While there is a uniform hardness of 206 to 212 HV0.1 over the cross-section of the blank, the hardness increases to values between 260 and 272 HV0.1 for the cold-formed ring. As explained and aimed for in the concept chapter, there is an additional increase in the hardness values as a result of the combination of heat treatment and forming. While the cold formed ring achieves an average hardness of 265 HV0.1, the value is even increased up to 314 HV0.1 as a result of the in-process heat treatment during ring rolling.

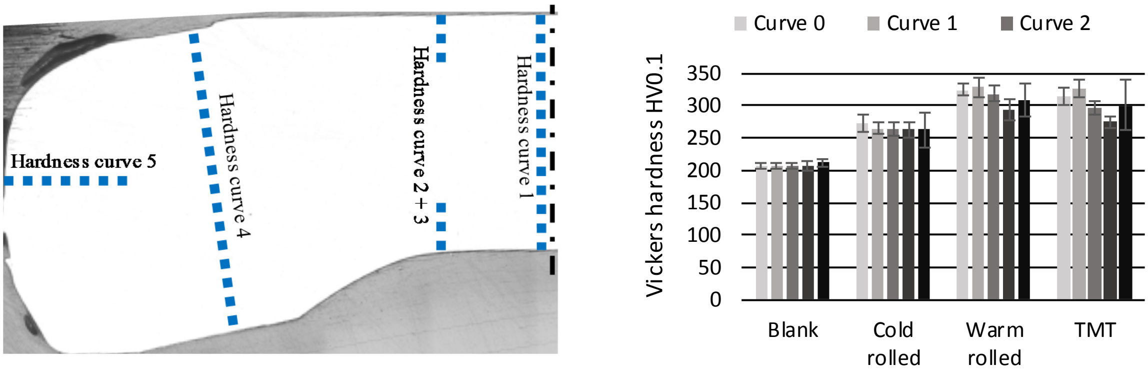

Figure 7: Cross section of final ring and hardness

The distribution of the hardness over the cross section after forming and thermomechanical forming is shown in Figure 8. The increase in hardness as a result of the work hardening is clearly visible, whereby regions with higher forming strain also exhibit greater hardness. The influence of simultaneous heat treatment during forming can also be seen in form of an additionally increased hardness, shown in Figure 8 b) and c) compared to Figure 8 a). However, there are no differences in the hardness values when comparing the hot-rolled and thermomechanical rolled rings, Figure 8 b) and c).

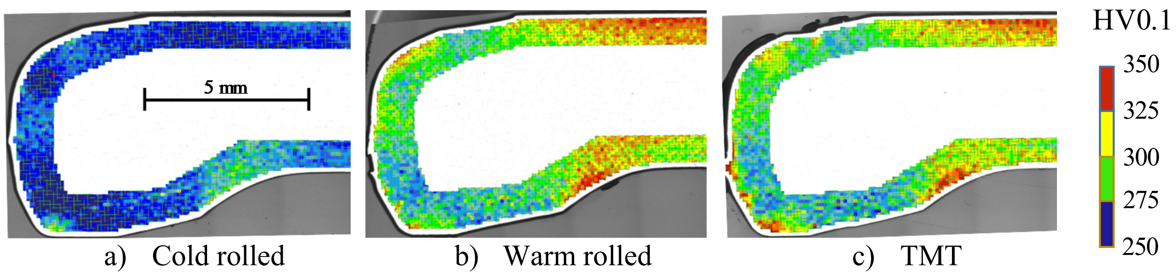

Figure 8: Distribution of hardness in different formed rings

The main reason for this is the insufficient cooling rate of the workpiece core, so that no thermal transformation of the microstructure across the cross section of the ring occurs due to the cooling. The initial and final temperature of the thermomechanical rolled rings are shown in Figure 9. Only for air-cooled rings a change in temperature of approx. 90 K during the ring rolling process can be detected on the outer diameter, which results in a structural change, as already mentioned. The change in microstructure manifests itself in a change in strength or hardness of the material, particularly in the edge area, as shown in the Figure 9. The numerical results show a similar distribution of the strength compared to the experimental determined hardness.

