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The Effect of Tooling Deformation on Process Control in Multistage Metal Forming

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Abstract. Forming of high-strength steels leads to high loads within the production process. In multistage metal forming, the loads in different process stages are transferred to the other stages through elastic deformation of the stamping press. This leads to interactions between process steps, affecting the process forces in each stage and the final geometry of the product. When force measurements are used for control of the metal forming process, it is important to understand these interactions. In his work, interactions within an industrial multistage forming process are investigated. Cutting, deepdrawing, forging and bending steps are performed in the production process. Several test runs of a few thousand products each were performed to gather information about the process. Statistical methods are used to analyze the measurements. Based on the cross-correlation between the force measurements of different stages, it can be shown that the interactions between the process steps are caused by elastic deformation of the tooling and the stamping press.

INTRODUCTION

The competition between metal forming and machining balances between the superior cost and production speed of metal forming versus the superior accuracy of machining. Therefore, increase of production accuracy of metal forming processes is needed to improve its competitiveness. The main components needed to achieve this goal are better understanding of process variations, development of measurement systems to track the state of the production process, and development of control systems to compensate for the observed variations. In this work, the use of force measurements for the purpose of process control is investigated. Due to elastic springback of the product, its final geometry can only be measured after release of the product. Consequently, no control action can be performed after this measurement. Therefore, it is required to include other types of measurements when aiming for control of product-to-product variation. Using force measurements is a good option because the implementation is fairly easy and cheap and because the process forces reflect the variability of the process.

In metal forming research, some examples of control systems based on force measurements can be found. Force and curvature measurements have been used for control of a roll straightening process [1] and a wire straightening and bending process [2]. Control of an air bending process was developed using a database with force measurements and fuzzy logic [3] or using a neural network based on certain characteristics of the force curve [4]. A more thorough overview of research on control in metal forming can be found in the work of Polyblank, Allwood, and Duncan [5]. In studies on the control of metal forming processes, a common factor is the use of process models which are valid in a wide range of process conditions, such as with different materials or lubrication conditions. However, these models are inadequate for the control of product-to-product variations, because they lack the accuracy needed to identify the variations within a single set of process conditions.

When using process forces in the control of a forming process with multiple process steps, it is essential to understand the interactions between the different process steps. A conventional approach for forming processes with multiple steps, is to perform these steps on a single stamping press, and move all products to the following position after every stroke of the press. Therefore, different products undergo different forming steps during every stroke of the stamping press. Every step executes a load on the tooling and on the press. The sum of all loads determine the total elastic deformation of the tooling. Hence, the interaction between different process steps is determined by the forces

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acting at every position and by the stiffness of the tooling. Variability of the process force in one position may affect the tooling deformation at another position, influencing the forming process. Some researchers have investigated the effect of tooling deformation on forming. An overview can be found in the work of Brecher, Esser, and Witt [6].

In the present work, interactions in an industrial forming process with multiple steps are investigated. In the first section, the demonstrator process is presented. Thereafter, the interactions between the different process steps are identified. Finally, the consequences for control of the forming process are discussed.

DEMONSTRATOR PROCESS

To investigate the feasibility of control of product-to-product variations in forming processes, a demonstrator process with multiple process steps has been developed within the MEGaFiT project. The demonstrator product is a round cup with 20mm diameter and 4mm height (Fig. 1a). The bottom of the cup has three flaps oriented in different directions. At the outer side of the bottom of the cup, six parallel ribs are formed with a forging process. The used material is a 0.3 mm thick stainless steel strip. The cup remains attached to the strip during the full production process. The production speed is one product per second.

