Potentials of an adaptive blank positioning to control material and process fluctuations in deep drawing

David Briesenick*, Mathias Liewalda and Patrick Cyron*

Institute for Metal Forming Technology, University of Stuttgart
Holzgartenstr. 17, 70174 Stuttgart, Germany

*david.briesenick@ifu.uni-stuttgart.de

Abstract. Series production of sheet metal components in press shops is permanently subjected to an increasing pressure in time, cost and quality. Varying sheet metal properties due to batch fluctuations and changing process conditions lead to an increase of try out time phase and scrap rate, resulting in a demand for adaptive control strategies for deep drawing. Today, these challenges are met by integrating sensors and actuators into tool structure which measure and control part quality, mainly through blank draw-in. However, such tool-based control systems require a complex and cost-intensive modification of the existing die or press technology. Against this background, the active adjustment of blank position prior the deep drawing process realized with an intelligent transfer and positioning system as a promising approach towards economic and technical aspects. This paper deals with blank positioning and its sensitivity to quality-related failures of deep drawn sheet metal components like splits and wrinkles. Therefore, a numerical study was conducted on a deep drawing process of an exemplary structural part geometry, wherein a typical fluctuation of material parameters and variation of local friction conditions was simulated. Subsequently, correlations between process disturbance and blank draw-in were elaborated, thus using local draw-in values as controlled variables for a closed loop system. Simulation results showed that the manipulating parameter, i.e. the blank position prior deep drawing, reveals a significant influence on the draw-in and therefore on the component’s quality. An essential finding of this study is the numerical proof of concept for this new deep drawing control strategy, demonstrated for different process conditions. Finally, disturbances in the deep drawing process considered could be successfully controlled by adapting the blank position.

1. Introduction
In large-scale production, quality of deep drawn sheet metal components is substantially affected by material and process fluctuations. Controlling such production fluctuations therefore poses a major challenge for the robust and economical design of respective series forming processes [1]. In this respect, process monitoring strategies and active control systems for forming processes have been developed in the course of various research activities and constantly advanced during the recent decades.

Implementation of closed loop control or plain monitoring requires measurement of quality related control variables, allowing direct or indirect identification of commonly used failure criteria such as splits and wrinkles. Here, indirect identification of splits and wrinkles is enabled, for example, by measuring process forces or blank draw-in. Latter is frequently used in practice and can be detected by using laser-optical [2], tactile [3], inductive [4] or piezo-resistive [5] measuring methods. Reliable detection
of component defects via force measuring depends heavily on the positioning of the sensors and is limited for irregularly shaped components [6]. On contrary, measuring the part wall stress by using piezo force transmitters integrated beneath tool surface allows reliable assessment of emerging splits and wrinkles [7], [8]. Split detection during deep drawing can additionally performed by using highly sensitive sensors for noise emissions [9], [10]. In-situ measurement of wrinkle formation in part wall and flange areas, however, requires sophisticated sensor concepts applying for example eddy current [11] or strain gauge sensors [12], [13] and is therefore today only used in research applications.

Tool based measuring devices, such as those mentioned above, are usually subjected to high mechanical and thermal loads and can only detect small gauge regions. Thus, additional optical measuring technology is regularly integrated prior to or directly in subsequent operations in order to detect blank draw-in with wide resolution [14], [15]. An immediate classification of part quality can also be based on visual and contactless sensors such as thermal imaging cameras [16] or monochrome cameras [17]. Common practice in press shops is nevertheless a visual inspection by workers at the end of the line or off-line sampling [15].

Active control interventions for deep drawing mainly address adjustment of the sheet metal blank’s draw-in. Therefore, different actuator concepts have been developed in the past years which are used to influence restraining forces in flange areas. In this respect, segment elastic blankholders and correspondingly placed hydraulic pistons enable a customized pressure distribution [18]. Height adjustable draw beads also provide a sensitive but technologically complex controllability of restraining forces [19]. Active spacers, which are mounted on the binder along the blank boundary, allow a controlled bypass of blankholder forces and thus a local controlling of material flow [20]. A comprehensive summary of sensor and actuator concepts for closed loop process control in press shops is given by [1], [6] and [21].

Variation of blank position prior to deep drawing is usually classified as process uncertainty and therefore prevented in most tool structures by using gages. However, the study presented in this paper aims to identify existing correlations between an adaptive blank position and part quality related failure criteria such as splits and wrinkles in order to use them for active process control.

