Iterative model of collar height in hole rolling for application in a closed-loop model predictive product property control

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Abstract. Closed-loop controls enable improvements of quality and resilience in production processes. In hole-rolling, there are currently no suitable models for predicting collar height that could be used in a closed-loop model predictive property control. In this paper, we present a novel model that enables this use case. To implement this approach, a novel state variable is defined, capturing the shape of the formed collar in addition to its height. This enables the prediction for changing process parameters. Finally, the model is deployed in a closed-loop control within the simulation program Simufact Forming to test its projection quality.

Introduction

Hole-rolling is a novel forming process, which was developed at the Institute for Production Engineering and Forming Machines at the Technical University of Darmstadt in cooperation with the Institute for Applied Materials at the Karlsruhe Institute of Technology. The process is used to create a collar around a hole situated in a piece of sheet metal. Due to the flow of the material, the process is classified as bulk sheet metal forming according to definition of Merklein et al. [1]. A schematic of the process is shown in Fig. 1. Before the process starts, a hole must be created at the desired location in the piece of sheet metal. The diameter of the hole must be larger than the roller to be used. At the start of the process, the roller is inserted into the workpiece, as depicted in Fig. 1 on the right-hand side. After this, the roller performs a spiral movement, which is usually achieved by combining a rotational and a linear movement. The process parameters radius r and rotational speed ω as well as their derivatives describe this movement and influence the result of the process. During the process, the hole is incrementally widened, and the displaced material is formed into a symmetric collar on both sides of the sheet metal around the circumference of the hole. At the end, at least one circular rotation is performed after either the desired collar height or hole diameter has been achieved. Due to the high deformations achieved a significant amount of cold hardening takes place in the collar [2]. Using the beneficial material properties and the unique geometry, the process has a high potential for use in multiple applications. So far, the process has been tested in the production of ready-to-use integrated outer bearing rings of roller bearings and bearing seats in sheet material for conventional bearings. Additionally, the production of polygon shaft couplings in sheet material is looked at by Arne et al. [3]. The suitability of hole-rolled parts is further enhanced by the ability to vary the collar height at a specific diameter. As shown by Spies et al., the collar height achieved can be influenced by varying the feed rate which directly changes the linear movement speed $\dot{r}$. Higher feed rates result in a lower collar and lower feed rates in a higher one. [4] Unfortunately, this correlation is highly nonlinear, as is the trend in which the collar height is formed. Therefore, it is difficult to predict the resulting collar height for a given feed rate. Because of this, it is usually necessary to try different feed rates until the one that produces the desired collar height is determined. Closed-loop product property controls can solve this challenge. By controlling the feed rate during the process, such a control can produce the desired collar height in every operation. Compared to an open loop control, the requirements for the model are lower. Additionally, the closed-loop control is able to react to unforeseen disturbances, such as fluctuations in the sheet metal thickness, which would otherwise completely throw off the result [5]. However, previous tests have shown that even with closed-loop control, detailed process knowledge is required to achieve a satisfactory result due to the unique challenges of controlling hole rolling.

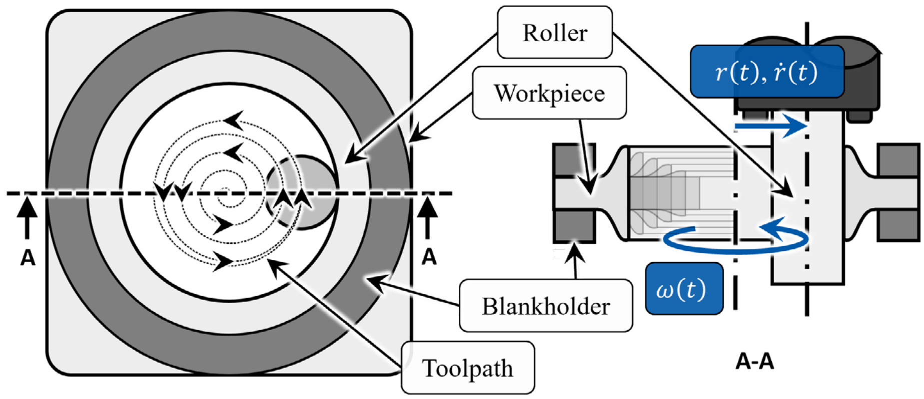

Figure 1 – Schematic of the hole-rolling process with the primary components and relevant process parameters marked. cf. [6]

