A Structure for the Control of Geometry and Properties of a Freeform Bending Process
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Abstract: Today, in production shaping processes, the application of closed loop control is often limited to controlling the geometry. For freeform bending processes the geometric deviations are compensated by numerous experimental iterations, without regarding the mechanical properties. Especially for freeform bent parts also the internal properties are important because, e.g., the residual stresses strongly influence the downstream process steps. In this work a multivariable feedback control structure is proposed that is able to control both, the geometry of the workpiece as well as selected mechanical properties of the material.

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Keywords: Freeform bending, Rheological models, Feedback control, Feedforward control, Process control

1. INTRODUCTION

The application of feedback control for freeform bending processes mostly focuses on forming the workpiece geometry within the tolerances. For freeform bending with movable die the tolerances are reached by appropriate movement of the bending die. The compensation of the geometry happens without considering the mechanical properties of the workpiece itself. In (Staupendahl et al., 2016) a control algorithm for kinematic 3D profile bending has been proposed in order to compensate the springback effect. In (Sun & Stelson, 1997) the same problem has been addressed using an adaptive control scheme based on system identification of the process models. In this work, a feedback control loop structure for controlling freeform bending with movable die is proposed considering the geometry and at the same time mechanical properties, like residual stresses and hardness, of the material.

1.1 Freeform bending with movable die

For freeform bending with movable die, a bending die with multiple degrees of freedom is used to bend a steel tube with multiple radii in different orientations. The freeform bending machine being used in this work (see Fig. 1) is a 6-degrees-of-freedom (6 DOF) machine, manufactured by J. Neu GmbH (Grüningen, Germany). It consists of a bending die with 5 DOF, a feeder with 1 DOF, a bending mandrel, a guider and a down-holder (see Fig. 2). The bending die is capable of moving linearly along the x and y axes as well as rotating about the x, y and z axes, whereas the feeder moves only linearly along the z-axis (see Fig. 2). The mandrel supports the tube from inside during bending to avoid material fracture and failure due to shear stresses, while the guider serves as a fixing support during the bending process. Inside the guider unit and the mandrel is an oil ring, which lubricates the tube before entering the bending die. This not only facilitates the smoothness of the tube feeding, but also protects the outside and inside layer of the material from scratches. Before the start of the tube feeding, the down-holder moves down and holds the tube in place to guarantee the stability while the feeder pushes the tube through the bending die.

Fig. 1 Freeform bending machine with movable die

Currently, to control the bending die geometry a software tool of the manufacturing company J. Neu GmbH is used. This Software tool generates a G-Code, which contains the step by step instructions for the actuator motion. This G-Code is then sent via Ethernet-Cable to the PLC unit, which in turn sends control signals to the Motor-drivers of the bending machine. After bending, the geometry of the tubes is measured offline, by using an optical measurement system. By comparing the actual geometry with the desired geometry, the technician estimates the correction factors and repeats the process again until an acceptable error range is reached (see Fig. 3). This
process not only consumes time, energy and material, but also has a relatively low accuracy. Also, this process lacks flexibility; changing the material type or the profile of the tube will require a change in the correction factors, which depends mostly on the experience of the technician. In addition, the mechanical properties of the workpiece (such as the residual stresses) are not taken into consideration, which leads in turn to lower product quality in terms of durability. In this work and prospective works, a control algorithm is proposed in order to include the mechanical properties of the workpiece altogether with its geometry inside the control loop. Hence, reducing the required human intervention as well as the material consumption and improving the accuracy.

The final bent tube can be divided into three zones. The entry zone where the bending die starts moving to its final position, the constant zone, where the bending die holds steady, and the exit zone, where the bending die returns back to its original position (see Fig. 4 and Fig. 5). For experimental freeform bending a P235 TR1 steel tubes are used with outer diameter 42.4 mm and thickness of 2.6 mm. A strain-stress curve of the material can be seen in Fig. 7.

1.2 Goals and Assumptions

In this paper, a control structure is proposed for the bending process. Hereby, the geometry of the profile, namely the curvature (the reciprocal of the radius), as well as mechanical properties, like the material hardness, the material strength and residual stresses, can be integrated inside the closed loop control system. For the sake of simplicity, the 6 DOF of the bending machine are reduced to 3 DOF, a translational movement along the y-axis and a rotation around the x-axis for the bending die as well as pushing the tube forward along the z-axis with the feeder. It is assumed that the tube undergoes only a single bending on the yz-plane. Moreover, the actuators are assumed to have an ideal response and hence their dynamics are neglected.

