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Technical Paper

Feedforward control of sheet bending based on force measurements

Jos Havinga [a,*], Ton van den Boogaard [a], Franz Dallinger [b], Pavel Hora [b]

[a] Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, Enschede, The Netherlands
[b] Institute of Virtual Manufacturing, ETH Zürich, Tannenstrasse 3, Zürich, Switzerland

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ABSTRACT

The accuracy which can be reached with feedback control in industrial metal forming processes is limited by product-to-product variations in the process. These variations may be controlled with a feedforward control system. To do so, a measurement system and a process estimator are needed to measure and correct for these variations. In this work, the use of force measurements for feedforward control of a steel sheet bending process is investigated. A multi-stage demonstrator process is developed with cutting, deep drawing and bending stages and a large number of force sensors. Several relations between process forces and the product geometry are studied in an extensive analysis of measurement data from the production process. It is proposed to build a moving window process estimator using the LASSO regression method. The parameters of the regression model are updated during production based on historical data of the production line. Several simulation runs are performed to estimate the effect of feedforward control on the process accuracy. These simulation runs are based on measurements from the real production line and minor assumptions. The proposed approach leads to an estimated decrease of 24% in the root mean square error of the final angle with respect to a simulation run with feedback control only.

1. Introduction: control of metal forming processes

Metal forming processes suffer from variations of material properties and process conditions. These disturbances affect the final properties of the product. For products with narrow tolerances, closed-loop control may be used to ensure product quality. A driving factor for recent developments in control of forming processes is the use of information technology, enabling for real-time processing of increasingly detailed sensor data and process models [1].

An extensive review on control of metal forming processes is given in the work of Polyblank et al. [2]. They observed that control systems in forming processes are usually designed to control the movement of the tooling, but lack the ability to control the final state of the product, such as its geometry or stress distribution. On the other hand, they foresee an expansion in the applications of closed-loop control in metal forming, based on the accessibility of the main components needed for process control: sensors, actuators and process models. Given the ongoing development of computing power, increasingly detailed process models and control systems may be developed in pursuit of a higher accuracy of forming processes.

An important factor for the design of manufacturing control systems is the rate of change of the process disturbances. Disturbances which change slowly over time may be controlled with feedback systems, adapting the process settings based on measurements from finished products. However, product-to-product variations cannot be eliminated with such systems and must be controlled with feedforward control based on measurements from the semi-finished products. In the current work, the eligibility of the use of force measurements in a feedforward estimator of a sheet bending process is investigated. The question is whether the variations in the process are reflected by the force measurements. Several researchers have investigated the use of force measurements in control of forming processes (Section 2). Different methods have been developed to adjust for changes in production conditions (e.g. changes in nominal sheet thickness or in used material). However, little work has been published on control of product-to-product variations in metal forming processes. This is reflected by the small number of products used for training of control models and for validation of the control methods: for most studies the dataset size does not exceed 100 products (Table 1).

To study product-to-product variations in metal forming, large data sets with measurements from every product in the production line are needed. To the best of our knowledge, no studies

* Corresponding author.
E-mail address: joshavinga@gmail.nl (J. Havinga).

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Table 1
Studies on control of forming processes which relate force measurements to final product properties and include experimental results.

Publication	Process	Model	Variation in process conditions	Number of products	
				Training set	Validation tests
Hardt et al. [4]	Roll straightening	Linear analytical	Two materials	n/a	8
Müller-Duysing [5]	Air bending	Linear regression	Three materials, multiple thicknesses and cycle times	Unclear	44
Yang et al. [6]	Air bending	Fuzzy model with experimental data	Seven lots of one material	Unclear	Unclear
Forcellese et al. [7]	Air bending	Neural network with experimental data	Three thicknesses with two lots each	30/60	84
Nastran and Kuzman [8]	Wire straightening and bending	Numerical model linearized around operating point	No	n/a	Large number
Viswanathan et al. [9]	Channel forming	Neural network with experimental data	Six materials, varying thicknesses in between 0.70 and 0.85 mm and five lubrication conditions	80	12
Heller et al. [10]	Air bending	Linear model with semi-analytical simulation data	Three materials, three thicknesses and four target angles	n/a	72
Longo and Maccarini [11]	Air bending	Linear interpolation with simulation data	No	n/a	5
Groche et al. [12]	Air bending	Linear regression	Three materials, three thicknesses and three target angles	Unclear	30