Modelling

On the one hand, it is obvious that controlling the hole-rolling process brings significant benefits. On the other hand, it also presents many challenges. As discussed earlier, even with a closed-loop control, a precise understanding of the process is necessary and a realistic model of the process behavior is required. In some cases, only a very limited number of control loops can be performed until the final dimensions of the component are reached. Due to the design of the process and tooling, it is not possible to measure the collar height more than once per revolution and thus perform the control loop. If a low collar height is desired, it is advisable to use a high feed rate, as shown by Spies et al [4]. In this limiting case, the component can be produced in a few revolutions. This in turn allows only for a few control corrections. Additionally, the projection must make a more distant prediction because each revolution covers a greater distance, which amplifies the model error. Therefore, the process parameters directly influence the controllability due to the properties of the process. This means, a precise process model is necessary to predict the state after the next revolution accurately. Compared to an open-loop control system, closed-loop control with the same underlying model has the advantage that only the error of the last revolution must be tolerated. However, creating a suitable model is a major challenge. For an open-loop control, the model can be set up to use just one feed rate from the start of the process to the end. In his doctoral thesis, Knoll presented such a model that can be used to describe the collar formation during hole-rolling by increasing the radius [7]. This model is sufficiently accurate and can also depict the process for different feed rates. However, the model is only valid for a constant feed rate. The change in the feed rate during the process cannot be depicted. The aim of this paper is to develop a novel model, which overcomes this shortcoming of the model by Knoll and is analytically defined to be used in a model predictive control.

For the development of the model in this paper, a simulation of hole-rolling in Simufact Forming 2022, which was previously verified is used. In this simulation, the feed rates are varied, while the starting radius is kept at 20.3 mm. The simulation is always ended at a collar diameter of 30 mm. The thickness of the sheet metal in the simulation is set to 6 mm. In Fig. 2, two trends for the collar height from two of these simulations are shown. In both simulations, the feed rate is switched when reaching an inner radius of 25 mm. The dashed lines represent an appropriately fitted model by Knoll. It can well describe the area before the change in feed rate, but it is not able to deal with the change in feed rate at all. When using a model in a closed-loop control system, as intended, the feed rate is inevitably adjusted again and again. Accordingly, the model in its present form is not suitable for the intended application.

To determine whether Knoll's model can be enhanced to meet the new requirements, the gradient of the individual curves is examined in more detail. There is a sharp increase in collar height when changing from a fast to a slow feed rate. This increase is greater than it would be the case with a constant utilization of this lower feed. Therefore, it can be seen that the current state of the collar has a significant influence on the collar formation, exceeding the influence of its height alone. Since this requires an approach, which can consider the forming history of the collar, a pure enhancement of the model by Knoll is not suitable.