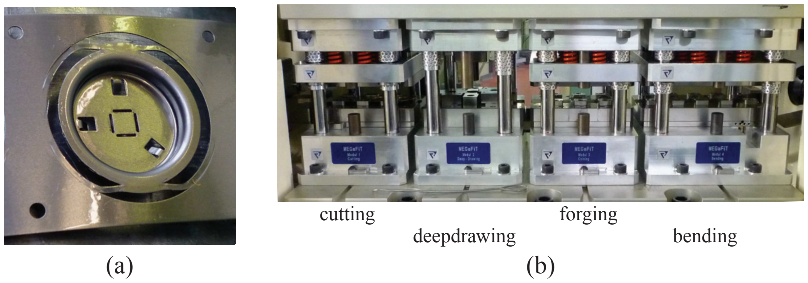


Figure 1. Product (a) and tooling (b) of the demonstrator.

The tooling consists of four modules which are mounted in an industrial stamping press (Fig. 1b). Each module consists of many parts, mostly made from tool steel and aluminum. In the first module, pilot holes are cut for positioning of the strip (see Fig. 1a) and the cuts needed for deepdrawing are made. In the second module, the cup is deepdrawn. The shape of the flange after deepdrawing is not round due to the anisotropy of the used material. To control the roundness of the flange, four blankholder sections are used, each one covering one quarter of the flange. The pressure of each blankholder can be set independently and is controlled with a hydraulic system. In the third module, four slots are cut into the center of the cup, and six parallel ribs are forged into the area in between the slots. The purpose of the slots is to isolate the forging area and prevent interaction with other process steps. The maximum forging force is determined by a gas spring that supports the forging counterpunch. In the last module, three flaps are bent during two different stages. In the over-bending stage, the flap is bent to an angle of 50°. This stage has a punch and a counterpunch as shown in Fig. 2a. Thereafter, there is a back-bending stage, where the flap is bent back to a desired angle with a free bending process. The amount of back-bending can be set independently from product to product.

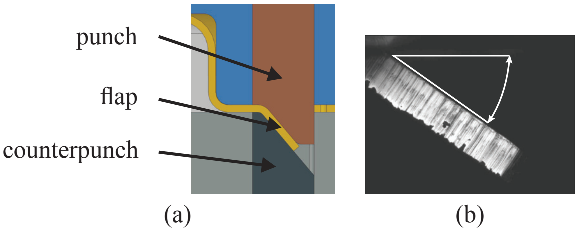


Figure 2. Tooling of over-bending stage (a) and picture of flap for angle measurement (b).

A large number of sensors have been built into the tooling to track the variations in the process. An overview of the measurements is given in Table 1. Note that many positions in the tooling are not occupied with forming steps. The process forces in all forming steps except the back-bending step are measured. Furthermore, the thickness of the incoming strip and the final angle of one of the flaps are measured. To determine the angle directly after forming, a picture from the side of the flap is taken with a built-in camera (Fig. 2b) and the angle is calculated with image processing. The standard deviation of the measurement error is determined to be around 0.01°.

Table 1. List of measurement systems in the demonstrator tooling.

Process step (position)	Description	Range	Amount
	Thickness	0-1 mm	1
Cutting (1)	Pilot hole cutting force	0-7 kN	1
Deepdrawing (7)	Punch force	0-14 kN	1
Deepdrawing (7)	Blankholder pressure		4
Forging (12)	Punch force	0-26 kN	1
Bending (16)	Punch force	0-3 kN	3
Bending (19)	Flap angle	20-80 deg	1

Actuators have been built into the tooling to enable product-to-product control in the demonstrator process (see Table 2). In the deepdrawing stage, the pressure of all four blankholder sections can be set independently. Changing the blankholder pressure influences the roundness of the flange. If the blankholder pressure is set too low, wrinkling occurs. In the forging stage, the maximum force of the gas spring can be changed. This action influences the height of the forged ribs. In the bending stage, the depth of the back-bending stroke can be set independently for all three flaps. This can be adapted from product to product and obviously influences the final angle of the flaps.

Table 2. List of actuation systems in the demonstrator tooling.