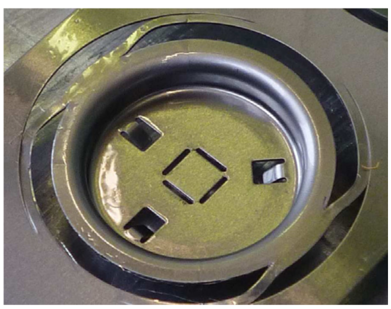

Fig. 1. Demonstrator product.

with an extensive analysis of a large number of measurements have been presented in the literature on metal forming processes. In the MEGaFiT project [3], a metal forming demonstrator process has been developed to investigate the feasibility of control of product-to-product variations in metal forming. The demonstrator process includes deep drawing, forging and bending steps. In this work, the use of force measurements for control of the bending stage is investigated. Section 2 is a literature study on the use of force measurements for control of metal forming processes. In Section 3 the demonstrator process is presented. In Section 4 several correlations between measurement data are shown to deepen the insight into the demonstrator process. In Section 5 a proposal is made for a model based on experimental data to be used in the control of the bending process. A series of simulation runs are performed using the proposed method in combination with measurement data obtained from the demonstrator process in order to assess the potential effect of a feedforward control system based on force measurements. Finally, conclusions and discussion are found in Section 6.

2. Literature: force measurements for feedforward control

The following overview is limited to studies with experimental data on the relations between force measurements and product properties, whereas purely numerical studies are neglected. A summary of the discussed papers is given in Table 1.

Hardt et al. [4] implemented force and curvature measurements in a roll straightening process. They estimated the curvature after unloading based on a user-defined value of the elastic bending stiffness and force and curvature measurements. In a set of eight experiments, they achieved a reduction of 53–95% for the maximum lateral deflection of the product.

Müller-Duysing [5] developed a control system for air bending based on measurement of the intermediate angle and the force during bending. The intermediate angle at three different positions of the punch and the bending force at two different positions of the punch were used as input of a linear regression model. After optimizing the regression coefficients based on measured data, the Root-Mean-Square Error (RMSE) of the prediction error of the model was 0.17° over a set of 44 products with three different materials. The RMSE of the prediction error of the best model without force measurement was 0.24°.

Yang et al. [6] created an experimental database of an air bending process with force and angle measurements and other information such as sheet thickness, ambient temperature and material name. For the control of a new workpiece, data from the database was selected based on a fuzzy logic system. Using this selection, they compared the experimental force curves with the measured force curve and determined the maximum force needed to achieve the desired angle. An accuracy of 0.1° was reached when the database was filled with information similar to that of the processed workpiece. An accuracy of 0.25° was reached when a database with a large variety of experimental data was used in combination with the modified fuzzy models. The uncontrolled accuracy is not mentioned in the paper.

A study on air bending with three different sheet thicknesses was performed by Forcellese et al. [7]. They fitted the force curve to a regression model with five parameters and related the parameters to the final angle of the strip using neural network models. They studied the effect of the training set size of the neural network models on the bending accuracy and found standard deviations in the range of 0.11–0.23° for the angle with the different training set sizes and thicknesses. The uncontrolled accuracy is not reported.

Nastran and Kuzman [8] examined a wire bending process which is preceded by a straightening process. They observed a strong correlation between the force on the rollers during straightening and the final geometry after bending. They developed a model to relate the variation of the force to variation of the yield stress and proposed to control the position of the rollers to affect the amount of plastic work during straightening and keep the yield stress of the incoming wire for the bending process at a constant level.

Control of a steel channel forming process by adjusting the binder force trajectory was investigated by Viswanathan et al. [9]. The coefficients of a third order polynomial fit of the force curve