

Adaptive process control strategy for a two-step bending process

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Abstract A robust production is an important goal in sheet metal forming in order to make the process outcome insensitive to variations in input and process conditions. This would guarantee a minimum number of defects and reduced press downtime. However, for complex parts it is difficult to achieve robust settings. Parts without defects can only be realized if the process parameters are adapted to the changed conditions.

In this paper, an approach for adaptive process control is presented, taking the uncertainties and tolerances of the process and material into consideration. The proposed control approach combines feedback and feed-forward control strategies. The most significant improvement is to incorporate feed-forward control with knowledge about the system (also known as predictive models). To create these models high fidelity numerical models have been created. Furthermore, a procedure is presented to update the coefficients of the predictive model to adapt it to the actual process state.

To evaluate the control strategy prior to its implementation, a testing environment has been developed. Different test scenarios for common states of the process have been generated to evaluate the improvement of the proposed control strategy.

1. Introduction

Today, the procedure to get a robust process in sheet metal forming is to layout the process in the planning phase as stable as possible. However in a production line, the tools will for instance show wear effects and the quality of the process will show a trend towards the upper or the lower tolerance limit. Not only tool wear, but any change in the influencing parameters on the process will result in a deviation in the quality of the product. These deviations require an operator, to manually adjust the process settings or the tools to avoid producing outside specification limits. These manual control loops are typically slow and have to be repeated over and over again.

Therefore, the goal is to get constant output parameters, subject to variability in the input parameters like sheet thickness and the yield stress of the material. This input scatter is not controllable, so the process has to be continuously adapted. A short summary about control strategies for forming processes is summarized in the following section.

Hora et al 2011 [1] present a proposal for a Zero Defect Production Control. The idea is based on a three component approach. The first component is based on the incorporation of process knowledge within the controller strategy by using a Process-Integrated-Virtual-Control to map the system behavior and then building up metamodels that capture the physics of the process. Applying a FEM sensitivity analysis on the process, it is possible to extract the information needed to build up a virtual process control. The second component is the use of an in-line material monitoring system in a non-destructive way to determine the non-constancy of measureable process parameters [5], [6]. The third component consists of an in-line control of process parameters directly on the tools. This creates the possibility to change the process settings automatically and allows the implementation of a closed loop regulation.

Müller-Duysing 1992 [3] focused on the adaptive control of a three point bending process. Based on some principal possibilities for the correction, an adaptive control procedure has been developed and experimentally validated. Ruzovic 1999 [4] has developed an adaptive control system, which is able to react on changing process conditions to ensure the quality of the produced parts. The control concept can be divided in two parts, the diagnostic of the process state and the correction. Annen 2012 [6] is using the robustness analysis to realize a process control. Therefore, stochastic simulations are conducted and process windows, which signify a capable process, are determined by simulations or experiments. The idea is to control the process on the basis of these allowed process windows.

The general goal is to develop an adaptive control system for a two-step bending process. This includes the following tasks: Analyzing and modeling of the process, definition of a measurement concept, development of a control strategy and check this concept virtually. Finally the approach can be tested on the real process [4]. In this paper, the modeling of the process and the control strategy is addressed in section 2 and 3. Section 4 shows the simulation of the entire process applying the developed control strategy.

2. Modeling of the bending process

In this section the modeling of the bending process will be addressed. Therefore, the investigation of the process is done in 2 parts: The model of the process is built and the material properties are tested and modeled. Explanations about the whole demonstrator process can be found in [2].

For this study only a sub-part of the full demonstrator part is modeled. This sub-part includes the bending flap and its neighborhood. The size of the neighborhood has been chosen in order to apply reliable boundary conditions. The simulation is divided in 2 steps like in the process. In the first step, over bending to an angle of 50° takes place. The punch force as well as the design of the punch and the die geometry determines the final form of the bended part. Spring back occurs after the bending process for materials with elastic deformation. After the pre-bending process, the flap is bended back. The punch will move upward and will change the angle of the flap to a lower value.