2. MATERIALS AND METHODS

For the design of a model-based controller, a rheological mathematical model for the material is sought. This model should be able to give information about the geometry and the mechanical properties as well. Based on this model a control structure is developed.

2.1 Mathematical Modelling of the tube

As mentioned before, a rheological conceptual model is sought that is able to mathematically represent the geometry of the tube after freeform bending. One way to do that is by using Hysteresis based material models like Masing models (Chiang, 1999). Masing models can be implemented for example by using a spring connected in series with a system of Saint Venant Elements (St. Vt.) (see Fig. 6). The idea behind this model is that the bending process has two different phases; the elastic phase (elastic zone) and the plastic phase (plastic zone). In the elastic phase, the energy of the bending is stored so that when the bending force is relieved, the material returns back
to its original form, which is the same behaviour of an ideal spring. However, in the plastic phase the bending energy is dissipated in the change of form, i.e. after the relief of the bending stress, the material does not return back and the deformation is sustained. This behaviour is represented by a linear spring parallel to a St. Vt. Element, i.e. the St. Vt. dissipates the energy in the form of material deformation.

During bending, the elastic spring \( K_e \) starts deforming until the limits of the elastic zone are reached. If the bending stress exceeds these limits, the plastic spring starts deforming. However, due to the presence of the St. Vt.-Element, the plastic spring does not return back to its original place after unloading. i.e. The whole energy is dissipated in the St. Vt. Element. The concept of Masing models can then be generalized along the length of the tube. Hereby, the tube can be considered as a distributed parameter system of Masing models that are connected in series to each other. i.e. The tube is discretized evenly into segments connected to each other at the rotating point of the Masing model.

2.1.2 Plastic deformation modelling

During plastic deformation the system stiffness can be linearized. This can be accepted since the plastic deformation zone of the material under investigation can be considered linear (see Fig. 7). In this case the whole stiffness is considered to be the stiffness of two springs connected serially to each other:

\[
K_{Sys} = \frac{K_e K_p}{K_e + K_p}
\]  

\( K_{Sys} \) Total system stiffness 
\( K_e \) Stiffness of the elastic spring
\( K_p \) Stiffness of the plastic spring

As previously mentioned, in the plastic zone the two springs are connected serially. That means that the acting moment from the actuator is equal to the moment exerted on the elastic spring which in turn is equal to that of the plastic spring:

\[
M_{Mot} = M_p = M_e
\]  

\( M_{Mot} \) Moment applied by the motor of the bending die 
\( M_p \) Moment applied on the plastic spring 
\( M_e \) Moment applied on the elastic spring

By applying the principle of angular momentum, it can be proven that the motor moment is equal to the total system stiffness multiplied by the total angular displacement of the tube:

\[
M_{Mot} = M_{Sys} = K_{Sys} \alpha_{Mot}
\]  

By substituting (1) into (3) we find:

\[
M_{Mot} = K_p K_e \frac{\alpha_{Mot}}{K_p + K_e}
\]  

From Hooke’s law, the moment exerted on the plastic spring is equal to the plastic stiffness multiplied by the plastic deformation:

\[
M_p = K_p \varphi_p
\]  

From (2), (3), (+) and (5) it can be deduced that the plastic deformation after unloading is:

\[
\frac{K_e}{K_p + K_e} \alpha_{Mot} = \varphi_p
\]  

\( \varphi_p \) Angular plastic deformation after unloading 
\( \alpha_{Mot} \) Total deformation exerted by the actuator

Geometrically the bending angle can be related to the bending radius via the following relations:

\[
\alpha_{Mot} = \frac{d_a}{R_B}
\]  

\( R_B \) Nominal desired bending radius.
\( d_a \) Horizontal distance between bending die and guider

This means that (6) can be reformulated as follows:

\[
R_{act} = \frac{K_e + K_p}{K_e} R_B
\]  

The curvature \( \kappa \) is then calculated by inverting the radius.

\[
\kappa_{act} = \frac{1}{R_{act}}
\]  