Process step (position)	Description	Amount
Deepdrawing (7)	Blankholder pressure	4
Forging (12)	Maximum punch force	1
Bending (18)	Back-bending depth	3

PROCESS INTERACTIONS

In a multistage metal forming process, different types of relations between measurements of the different process steps can be identified. Firstly, certain variations such as variation of thickness or material properties affect the same product during all production steps. Secondly, variability within a single process step may affect the product properties and consequently affect the measurements in a later process step. An example is a bending process which is performed in multiple stages. In the demonstrator process, it is expected that this type or interaction is only weakly present, because it has been designed in such a way that each process step acts on a different region of the product. Thirdly, there may be interactions which are transferred through the tooling. Variability of the deepdrawing force affects the elastic deformation of the complete tooling. Hence, the positioning of the tooling at a different stage may be affected. The significance of this effect depends on the magnitude of the variability and on the stiffness of the tooling.

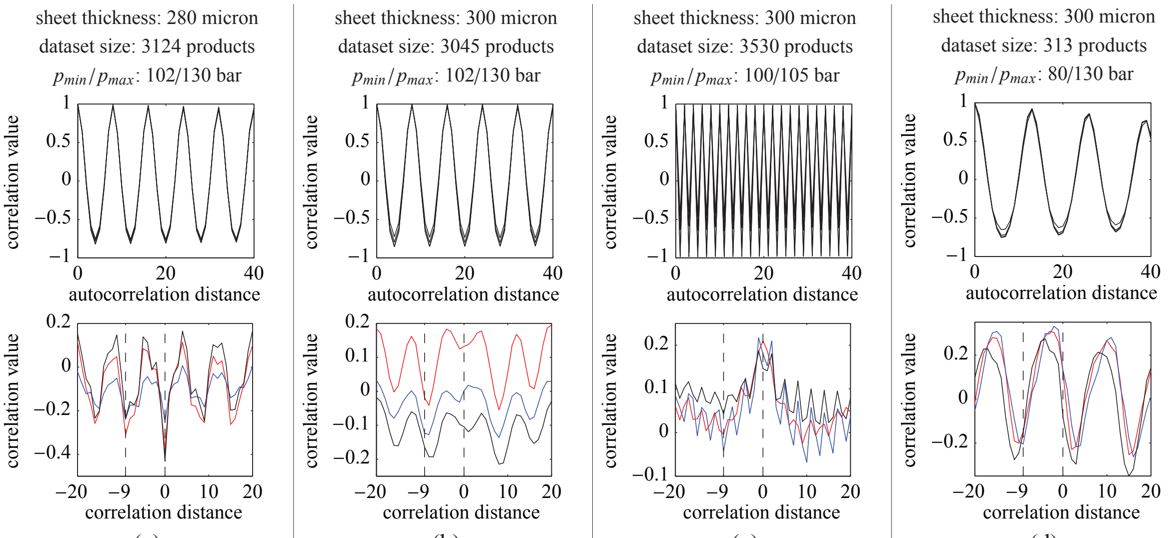
Even a simple metal forming process is affected by many sources of variation and interaction. It is often very difficult to clearly distinguish between these sources of variation and interaction as they act simultaneously on the process. However, statistical analysis of large datasets can be used to gain insight into these variations and interactions. The amount of interaction can be estimated based on the correlation between measurements of different process steps. Furthermore, the location of the peaks in the cross-correlation plots can be used to distinguish between the first two types of interaction - which are transferred through the product - and the third type of interaction - which is transferred through the tooling.

In the following sections, different types of interaction between the deepdrawing, forging and bending stages in the demonstrator process are investigated based on multiple datasets. It is shown how variability in the process forces causes interaction between process steps which is transferred through the tooling and the press.

Interaction Between Deepdrawing and Bending

The four blankholders in the deepdrawing stage are controlled with a hydraulic system. All blankholders are connected to a main oil reservoir, which is kept within a pressure range with a separate control system. If the pressure drops below p_{min}, the reservoir is repressurized to p_{max}. Due to the length of the tubes and the small size of the oil reservoir, the stability of the hydraulic system is inadequate. This causes large variations of the blankholder pressure from product to product. In the top row of Fig. 3, the autocorrelation of the pressure of the four blankholders is shown for different datasets. A large range between the p_{min} and p_{max} settings of the hydraulic system results in a longer period of variation. Obviously, a larger range also results in a larger magnitude of variation.