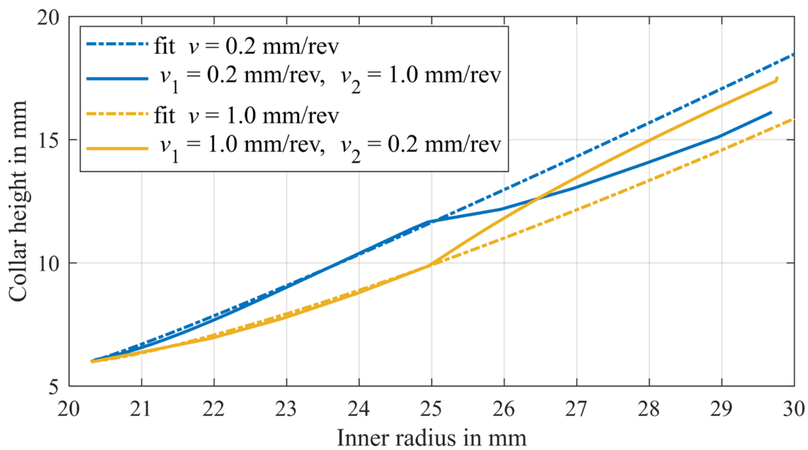

Figure 2 – Trend of the collar height for two simulations, where the feed rate is changed at a radius of 25 mm; the dashed lines show an approximation done using the model from [7] with the respective starting feed rate.

To develop a more appropriate model, it is necessary to understand how the previous feed rate affects the future collar creation. It is known that collar height cannot be the only factor influencing the collar growth. In addition to the height of the collar, the shape of the collar changes as the feed rate changes. Metal can generally be considered incompressible. The material which is pushed into a high collar at a low feed rate, must therefore be displaced in a different direction when using a higher feed rate with a lower collar. Looking at the shape of the collar, it is noticeable that although higher feed rates will form a lower collar, the decrease in height is less steep than with a higher collar. To describe the shape of the collar condensed, the so-called collar area ratio is newly defined. The calculation of this ratio involves defining two sections in the cross-section of the collar and determining their areas. This definition is also depicted in Fig. 3. The frontal section runs from the front edge to the dividing line and is colored orange. This dividing line is defined by the point at which the collar drops to half the height of the maximum, as it is described in Eq. 1. The height refers specifically to the additional height above the base material thickness. The rear section starts at the dividing line and ends when it reaches the same width as the front section. It is colored in blue. The areas are calculated by adding the approximations for the areas between the data points on the upper edge of the collar, as shown in Eq. 2 and Eq. 3. The quotient of the area of the front section and the rear section then gives the collar area ratio in Eq. 4.

$$h(r_{\mathrm{cut}}) \overset{!}{:=} \frac{1}{2} \cdot h_{\max}. \tag{1}$$

$$A_{\text{Collar\_front}} = \sum_{x=r_0}^{r_{\text{cut}}} (x_0 - x_{-1}) \cdot \frac{h(x_0)+h(x_{-1})}{2}. \quad (2)$$

$$A_{\text{Collar\_back}} = \sum_{x=r_{\text{cut}}}^{2r_{\text{cut}}-r_0} (x_0 - x_{-1}) \cdot \frac{h(x_0)+h(x_{-1})}{2}. \quad (3)$$

$$C = \frac{A_{\text{Collar\_front}}}{A_{\text{Collar\_back}}}. \quad (4)$$

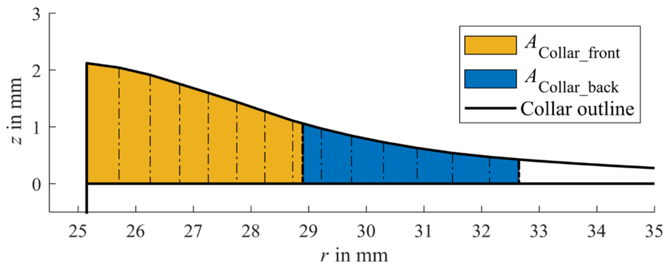

Figure 3 – Cross-section view of the collar, with the front and back sections to calculate the collar area ratio colored.

Due to its definition and the shape of the collar, the collar area ratio is always greater than 1, as can also be seen in Fig. 3. If the collar area ratio is plotted for various simulations with constant feed rates, a function can be defined for all area ratios as a function of radius and feed rate. This function can be used to approximate the area ratio for any radius and any feed rate. The function is determined empirically and is depicted in Eq. 5. By fitting it to the different simulation results, a good correlation is found.

$$C_{\text{const}}(v, r) = C_1 \cdot \log(v) + r \cdot (C_2 \cdot v^2 + C_3 \cdot v + C_4) + C_5. \quad (5)$$