2. Modelling and numerical study

The numerical study presented here included a sensitivity analysis and an exemplary compensation of process disturbances for the deep drawing process of the complex sheet metal component “Mini-Tunnel”. For modelling, simulating and evaluating this deep drawing process considered, commercial FEM code was used in combination with the AutoForm R8 user interface. The tooling setup consisted of a multiple curved blankholder, a tiered die face with different drawing depths and an octagonal trimmed blank (see Figure 1a)). Process fluctuations such as locally increased tool wear or inhomogeneous lubrication were modelled by defining two exemplary local friction areas on the punch surface. Here, the local friction coefficients $\mu_{\text{concave}}$ and $\mu_{\text{convex}}$, which were assigned to the punch radii as shown in Figure 1a), infact diverged from the standard value $\mu_{\text{global}} = 0.15$. Figure 1 b) further shows the geometric parameter space within which the blank position before deep drawing was varied during the numerical investigations. While the shape of the blank maintained constant, center of inertia was varied between +6 mm and -6 mm in x-direction, respectively in y-direction (see Table 2).

![Figure 1. a) Simulation setup of the Mini-Tunnel tool with local friction noise ($\mu_{\text{concave}}, \mu_{\text{convex}}$) and b) variation of blank position prior deep drawing.](image-url)
For the numerical investigations, cold rolled mild steel CR4 having a sheet thickness of \( t = 1 \) mm was selected as blank material. Properties of this sheet metal material are summarized in Table 1 and available in current standard database of AutoForm R8. To simulate process related batch variations of the material, fluctuations were estimated for the hardening exponent \( n \) (15 \%) and the anisotropy coefficient \( r_m \) (40 \%) according to \[22\]. The other material parameters maintained constant in order to limit non-identifiable noises and cross correlations and thus to directly assign calculated process influences to the simulation parameters under consideration.

**Table 1.** Material properties of CR4 and variation of hardening exponent \( n \) and anisotropy \( r_m \) according to \[22\].

| Material | \( t \) (mm) | \( E \) (GPa) | Yield Strength (MPa) | UTS (MPa) | U.E. (%) | \( n \) | \( r_m \) |
|----------|-------------|--------------|---------------------|-----------|----------|--------|--------|
| CR4      | 1           | 210          | 146                 | 286       | 25.4     | 0.22   | 1.87   |

Gained simulation results discussed in the following chapter were obtained by a numerical study in which both the local friction conditions and the described material parameters (\( n \) and \( r_m \)) were varied within mentioned limits in Table 2. The parameter setup was based on a Latin Hypercube Sampling (LHS) with over 100 runs and implemented in AutoForm-Sigma. For evaluation, result variables such as draw-in, splits and wrinkles were analyzed with regard to their correlation to design (blank position) and noise variables (\( r_m \), \( n \), \( \mu_{concave} \), \( \mu_{convex} \)). As reference, a baseline simulation was run with nominal process parameters (see Table 2).

**Table 2.** Process parameters and corresponding variations for deep drawing of a Mini-Tunnel.

| Parameter                  | Nominal | Variation         |
|----------------------------|---------|-------------------|
| Local friction \( \mu_{concave} \), \( \mu_{convex} \) | 0.15    | 0.05 \ldots 0.25  |
| Blankholder force \( F_{BH} \) (kN)      | 530     | constant          |
| Blank position X-direction (mm) | 0       | -6 \ldots +6     |
| Blank position Y-direction (mm)   | 0       | -6 \ldots +6     |

### 3. Results and discussion

#### 3.1. Sensitivity of process variations on blank draw-in

The above mentioned setup of the numerical study was initially evaluated in terms of correlations between process or material variations and the blank draw-in after deep drawing. Therefore, friction and material parameters were varied individually and independently within the boundaries defined in Table 1 and 2. Subsequently, the simulation results obtained via this parameter setup were assessed regarding calculated blank draw-in and measurement distance between blank edge and punch opening line (POL). Figure 2 reveals the influence of local changes in friction and material batch variations on the blank draw-in at four designated positions. This was done by varying only one parameter at a time while the others remain constant. In particular, it can be seen that the friction conditions at the large punch radii (\( \mu_{convex} \)) lead to a wide scatter of draw-in in the straight part areas (see Position 2 and 4). In worst case, the asymmetric part geometry combined with wide variation of friction conditions can cause edge movements beyond the punch opening line, thus resulting in scrap. Another remarkable finding is the impact of the fluctuating anisotropy \( r_m \) and material hardening behaviour (n-value), which can also lead to critical draw-in in straight part areas (see Position 2 and 4). Summarizing, the simulation results presented here reveal the sensitivity of local friction conditions and material fluctuations on the blank draw-in during deep drawing, which may lead to component failure. For this reason, an adaptive control of the blank positioning is recommended to compensate the mentioned process fluctuations.
3.2. Sensitivity of blank position on part quality

