Model approaches for closed-loop property control for flow forming

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ABSTRACT

The implementation of control systems in metal forming processes improves product quality and productivity. By controlling workpiece properties during the process, beneficial effects caused by forming can be exploited and integrated in the product design. The overall goal of this investigation is to produce tailored tubular parts with a defined locally graded microstructure by means of reverse flow forming. For this purpose, the proposed system aims to control both the desired geometry of the workpiece and additionally the formation of strain-induced α′-martensite content in the metastable austenitic stainless steel AISI 304 L. The paper introduces an overall control scheme, a geometry model for describing the process and changes in the dimensions of the workpiece, as well as a material model for the process-induced formation of martensite, providing equations based on empirical data. Moreover, measurement systems providing a closed feedback loop are presented, including a novel soft-sensor for in-situ measurements of the martensite content.

1. Introduction

The demands on materials, tools and processes within manufacturing companies are increasing as a result of increasing customer requirements (Yang et al., 2018). Metal forming offers a number of advantages, like improved mechanical properties due to strain hardening and material scrap reduction. In addition to the efficient use of resources, the metal-forming manufacturing sector is also faced with a number of novel challenges, such as customization (Yang et al., 2018; Ingara et al., 2011; Tekkaya et al., 2015). Ideally, the specified properties of a workpiece should be adjustable locally in a reproducible manner. Closed-loop process control represents a promising approach in this context (Tekkaya et al., 2015). One example is the manufacture of tube components with axially graded product properties by means of flow forming – to create e.g. a defined hardness distribution or tamper-proof and invisible product identification, e.g. by a unique microstructure profile. One material offering appropriate characteristics in this context is austenitic stainless steel with its metastable austenitic phase, which can be transformed by forming into α′-martensite (Knigge, 2015). The α′-martensite has different mechanical and magnetic properties than austenite, which can be measured and used to advantage (Talonen et al., 2005). In order to meet customer expectations, it is generally necessary to achieve not only the desired geometry of the component, but also specific local properties for the final application in question.

For property-controlled forming processes, interdisciplinary cooperation between forming, materials, measurement and control engineering is essential. To our knowledge, no research or applications exist with a simultaneous closed-loop control for the microstructure and geometric product properties. The goal is a closed-loop process to control the local product properties of flow-formed tubes, i.e. a desired local α′-martensite content and a predefined target geometry. To achieve this, the controller requires models which describe the changes in geometry and the material properties during the flow forming process. Some of these models must be designed for a softsensor concept, since key parameters such as α′-martensite fraction cannot be measured directly during production with the required temporal and spatial resolution. This paper presents geometry and material model approaches that can be used in control systems during the reverse flow forming of metastable austenitic steel AISI 304 L. In addition, in section 3.4, a design for the sensor setup is presented in order to control the geometrical characteristics and the material properties during the production process.

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1.1. Process and experimental setup

1.1.1. Flow forming process and application

Flow forming is an incremental forming process offering numerous advantages in terms of flexibility and efficiency (Runge, 1993). It is based on a defined reduction in wall thickness on prefabricated tubular components, in this case drive shafts for jet engines by Winkelmann MSR Technology (Ahlen, Germany). Flow forming can produce hollow bodies with excellent shape and dimensional accuracy as well as prime surface qualities (Sivanandini et al., 2012). The benefits have been recognized by the aerospace industry, among others, and therefore applied in many components. Flow-formed components achieve the extremely high qualities (Sivanandini et al., 2012). The benefits have been recognized by the aerospace industry, among others, and therefore applied in many components.

