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Model-based control of strip bending in mass production

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ABSTRACT

The bending angle in an industrial strip bending process for mass production is influenced by uncontrollable process and material variations like thickness, strength and friction. Most of these variations are not directly measurable in the production line. In a two stage bending operation, the force–time curve of the pre-bending step is measured and used to adapt the back-bending displacement. In this study several measurements from long test runs are evaluated and the feasibility of model-based control in metal forming is discussed. It is concluded that a model-based control scheme is required to reach an angular accuracy of 0.1°.

1. Introduction

The strong development of information technology in the past decades clears the way for a new level of intelligent control systems in metal forming industry. In the pursuit of cheaper and more accurate production, in-line sensing and actuation mechanisms can be coupled to high-fidelity process models to enable a drastic increase in production accuracy. Such systems may cancel out inevitable disturbances such as variation in material and lubrication properties and tool wear.

However, control of metal forming processes is still in an immature state. Closed-loop control is widely used to ensure the robustness of the production processes, but is hardly used to control the state of the product itself. That is, metal forming machines are controlled to accurately perform a certain task, such as to follow a certain "tool-path", but fail to control the actual production target: the desired final properties of the product (such as geometry, residual stresses or surface quality) [1].

Two key factors for the control of metal forming processes are the observability and controllability of the product properties of interest. If one fails to either measure or adapt the desired properties in a direct or indirect way, closed-loop control will be infeasible. However, direct measurements of the final product properties are often not practical for control since no correcting actions can be taken after production is finished. Therefore measurements of the intermediate state of the product should be used for closed-loop control. In addition, these measurements must be fast and easy to process to keep up with the high production speed of mass production processes.

When using indirect measurements for control, they have to be interpreted and a decision has to be made on the correcting action that follows to the measurements. That is, a control strategy has to be designed. To do so, high-fidelity process models can be used to predict the final state of the process based on the intermediate measurements. Both theoretical models such as a homogenized energy model for shape memory alloys [2], a finite element model for bending [3] and an analytical strain model for open die forging [4] as well as empirical models such as a linearized model of tool path influence in flexible metal forming [5] and a neural network [6] or a regression model [7] for bending have been used for this purpose. The development of these models is a key factor for successful increase of production accuracy through closed-loop control.

The current work is a preliminary study on the feasibility of model-based control of a strip bending process. The aim is to decrease the product-to-product variation using indirect measurements and large datasets, whereas other studies on bending control either neglect product-to-product variations or apply direct measurements. A demonstrator process that has been developed within the MEGaFiT project [8] is used to illustrate the complexity of the control of a seemingly simple process. The demonstrator product is a deepdrawn cup with three bended flaps and a forged micro-profile (Fig. 1). Production occurs at 60 strokes per minute and many in-line measurements are recorded during production. Several actuators enable product-to-product control of the process. In the current work we focus on the bending process. In Section 2 the demonstrator process is explained. In Section 3 the results of a test with linear control are presented. In Section 4 the structure of the process model for control is explained. A detailed discussion on the actual measurements and their implications for model-based control are given in Section 5. Finally, discussion and outlook on future steps are given in Section 6.

2. Test setup

A demonstrator process has been developed within the MEGaFiT research project to study the feasibility of control of a metal forming process. The product is formed from a 280 μm or

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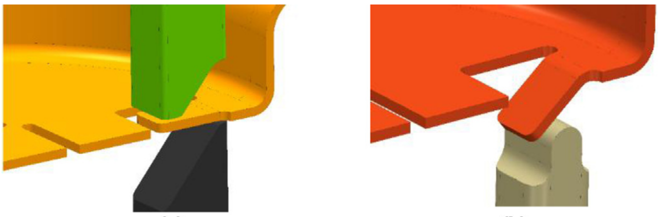
300 μm thick AISI420 steel strip. During production the product stays connected to the strip. All cutting and forming occur in a total of 10 steps, divided over four modules: cutting, deepdrawing, forging and bending. During production several measurements are recorded, such as sheet thickness, tooling temperature and process forces. Furthermore an in-line camera is built into the bending module, which is used to measure the angle of the flap in rolling direction of the strip for every product. To study the variation of the process, six long tests of more than 3000 products each have been run.

In the current study the process of interest is bending. Two bending steps are used to reach the final geometry. The first step is pre-bending to 50° (Fig. 1a). During this step the bending force is measured. Subsequently the flaps are bent to 35° in a back-bending stage (Fig. 1b). During this stage the total amount of punch displacement is controlled from product to product by a servo motor.



(a) (b)

Fig. 1. First bending stage (a) and second bending stage (b).