The instability of the hydraulic system has a negative effect on the stability of the production process. The periodicity observed in the deepdrawing punch force is also present in the angle measurement data, indicating interaction between the deepdrawing and the bending stage. To identify whether this interaction is transferred through the product or through the tooling, the cross-correlation between the deepdrawing and bending force can be analysed (see bottom row of Fig. 3).



sheet thickness: 280 micron
dataset size: 3124 products
p_{min}/p_{max}: 102/130 bar

sheet thickness: 300 micron
dataset size: 3045 products
p_{min}/p_{max}: 102/130 bar

sheet thickness: 300 micron
dataset size: 3530 products
p_{min}/p_{max}: 100/105 bar

sheet thickness: 300 micron
dataset size: 313 products
p_{min}/p_{max}: 80/130 bar

(a) (b) (c) (d)

Figure 3. Autocorrelation of the maximum pressure of the four blankholders (top) and cross-correlation between maximum deepdrawing force and maximum bending force for the three benders (bottom) for different datasets.

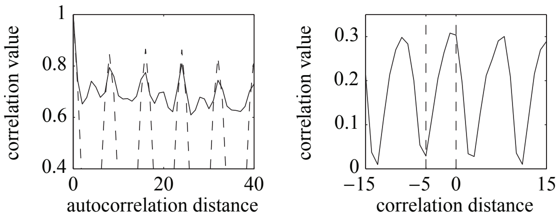
The correlation plots are based on data which is affected by many variations and interactions. Furthermore, the correlations between the maximum deepdrawing and bending forces are relatively weak. However, some information can be extracted from the cross-correlation plots. The variability caused by the hydraulic system of the deepdrawing stage is either transferred to the bending stage through the product or the tooling or through both. Interaction which is transferred through the product can be observed at zero cross-correlation distance, whereas interaction which is transferred through the tooling deformation can be observed at −9 cross-correlation distance, which is the distance between the deepdrawing stage and the first bending stage (see Table 1). In the bottom row of Fig. 3a and Fig. 3b, it is difficult to distinguish between these types of interaction, because the variation of the hydraulic system has a period of eight products, which interferes with the distance of nine products between the deepdrawing and bending stage. Therefore, a short test with a wider range for the hydraulic system settings was performed. The results of this test are shown in Fig. 3d. The period of variation is thirteen products. It can be observed that the maximum negative correlation is found close to −9 correlation distance, and no minimum or maximum correlation is found around zero correlation distance. This corresponds with the idea that the interaction between the deepdrawing and bending stage is at least partly caused by elastic deformation of the tooling.

Another point of interest is the behavior of the cross-correlation around zero. Larger values for properties such as thickness and yield stress are expected to result in an increase of both the deepdrawing as well as the bending force. Therefore, a local increase of the correlation value around zero cross-correlation distance is expected. This is clearly observed in Fig. 3c. In Fig. 3b, a similar effect is observed, although it interferes with the periodicity caused by the variation of the hydraulic system. On the other hand, a decrease of the correlation around zero is observed in Fig. 3a. For this test, a thinner sheet is used compared to the other tests. It is not clear from the data what kind of interaction causes the negative correlation between the maximum deepdrawing and bending forces.

Interaction Between Deepdrawing and Forging

The forging stage is also affected by the variability of the hydraulic system in the deepdrawing stage. In Fig. 4a, the autocorrelation of the maximum deepdrawing and forging forces are shown. The peaks in the autocorrelation of the maximum forging force appears every eight products, which is equal to the period of variation of the deepdrawing force. The cross-correlation plot (Fig. 4b) can be used to verify whether this interaction is caused by elastic deformation of the tooling and press. The force on the deepdrawing punch acts in upward direction. Therefore, a higher force in the deepdrawing stage results in a larger upward deflection of the stamping press ram. Consequently, the forging punch reaches a lower depth and the forging force decreases. This corresponds with a negative correlation between the deepdrawing and the forging force at the distance between these process steps. The distance between the deepdrawing and forging stages is five products (Table 1), which matches with the position of the local minimum in Fig. 4b. Therefore, it is plausible that the interaction between the deepdrawing and forging stage is caused by elastic deformation of the tooling.