Fig. 1a shows examples of industrial applications for flow-formed components, in this case drive shafts for jet engines by Winkelmann MSR Technology (Ahlen, Germany). Fig. 1b illustrates a typical reverse flow forming setup in motion during the forming process, with an illustration of the movement directions of the tools. Here (Fig. 1b), three identical co-rotating roller tools generate the necessary deformation forces to manufacture axisymmetric products on a rotating mandrel by plastically deforming a tube, either in consecutive passes or in one single pass. The spinning roller tools, which are included in the support, are arranged at an angle of 120° to each other (in this case) and move in a radial direction. In reverse or backward flow forming, the material flow occurs in the opposite direction to the axial movement of the roller tools (Marini et al., 2016). Fig. 1c shows a magnification of the feed depth \( \Delta r \) of one roller tool and depicts the outer radius of the workpiece \( r_w \) exemplarily. The feed of the roller tools in the axial direction \( z \) is controlled by the support feed. For future investigations and the current machine setup, the use of only one flow forming roller tool is envisaged in order to create space for the sensor application.

1.2. Specimens for experimental investigation

The experimental data for modeling the geometry and material behavior have been obtained from flow-formed components of seamless AISI 304 L (X2CrNi18-9, 1.4307) stainless steel tubes, with an outer diameter of 80 mm and an initial wall thickness \( w_0 \) of 4 mm. The specimens were produced isothermally at room temperature with a rotation speed of \( \omega = 30 \) rpm and feed rates between \( f = 6 \) and 60 mm/ min. Three equidistant roller tools performed flow forming by reducing the initial wall thickness. Within the scope of this work, special demonstrator workpieces will be considered. The dimensions of the specimens are illustrated in Fig. 1d.

1.3. Austenite-martensite transformation of metastable austenite

In the scope of this work, the strain-induced phase transformation of
metastable austenitic steels into martensite is key to obtaining tailored components with graded properties in order to gain advanced functionality. This entails the modeling of these microstructural and dependent property changes. This section introduces the scientific foundations for a material modeling approach to strain-induced α'-martensite formation, to be incorporated in the control scheme.

The stainless steel AISI 304 L belongs to the group of high-alloy austenitic steels. The martensite formation characteristic of these steels is a diffusionless phase transition, that occurs through the displacive movement of larger groups of atoms relative to their neighbors. This displacive movement is carried out by shear, dilatation/contraction and shuffling of the austenitic phase atoms. Generally, the austenite-martensite transformation could take place in two ways: i) temperature-induced due to heating and cooling (quenching), or ii) strain-induced triggered by mechanical loading, leading to plastic deformation (Weidner, 2020).

The kinetics of the strain-induced α'-martensite formation have been modeled by means of sigmoidal equations, based on the Gompertz function (Gompertz, 1825). This function has been used in science to describe phenomena constrained by horizontal asymptotes, as is the case for strain-induced α'-martensite. The model of Olson and Cohen (1975) describes the nucleation and growth of strain-induced α'-martensite in relation to the formation of deformation bands. The intersection points of these deformation bands are the favored nucleation places of α'-martensite. According to Olson and Cohen, the evolution of α'-martensite volume fraction, with respect to increasing true strain φ, can be represented by means of equation (1). a and b are parameters related to the rate of shear band formation and intersection respectively, and n is a fixed parameter (Olson and Cohen, 1975). This model fits well with the experimental data obtained by Angel (1954). A modification of the Olson and Cohen model was proposed by Mansourinejad and Ketabchi, including the influence of the stress state (Mansourinejad and Ketabchi, 2017).

\[
\dot{\alpha} = 1 - \exp\left( - b (1 - \exp(-a \phi)) \right)
\]

(1)

Another sigmoidal equation for the formation of α'-martensite in stainless steel is shown in equation (2). This model is based on the Gompertz function and was used by Tavares et al. to describe the phase transition during plastic deformation of stainless steel AISI 201. In equation (2), \( f \) is the saturation value of α'-martensite, \( c \) is a parameter related to the rate of transformation, \( \phi \) indicates the true strain value and \( \phi_n \) a true strain value reference. Experimental results were found to be consistent with the model and a comparison was done with AISI 304 in (Tavares et al., 2009). Ahmedabadi et al. derived a model based on the previously described works and found the fitting parameters for AISI 304 (Ahmedabadi et al., 2016).

\[
\dot{\alpha} = f_c \exp\left( - \exp\left( - c(\phi - \phi_n) \right) \right)
\]

