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Blanking-bending process chain with disturbance feed-forward and closed-loop control

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ABSTRACT

Bending and other manufacturing processes are subject to uncertain process conditions like varying properties of the semi-finished parts. In order to obtain precise bending angles, these variations have to be compensated. Upstream processes often deliver valuable information about the actual part properties. This paper presents a blanking-bending process chain in which information from the blanking process is passed on to the bending process. A feed-forward bending controller uses this information as input state and compensates deviations from the nominal state. In a second instance, a closed-loop controller addresses model uncertainty of the feed-forward controller as well as unknown disturbances. A model-based closed-loop control design is shown which increases stability, stationary accuracy and time-optimality.

1. Introduction

The rising need for accurate product properties and highly productive manufacturing processes requires stable process conditions. However, uncertain process conditions such as batch variations can be minimized at the expense of higher effort but never eliminated entirely [1]. Different uncertainties from material properties chain up with production line uncertainties, e.g. repeatability, and lead to variations in product properties. The higher the demand for accuracy, the larger the potential risk for producing scrap becomes. Therefore, measures to cope with uncertainties in manufacturing processes are badly needed.

New technologies that adapt the process to each individual condition have been developed to control these variations. Adaptions can be realized by measuring the input state of the process and compensating the disturbances by means of a feed-forward control [2]. Since the quality of the compensation depends on the open-loop control, an accurate process model is required. In many applications, a measurement of variations in the input state is infeasible or the process model is only roughly known and therefore uncertain. In order to control disturbances and uncertainty under these conditions, closed-loop control has been widely used [3]. This requires the control variable to be measurable or observable during or after the process. Since the effect of input variation on the control variable is only observable after some delay, a feed-forward control takes action earlier and therefore is more suitable for controlling short-term disturbances.

The paper at hand reveals the potentials of a combined conventional closed-loop and feed-forward control. Semi-finished part fluctuations are detected and compensated based on a knowledge base, which is built up in the course of a production run. The benefits of a feed-forward and a closed-loop control are merged in a combined blanking and bending process. Dallinger et al. have shown in a simulated two-step bending process that the addition of a feed-forward control can improve the product quality if disturbances can be measured [4]. The blanking-bending process consists of a blanking operation in which a star like shape is cut out of a circular blank. The second tool allows for bending the fingers with arbitrary angles. Necessary tools are developed for the 3D Servo Press (3DSP). Due to the spatio-temporal decoupling, no interaction between the blanking and bending processes occurs. After the end of a bending process the bending angles are measured and stored. Since all collected data are assigned to an individual part in a product pass they can be used in further process steps to adapt process conditions to individual part properties.

The benefit of a feed-forward control can be investigated with the described process chain. Due to variations in the semi-finished part, variations in springback and, therefore, the resulting bending angle occur. Variations in semi-finished parts can be observed not only between two material batches but also within one batch [5,6].

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In order to react proactively to these variations, knowledge about the individual part has to be gained prior to the bending process. Therefore, relevant information is collected during the blanking process.

The influence of variations in sheet thickness and material has been pointed out in [7] to be of high importance. Inamdar et al. as well as Wang et al. showed that springback in air bending is most sensitive to variations in yield strength, sheet thickness and Young's modulus [8,9]. De Souza and Rolfe identified yield strength, sheet thickness and work hardening index as most influential on springback in deep drawing [10]. By estimating these parameters during the blanking operation important parameters for the feed-forward control are available. It can be expected that the result of the bending process is improved by using feed-forward control. This control makes use of a model of the bending process. All models of bending processes neglect some kinds of further uncertainties. In order to control such kind of uncertainties a closed-loop controller can be used [11,12].

2. Combined blanking and bending process

2.1. 3D Servo Press

The 3D Servo Press is a multi-technology machine, which performs a flexible ram motion with various degrees of freedom. The press combines a force-controlled mode provided by servo motor driven screws and a stroke-controlled mode, which is provided by servo drives in conjunction with a crank mechanism. A detailed description of this technology can be found in [13].