It is planned to modify the speed of the collar growth in the model at the end. This is done in accordance with the relationship between the existing collar ratio and the expected collar ratio for a collar of the same diameter formed at a constant feed rate. For this purpose, a further two-dimensional function is set up, which represents the derivation of the collar height in relation to the radius. This makes it possible to calculate the change in collar height for each radius for each feed rate within the defined area, assuming a constant feed rate. As no ideally suitable function has been identified for this purpose, a two-dimensional polynomial function of the fifth degree is used instead. This function can be observed in Eq. 6.

$$dhdr(v, r) = p_{00} + p_{10} \cdot v + p_{01} \cdot r + p_{20} \cdot v^2 + p_{11} \cdot v \cdot r + p_{02} \cdot r^2 + p_{30} \cdot v^3 + p_{21} \cdot v^2 \cdot r + p_{12} \cdot v \cdot r^2 + p_{03} \cdot r^3 + p_{40} \cdot v^4 + p_{31} \cdot v^3 \cdot r + p_{22} \cdot v^2 \cdot r^2 + p_{13} \cdot v \cdot r^3 + p_{04} \cdot r^4 + p_{50} \cdot v^5 + p_{41} \cdot v^4 \cdot r + p_{32} \cdot v^3 \cdot r^2 + p_{23} \cdot v^2 \cdot r^3 + p_{14} \cdot v \cdot r^4 + p_{05} \cdot r^5. \quad (6)$$

All the functions that have been set up so far have the same limitation as Mr Knoll's, as they do depict the circumstances well, but only for a constant feed rate. This will be rectified in the next step. It is important to understand, that in the end the collar height is not calculated with a single function, but in an iterative process. The next iteration of the corresponding state is always calculated based on the current state and the specified process parameters given. As described at the beginning, the control loop is only run through once per revolution, i. e. the next state is always reached after a full revolution. The state parameters that sufficiently describe this state are the radius on the inside of the collar r, the collar area ratio C, and the height of the collar h.

The radius after the next step can be calculated immediately. As one step always corresponds to one revolution and the feed rate v is always specified per revolution, the new radius r_1 is the sum of the current radius r_0 and the feed rate v times one revolution as depicted in Eq. 7. Different states of the collar have no influence on this.

$$r_1(v) = r_0 + v \cdot 1 \text{ rev.} \tag{7}$$

Mapping the collar ratio is necessary to adjust the prediction according to the current state of the collar. This first requires a prediction of the resulting collar ratio. For this purpose, the expected collar ratios for the current feed rate are calculated for a supposed permanently constant feed rate for the current and future radius. The difference between the two values is also calculated. This change in collar ratio, assuming a constant feed rate, serves as the basis for further modeling and is shown in Eq. 8. Based on the expected collar ratio, the ideal change of the collar ratio, and the current collar ratio, the difference between the expected collar ratio for the next step and the ideal collar ratio is calculated using Eq. 9, which was determined empirically, considering the results for the especially relevant collar ratio combinations.

$$\Delta C_{\text{const}}(v,r) = C_{\text{const},1}(v,r) - C_{\text{const},0}(v,r). \tag{8}$$

$$\Delta C(v,r) = C_{\text{const},1}(v,r) - \frac{C_{\text{curr}} + 9 \cdot \Delta C_{\text{const}}(v,r) \cdot C_{\text{const},0}(v,r) + \Delta C_{\text{const}}(v,r)}{1 + 9 \cdot \Delta C_{\text{const}}(v,r)}. \tag{9}$$

In the final step, the change in collar height for the next revolution is calculated with Eq. 6 and Eq. 9. Eq.uation 6 is used to provide a base value. This is then modified by the value from Eq. 9 to account for the deviation of the current collar ratio from the ideal state assumed in Eq. 6.

$$\Delta h = dhdr(v,r) \cdot v \cdot \left(e^{\frac{\Delta C(v,r)}{2}} + 1.9 \cdot \Delta C(v,r) - 3 \cdot \Delta C(v,r)^2\right). \tag{10}$$