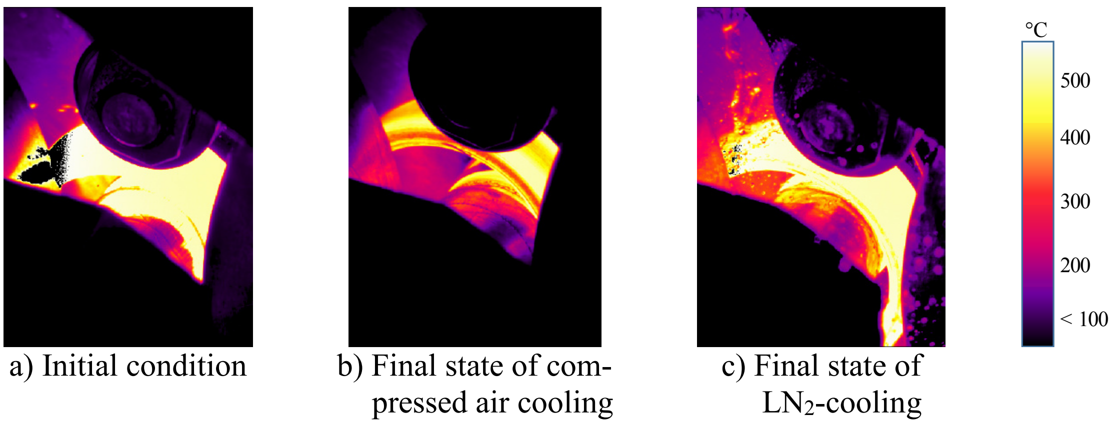

Figure 9: Temperature development due to chosen cooling strategy

4 PROCESS MODEL

4.1 FE-Modelling

In order to investigate the relevant mechanisms and effects during this thermo-mechanical transient deformation process, a simplified finite-element-model was build using the FE-code msc.marc v2013.1 with an implicit time integration schema. To achieve a short simulation time, a 2D model was generated using the plane strain assumption. Therefore, the model neglects the cross section deformation at the inner side of the ring caused by the mandrel. Nevertheless, the effects of the local and time depending cooling, realized by pressurized air or liquid nitrogen can be observed. For this reason, a subroutine is implemented to ensure a constant heat transfer coefficient of $3 \cdot 10^{-3}$ $W \cdot m^{-2} \cdot K^{-1}$ at a defined single position at the outer diameter and a heat loss due to the contact to the roll with a heat transfer coefficient of 10^{-4} $W \cdot m^{-2} \cdot K^{-1}$. Friction was realized by the shear factor model with the friction coefficient $m = 0.9$. The material behavior is modelled temperature dependent by the equation of Johnson-Cook:

$$\sigma(\varphi, \vartheta) = (504 \text{ MPa} + 370 \text{ MPa} \cdot \varphi^{0.17}) \cdot \left(1 + 0.025 \cdot ln\left(\frac{\dot{\varepsilon}}{1 \text{ s}^{-1}}\right)\right)\left(1 - \left(\frac{(\vartheta - 20°)}{\vartheta_{\text{melt}} - 20°}\right)^{0.793}\right) \quad (1)$$

Figure 10 shows the geometry of the model (a) and the results of the temperature distribution at the process time of 0.25 sec, 0.50 sec, and 1 sec (b to d).

