Improved process robustness by using closed loop control in deep drawing applications

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Abstract. The production of irregular shaped deep-drawing parts with high quality requirements, which are common in today’s automotive production, permanently challenges production processes. High requirements on lightweight construction of passenger car bodies following European regulations until 2020 have been massively increasing the use of high strength steels substantially for years and are also leading to bigger challenges in sheet metal part production. Of course, the more and more complex shapes of today’s car body shells also intensify the issue due to modern and future design criteria. The metal forming technology tries to meet these challenges by developing a highly sophisticated layout of deep drawing dies that consider part quality requirements, process robustness and controlled material flow during the deep or stretch drawing process phase. A new method for controlling material flow using a closed loop system was developed at the IFU Stuttgart. In contrast to previous approaches, this new method allows a control intervention during the deep-drawing stroke. The blank holder force around the outline of the drawn part is used as control variable. The closed loop is designed as trajectory follow up with feed forward control. The used command variable is the part-wall stress that is measured with a piezo-electric measuring pin. In this paper the used control loop will be described in detail. The experimental tool that was built for testing the new control approach is explained here with its features. A method for gaining the follow up trajectories from simulation will also be presented. Furthermore, experimental results considering the robustness of the deep drawing process and the gain in process performance with developed control loop will be shown. Finally, a new procedure for the industrial application of the new control method of deep drawing will be presented by using a new kind of active element to influence the local blank holder pressure onto part flange.

1. Introduction and state of the art
Today’s metal forming processes are faced with multiple challenges whose resolution is crucial for future metal forming processes. Deep drawing of irregular shaped parts suffer from process
uncertainties and insufficient process parameters and as mentioned by Allwood [1], this leads to high scrap rates. Lightweight construction and tight crash requirements set by the legislator even worsen the situation. Metal forming faces these challenges by researching new highly sophisticated material flow control methods. Different kinds of actuators as well as different kinds of sensors for gaining a convenient state variable of deep drawing process were investigated.

Neugebauer [2] used piezoelectric actuators for manipulating the blankholder force. The used state variable was the edge draw-in that was measured by a laser displacement sensor developed in the work of Bräunlich [3]. The main drawback of this approach was the sensitivity of the piezo-electric actuators on mechanical lateral forces. They were not suitable for the harsh environment in an industrial press company. Faß [4] and Mork [5] use the edge draw-in, which was also measured by a laser displacement sensor, as state variable as well. The used actuators were height adjustable blankholder distance blocks. This kind of actuator was also used by Kraft [6]. He also used the edge draw-in as state variable, but was measured on the whole circumference of the part for a better understanding of the process. The measurement was carried out with an image data processing program which compares the part after the forming with simulation data. Häussermann [7] developed a segment elastic blankholder with 10 segments for providing the desired blankholder force. The ten segments were powered by ten hydraulic pistons, which were all controlled independently. The segment elastic blankholder is comparable to a die cushion with full independently controllable pistons. Siegert [8] used flange draw-in measured with an induction coil as state variable. He used height adjustable drawbeads powered by a servomotor for controlling the material flow as well as a segment elastic blankholder [9]. Danckert [10] used the flange draw-in, which was measured by laser displacement sensors, as state variable. Hydraulic cushions were used as actuators. It was the first approach which features a real closed loop control during the deep drawing stroke. The used hydraulic cushions were not suitable for a curved blankholder and this lets anticipate an industrial application of this system.

One approach for gaining a state variable disregarding the flange draw-in is the part-wall stress sensor developed by Beck [11]. This piezo-electric sensor determines the stress in the part-wall by measuring the elastic deformation of the tool. This sensor was improved by Liewald [12] and Blaich [13] so that it can be installed in the tool structure without disrupting the tool surface. Blaich demonstrated the validity for state description of deep drawing process.

The approaches for material flow control in deep drawing process mentioned so far were nearly all open loop if you merely consider the deep drawing stroke. There was only one first approach for controlling the material flow at deep drawing stroke during the deep drawing stroke. Former approaches were limited except for Danckert to intervention between two working strokes, lack of measurement robustness and proper state description of the deep drawing process not applicable to curved blankholder which are standard in industry. This work will be concerned with this deficiency.