The result provides a good approximation of how the collar height will change for the feed speed v based on the current state. In Fig. 4, the presented model is used to predict the trend for the collar height for the simulations from Fig. 2 based solely on the predefined feed rates. On the left hand side, the trend for the collar height can be seen. The new model follows the results from the simulation quite well. To look at the properties of the model in more detail, the rate at which the collar height is changing per mm of radius increase is compared for the model and the simulation on the right. At some points, a deviation can be seen. To put this into perspective, two things need to be noted. Firstly, when used in a closed-loop model predictive control, there is a regular comparison with the process, which means that the errors do not add up. Secondly, the error shown in the graph is always referred to 1 mm of radial increase in size. Since the feed rate is usually less than this, and is based on diameter rather than radius, the actual error will be a fraction. Considering these facts, the model is well suited to predict the future collar height in hole-rolling.

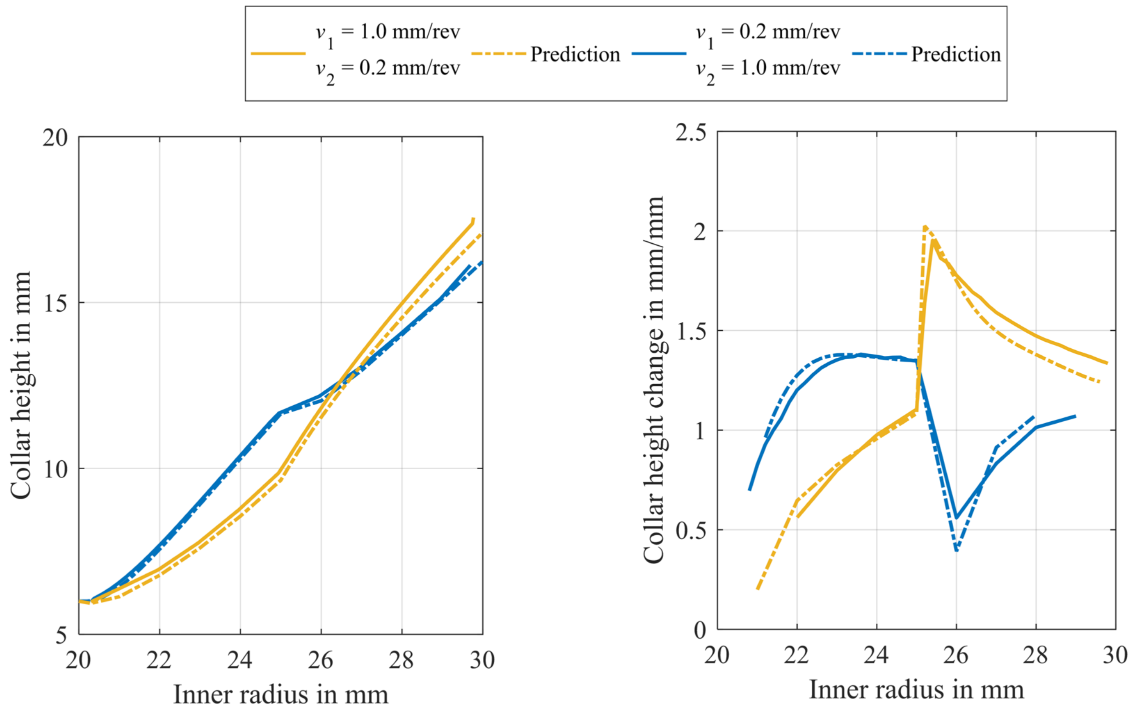

Figure 4 – Left: Trend of the collar height for the two simulations shown in Fig. 2, where the feed rate is switched at 25 mm. Right: Trend for the rate of change of the collar height, for the same simulations. The dashed lines represent the trends that the presented model predicted respectively.