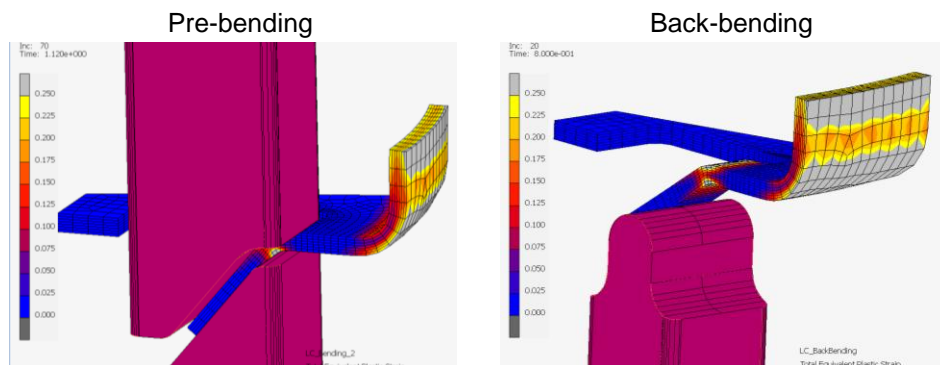


Figure 1: FE-model of the two step bending process

Spring back has a major influence on the accuracy of the bended part. Given the fact that especially the spring back behavior is highly sensitive to material properties, it is clear that a good material model is necessary for a sufficiently accurate virtual description of the process.

The tested material is AISI420, a martensitic stainless steel in a stable ferritic state. The material behavior has been studied using advanced experimental testing devices. The plastic material behavior under different stress states is described using tensile tests in three directions and a hydraulic bulge test. Within the demonstrator process, the work piece undergoes also one cycle of bending-unbending. Therefore, it is important that phenomena, which occur during this deformation cycle, are also described. Cyclic shearing tests have been conduct-

ed by using a biaxial testing device. Although the sheet thickness amounts only 0.3 mm, cyclic tests could be performed without showing wrinkling effects. The identified material properties are summarized in [Table 1](#).

Table 1: Identified material properties for the stainless steel AISI 420

Material	σ_0 [MPa]	σ_{45} [MPa]	σ_{90} [MPa]	σ_b [MPa]	r_0	r_{45}	r_{90}
AISI420	362	368	368	384	1.23	1.17	1.53

An anisotropic yield function in combination with a kinematic hardening model is used to describe the observed material behavior. As yield condition, the yield function Yld91 is chosen. The yield surface can be expressed as follows:

$$\bar{\sigma}^m = \frac{1}{2} [|S_1 - S_2|^m + |S_2 - S_3|^m + |S_3 - S_1|^m]$$

where $S_{i=1,2,3}$ are the principal values of the S matrix which is depending on the Cauchy stress.

To describe the hardening behavior, a combined hardening model is used. This formulation assumes that the hardening is divided in two parts, the isotropic part and the kinematic part. The fraction f_h between both is a material parameter. The Prager linear kinematic hardening law is used in combination with the Hockett-Sherby law. The Hockett-Sherby equation is defined as follows:

$$\sigma_y(\bar{\varepsilon}_p) = A - (A - B)e^{(-m\bar{\varepsilon}_p)^n}$$

where A , B , m and n are material parameters defining the slope of the stress-strain curve.

The calibration results and the mechanical responses of the model compared to the experimental data are shown in [Table 2](#) and [Figure 2](#). The yield locus is calibrated to the stress values, therefore the results in term of r -values are not sufficient (Figure 2c). But the trend of the r -value regarding the rolling direction is the same as the one shown by the experimental results. The hardening behavior is in good agreement with the experimental results (Figure 2d). The cyclic behavior is shown in Figure 2e.

Table 2: Identified parameters of the material model

Isotropic hardening: Hockett-Sherby				Fraction of kin. hardening
A [MPa]	B [MPa]	n [-]	c[-]	f [-]
920	346	0.56	3.16	0.07