(2)

1.4. Measuring devices

During the process, undesired thermal and mechanical effects can disturb the tool and cause deflections. Their compensation is crucial for successfully controlling the workpiece geometry, ensuring dimensional accuracy and reproducibility. This requires online data for a feedback loop, which provides the basis for further property control. Moreover, sensors measure the wall thickness \( w \) right in front and behind of the main forming zone during the process. Their difference yields the current wall thickness reduction \( \Delta w \). For these setups, tests with OM70 laser distance sensors from Baumer Electric (Frauenfeld, Switzerland) are designed. Section 3.4 discusses this concept and shows their application.

Additionally, the property control requires a material model to describe the strain-induced α'-martensite formation as a function of the geometrical changes and the process parameters. These models require empirical data of the variables involved in the phase transformation process. The strain-induced α'-martensite content was measured directly by means of the Feritscope FMP30 system (Helmut Fischer, Sindelfingen, Germany). However, this sensor lacks an interface for data transfer and is not suitable for online applications. Instead, it was possible to use the 3 MA-II system (Fraunhofer IZFP, Saarbrücken, Germany) for property control. Its sensor can operate without physical contact with the workpiece and under the dynamic conditions of the flow forming process. 3 MA-II measures the maximum amplitude of the magnetic Barkhausen noise \( M_{\text{max}} \). This parameter can be correlated with microstructural characteristics like phase transformation. Some studies have reported matching correlations between the evolution of strain-induced α'-martensite and \( M_{\text{max}} \) parameter in austenitic stainless steels (Astudillo et al., 2015; Gorkunov et al., 2009; Arian et al., 2021). Determining the α'-martensite fraction by means of the physically measurable \( M_{\text{max}} \) parameter fits within the softsensor concept, described in section 3.3.

1.5. Basic control system scheme and governing models

Implementing closed-loop control in forming processes permits the reproduction of tool paths in a highly precise manner, thus raising productivity. Current processes still disregard the actual state of the workpiece (Polyblank et al., 2014). In situ material property measurements, however, enable closed-loop control of these properties during the process. This opens up novel possibilities for forming processes, since it becomes possible to locally control favorable characteristics in the final product. In the scope of this work, the goal is to develop a closed-loop control for a reverse flow forming process for producing tubular parts with desired, axially graded properties, like the martensite fraction, and the desired geometry. Hence, the control variables comprise both wall thickness and martensite fraction, while material failures are currently not considered. Fig. 2 illustrates the proposed control scheme.

The reference input defines the desired final workpiece geometry \( G_{\text{des}}(z, \theta) \) and desired local martensite fraction \( \alpha_{\text{des}}(z, \theta) \). To produce the part, appropriate toolpaths for each pass need to be precalculated. First, intermediate products for each pass are defined for the desired geometry \( w_{\text{des}}(z, \theta, t, p) \) or thickness reduction \( \Delta w_{\text{des}}(z, \theta, t, p) \) respectively; as well as the local martensite fraction \( \alpha_{\text{des}}(z, \theta, t, p) \). Secondly, the process parameters of depth infeed, roller tool feed, rotation speed and the number of passes \( [\Delta r f, o f, \omega]_{\text{des}}(z, \theta, t) \) are determined to form the desired parts. Precalculation is performed manually, based on experience from proper process design, taking into account valid process windows, e.g. the maximum deformation per pass or forming forces. A comprehensive methodology was described by (Marini and Corney, 2017). In our case, designing the tool paths is aided by a geometry process model and a material property model, whose foundations are introduced in section 3.1 and 3.2. In the future, the feedback could be used to update the feedforward process parameters by the precalculation block. This allows run-by-run updates for each pass and, depending on required computational effort, gradually adapting process parameters during quasi-static forming conditions. The basic idea is to locally model the material behavior of the forming zone, and thus to calculate appropriate process parameters. It is planned to incorporate a geometry, and a material property model for the martensite fraction. Two of the authors contributed to an analytical stress-strain model for shape memory alloys and successfully controlled precision actuators (Pai et al., 2016a, 2016b, 2018). The easy-to-calculate approach is capable of modelling forming history and provides an appropriate approach to model rate-dependent or state-dependent material behavior.