2. Tool Design
Used tool geometry is according to the work of Häussermann [7] at the author’s institute. The used tool features a segment elastic blankholder with ten hydraulic pistons and there is one for every segment. Each piston applies a different blankholder force to the corresponding segment. The segment elastic blankholder is used as an actor for the developed closed loop control. It is designed in a way that it provides a homogenous contact pressure distribution. A Bosch Rexroth servo valve controls the hydraulic pressure in each piston. These ten Servo valves allow a step function response time of 15 ms and this high sensitivity allows a high system dynamic. They calculate autonomously the valve aperture based on the current pressure in the hydraulic piston together with the demanded force by the orifice formula. Closed loop controller merely requires the demanded force. At maximum hydraulic pressure each piston provides 250 kN of force which accumulates to 2500 kN. This force is completely transferred into blankholder force. Increasing the pressure in a piston is increasing the contact pressure(blankholder force in the corresponding blankholder segment. This tool layout allows
a theoretical drawing depth of 150 mm where only 120 mm are usable for this part geometry. In Figure 1 the segment elastic blankholder and its working principle is presented.

![Enhanced Contact Stress](image)

**Figure 1.** The working principle of the segment elastic blankholder, which is used in the experimental tool for verifying the new closed loop control approach as actuator.

A valid state variable, which describes the state of forming process properly, is crucial for a suitable closed loop control. The best is to establish a direct correlation between the in- and output of a system. As state variable in current closed loop control, the part-wall stress is used as state variable in current closed loop control. It is measured by a piezo-electric sensor Kistler 9247a which is installed in the tool punch. The Kistler 9247a measures the elastic deformation of the tool punch which correlates directly to the stress in the part-wall. The advantage of using the part-wall stress for a constant product quality in deep drawing processes is that large parts of the process variables such as tribological effects, material properties as well as the temperature of the drawing tool are implicitly taken into account. So the control quality is higher compared to control loops using edge draw-in which suffers from limited sensitivity with respect to strain distribution induced in part bottom and part wall zone during ram stroke which displays the true quality of drawn shell. The measurement of edge draw-in is not applicable to complicated deep-drawing parts with curved blankholders either. Another advantage of the used part-wall stress sensor is that it finds its position independently in the tool structure. In that way possible problems with curved blankholders are avoided just as the sensor can be positioned as close as possible to the forming zone that is needed. This reduces possible measuring noise, strengthens the measuring robustness and reduces the influence of local effects like scattered lubrication. The sensor is positioned 10 to 15 mm below the surface of the punch in the bissectrix of the corner, the experimental tool and its features are shown in Figure 2.

![Experimental Tool and Features](image)

**Figure 2.** The used experimental tool (a), the schematic illustration of the position into punch structure of Kistler sensor (b/c), the laser displacement sensors (d), and used servo valves (e).
Blaich and Liewald conducted various studies on the validity of the measurement and showed that part-wall stress correlates directly with the strain distribution in the part which represents the main influence on part quality. The part-wall stress sensor provides a nearly linear proportional correlation between the signal and the acting part-wall stress. Additionally, there were 4 laser displacement sensors installed for measuring the edge draw-in and they are only used for scientific analyses.

3. Control loop

For affording a control intervention during the deep drawing stroke, a convenient and efficient closed loop has to be established. It has to integrate a sufficiently fast sensor and must provide high frequencies in data conversion as well as calculating the manipulated variable. Moreover, the delay of the system itself and the servo valves have to be considered. The controller itself is conducted as a PI-Controller. It calculates the needed manipulated variable as desired pressure in the corresponding hydraulic pistons by a transfer function. This leads to a factorial modified retention of the part flange which is caused by action of force of the corresponding hydraulic piston and the surface pressure between blankholder and matrix. The current feedforward follow-up closed loop controller is realized on a Beckhoff PLC. The used time step was selected with 500 ns which leads to a threshold frequency of 1000 Hz. In retrospect to the dynamic of deep-drawing process, this selection provides a sufficient robustness. The ten analog inputs of the part-wall stress sensors and the 4 analog inputs of the laser displacement sensors were filtered by an FIR-lowpass filter with a threshold frequency of 96 Hz for reducing the white noise.