2.1.3 Modelling of the residual stresses

In this work, a model for the residual stresses is proposed and simulated. The model is based on the results of (Maier et al., 2021), where freeform bending process parameters, the resulting geometry and residual stresses for steel tubes were
related to each other. It is to be noted that in this paper the hydrostatic pressure is chosen as an indicator for residual stresses. For better comparability, the average value of the hydrostatic pressure over the constant range on the inner side and outer side of the tube is used. Changes in the hydrostatic pressure can be correlated to changes in the residual stress state. (Maier et al., 2021) showed that the curvature $\kappa$ depends on different freeform bending process parameters $\kappa(d_a, \Delta y, \alpha_{Mot})$, where $\Delta y$ is the deflection of the bending die in y-axis direction.

For freeform bent steel tubes, the residual stresses can be separated into the residual stress state on the outside and the residual stress state on the inside of the tube (see Fig. 4). Both residual stress states depend on geometric parameters of the tube, outer diameter $d_o$ and thickness $t$ as well as on the curvature $\kappa$ and Temperature $T$.

This relation can be put into the following general equation for modelling the residual stresses in freeform bending with movable die for steel tubes:

$$\sigma_{Inside/outside} = a * \kappa + b * \Delta T$$

(11)

$a$ and $b$ are two coefficients that need to be identified. In (Maier et al., 2021) a relation between residual stresses on the outer side and inner side of the tubes with the curvature is done. To determine $a$ the simulation results of (Maier et al., 2021) are used. Therefore, Fig. 8 represents the residual stresses and the resulting curvature for the inside of the tube. The same can be done for the outside of the bent tubes.

![Fig. 8 Resulting curvature and residual stress state for the inside of the tube](image)

The simulations and experiments in (Maier et al., 2021) have been done at room temperature without changing the temperature. So, for the temperature dependency term a value according to the literature (DIN EN 10217) is calculated. Therefore, a material data sheet for P235 GH is used to find a linear relation. With the minimum values for the 0.2 %-proof strength at elevated temperatures the value for $b$ is calculated. The calculations can be done for the inside and the outside of the tube and lead to the following equations, that are used in the control model:

$$\sigma_{inside} = -3.509 \times 10^{-4} \frac{kN}{mm} \kappa - 0.2781 \frac{kN}{mm^2 K} \Delta T$$

(12)

$$\sigma_{outside} = 2.098 \times 10^{-4} \frac{kN}{mm} \kappa - 0.2781 \frac{kN}{mm^2 K} \Delta T$$

(13)

2.2 Control System design

2.2.1 Deriving the equations of the characteristic curve

In Fig. 9 the geometry of the bending machine is sketched. Here, the mathematical relation between the desired bending radius ($R_B$) and the respective bending die motion can be derived according to (Werner et al., 2021) as follows:

$$R_B = R_B \cos(\alpha_{Mot}) + \Delta y$$

(14)

$$\Delta y = R_B (1 - \cos(\alpha_{Mot}))$$

(15)

The Motor Angle ($\alpha_{Mot}$) can be calculated as follows:

$$\alpha_{Mot} = \arcsin\left(\frac{d_a}{R_B}\right)$$

(16)

For small angles, it is

$$\alpha_{Mot} \approx \frac{d_a}{R_B}$$

(17)

![Fig. 9 Bending machine Geometry](image)

2.2.2 The Control law

Based on the previously suggested model (6), (12) and (13) a control law has been developed, consisting of a feedforward controller (static inversion of the characteristic curves (15) and (17), neglecting the springback effect), and two PI feedback controllers. In order to measure the internal mechanical properties, a sensor, based on Barkhausen-noise, is under development. Moreover, an optical measurement tool is planned to be installed in order to measure the curvature of the tube during bending. In Fig. 10 the overall control structure with the sensors, actuators and the control plant is illustrated. The Barkhausen-noise based sensor (sensor of the mechanical properties) as well as the optical measurement tool are modelled as time-delay on their respective feedback branch.

To control the mechanical properties, i.e. the residual stresses, the hardness and the strength, it is planned to equip the machine with a heating element. In Fig. 10 the heating element is modelled as a first order system with the time constant ($T_i$) and a time delay function. The reason behind this choice, is that the response of heating systems is relatively slow and has to be taken into consideration during design. The motors of the bending die, however, respond more quickly, and it is assumed that the parameters of the internal controller of the motor driver are well setup from the manufacturing company. That is why the motors in this work are considered to have an ideal response. In Fig. 10 The translational and rotational movements of the bending die are implemented using (15) and (16).