During the real process, both modeling errors and disturbances occur. A closed-loop controller contributes to the plant input variables of depth infeed, roller tool feed and rotation speed \( [\Delta r f, o f, \omega]_{\text{fb}}(z, \theta, t) \), to eliminate both geometry and material property control errors.

Current work focusses on identifying a suitable state space model of the forming process and thus establish a state space control. The exact
controller design is the subject of current research. Hence, questions regarding controllability and observability will be addressed by means of a model for control design, yet under development. The following sections introduce the models, measurements and feedback loops for the given control scheme.

1.6. Geometry model

This section introduces an idealized geometric model for the reverse flow forming process. It models the changing shape of the workpiece with respect to simplifications. Furthermore, it describes the position of the roller tool over time \( t \) and therefore the location of the current forming zone. Fig. 3a shows the coordinates and variables used to model a flow forming pass. The following assumptions are made: First, the mandrel is an ideal rigid cylinder with radius \( R_M \) equal to half the inner diameter of the workpiece. The shape of the workpiece, i.e. any point on the outer surface, is described by \( r_W(z, \theta, t) \) with \( 0 \leq z \leq L(t) \) and \( 0 \leq \theta < 2\pi \). The total length is given by \( L(t) \) while the initial length is \( L_0 = L(t_0) \). The forming is assumed to occur at point \( [z_{RT}(t), \theta_{RT}(t), r_{RT}(t) - R_M] \), with a depth infeed \( \Delta r(t) \) causing a persistent wall thickness reduction \( \Delta w(t) = w(t) - w(t_0) \) after a time increment \( dt \).

In this model, the wall thickness reduction is regarded as the primal desired forming operation, while the elongation of the workpiece occurs as a consequence of volume constancy (Marini and Corney, 2017). As depicted in Fig. 3b, the elongation is modeled for an element of infinitesimal width and length \( (d\theta, dz) \), whose location is given by \( z, \theta \). In this first simple approach, infed depth \( \Delta r \) equals the persistent wall thickness reduction \( \Delta w \) in radial direction. Furthermore, it is assumed that \( \Delta w \) causes an elongation \( \delta z \) in axial direction with respect to a constant volume, so that \( V_0 \) before forming equals \( V_1 \) after forming (see equations (3)–(5)):

\[
d V_0 = \frac{1}{2} \left( r_W^2 - R_M^2 \right) d \theta dz \quad (3)
\]

\[
d V_1 = \frac{1}{2} \left( (r_W - \Delta w)^2 - R_M^2 \right) d \theta (dz + \delta z) \quad (4)
\]

\[
d V_0 = d V_1 \iff \delta z = \frac{2r_W \Delta w - \Delta w^2}{r_W - 2r_W \Delta w + \Delta w^2 - R_M^2} dz \quad (5)
\]
Elongation and true strain values can easily be derived from the absolute values by the equations in 6, where subscript r indicates the radial direction and z the axial direction respectively (Doege and Behrens, 2010).

\[
\varepsilon_r = \Delta w / w; \quad \varepsilon_z = \delta z / dz; \quad \phi_r = \ln(1 + \varepsilon_r); \quad \phi_z = \ln(1 + \varepsilon_z)
\]  

(6)

These elongations or true strains can serve as input variables for the material property model. Furthermore, they characterize the forming history of the volume element.