sheet thickness: 280 micron
dataset size: 3268 products
p_{min}/p_{max}: 102/130 bar

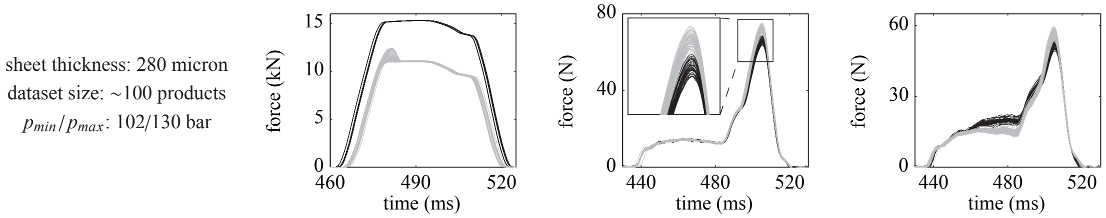


(a) (b)

Figure 4. Autocorrelation of maximum deepdrawing punch force (dashed line) and maximum forging force (solid line) (a) and cross-correlation between maximum deepdrawing and forging force (b) for the same dataset.

Interaction Between Forging and Bending

In the forging stage, a high force is needed to form six ribs in the center of the cup. The maximum forging force can be adjusted in the range of 10kN to 20kN with a gas spring which supports the counterpunch. A detailed description of the forging process can be found in the work of Stellin, van Tijum, and Engel [7]. To illustrate the effect of these forces on the tooling deformation, a test is performed where the maximum forging force is lowered halfway the test. Figure 5a shows that the forging force drops from 15kN to 11kN. A smaller force in the forging stage affects the press ram plate deformation in such way that a deeper stroke is reached in the bending stage, leading to a higher maximum force for the benders (bender 2 in Fig. 5b and bender 3 in Fig. 5c). Furthermore, a higher forging force also affects the force of bender 3 during free bending (Fig. 5c). During the first part of the bending stroke, up to 485ms, the bending force is reasonably constant because the flap does not yet touch the counterpunch (see Fig. 2a). However, misalignment of the punch may lead to contact between the punch and the die during free bending, leading to a higher force [8]. The effect of misalignment is observed for the third bender when the forging force is at 15kN (Fig. 5c). Hence, the elastic deformation of the bending module due to the force in the forging stage is so severe that misalignment issues in the bending stage occur.



(a) (b) (c)

Figure 5. Force curves of approximately 50 products before (black) and 50 products after (gray) changing forging settings, for the forging stage (a) and bender 2 (b) and bender 3 (c) of the first bending stage.

OUTLOOK

To be able to use force measurements for the control of product-to-product variations in metal forming process, it is important to understand what affects these measurements. For a demonstrator production process, the interactions between its deepdrawing, forging and bending stages have been studied. It is shown that the tooling and stamping press are elastically deformed by process forces in the deepdrawing and forging stage. Consequently, the tooling movement at the bending stage is affected. This influences both the final angle of the flaps as well as the bending forces.

In the deepdrawing stage, the variability of the process force is caused by instability of the hydraulic blankholder system. Therefore, the measurements in the deepdrawing stage must be taken into account in the control system for the bending stage. Furthermore, changing the settings of the actuators in the deepdrawing and forging stage also affects the bending stage. Hence, a coupled control system is required when applying simultaneous control in all three process steps.

A key factor for the development of control systems for metal forming is the development of process models. These models describe the relation between force measurements and actuator settings with the final geometry of the product. They may be either based on empirical data or on numerical simulations. Taking the interactions between process steps into account is essential to reach the desired degree of accuracy needed for product-to-product control.

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