Novel concept for measurement of global blank draw-in when deep drawing outer skin automotive components

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Abstract. Modern press shops in the automotive industry have to deal with many challenges. One challenge is to achieve a consistent part quality. In order to reach this target, modern press systems and tools are equipped with several types of sensors. For example, there are sensors to measure characteristic values of blanks or sensors to measure the temperature in the tools. Often several sensors are used simultaneously. A significant parameter for determining the quality of draw panels is the draw-in amount. Previously, it was only possible to measure selective points of the draw-in amount due to sensors in the tools. All the known sensors have disadvantages, for example, they are exposed to wearing or susceptible to contamination. In this paper, a sensor system will be introduced that allows the measurement of the global draw-in amount of a drawn panel. Here, the draw-in amount is not measured in the draw die, it is measured during the transportation of the part to the following operation. Within the short transport time the part can be fully covered by an optical system. This leads to a multitude of advantages compared with previously known systems. For example, it is no longer necessary to equip every tool with sensor technology to measure the draw-in amount. Now it is sufficient to equip every press line with a single system to measure the draw-in. This fact leads not only to lower costs, it also simplifies the tool design. In addition, the risk of contamination of the sensor system is greatly reduced. The paper will also introduce an actuator that was built to locally vary the blankholder forces for a sheet metal forming process. Furthermore, an FEM model is presented that allows the determination of the effective range of these actuators. With the knowledge from the FEM simulation, an approach for an open loop control is presented. With this approach, the press shops at Opel are developing a control procedure in order to influence the stamping process positively.

1. Introduction
From the earliest days of manufacturing sheet metal parts, stamping plants were challenged to reduce their production costs and linked lead times. During the last years, this demand was further intensified. At the same time, the complexity of part geometries has increased, while the requirement for improved
part quality has not diminished. To address these challenges a variety of optimizations have to be performed in the production process as well as in the production engineering. In this paper, a project is presented that deals with the control of the draw-in amount of the blank edge. The draw-in of a sheet is recognized as an essential quality criterion. Especially for formability sensitive parts, there is a large control potential because of small process windows. There is also a large number of process disturbances that have an impact on the part quality like material property fluctuations, temperature and friction.

The target of this project is to build up a complete system to control the draw-in of the sheet metal while forming. The system consists of a sensor system, an actuator and a control strategy. The control should take place between the strokes of the press.

This paper focuses on a sensor system to measure the global draw-in amount of the blank. It also shows an actuator that was built to locally vary the blankholder forces for a sheet metal forming process and the FEM simulation to identify the effective range of this actuator. A luggage compartment door (panel liftgate upper) from an actual car body was investigated to develop and validate the control process (Figure 1).

2. State of the art

For many years, scientific works have investigated the development of sensor systems and control strategies for measurement and optimization of deep drawing processes. The measurement of the draw-in amount has been found as an especially useful control variable. Figure 2 [1 modified] shows an overview of the known systems from the literature, identifying the advantages (+) and disadvantages (-). The sensor systems can be divided in tactile and contactless sensors [2-11].

All listed sensors can only measure the draw-in amount of the blank locally. This implies that a sensor is required for all relevant measuring points. Normally tools with a complex geometry have multiple critical areas. That means the number of needed sensors can increase and generate high costs. Furthermore, it must be recognized that the positioning of the sensors must be considered in the engineering phase. This could lead to difficulties later on in the production process when a repositioning of the sensor is necessary. The positioning of the sensors is determined in advance as precisely as possible through numerical simulation [11-12].

All the systems known from the literature measure the draw-in amount during the deep drawing process. Open loop control of the next press stroke is based on the measurements from the previous stroke. Normally, the regulation of the press stroke takes place by adapting the blankholder force [13-14]. To achieve this, there are a variety of possibilities. One way to influence the process is the increase or decrease of the blankholder load. More complex systems work, for example, with multi-point die cushions [10] or segmented blankholders [5] to generate local load distributions. Also the use of gas springs has been realized to locally adjust the load [8]. Actual studies are using adjustable storage blocks to adjust the blankholder forces locally. Thus, the local blankholder pressure can be independently influenced by the die cushion [4; 6].
During the tryout phase of the tools, measurements are done to determine the effect of the actuators to the blank draw-in. These results serve as a database for the calibration of the control systems. Two approaches can be implemented. In the first one, the process window is determined during the tryout and the information for the maximum and minimum draw-in is stored in the controller. Based on this information, the controller decides after each stroke, if an intervention is required [8]. If the draw-in deviates from a locally predefined range, the controller varies the parameter for the following stroke. If the measured values don’t differ from the nominal ones, no intervention of the controller is necessary. The second approach is based on a neural network [6]. These networks represent the correlation relationships between the measured parameters and the quality of the drawn parts. The advantage of neural networks is the ability to use additional sensor data such as process temperatures or mechanical material properties.