The elongation of one volume element affects the overall geometry of the workpiece, since it shifts all the elements that have already been passed by the roller tool (i.e. for which \( z > z_0(t) \) applies) to the right by \( \delta z \). This holds true for all elements with the same angular coordinate \( \theta \). Equation (7) calculates the total shift \( \Delta z \) until time \( t \) for a particular point in \( z \), or a particular volume element respectively.

\[
\Delta z(\varepsilon, z_0(t), t) = \int_{z_0(t)}^{t} \frac{2r_W(\zeta) \Delta w(\zeta) - \Delta w^2(\zeta)}{W^2(\zeta) - 2r_W(\zeta) \Delta w(\zeta) + \Delta w^2(\zeta) - R_w} d\zeta
\]  

(7)

The total increase in length of the workpiece after one pass is expressed by equation (8).

\[
\Delta L = \int_{z_0}^{L_0} \frac{2r_W(\zeta) \Delta w(\zeta) - \Delta w^2(\zeta)}{W^2(\zeta) - 2r_W(\zeta) \Delta w(\zeta) + \Delta w^2(\zeta) - R_w} dz
\]  

(8)

The proposed model assumes that material flow only occurs in the direction opposite to the roller tool feed. It neglects the effects of bulging, tangential material flow and springback, which causes deviations between the depth infeed of the roller tool \( \Delta r \) and the actual persistent wall thickness reduction \( \Delta w \). Another example is the increase in volume by approximately 2% due to phase transformation and an increasing martensite fraction (Moyer and Ansell, 1975). When designing a flow forming process, toolpaths for consecutive passes have to be calculated, giving consideration to each intermediate geometry of the workpiece. The model presented serves as a tool to illustrate the process parameters of the machine to the resulting product geometry. This is vital for advanced material models, which take into account forming history and microstructure development, since they require the updated coordinates of volume elements at any one time. The necessary strains are easily calculated according to equation (6). First approaches for material models are given in the following paragraph.

1.7. Material model

Property control during the flow forming of metastable austenitic stainless steels requires the modeling of the phase transformation process. This model must describe the \( \alpha' \)-martensite content as a function of the desired dimensions of the workpiece and the process parameters during flow forming. In this approach, the thickness reduction, specifically the true strain \( \varepsilon_r \) and the feed rate \( f \) of the forming tool, are chosen as the variables for the model. In this way, the material model must be an equation where \( \alpha = g(\varepsilon_r, f) \). Other authors discussed the formation of \( \alpha' \)-martensite in terms of strain rate, which is a more general way to express the rate of deformation in metal forming (Sunil and Kapoor, 2020; Hahn, 2003). Hahn, among others used a “Johnson-and-Cook” approach to determine flow curves as a function of deformation, strain rate and temperature (Hahn, 2003). However, in contrast to classical flow-forming processes, this work focusses exclusively on low strain rates, and variation range, due to low rotational speed (\( n \leq 30 \) rpm) and feed range (\( 6 \leq f \leq 60 \) mm/min). Therefore, known rate-dependent effects can be omitted. The approach in this work aims to correlate the process parameters of the machine to the resulting product properties.

The measurements of \( \alpha' \)-martensite by means of Feritscope FMP30 system were carried out close to the outer surface of the flow-formed components, as explained in section 2.4. The experimental data of...
α’-martensite for different values of $\varphi_r$ and $f$, are illustrated in Fig. 6a. Here, $\varphi_r$ is calculated according to equation 6. The fitting curves were obtained using the OriginPro 2019 software and the results are illustrated in Fig. 6b. Those fitting curves were computed as sigmoidal functions and correspond to equation (9). This equation is similar to the Olson-Cohen model (equation (1)) and the Gompertz function (equation (2)) discussed above. The similarities between the two functions agree with the fact that the growth of strain-induced α’-martensite is associated with the increase in the deformation bands and their intersection points (Mansourinejad and Ketabchi, 2017). The authors evidenced this fact in previous studies by means of microscopic investigations performed on AISI 304 L flow-formed components. Using electron backscatter diffraction (EBSD) analysis, characterization of the nucleation of the strain-induced α’-martensite at the intersection points of the deformation bands was carried out successfully and reported in (Rozo Vásquez et al., 2020).

$$\alpha' = A_0 + A_1 \exp \left(-\frac{\varphi_r}{A_2}\right)$$

(9)