Further, on in the numerical study, the impact of blank positioning prior to deep drawing on the part quality was investigated. To identify existing correlations between blank position and part quality, high-stress part areas were first identified (see Figure 3 a), b)). Subsequently, the simulation results obtained were evaluated in terms of split and wrinkle formation, especially in high-stress areas. For all simulation runs \( m \) and each parameter value \( x_i \), maximum failure values \( y_i \) were extracted and accumulated to expected values \( x, \ y \). Afterwards, the Pearson’s linear correlation coefficient \( r \) was calculated according to formula (1) in order to determine strong positive \((+1)\) or negative \((-1)\) correlations between input and output variables.

\[
r = \frac{\sum_{i=1}^{m}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{m}(x_i-\bar{x})^2 \sum_{i=1}^{m}(y_i-\bar{y})^2}}
\]

Regarding splits, Figure 3 c) reveals a pronounced sensitivity to the blank positioning in X-direction in the blank area S-2 and to positioning in Y-direction in S-1. For example, a displacement of the blank in positive X- and Y-direction leads to a risk of splits in S-2 but increases safety margin in area S-1. On the opposite, wrinkling occurs reciprocally in W-1 and W-2 when moving the blank in X-direction. This behaviour corresponds to the state of knowledge and proves the validity of simulation but raises questions whether an optimal blank position exists for different process conditions.

![Figure 2. Influence of process and material variation on blank draw-in measured and represented by the distance between blank edge and Punch Opening Line (POL).](image)

![Figure 3. Impact on a) splits and b) wrinkles of blank position prior deep drawing and c) corresponding linear correlation coefficients.](image)
3.3. Exemplary disturbance and process control

For assessing the potential of adaptive blank positioning with regard to forming process control, a metamodel-based optimization study was performed using exemplary practical use cases. The parameter variations assumed in these cases are described in the following and refer to nominal settings already listed in section 2. Firstly, it was assumed that due to tool wear and lack of lubrication, friction ($\mu_{concave}$) is locally increased up to 60 % in the tiered punch area. Secondly, batch change was considered to cause fluctuations in the anisotropy $r_m$ of up to 6.1 % and in the hardening exponent $n$ of up to 1 %. Compared to the nominal process design (Figure 4 a)), such process and material fluctuations assumed do result in part defects like splits and excessive thinning localized on the tiered part geometry, as shown in Figure 4 b). Afterwards, a new blank position was searched to compensate the above mentioned defects based on a calculated metamodel and the sensitivities received before. Figure 4 c) shows the simulated forming results for this adapted blank position, whereby the blank is moved 3.5 mm in negative X-direction and 1.5 mm in positive Y-direction. This displacement leads to a change of restraining forces in the flange area and entails different strain paths. Consequently, the risk of splits and excessive thinning is strongly reduced and the process is stabilized again. Furthermore, part quality relevant shape deviations due to springback are kept constant at a maximum of 0.9 mm at the left straight part area. In addition, the edge of the blank still provides a safety margin towards POL and part quality is ensured. In the end, the flange area reveals a distribution of thickening and compression comparable to the nominal setup.

Figure 4. Nominal process design a) and the impact of process variations b) and blank positioning c) on the forming result.

4. Conclusions and outlook

The numerical study presented in this paper demonstrated a new approach for controlling the deep drawing processes of complex sheet metal parts using adaptive blank positioning. To identify correlations between part defects (split, wrinkles) and blank position prior deep drawing, a sensitivity analysis based on numerical studies was carried out, taking into account commonly appearing material and process fluctuations. Overall, a dominant and sensitive correlation was observed between blank position and failure criteria in critical part areas of the given tool geometry. Based on these findings and as a proof of concept, exemplary process disturbances were numerically induced and compensated by a metamodel based optimization of blank positioning. Further, the investigations revealed and confirmed a detectable influence of commonly process disturbances on the blank draw-in. Thus, the manipulating parameter blank position and a simple and state of the art measurement of controlled variable blank draw-in provide a solid basis for such applicable closed loop system in future.
Figure 5 shows concepts of practical implementations of such a new control approach. Today, many press lines are already equipped with flexible transfer systems such as multi-axis robots which could be used to easily adapt blank position prior to the deep drawing process (Figure 5 a)). In general, robust and high productivity is ensured by fixed gages installed along blank circumference. According to Figure 5 b), the implementation of the new control approach for the given blank guide system could be achieved by using uniaxial movable and cooperating gages. The proposed control system is able to adapt blank position prior to deep drawing and may even react automatically to changes of blank size, by using control concepts as analytical models or artificial neural networks. In comparison to conventional tool based control systems, an adaptive blank positioning system promises a cost-effective, insignificant stressed and tool independent applicable solution. In future work, extended numerical studies and experiments for different part geometries need to demonstrate the viability of the proposed control strategy. Development of a blank positioning system like the below proposed adaptive gages enables endurance testing to evaluate the potentials of scrap reduction.