3. Development of an open loop control
Initially the assembly of the control set-up will be explained. It consists of a sensor system, a mechanical actuator and an algorithm to control the process.

3.1. Sensor system
The sensor system consists of a novel optical set-up that allows the measurement of the entire blank perimeter. This makes it no longer necessary to define positions for measuring equipment in the drawing tool during the engineering phase. The sensor system is located between the drawing- and following operation in the press line. Thus, only the information of the tool that is mounted in the press is necessary to adjust the process control. Furthermore, no tool surfaces are affected by the insertion of the sensors in the tool. This makes it possible to perform a complete control of the drawn parts.

Figure 3 shows the schematic structure of the sensor system, which consists of two line scanning cameras. It is based on the principle of double image photogrammetry. Therefore, the exact position and orientation of the cameras must be known. Both cameras are scanning the same field of vision during the drawn part transportation in the press line. The sampling rate of the camera sensors is directly controlled to the speed of the transport system. A special software implemented to an industrial PC merges the recorded images together to a whole picture. This leads to a picture that can
be compared with the reference picture of the ideal draw-in. In addition, the deviations of pre-defined areas on the blankholder are displayed. These deviations are important to control the actuators.

![Figure 3: Schematic structure of the optical sensor system](image)

To be able to predict the variations of the draw-in amount, numerical FEM investigations are carried out in advance. This is done by using two different types of FEM simulations. First a robustness study for the deep drawing process was performed with a software tool developed by Emrich [12]. The study shows the critical areas of the part. Thereby the places with the largest draw-in amount/influence can be determined. These are the locations on the blankholder where the actuators must be placed. Also, the variables leading to process fluctuations are shown. Subsequently, an FEM study of the blankholder and its elastic deformation is done as a solid body. These results can be used to understand the influences of the height adjustment of the adjustable storage blocks. Based on these studies the control strategy can be defined. The focus is put on a fault-tolerant robust control system.

3.2. Actuator

Electric driven adjustable storage blocks are used as actuators (Figure 4) located around blankholder outer edge. They consist of a servo motor that is connected with a clutch to a gear. By driving the motor, the gear varies the height of the storage blocks. The height can be changed by a maximum of ± 0.3 mm. This corresponds approximately to the height adjustment in press plants. The adjustment can take place in a few milliseconds. The storage blocks are solidly constructed and are made of hardened steel to resist the rough environment in press systems. Due to their size, a sufficiently large area must be provided in the tool during the engineering phase. The positioning of the storage blocks takes place at those locations in the tool, where the largest draw-in amount is expected.

![Figure 4: Electric driven storage block (left) and a sectional view (right) that shows the functionality](image)

3.3. Numerical investigations

First, a numerical analysis of the part can be made in the FEM. Varying the material parameters, the sheet thickness, the blank position and the friction of the part can be investigated to examine the sensitivity of the stamping to these processing variables. This study is important, because only a
sensitively reacting part provides regular potential for building up an effective control system. Normally, a design of experiments (DOE) matrix with 150 simulation runs is used for a robustness analysis. In order to facilitate the simulation set-up, the previously mentioned robustness software was used. For example, the FLD results of the panel liftgate upper showed especially a large sensitivity regarding the coefficient of friction (41%) and blank positioning (15%). These are variables that can be easily adapted in experimental studies later to test the control. The influences of yield stress, tensile stress, n-value, r-value and thickness are insignificant in this case (together 7%). There are also unknown areas in that the influence of the variables cannot be calculated (37%). Furthermore, large varying draw-in amounts were detected in two areas (Figure 5). Each of the red points is a representative for a simulation result.

![Figure 5: Variance of the draw-in for two evaluated positions on the panel. Each of the red points represents one simulation run.](image)

FE-Simulation of the blankholder design can determine to what extent an adjustment of the storage blocks affects the elastic deformation of the blankholder. By using a simplified simulation model (Figure 6), simulation time can be saved. Structure and components of this model will be explained in the following. In addition to the removal of non-relevant components of the assembly, minor changes to the component geometry can also be made. For example, the servo-motors can be removed from the storage blocks because they have no effect on the simulation result. Furthermore, simulations show that an analogous model for the storage blocks can be used without deteriorating the results. The blankholder must be charged with the original boundary conditions and forces. The die is considered as a rigid body and is represented by a surface, without the underlying die structure used to obtain the required rigidity during forming. The adjustment of the storage blocks can be simulated by varying their height from -0.3 mm to +0.3 mm.

