Analysis of high speed bending operations as basis for integrating self-correcting components to increase process reliability

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Abstract

When employing forming processes like punch bending for producing parts for electrical connection technology, unintended geometrical deviations can occur. Currently, the manual setup and adjustment of the bending machines is based on operator experience and is a highly time-consuming and expensive process. Furthermore, the unintentional geometrical deviations lead to high scrap rates and long downtimes for the production machines. To solve these problems, self-correcting control strategies based on a closed-loop control approach are thus under development. In combination with additional measurement devices and actuators, it will be possible to take corrective action during the process so as to guarantee a consistent product quality on a continuous basis.

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1. Introduction

Complex metal parts like the contact springs used in electrical-connection technology are subject to increasing requirements regarding miniaturization and functional integration. This is giving rise to more complex production...
processes in a bid to guarantee consistent product quality in the continuously-produced parts (Nguyen et al., 2005). To produce large batch sizes, contact springs are manufactured on cam-disc-based punch-bending machines. In these machines, parameters such as the punches are mechanically driven and consequently fixed in their positions. Disturbance variables, such as changing parameters in the semi-finished material or the influence of the general and mechanical machine behavior subsequently lead to unintended geometrical deviations in the products. Finding the correct machine parameters is currently performed on the basis of the operator’s experience. Unfortunately, systematic interventions of this type are only possible when the machine is not running. Consequently, this procedure is particularly time-consuming, especially when it is repeated several times over. In addition, frequent overrunning of the tolerances leads to a high scrap rate.

2. Objective

The aim of an ongoing project at the University of Paderborn is to increase the reliability of a punch-bending process by developing a self-correcting closed-loop control system. With the new development it will be possible to react adaptively to the process properties as well as to variations in the semi-finished product used. Initial investigations are based on a V-shaped sample part, a so-called contact spring. The contact spring has to be produced in large batch sizes at a rate of about 300 parts per minute, so a cam-disc-based punch-bending machine is to be used. There are punch-bending machines with an NC-controlled axis, where a self-correction is possible already (Damerow et al., 2012; Borzykh et al., 2012) but these machines run presently only at production speeds of up to 60 parts per minute, depending on the part geometry produced, and are usually used for small batch sizes. The contact spring is made of a high-strength flat wire in two process steps as shown in Fig. 1. In the first step, two punches and dies shape the flat wire. In the next step, the shaped flat wire is bent around a bending core, and the critical dimension, in this case the opening length, is adjusted.

![Fig. 1. Production steps of contact spring.](image)

The critical dimension is relevant for the functioning of the contact spring and thus has to be kept within the tolerances. In order to develop a self-correcting control strategy, all the components of the process have to be taken into account. Process parameters that affect the critical dimension directly or indirectly have to be measured to find correlations that can be used for the self-correcting control strategy later on. Typical process parameters could be the punch movement, the punch force, the positional accuracy of the punch-bending machine axis, and also the physical and geometrical properties of the semi-finished product. This paper will outline current results on increasing the reliability of bending operations by developing a self-correcting closed-loop control system.

3. Analyzing the process

3.1. Cam-driven punch-bending process

During the cam-disc-based punch-bending process, different kinds of errors occur at different times or on different time scales. Stochastic errors need quick reactions within milliseconds due to e.g. different local material properties (Fig. 2). Additionally, the stochastic errors are often overlaid by errors showing trend behavior. They reveal noticeable long-term behavior with required reaction times running into minutes or even hours, on account
of the warming up of the production machine, for example. A further kind of error appears only several hours later, after the production process, due to the relaxation of the material used. To investigate these kinds of errors, different tests were performed.

In order to analyze the process behavior, the contact spring presented is produced on a cam-disc-based punch-bending machine under series production conditions. For the tests, the selfsame semi-finished product is used from three different suppliers so as not to be dependent on just a single supplier. In an initial investigation, 10,000 parts are produced at a production speed of 300 parts per minute. During the test, the V-shaped sample part with a height of 15 mm is produced using air and die bending setups. For the die-bending operation, tolerances of up to ± 0.02 mm are attainable and, for the air-bending operation, tolerances of up to ± 0.2 mm. Fig. 2 shows a reduced or schematic representation of the critical dimension deviating from the nominal value. The variance of the rapidly-occurring stochastic errors from two suppliers are in excess of the acceptable tolerances over the short term within 10,000 parts. Errors of the third batch occur only over the long term, illustrated by the trend curve. The simultaneous occurrence of both the rapid stochastic errors and the long-term trend errors make an online closed-loop control appropriate.

![Fig. 2. Non-controlled process running out of tolerances shown by trends.](image)

Only several hours later do errors still occur that affect the critical dimension of the contact spring. These errors can be traced back to relaxation phenomena after the forming operation, due to the relaxation of residual stresses. The relaxation occurs directly after the bending and spring-back have finished and influences the critical dimension of the contact spring directly, but only after a number of hours. Besides the errors occurring directly during or after the process, this can cause additional exceeding of the tolerances (Daxin and Liu, 2010). Appropriate experiments have shown that most of the relaxation has finished after 8 hours, and it is supposed to be completely finished after 48 hours. To ensure that the relaxation can be regarded as reliable, appropriate tests are performed. The relaxation test is based on the die-bending operation (Fig. 3) used for the contact spring. To avoid the influence of more than one bending operation on the relaxation phenomena, the test is confined to a single bending operation. The specimen made of a spring steel X10CrNi18-8 is positioned on the bending core and fixed by a downholder. It is then bent by the punch traveling at a constant speed in a fixed position, as in the manufacturing process. Having reached the bottom dead center, the punch is lifted immediately, and the specimen springs back. To define the point between the end of spring-back and the start of relaxation, use was made of the loss of contact between the punch and the specimen. From this point onwards, the distance X is measured by an optical measurement system for 24 hours in a first test. Fig. 3 shows the relaxation of the specimens from the three different suppliers with three specimens each for the first test. All the specimens show similar relaxation behavior. The maximum relaxation occurs for supplier 1, at 0.71 mm, whereas the minimum relaxation occurs for supplier 3, at 0.46 mm. The biggest scatter of distance X ranges from 0.03 mm (supplier 2), via 0.05 mm (supplier 1), to 0.07 mm (supplier 3). Some of the scatters could be attributable to different physical or chemical material
characteristics for the three suppliers, others could be caused by different geometrical parameters in the wires. Within the last hour of the tests, hardly any changes were detected. A more precise optical measurement will thus be chosen for longer tests so as to make it possible to define the end of relaxation. The relaxation process cannot be detected in its entirety in the short period of time during the production process.