Anisotropic plasticity: Barlat91				
m [-]	C1	C2	C3	C6
6	0.926	0.959	1.040	0.997

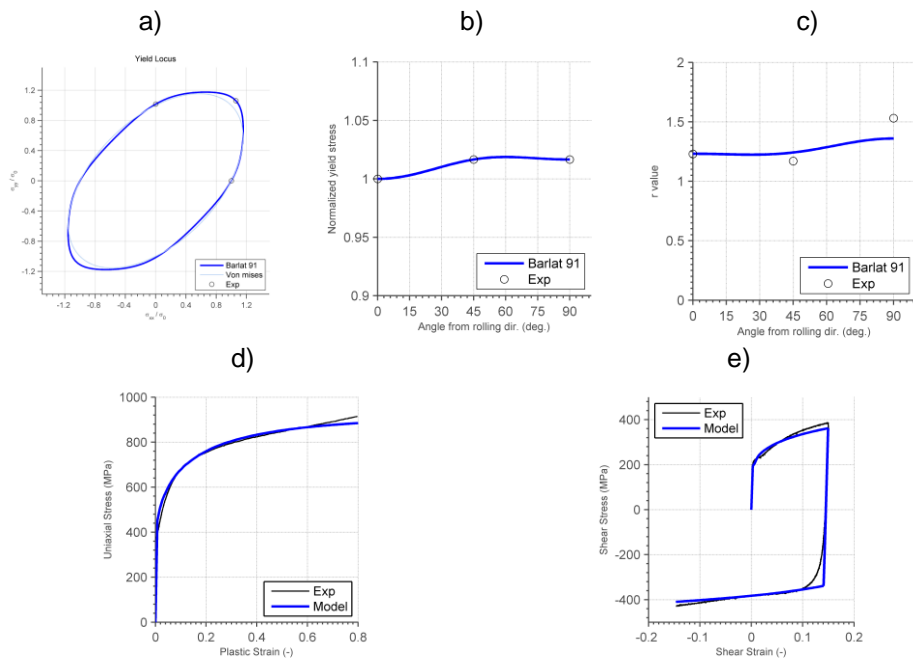
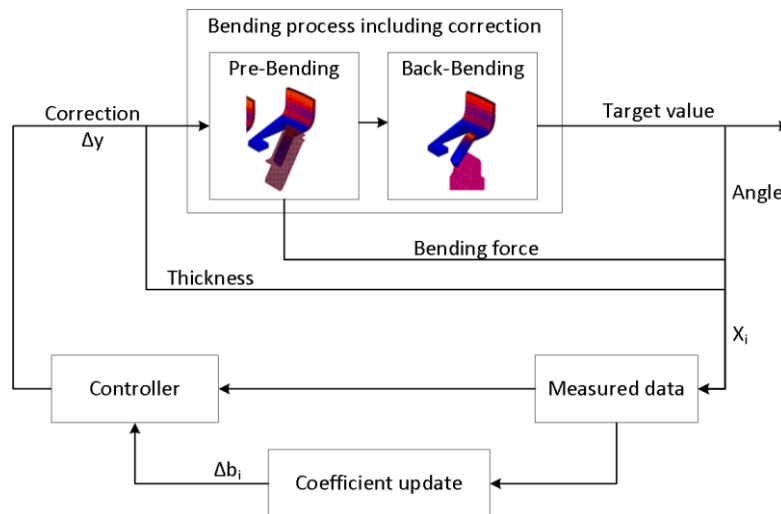


Figure 2: AISI 420 – Barlat 91 yield locus and hardening law calibration – a) yield locus b) Normalized yield stress c) r values d) uniaxial tension stress / strain curve e) cyclic shearing stress / strain curve

3. Control strategy

In this section the control strategy is explained. The basic task of the control system is to adapt the process on changing conditions to ensure the quality of the products. To realize an algorithm, which conducts the adaption automatically, the relation between measurement and control parameters must be known. In a very simplified manner, the question is to find a function, which defines the dependencies of the measurement and the control parameters.

The control approach will be applied on a two-step bending process. In the first step, the over bending to an angle of 50° takes place. In the second bending, the flap is bended back. Measured parameters are the sheet thickness, the bending force during the first bending and the final angle after the process. To control the final angle, the punch displacement in the back-bending step can be set. The control algorithm calculates the amount of correction of the punch displacement Δy by using all available measurement data X_i . During the process, the coefficients b_i in the control algorithm will be continuously updated. The control concept is summarized in [Figure 3](#).



[Figure 3](#): Control concept of the two step bending process

The control approach combines feedback and feed forward control strategies. The most common method of feedback process control is the proportional-integral-derivative (PID) controller as described by N. Minorsky and it is widely used in industrial applications [8]. This feedback consists of a Proportional, an Integrative and a Derivative part concerning the error between the output and a reference value of the controlled system. In absence of knowledge of the underlying

ing process, a PID controller has historically been considered to be the best controller. The fundamental drawback with PID control is that it is a feedback system, with constant parameters, and no direct knowledge of the process, and thus overall performance is reactive and a compromise.