Closed-loop control

To test the developed model, a closed-loop model predictive control for hole-rolling is prepared in the modeling software Simufact Forming 2022. The tasks of measuring the collar, calculating the collar area ratio, and determining the appropriate feed rate, are performed in a custom user subroutine which is written in Fortran. At the start of the simulation, a constant feed rate of 0.5 mm/rev is used until an inner radius of 21.5 mm is reached. This is done to create a suitable collar, which allows for the calculation of a realistic collar area ratio. After this criterion is met in each rotation, the collar is measured at a specified point around the circumference. Based on these measurements, the new appropriate feed rate is determined. For that, the desired change in collar height is calculated. To keep the model simple, it is assumed that the collar rises linearly from the current point to the targeted point, and a collar height change that intersects this line is desired. Due to the complexity of the developed model, it is not possible to reverse it. Therefore, an inner control loop based on a simple P-controller is used to find an approximation with less than 0.005 mm error for the desired feed rate. Fig. 5 shows the results of this control for a desired collar height of 19 mm and an inner radius of 30 mm. The trend for the collar height is shown in orange. The course of the feed rate is marked in blue. Noticeable is the stepped nature of the feed rate, which is due to the fact that the feed rate is adjusted only once per revolution. Additionally, it can be seen that the control reaches the lower threshold for the feed rate at about 26.8 mm. However, this does not seem to affect the end result significantly,. Overall, the control hits the targeted values with an error of about 0.16 mm.

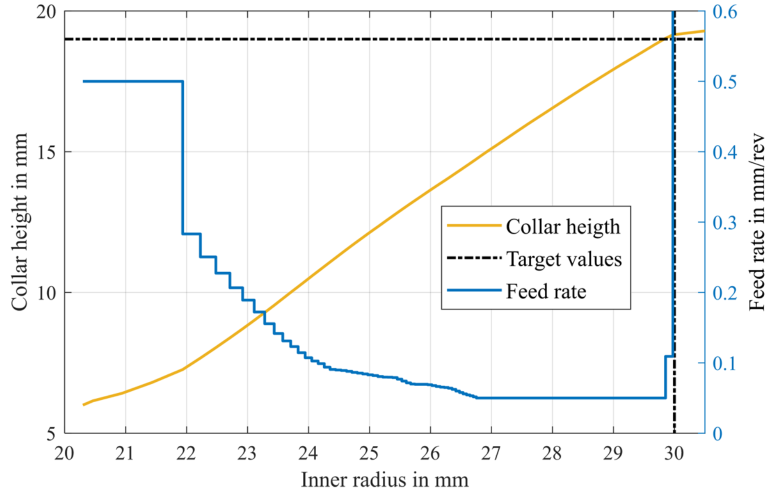

Figure 5 – Trend for the collar height (orange) and feed rate (blue), for the simulation to test a closed-loop model predictive control using the model presented in this paper. The target values are a collar height of 19 mm at an inner radius of 30 mm.

Summary

In this article, a novel model for predicting the collar height in hole-rolling was presented. Compared to previous approaches, the presented approach can work with changing process parameters during the process. To achieve this, an iterative approach was chosen for the model, which calculates the next step, considering the current state and the upcoming process parameters. Furthermore, it was determined that the state variables used so far to describe the collar in hole-rolling are not comprehensive enough to describe the formation of the collar. Therefore, a new state variable was introduced that considers and describes the form of the collar at a given point. The developed model shows a good correlation to simulation results with changing feed rates. In the end, the model was implemented in a closed-loop model predictive control system to control the collar height during the forming process. The results of the control seem promising and demonstrate the model's suitability for such a use case. In the future, it is planned to test the model in more detail. For example, observing the reaction to a thicker or thinner metal sheet or to different materials. Additionally, the presented closed-loop predictive control will be improved and expanded. One aspect that will be enhanced is the inner closed-loop control for finding the appropriate feed rate for the upcoming revolution. It is planned to replace the simple P-controller with a PID-controller, which will be able to find the approximation much faster. Furthermore, the control and model will be transferred to real-life hole-rolling tests and expanded to implement a second product property of the hole-rolled part.

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