![Figure 5. Concepts of the implementation of adaptive blank positioning with a) press transfer system and in case of gages b) a linear movable and controlled blank guiding system.](image)

References

[1] Allwood, J.M. et al., 2016, Closed-loop control of product properties in metal forming, CIRP Annals - Manufacturing Technology, vol. 65, no. 2, pp. 573–596.
[2] Munser, R., Jacubasch, A., Wagner, U., 2004, Messen beim Pressen, wt Werkstattstechnik online, vol. 94, pp. 544–545.
[3] Straube, O., 1994, Untersuchungen zum Aufbau einer Prozeßregelung für das Ziehen von Karosserieteilen, Dissertation, Technische Universität Berlin.
[4] Forstmann, U., 2000, Induktive Wegsensoren zur Überwachung und Regelung des Blecheinzugs beim Tiefziehen, Dissertation, Technische Universität Berlin.
[5] Biehl, S., Staufenbiel, S., Hauschild, F., Albert, A., 2010, Novel measurement and monitoring system for forming processes based on piezoresistive thin film systems, Microsystem Technologies, vol. 16, pp. 879–883.
[6] Beck, S., 2004, Optimierung der Zargenspannung beim Ziehen unregelmäßiger Blechformteile, Dissertation, Universität Stuttgart.
[7] Blaich, C., 2012, Robuster Tiefziehprozess durch Erfassung und Optimierung der örtlichen Bauteilqualität, Dissertation, Universität Stuttgart.
[8] Barthau, M., Liewald, M., Held, C., 2017, Improved process robustness by using closed loop control in deep drawing applications, Journal of Physics: Conference Series, vol. 896, no. 1.
Haupt, H., 2003, Ein auf der Schallemissionsanalyse basierendes Verfahren zur Risserkennung in Umformprozessen, Dissertation, Universität Paderborn.

Behrens, B.A., Hübner, S., Wölki, K., 2017, Acoustic emission—A promising and challenging technique for process monitoring in sheet metal forming, Journal of Manufacturing Processes, vol. 29, pp. 281–288.

Hengelhaupt, J., Vulcan, M., Darm, F., Ganz, P., Schweizer, R., 2006, Robust Deep Drawing Process of Extensive Car Body Panels, in Neuere Entwicklungen in der Blechumformung, pp. 277–304.

Han, F., Radonjic, R., 2015, New approach for wrinkle prediction in deep drawing process, Key Engineering Materials, vol. 639, pp. 459–466.

Liewald, M., Han, F., Radonjic, R., 2015, New criterion for prediction of the wrinkle formation in deep drawing process, Key Engineering Materials, vol. 651–653, pp. 71–76.

Kraft, M., Bürgel, U., 2017, Novel concept for measurement of global blank draw-in when deep drawing outer skin automotive components, Journal of Physics: Conference Series, vol. 896, no. 1.

Maier, S.J., 2018, Inline-Qualitätsprüfung im Presswerk durch intelligente Nachfolgewerkzeuge, Dissertation, Technische Universität München.

Thamm, U., 1998, Bewertung von Tiefziehprozessen durch Infrarot-Thermografie, Dissertation, Technische Universität Chemnitz.

Gayubo, F., González, J.L., De La Fuente, E., Miguel, F., Perán, J.R., 2006, On-line machine vision system for detect split defects in sheet-metal forming processes, in International Conference on Pattern Recognition, pp. 723–726.

Siegert, K., Ziegler, M., Wagner, S., 1997, Closed loop control of the friction force. Deep drawing process, Journal of Materials Processing Technology, vol. 71, pp. 126–133.

Siegert, K., Liewald, M., Blaich, C., Kauschinger, B., 2007, Robuster Tiefziehprozess durch Ziehsickenstabhöhenregelung, vol. 97, pp. 781–791.

Faaß, I., 2009, Prozessregelung für die Fertigung von Karosseriebauteilen in Presswerken, Dissertation, Technische Universität München.

Liewald, M., Barthau, M., 2018, Adaptive control strategies for deep drawing of high performance sheet metal materials, in presented at the IDDRG 2018, Waterloo, Canada.

Sturm, V., 2013, Einfluss von Chargenschwankungen auf die Verarbeitungsgrenzen von Stahlwerkstoffen, Dissertation, FAU Erlangen-Nürnberg.