Typical results from the bending forces of all three flaps of one product are shown in Fig. 2a. The punch reaches the deepest point of the stroke at 0 s. The punch makes contact with the flap at around −0.075 s. During the first part of the bending stage the force remains reasonably constant for two of the flaps. For the third flap, a higher force is observed, which is caused by misalignment of the tool: the punch makes contact with the lower tooling. This has been verified with simulations of the process [9]. At around −0.025 s the tip of the flap makes contact with the lower tooling. This causes a strong increase of the bending force. The maximum force occurs at around −0.005 s, just before the deepest point of the stroke. This may be caused by the strain rate sensitivity of the material in combination with the deceleration of the punch. During production pictures of the flap in rolling direction are taken and processed in-line, allowing for fast correcting actions. The accuracy of the measurement stage has been verified through multiple measurements of the same product under standard production conditions, to make sure that disturbance of tooling vibrations on the measurement is accounted for. This test was performed for six different products, each one being measured at least 50 times. A standard deviation of the measurement error of less than 0.01° has been found.

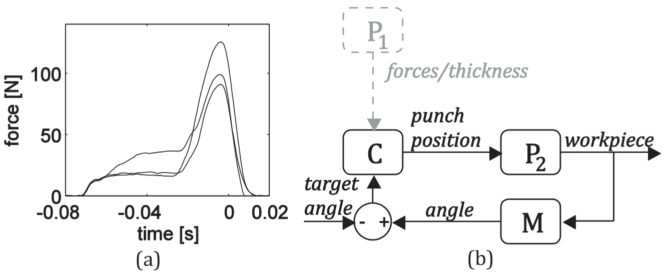


Fig. 2. Bending forces for the three flaps (a) and control diagram (b): P_1 is the first bending stage, P_2 is the second bending stage, M is the measurement stage and C is the controller. Linear control corresponds with the black part; model-based control includes the grey dashed part.

With the in-line angle measurement, a linear control algorithm can be used to control the final angle of the flaps (Fig. 2b). In Section 3 it will be shown that a limited improvement of the angle accuracy can be reached with linear control due to strong product-to-product variation of the process. Hence, model-based control should be used by estimating the variations of the current product based on measurements made on the previous process steps of the same product, as discussed in Sections 4 and 5.

3. Linear control

The effect of linear control on the accuracy of the bending angle has been tested with four runs of 3000 products each (Fig. 4a–d): one run with and one run without control for two different sheet thicknesses (280 μm and 300 μm). Strong variation of the final angle from product to product was observed in the uncontrolled tests (Fig. 3b). Therefore it is clear that most variation cannot be controlled with linear control. However, some long term effects can be compensated for with linear control. As an example, a sudden drop of the angle of the 300 μm uncontrolled run is shown in Fig. 3a. Linear control is perfectly suitable for compensating these variations.

The control algorithm is designed as follows: a linear relation is assumed between the control parameter x (depth of back-bending stroke) and the final angle α:

$$\alpha = c_0 + c_1 \cdot x \tag{1}$$

The coefficient c_1 is determined experimentally based on earlier tests. Obviously, the punch displacement is not the only parameter that affects the final angle. Hence, it is assumed that c_0 is a function of all other variations. The coefficient c_0 can be calculated for every product after measuring the final angle. Therefore the calculated coefficients c_0 of the last measured products can be used as an estimate for the coefficient c_0 of the next product n:

$$c_0^n = \frac{1}{8}\sum_{i=n-9}^{n-2} c_0^i \tag{2}$$

Averaging over the last eight products is determined to be optimal based on the evaluation of earlier tests. This enables to control for long term variations while not reacting too strong on short term variations. Product $n-1$ is not included in the averaging because its measurement is not yet available when the punch displacement for product n has to be set. Linear control leads to a slight increase of the production accuracy, as shown in Fig. 3c and d and Table 1. However, the reached accuracy is still far from the 0.1° objective. The coefficient c_1 is determined based on data of the 300 μm thick sheet, causing slightly less improvement for the 280 μm test (Figs. 3c and 4b).

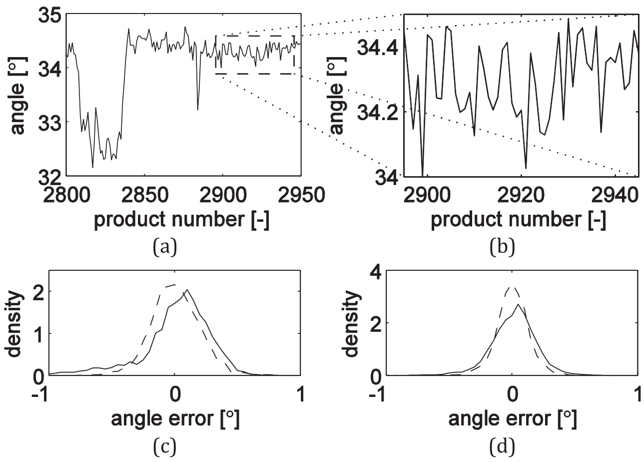


Fig. 3. Angle results for 300 μm run without control with different magnification factors (a, b). Histogram of bending angle error for the uncontrolled (solid line) and the controlled (dashed line) run for the 280 μm (c) and 300 μm sheet (d). For the uncontrolled run, the average angle of the data set has been taken as the target angle.

4. Model-based control

From the linear control test it is clear that product-to-product variations dominate in the demonstrator process. To compensate