To be able to consider the relaxation in the process with the desired level of accuracy it is necessary to measure the relaxation procedure in an outsourced test, aiming at a description of the relaxation behavior. This description can then be used for a corrective strategy based on a closed-loop control to better keep the process within the tolerances. Furthermore this description can be used for simulation models to increase the accuracy of the simulation.

3.2. Tool and machine behavior

For a holistic examination of this bending process, it is also necessary to analyze the tool and machine behavior during the forming process. Test facilities were thus set up to be independent from the series production machines. This setup makes it possible to identify appropriate options for taking corrective action during the process based on (speed-independent) tool and process parameters. And, with that, it will be possible to keep the critical dimension within the tolerances during the process.

This is why investigations are carried out in isolation from the mechanical cam-disc based process and static bending tests conducted. The same tool setup is thus used as for the relaxation tests, operated on a universal testing machine. This permits the precise setting and measurement of the punch position and punch force. One key test aims to determine the influence of the punch position on the bending result, for example (Fig. 4).
For the tests, the specimen is positioned on the bending core and fixed by a downholder. The specimen is bent by the punch traveling at a constant speed in a fixed position, as in the manufacturing process. Having reached the bottom dead center, the punch is immediately lifted, and the specimen springs back. After the bending operation, the distance X (Fig. 4 a) is measured, together with the punch force as a function of the punch position. To influence the distance X, while still having a sufficiently formed radius R, the punch position is reduced by 0.05 mm. Fig. 4 b shows the punch position usually used for this die bending operation, and Fig. 4 c shows the reduced punch position.

For the bending test, specimens from the same three different suppliers are used as for the process analyses. While distance X varies between the three suppliers at a punch position of 0 mm, the focus of interest is on the change of distance X brought about by reducing the punch position (Fig 5 a). When reducing the punch position by 0.05 mm distance X increases and shows similar behavior for all three suppliers. Distance X can thus be increased by 0.5 mm (supplier 1), 0.58 mm (supplier 2) and 0.63 mm (supplier 3). The decreasing punch force resulting from the punch reduction is shown in Fig. 5 b. Depending on the bending operation and bending geometry, it is possible to influence distance X by a factor of up to ten by changing the punch position. This information can subsequently be used for a self-correcting strategy.

Fig. 5. Influences of punch position affecting a) the distance X and b) the punch force.

In order to investigate the dynamic behavior (or speed-dependent influences) of the punch-bending machine, a test facility was constructed consisting of an original cam slide unit from a series production machine. The punch is always moved by the cam-driven slide unit on the same flat piece of wire, because a wire feed is not available yet, but the conditions are still approximately the same as the production conditions (Fig. 6 a). Fig. 6 b shows the dynamic effect of an increased machine speed on the punch position. At 300 parts per minute, the punch position increases by 0.027 mm due to the higher acceleration leading to higher process forces (Fig. 6 c) and causing free play in the slide unit and punch mount. Reducing the punch length by 0.05 mm directly affects the punch position but still gives rise to the same dynamic behavior. A decreased punch position is directly reflected by the punch force (Fig. 6 c).

Fig. 6. a) Principle of test facility with cam-driven slide unit, b) dynamic influences on punch position and c) on punch force.
This shows that influencing a mechanical cam-disc driven process is nonetheless possible. This option can be used to influence the critical dimension of the contact spring. To confirm this observation, more tests with different punch lengths will soon be carried out. These results are used for building up a simulation model of the process, allowing further process analysis. This analysis will be used for detecting further influencing parameters as well as for designing actuators and a possible corrective strategy.

4. Control system

The process analyses can be used as a basis for developing a self-correcting closed loop-control system. First, the critical dimension of the sample part has to be measured using a camera-system, for example, to detect unintended errors. For correcting short-term and stochastic errors, all the parts have to be measured within the process and corrected in the context of statistical process control, for example. This constitutes a particular challenge for the displacement time of the actuator systems needed, due to the high production speed of up to 300 parts per minute. Long-term trend errors can be corrected more easily by taking measurements after the production process, for example, and correcting every nth part using a closed-loop control system (Doyle et al., 1995). For corrective action to be taken during the process, a correction variable has to be defined. The process analyses have shown that the critical dimension can be influenced by changing the punch position. The correction value required could be generated by a correction algorithm using information from a bending flow curve taken from a further bending step, for example. The parameters for the correction algorithm can be defined using a bending process model such as a multi-body simulation model. A number of modeling methods for metal bending processes are detailed in (Ridane et al., 2005; Schilling, 1993; Heller et al., 2006; Panthi et al., 2010), but a multi-body simulation model has major advantages for designing and testing a control strategy for corrective action in the process models (Brecher et al., 2013; Damerow et al., 2012; Borzykh et al., 2012). Once the parameters have been defined, the correction algorithm can be tested and optimized under real conditions on a test facility.

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