4. Control Strategy

For enabling a sufficient control intervention, a sophisticated and efficient control loop with a convenient model was developed. The feedback system for the closed loop control is modelled as a single input single output system (SISO) for each segment of the blankholder and its corresponding part-wall stress sensor. This feedback system is applicable to all other segment/sensor pairings, so the system can be easily expanded into the needed multiple input multiple output (MIMO) system. Controller design is always closely related to a valid model of the controlled system, which has to be established. It is used for the identification and calculation of the gain factors. A valid model is always crucial for the performance of the closed loop system. For gaining a highly sophisticated solution for the existing problem, a feed forward trajectory follow-up closed loop control is used. The basic model may be defined as:

\[ x(s) = \Phi x(s) + \Gamma u(s) \] (1)
\[ y(s) = C x(s) \]
\[ x^T(s) = [y(s)y_1(s) ... y_n(s)] \]
\[ u^T(s) = [u(s)u_1(s) ... u_n(s)] \]

Where \( \Phi \) is the system matrix, \( \Gamma \) and \( C \) represent the input and output matrices, \( x^T(s) \) represents the state vector and \( u^T(s) \) represents the input vector of the system. The displacement of the press ram is the argument \( s \) of the system. It is used because the ram displacement is always distinctive in a metal forming process. The scalar values \( x(s) \) and \( u(s) \) represent the current output and input of the system. The state variable used for governing the process is the part-wall stress as mentioned before. Its control deviation is defined by \( e(s) \) where \( y_d(s) \) is the desired value predetermined by the precalculated target trajectory. There are two possible methods for gaining the target trajectory. It is calculated by simulation or by measuring without a reference process stroke. The used controller is a PI-controller. The system showed no high dynamic behavior, so there is no need for a derivative term. The closed loop system is designed as a feed forward control system, so the system input consists of two terms, the feed forward term \( w(s) \) and the controller term \( AU(s) \). Both inputs are dependent on the argument of the system, the ram displacement \( s \):
\[ \Delta u(s) = K_G * e(s) \]  
\[ u(s) = w(s) + \Delta u(s) \]  

In Figure 3 the used closed loop is illustrated schematically. All features of the used closed loop are considered.

\[ \text{Figure 3. Illustration of the control loop, } y_d(s) \text{ is the reference part wall stress and } w(s) \text{ is the input of the feedforward controller, } u(s) \text{ is the pressure in the hydraulic piston, } s \text{ represents the punch displacement.} \]

5. Simulation

Desired trajectories for trajectory follow-up control could be generated by measuring the respective part-wall stresses at a reference stroke or by calculating them via stochastic simulation. For carrying out stochastic simulation, several programs have to be coupled in a cosimulation. In this cosimulation LS-Dyna calculates the single FEM-Simulation, OptiSlang is used for the stochastics and Excel carries out data processing. The cosimulation is coordinated by a batch script. The virtual part is graduated into 10 zones, correlated to the blankholder segments and the bottom of the part. This allows more accurate simulation results. The results of the sensitivity analysis and the zone graduation can be seen in Figure 4.

\[ \text{Figure 4. Illustration of the simulation approach for generating optimized desired trajectories for the feedforward trajectory follow-up closed loop control with OptiSlang and ARSM optimization algorithm.} \]
In the frame of stochastic simulation a sensitivity analysis was carried out at first. The sensitivity analysis determines the correlations between the blankholder segments and the part zones. The used input variables were the blankholder forces of the segments which were related to the output variables, thinning in the part zones and the wrinkling criterion according to Doege [14]. There were 120 single simulations carried out with a basic contact pressure of 2 MPa. This contact pressure was varied by +/- 50%. This study enables to determine the influence of every blankholder segment on the results of forming process. In the next step the optimized desired trajectories for the control loop were generated by this simulation approach. Providing the processed part with selective properties is one advantage of virtually generated desired trajectories. Rising the possible work flow in an economic one is another. For achieving these goals, an Advanced Response Surface Method (ARSM) optimization with current simulation approach was carried out. The objectives of the optimization were to achieve a thinning between 8 to 10 % in the 10 blankholder related part zones, 10 to 12 % thinning in the bottom of the part and a wrinkling criterion value as small as possible. The input of the optimization was the blankholder force of each segment varied in an interval of 0 to 150 kN. The ARSM algorithm determined the simulation which best meets the set optimization objectives. Each 4 mm of drawing depth in simulation the virtual part wall stress was written into a file, a discrete virtual measurement of the part-wall stress in the optimal simulation. In these discrete virtual measuring points A curved one by Matlab is fitted in these discrete virtual measuring points. The best fit method chosen was mathematical norm second order, the so called Euclidean norm.