The effect of the feed rate is determined by means of the data reported in Fig. 7a and their corresponding fitting curves in Fig. 7b. The plateau, especially prominent for the upmost curve ($\varphi_r, \text{Avg} = 0.8$) indicates a faster development and saturation of α’-martensite in specimens produced with lower feed rates. The data at a lower strain ($\varphi_r = 0.02$) are not considered, but the tendency of the other curves suggests a decreasing linear behavior of α’-martensite content with the increment of feed $f$. The suggested fitting curves correspond to the linear equation (10).

$$\alpha'_i = B_0 + B_1 f$$

(10)

Combining equations (9) and (10), for $\alpha'_{i1}$ and $\alpha'_{i2}$, allows the computation of α’-martensite with consideration to the effects of $\varphi_r$ and $f$ by means of equation (11).

$$\alpha' = [A_0 + A_1 \exp \left(-\varphi_r / A_2\right)] [B_0 + B_1 f]$$

(11)

Equations (9) and (10) were used as “Ansatz” equations in a Matlab® code to compute the numerical values of the coefficients in equation (11), using the experimental data for a specific infeed depth of 1 mm/pass. The computed coefficients by means of the implementation are: $A_0 = 107.4$, $A_1 = -107.67$, $A_2 = 0.2$, $B_0 = 1.05$ and $B_1 = -0.006$. This way, equation (11) can be written as shown in equation (12).

$$\alpha' = [107.4 - 107.67 \exp (-\varphi_r / 0.2)] [1.05 - 0.006 f]$$

(12)

2. Material model and softsensor concept

Since the α’-martensite fraction cannot be measured directly during the production process, it is necessary to derive correlations with physically measurable data, like micromagnetic parameters –
specifically $M_{\text{max}}$. As explained in section 2.4, this parameter is related to the strain-induced $\alpha'$-martensite development of austenitic stainless steels (Astudillo et al., 2015; Gorkunov et al., 2009). The modeling of the $\alpha'$-martensite fraction by means of the measured $M_{\text{max}}$ data matches the softsensor concept. The material models of this study, based on experimental data, correspond to a black box model. In future work, the integration of analytical calculations will allow migration into a grey model, to improve flexibility and the predictive abilities of the softsensor.

The $M_{\text{max}}$ measurements were carried out by means of 3 MA-II systems up to a depth of approx. 100 $\mu$m with respect to the outer surface of the flow-formed components, as set out in section 2.4. The experimental data and the corresponding correlation between $\alpha'$-martensite and $M_{\text{max}}$ are illustrated in Fig. 8a. In this first approach, a linear regression is proposed using the fitting tool of Origin Pro (2019), as shown in Fig. 8b. These curves correspond to equation (13), where $C_0$ is a positive coefficient, fitted to measured data. The measurements of $M_{\text{max}}$ contain the effects not only of phase transformation but also of surface damage, residual stresses and hardening, among others. Based on the actual data, it is clear that the phase transformation has a dominant effect on the $M_{\text{max}}$ measurements. More investigations will be conducted to separate those effects in order to adjust the data with respect to $\alpha'$-martensite formation. Those investigations are expected to verify the linear tendency of the correlation between $\alpha'$-martensite and $M_{\text{max}}$, or provide relevant information for improvement of the model. This will be refined to consider the effects of the gap between the sensor and the surface, which can be estimated by the distance measurements and establish means to correct corresponding measurement errors.

$$\alpha' = C_0 M_{\text{max}} \quad (13)$$

2.1. Multi-sensor concept

An optimal sensor arrangement is essential for robust measurements. Like already addressed in section 2.4, undesired thermal and mechanical effects can disturb the tool and cause deflections. Compensating these is critical for successfully controlling the geometry of the workpiece, which ensures dimensional accuracy and reproducibility. To provide proper feedback, measurements should be performed close to the forming zone to avoid dead time. Fig. 9 illustrates the sensor application developed for the given flow forming machine. Here, Fig. 9a shows the main tools and the sensor types used, in a full view from a current CAD-model, while Fig. 9b features a number of detailed views.