Inside the controller unit, nominal trajectories for the mechanical properties as well as the curvature are pregiven. Hereby, a two-degrees-of-freedom control scheme is used,
where the deviations of the actual states from the nominal states are introduced to a PI-Controller, which in turn produces an error compensation signal. If the deviation of the actual measurement from the nominal values is too high for the controller to compensate, machine learning techniques may be applied in the future, in order to further fine tune the parameters of the feedforward characteristic curves of both the geometry and the mechanical properties as well.

3. SIMULATION RESULTS

The previously explained model as well as the control algorithm were implemented in this work using Matlab/Simulink. Hereby, the desired geometry (curvature) is considered to be the feedforward signal, which in turn is introduced to the block named (Bending die motor). In this block the signal of the required curvature is translated into a linear movement along the y-axis and a rotational movement about the x-axis (see (15) and (17)). These two signals are then introduced to the workpiece block where the resulting curvature and residual stresses are calculated based on (10) and (12). The curvature deviation from the desired values are then introduced to a PI-Controller which in turn produces a curvature correction signal to compensate the springback effect.

Since the trajectory of the desired mechanical properties is still under investigation, the PI-controller of the mechanical properties was turned off. i.e. purely feedforward controlled. However, (just as a proof of concept) the course of mechanical properties, namely the residual stresses of the inside of the tube, was simulated in order to see the effect of temperature change on residual stresses.

3.1 Simulation results of the resultant curvature and controller response

Fig. 11 shows the trajectory course of the Nominal curvature, Curvature without controller and Curvature with controller. Since the tube is straight, its curvature starts with zero then increases gradually until it approaches a value of 0.001 mm\(^{-1}\), after that the curvature decreases again till reaching zero as the bending head returns back to its starting position. In Fig. 11, it can be shown that with the introduction of the PI-controller, the consistency of the measured curvature with the nominal curvature improves significantly. The controller parameters were chosen experimentally, so that the system response stays stable along the trajectory.

In Fig. 12, the response of the PI-Controller is shown. It can be seen that the response of the controller increases gradually until reaching a value of \(10^{-4}\) mm\(^{-1}\). Then at the end of the bending process, this value returns back gradually to zero after the bending process is finished.

3.2 Simulation results of mechanical properties and effect of temperature on the residual stresses

In this work, the course of the change in residual stresses due to bending and heating has been simulated. Fig. 13 shows the course of the residual stresses on the inner side (compression side) of the tube at constant room temperature. Here it can be seen that the change of the residual stresses drops continuously during the entry zone of the bending head until approaching a value of -32 MPa, then the change in residual stresses stays constant upon entering the constant bending zone, then rises up again during the exit zone. Fig. 14 shows the effect of the introduction of a heating element on the residual stresses of the inside of the tube. Here, the temperature difference \(\Delta T\) increases gradually starting from \(l = 300\) mm until reaching \(\Delta T = 500\) K. It can be seen that the introduction of the heating element has a significant effect on the residual stresses, where the residual stresses increase gradually from \(\approx -30\) MPa to
almost -170 MPa and then returns back to -140 MPa upon finishing the bending process. (Here the negative sign denotes a compression)

4. CONCLUSION AND PROSPECTIVE WORK

In this work, a control strategy has been proposed for controlling the geometry of a tube during freeform bending as well as controlling mechanical properties of the material. This control strategy has been tested (by simulation in MATLAB/Simulink) for its feasibility, controller response. Moreover, a preliminary model for the residual stresses has been analyzed. In prospective work, the modelling and control of material properties will be investigated in more details, and the Multiple Input Multiple Output (MIMO) control system will be implemented and tested on the freeform bending machine. Other controllers like Model-predictive-control (Negenborn & Maestre, 2014) are planned to be implemented and tested as well. A reason for choosing model predictive algorithms lies in the fact that, the measurement is performed after the tube is actually bent. This means when the error is recognised, error compensation is not anymore possible. For this reason, a controller has to be developed that is able to anticipate the future deviations before happening and is also able to compensate errors using the remaining part of the (unbent) tube. Moreover, the relationship between the

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Funding: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Grant number: 424334318.