In addition to the conventional vertical stroke, the two rotational degrees of freedom of the multi-technology machine are used to decouple the different steps of a multi-stage process in spatially and temporally separated sequences. In general, a blanking process has a high influence on the accuracy of concurrent process steps by the cutting impact and the associated abrupt impulse in the press or in the tool [14]. The decoupling approach is required in order to prevent an influence of the blanking process on the bending process. Simultaneously, the decoupling provides the required flexibility of the bending process. This is possible due to a special arrangement of the dies on the press bed in conjunction with several spherical bearings.

In the following, the process, an example product and the multi-stage tool is described.

2.2. Description of blanking and bending process

The demonstration part of the blanking and bending process is a component with three bent fingers, see Fig. 2.1 (final part) that for example can be installed in an elastic support [15]. Due to the flexibility of the 3D Servo Press, the process can also be transferred to many other components with similar geometry.

A circular blank as semi-finished part is inserted into the blanking stage, see Fig. 2.1 (left). The blanking process step occurs in two stroke-controlled levels. First, the hole in the center of the blank is punched. Subsequently, the remaining outer contour of the part is blanked. The ejection force is provided by springs in the upper and lower dies. By means of a pneumatic drive the opening and closing of the tools as well as ejection of the waste takes place at the end of the blanking process step.

A sensor is integrated into the upper die of the blanking stage, which detects all acting forces during the cutting process. The position sensor measures the difference in position of the upper die when a part is inserted.

After the blanking step the intermediate product is inserted in the bending stage, see Fig. 2.1 (right). The three fingers of the component can be bent independently. The desired angle α_{des} of each finger is assigned before the process has started and can be adjusted from component to component.

The bending angle of each finger is measured after the release of the part in a separate station and stored in a data base.

3. Process model for control

Semi-finished parts as well as the machine are affected by uncertainty. While machine uncertainty is mostly controlled by a closed-loop machine controller, uncertainty in the semi-finished parts is usually ignored. Ignored or unknown uncertainties will become visible as disturbances.

This semi-finished part uncertainty propagates through the process and results in uncertain properties of the finished part. Since the process alters the uncertainty of the semi-finished part into an uncertainty of the finished part properties, knowledge of a process model is mandatory to control this uncertainty.

The uncertainties of the semi-finished part, the machine and the finished part for an open-loop approach will be described in the following. Since a machine controller is not addressed in this work, the machine accuracy limits the maximum achievable accuracy of a closed-loop process control. In a second step, a process model will be derived which gives the possibility to analyze the propagation of uncertainty and will be used to identify a strategy to control this uncertainty.

3.1. Machine and semi-finished part uncertainties

The accuracy in stroke direction has been determined in experiments and can be described by a standard deviation $\sigma_z = 0.038$ mm.

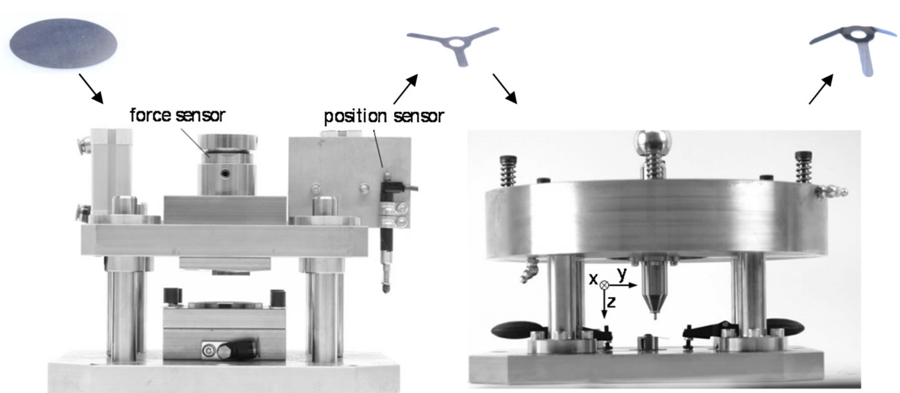

Fig. 2.1. Multi-stage process with blanking stage (left) and bending stage (right).