Four identical laser distance sensors by Baumer Electric are employed and arranged in pairs. Their large measurement range from 100 to 600 mm allows a reasonable safety distance from the forming zone, which will become relevant in the presence of high or low temperatures in future experiments. Two of the sensors point perpendicularly at the surface of the workpiece, close to the forming zone, and move axially along with the roller tool. They measure the wall thickness

\[\text{Fig. 7. Results of } \alpha'-\text{martensite contents (vol.-%) for different feeds, with the strain conditions of flow-formed specimens, for different true strain } \varphi_r \text{ (in thickness direction) conditions: (a) experimental data; (b) fitted curves.}\]

\[\text{Fig. 8. Results of } \alpha'-\text{martensite content correlated with the maximum Barkhausen noise amplitude } M_{\text{max}} \text{ of flow-formed specimens, produced with feed rates between 6 and 60 mm/min: (a) experimental data; (b) fitted curves.}\]
right in front of and behind the main forming zone. Additionally, the difference between these signals yields the actual wall thickness reduction by the current forming operation. To compensate for measurement errors caused by undesired deflection of the mandrel, two stationary sensors measure perpendicularly to the tip of the mandrel and therefore the middle axis of the mandrel and therefore the workpiece.

To determine the $\alpha'$-martensite content by the softsensor, as introduced in section 2.4, the 3 MA-II sensor has to be applied close to the forming zone. The softsensor calculates the $\alpha'$-martensite content, providing a property feedback loop. The micromagnetic sensor is positioned at a distance of approximately 1 mm from the tube surface for a contact-free measurement. The sensor moves along with the roller tool to perform the measurements near the current forming zone. The gap between surface and sensor affects the quality of magnetic measurements and generally decreases it. Since the laser distance sensors provide information about eccentricity during rotation, and therefore variable gap, this information will be used to correct corresponding systematic measurement errors within the softsensor.

3. Conclusions and outlook

This paper presents advances in the development of a novel feedback-controlled flow forming process. Its purpose is to manufacture tubular parts with a defined locally graded microstructure by exploiting the formation of martensite in the processed metastable austenite due to forming operations. The basic control scheme, incorporating geometry and material property control, has been introduced. Here, precalculated toolpaths, designed with the aid of an idealized geometry model and material model, define desired geometries and properties for each pass as well as nominal process parameters. In the scheme presented, the controller adjusts these process parameters online in order to correct detected control errors. The application of both distance and magnetic sensors, to provide the necessary feedback, was introduced and a number of design decisions were briefly discussed. A geometry feedback loop delivers the actual wall thickness and the thickness reduction. The values are directly measured by laser distance sensors. To gain insight into the microstructural properties during forming, which cannot be measured directly, a novel softsensor concept was described. This deployes material models to correlate process parameters and the measured maximum Barkhausen noise amplitude to provide a material property feedback loop for the controller. Currently, the softsensor deploys a black-box model, which is based on experimental data regression. It is planned to integrate analytical equations for a grey-box model approach, in order to improve flexibility and predictive abilities.

Future work will investigate the robustness and real time capabilities of measurements, information processing and actuators for the implemented control scheme, identifying the controllable process window. Both the geometrical and material models will be evaluated and refined by further experimental data, enhancing the predictive qualities. Moreover, it is planned to conduct forming in high and low temperature ranges and at a higher rotation speed. Since temperature is known to affect phase transformation, heating and cooling actuators will add an additional control variable and broaden the potential for flow forming products.

Author contributions

Conceptualization, M.R.; investigation, M.R., B.A., and J.R.V.; writing—original draft preparation, M.R., B.A., and J.R.V.; writing—review and editing, M.R., B.A., J.R.V., A.T., W.H. and F.W.; supervision A.T., W.H. and F.W.; project administration, A.T., W.H. and F.W.; funding acquisition, A.T., W.H. and F.W. All authors have read and agreed to the published version of the manuscript.

Declaration of interest

None.

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