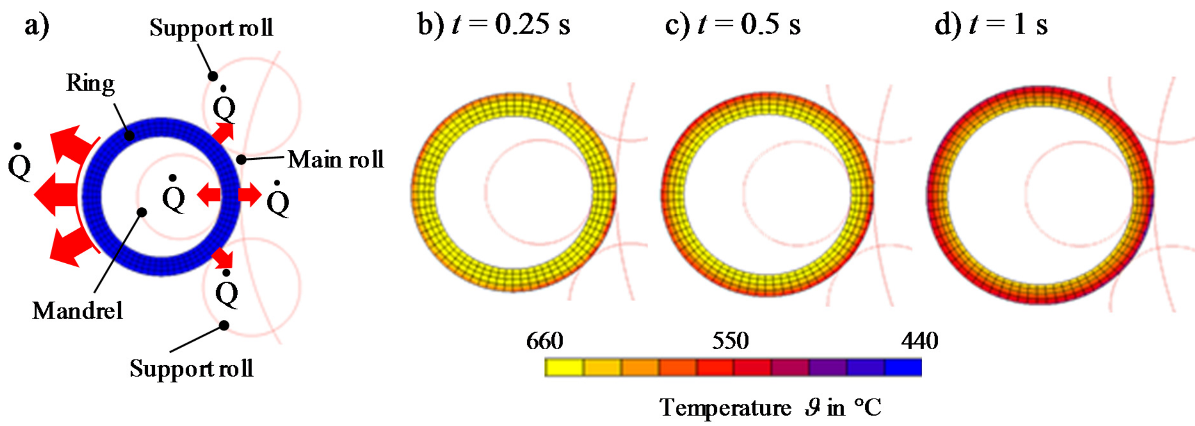

Figure 10: FE results of the temperature distribtion during thermo-mechanical ring rolling

As can be seen, the process runs without any instabilities the might occur during warm ring rolling. The local heat flux is realized by the contact on the right position and the location of applied fluid at the left position. The observed temperature drop is in the range of 110°C at a process time of 1 sec, which ensures the desired effects of thermo-mechanical ring rolling. Starting from an initial yield stress of 260 MPa, an increase in strength is achieved throughout the ring, with a significant increase in the outer ring area. The results of the numerical simulation show a similar distribution of the degree of deformation and the yield stress over the ring cross-section as the distribution of the hardness values in the experimental investigations. The highest strength is achieved at the outer diameter. The results are summarized in Figure 11.

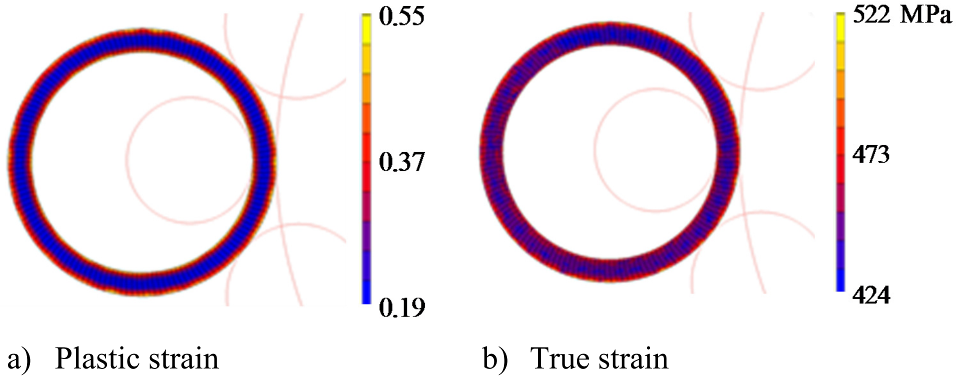

Figure 11: Distribution of plastic strain and true strain in the final ring

5 Conclusion and Outlook

In the course of the experimental and numerical investigations on thermomechanical ring rolling, an approach was implemented which enables the material properties to be influenced as a result of a forming process and simultaneous thermal treatment. A comparison of the experimentally measured micro hardness and the numerically determined strength in the ring cross-section shows that the areas with the largest deformation and highest strength also have the greatest hardness values and a comparable distribution exists. It can be shown that not only geometrical dimensions of the ring but also roughness as well as strength and hardness values can be adjusted by targeted Thermomechanical Treatment.

Further work concerns the development of a soft sensor in order to deduce the core temperature from the measured surface temperature of the ring during the ring rolling process. This soft sensor in combination with a fast simulation approach provides the basis for a later inline process control. Additionally, the cooling strategy will be improved in order to realise a higher cooling rate and thereby an improved control of the microstructure formation.

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