The most significant improvement is to incorporate feed-forward control with knowledge about the system. To estimate the control parameter in advance, indirect “online” measurements, like the trend of the force curve during the process, can be used. These approaches are known as “predictive model” and represent a mathematical replication of the process. The complete concept is shown in [Figure 4](#).

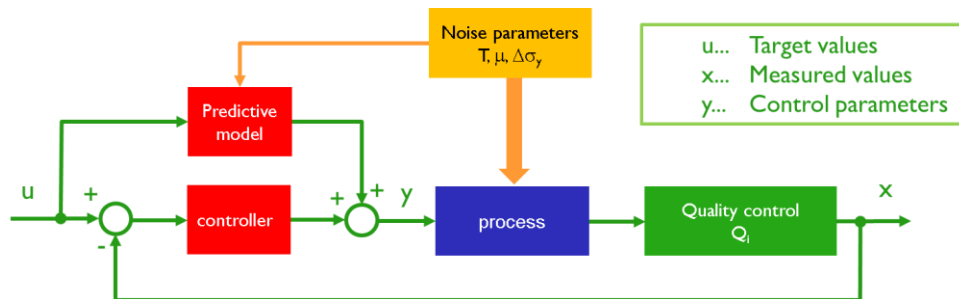


Figure 4: Control approach combining feedback and feed-forward control strategies

For the analytical description of the predictive models, different methods can be used. However, the construction of reliable and accurate models is not a trivial task. Based on accurate simulation models, a design of experiment is defined to generate a database to fit the models. A multiple linear regression method is used in this approach to define the relation between measurement and control parameters. In this way, it's possible to describe the dependency of certain measured values on the control parameter quantitatively [4]. The multiple regression describes the relationship between the variable y and the predictor variables x with the following basic model:

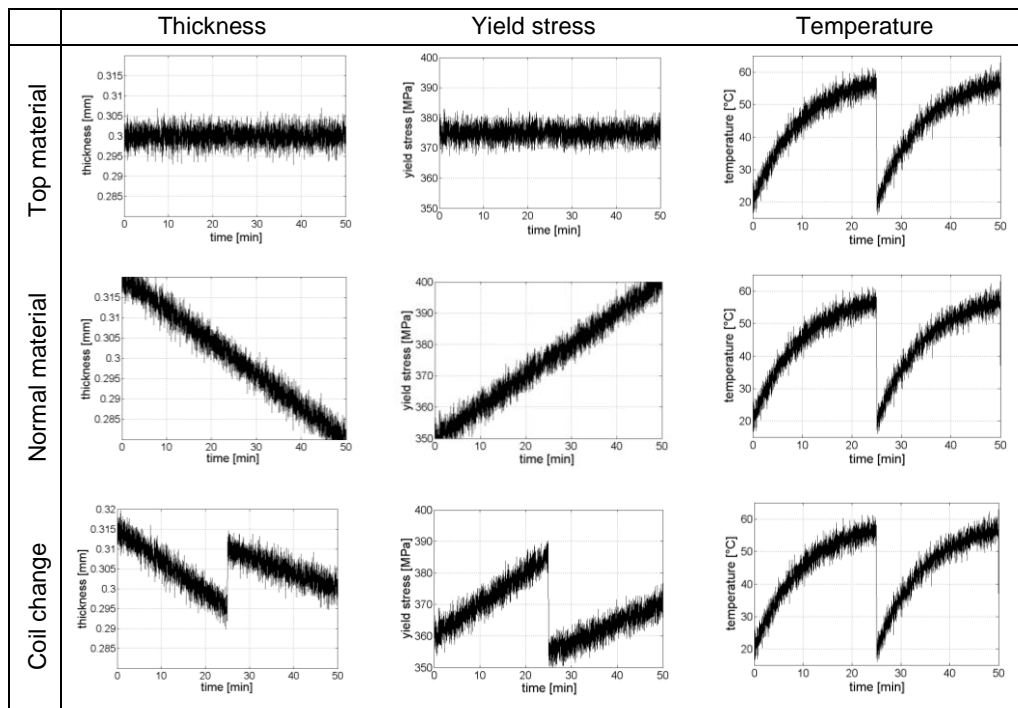
$$y_i = b_0x_{i0} + b_1x_{i1} + \dots + b_{k-1}x_{ik-1} = \sum_{j=0}^{k-1} b_jx_{ij}$$

A very important part of the control concept is the adaption of the predictive model on the current process state. The coefficients of the function can be optimized by using all available measurement data. The measured process data are the final angle α_2 , the punch displacement y , the thickness t and the force F . Regression techniques are applied to the whole amount of saved measurement data to update the coefficients of the predictive model at specific moments in time.