6. Experimental Result

The proposed control system described in Section 3 has been implemented into the experimental tool described in section 2 using the control hardware described in section 4. Multiple experiments were conducted for commissioning the closed loop controller and for determination the operational capability of the feedforward trajectory follow-up control. Also first experiments with desired trajectories generated by simulation were conducted. In Figure 5 it can be seen the graphs a set point and process variable as long as the part zone distribution.

![Graph of set point to the process variable of controlled blank holder segments 4 and 9 (plus workpiece) (a). Zone configuration of part and blank holder area (b).](image)

The control approach proved very suitable for the confronted tasks, the control deviation between the set point and the process variable were neglectable. For gaining more information about the robustness of the control approach there was conducted an extensive experimental design. The verified objectives were the robustness against wrong positioning in different directions, a wrong sheet size (sheet too big or too small on the circumference), inaccurate lubrication and aging material. The used sheet metal material was HX340 as a steel alloy and AA6016 as an aluminum Alloy. The aluminum alloy was aged 2.5 years. Every objective was conducted each with a controlled blankholder and a conventional blankholder, for comparison.
The results show, that the new control approach is convenient for practical applications. The PI-controller showed sufficient capabilities for the existing dynamics, but can be further optimized. Analyses of the results have proven that the closed loop is excellent for achieving repeatable part quality despite of strong process uncertainties. It is capable to settle wrong positioning of 10 mm in different directions, wrong lubrication and wrong sized sheet metal of 10mm on the whole circumference. The achieved drawing depths were significantly higher than with conventional blankholder even when there were process disturbances. In Table 1 a detail of the results of the robustness study is presented.

Table 1: Excerpt of the experiments on robustness carried out by use of the closed loop control.

| Mode       | Material | Drawing Depth (mm) | Disturbance          | Result | Max total Blankholder Force [kN] |
|------------|----------|--------------------|----------------------|--------|---------------------------------|
| conventional | AA6016   | 39                 | Wrong pos. 10 mm     | Ok     | 420                             |
| controlled | AA6016   | 51                 | Wrong pos. 10 mm     | Ok     | 461                             |
| conventional | AA6016   | 39                 | Sheet 15 mm smaller  | Tear   | 420                             |
| controlled | AA6016   | 51                 | Sheet 15 mm smaller  | Ok     | 451                             |
| conventional | HX340    | 64                 | Sheet 15 mm larger   | Tear   | 1040                            |
| controlled | HX340    | 83                 | Sheet 15 mm larger   | Ok     | 872                             |
| conventional | HX340    | 64                 | Sheet 15 mm smaller  | Wrinkles | 1040                           |
| controlled | HX340    | 83                 | Sheet 15 mm smaller  | Ok     | 881                             |

Additionally the installed laser displacement sensors, which are installed at the experimental tool, were used for analysis of the flange draw-in. For analyzing the accuracy of prognosis of the flange draw-in, there were conducted multiple experiments with identical drawing depth. By introducing different process disturbances like wrong positioning or bad lubrication, there were generated in-spec parts and scrap parts with the same drawing depth. The flange draw-in was not showing a clear tendency behavior which allows an exact determination if there is a good part or a scrap part on hand. The flange draw-in in these experiments showed more a scattered than a determined behavior, which is not convenient for a state variable in a controlled process. The flange draw-in was measured at four positions at the process, which all show comparable results. It is assumable, that the flange draw-in is too much affected by different process disturbances. A high sensibility of the measurement value is inappropriate for a state variable. Further investigations have to be conducted on this special objective for final assessment. In Figure 6 the results of the flange draw-in at the two laser displacement sensors are presented.

Figure 6. Flange draw-in of several experiments at segment 5 (a) and between segment 7 and 8. In-spec parts and scrap are not identifiable by flange draw-in.
7. Summary and Outlook
A novel approach for the closed loop control of deep drawing process with control intervention during deep drawing stroke was introduced. The control method chosen is a feedforward trajectory follow-up closed loop control. The experimental tool setup was described as long as the technical implementation of the closed loop control. Also the theoretical background of the control strategy was described. Additionally the simulation and optimization approach for gaining desired trajectories was introduced. Finally the experimental results were presented, the gain in robustness in deep drawing process due to the new control approach as long as the controller performance. Furthermore there was conducted a study on the ability of flange draw-in as state variable in deep drawing close loop control, which suppose its inconvenience.

Further investigations have to be conducted on control optimization and trajectory generation by simulation. Also there has to be done more detailed analyses on signal dynamics and the ability of flange draw-in as state variable.

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