![Figure 6: FE model of the blankholder indicating positions of the height adjustable storage blocks. Storage block five is highlighted as it is discussed below.](image)
As an example, the results for storage block five will be discussed in the following (Figure 7). Each of the seven displayed blankholders shows the numerical result for one setting of the adjustable storage blocks (-0.3 mm → +0.3 mm). The legend shows the numerical amount of the elastic deformation for each blankholder load set-up. In each image, a positive deformation can be recognized for the left area (red color). This is caused by the blankholder load because of missing stiffening in the casting structure. It also can be seen that the influence of a single storage block is very large. A reduction in the height reveal only small influence (0 → -0.3 mm). However, the area of influence expands for large positive height variations (0 → 0.3 mm). This can be recognized by the expression of the blue color in the right area of the blankholder. Thus, the elastic deformation is not limited to their immediate radius, it also affects the area of the storage blocks nearby. These type of simulations were done for all storage blocks to identify their area of influence. Based on this analysis, the blankholder has been divided into six effective zones. The results from the simulation were verified in reality.

![Figure 7: Numerical results for the elastic deformation (upper scale) of the blankholder by varying storage block 5 in 0.1 mm steps from -0.3 mm to +0.3 mm](image)

4. Experimental investigations

To validate the simulation results, experiments were done on a servo press (AIDA) at the Institute for Metal Forming Technology (IFU, University of Stuttgart). Figure 8 shows the experimental setup. The blank was engaged with an industrial robot. The forming operation was performed by a ram speed of 15 strokes/minute and 1300kN blankholder force (same conditions as in the forming simulation). After forming, the draw-in was measured while the part was transported out of the press with a gripper system. To determine measurement errors and reduce the influence of experimental variation in the determination of the average response, five sheets were formed for all simulated heights of the storage blocks.

![Figure: 8 Experimental set-up](image)
As an example, the results of the height variation of storage block five are explained. Figure 9 shows the draw-in amounts for each press stroke around the periphery of the die, with the locations of the six storage blocks shown by numbered circles. Here, the four bold outlines show the draw-in amount of the blank, with magnified views of the areas in proximity to storage blocks 2 and 5. The height adjustment of the storage block is displayed in color in the legend. By varying the maximum height difference of storage block five, the draw-in amount changes about 11.5 mm, as indicated in the view of the draw-in recordings near this storage block. It was found that the effective range of distance obtained for block five exactly corresponds with the simulated results. Furthermore, it can be seen that there is a significant graduation for each height adjustment. Due to tolerances in the measuring system, a small scatter is shown within the five repeat measurements. The results also show that the adjustment has an undefined impact on the draw-in amount of the opposite side of the part (max. 4 mm). This must be considered when the control is developed.

![Figure 9: Results of measured draw-in amount by varying height storage block five. Each color shows the scatter band of the draw-in for one defined height of the storage block.](image)

5. Results and discussions
In this paper, a novel sensor system was presented. With this system, it is possible to measure the global draw-in amount of a blank after forming. The measurement takes place while the drawn panel is transported from the forming operation to the following operation. The system is based on the double image photogrammetry principle. First investigations have shown that the accuracy of the measurement is sufficient to develop an open loop control. As an example, a first application based on the sensor system was presented. In the presented analysis, it was shown that it is possible to simulate the elastic deformation of a blankholder to identify the influential areas of electrically driven height adjustable storage blocks. After the evaluation of the simulation results, the blankholder was divided into effective areas. An evaluation of the FE simulation confirmed the results from measurements in the press. Hereby, the influence of the height adjustment of the storage blocks on the draw-in amount was determined. It was also shown that the adjustment of the storage blocks had a large influence on the draw-in amount. With this information, a control of the blank edge for the sensitive reacting experimental part is possible.

6. Conclusion and outlook
In times of volatile markets, shorter product life cycles and increasing demands on product quality, there is a need for new or improved technologies. As part of this paper, the terms and conditions of a
new approach for process monitoring and control in press shops has been demonstrated for use in the automotive industry. This involves a control strategy, which is based on FEM simulations and real measurement results of the draw-in amount of the blank. Initial studies on the feasibility of the proposed concept were carried out. This study involved the numerical simulation and the verification on an experimental tool. In a next step, a control set up using the knowledge from these results is planned to be build up.

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