4. Proof of concept

To test the control strategy, models of the process steps have been generated, with which the behavior of the system can be replicated. Subsequently the control approach can be simulated and validated together with a model of the controlled system. This enables the design and test of different control approaches.

The specific characteristics of the forming process have to be considered in the design and development of the control system. Primarily, it's the slowness with which the forming process reacts on changing conditions. This means that abrupt changes of the process conditions mostly take place, when a new coil of material is used in the production. Otherwise only smoothly varying changes can be expected [4]. In [Figure 5](#), some scenarios for common states of the process and material parameters are summarized.

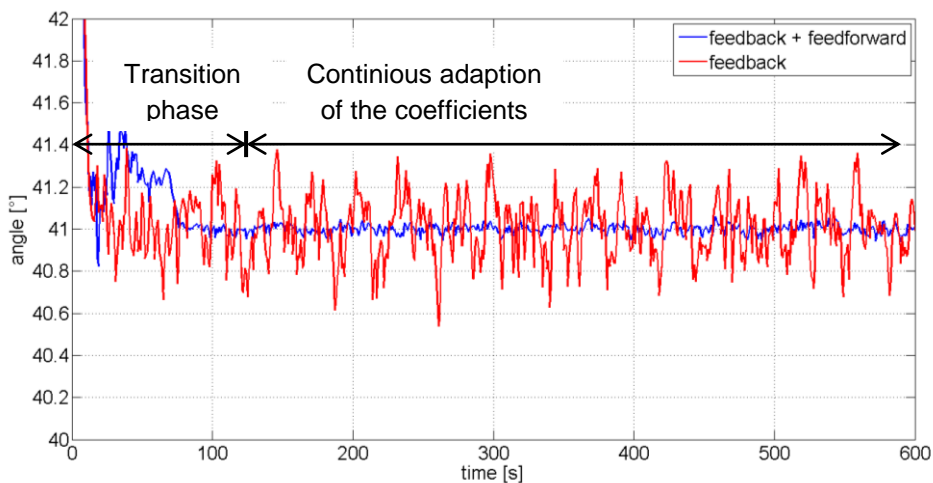


[Figure 5](#): Scenarios

Top conditions show relatively constant values for the sheet thickness and yield stress. Normally, these parameters show an increasing or decreasing trend. If a coil change takes place, an abrupt change of the parameters occurs. The temperature, which mostly influences the friction conditions and the yield stress of

the material, is assumed to increase at the beginning, suddenly decreases due to a break of the production and increase again.

A result of the proposed control strategy, which combines feedback and feed-forward control, is shown in [Figure 6](#). The big improvement in the achieved accuracy of the bended part can be seen compared with standard feedback control. However, the used input data for this test shows a lot of deviations from product to product which leads to the relatively bad results of the feedback control.



[Figure 6](#): Simulated results for the final bending angle using different controllers

Additional attention has to be paid on the topic of the transition phase and size of measurement dataset for the update of the coefficients. As soon as enough data is available, the coefficients can be updated to improve the model. It is necessary to have a smooth transition from old to corrected parameters to avoid instabilities of the control approach.

For the amount of used measurement data, different approaches are possible. The parameters of the predictive model can be continuously updated using a moving window approach when actual measurement data is available [9]. Speed of adaption of the model (requiring smaller size) and avoiding response to noisy data (requiring larger size) have an impact on the size of this window.

5. Conclusions and outlook

It still has to be clarified how the complexity of the predictive model and more noise on the measurement data influence the results. Till now, only linear models for the process control are used. Also the chosen approach of combining the output of the predictive model and the conventional controller has to be validated. Other approaches exist, which have to be tested.

Furthermore, the appropriate algorithm has to be programmed in a PLC. For the initial test of the control approach the models of the process steps will be used. After that the control program can be used in the machine.

Acknowledgement

The work leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement n° FP7–285030.

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