

Process Windows for Sheet Metal Parts based on Metamodels

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Abstract. Achieving robust production of deep drawn sheet metal parts is challenging. The fluctuations of process and material properties often lead to robustness problems. Numerical simulations are used to validate the feasibility and to detect critical regions of a part. To enhance the consistency with the real process conditions, the measured material data and the force distribution are taken into account. The simulation metamodel contains the virtual knowledge of a particular forming process, which is determined based on a series of finite element simulations with variable input parameters. Based on the metamodels, process windows can be evaluated for different parameter configurations. This helps improving the operating point search, to adjust process settings if the process becomes unstable and to visualize the influence of arbitrary parameters on the process window.

Keywords: Deep Drawing; Numerical Simulation; Metamodeling; Process Optimisation; Process Window

INTRODUCTION

Scattering of process parameters and material properties as well as the increasingly higher tolerance requirements often lead to robustness problems during production [1], [2]. The factors influencing robustness are not systematically measured and online action is limited to a manual intervention on a trial-and-error basis. Thus the quality of the outcome is strongly correlated to the experience of the staff and eventual corrections on the tools are costly. Other circumstances, such as the reduction of material thickness, complex geometries with sharp radii and the flexible choice of the press, limit the process stability even further.

In order to increase the significance and accuracy of the simulations, a variety of different measures are taken into account, such as the use of more accurate material models based on experiments, the consideration of the press construction and the implementation of digitised tool geometries [3]. The purpose of this work is to evaluate the influences of the process settings on the critical regions of the part. A methodological approach based on simulation metamodels is developed to find a suitable operating point, particularly by means of two-dimensional process windows. Thus the influence of a particular process parameter can be visualised and the understanding of a specific process can be improved.

PROCESS DESCRIPTION

The part presented in this work is the trunk lid of the actual B-class of Daimler, which can show several imperfections during production, such as splits, wrinkling and insufficient stretching, which can be predicted well in simulation (see Figure 2a). However, skid impact lines and sink marks are not easily detectable, because of missing meaningful, virtual result variables.

To enhance the accuracy of the material model of the DC06 steel, various experiments are used, such as tensile experiments, Bulge-Tests and Nakajima experiments. The evaluation of the material model with all its details is shown in [3]. Another improving adjustment is considering the coordinates of the cushion quills in the press construction. The acting forces from the die cushions are transferred via cushion quills to the blank holder (see Figure 1) [3].

In simulation it is common practice to use initial pressures, which are distributed homogeneously. As the tools are assumed to be rigid in AutoForm, the deflection of any tool is locked. Because of the equilibrium condition all acting forces can be reduced to one total force with a specific force application point. These simulative adjustments do not influence the simulation result [3]. This measure allows in simulation to redistribute the acting forces inhomogeneously on the binder surface by moving the force application point, in order to better map the set values on serial press.



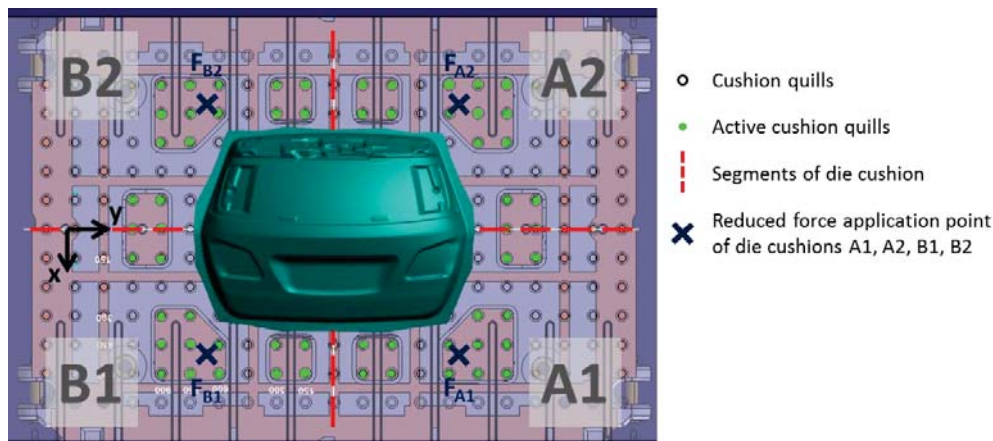


Figure 1: Binder suspension on cushion quills and segments of die cushion [3]

Once the tools have been milled, the surfaces have to be processed by hand in tool tryout. Regions, where splits, wrinkles, sink marks or skid impact lines occur, are then reworked. Furthermore, most of the efforts are put into the tryout of the drawbeads to adjust the draw-in of the blank, which is done in many loops. The influences of the adjustments made on part quality are checked after each loop in the tryout press. Therefore tool geometries after tool tryout vary strongly from the designed tool geometries of the process plan. Because of large differences between the simulations coming from the process engineering and the simulation with digitised tool geometries (with identical simulation settings), the tools are digitised after the first tryout loop with a GOM ATOS measurement system. Thus the major problems are remedied, but the complex fine-tuning is still pending.

The simulation is then built up and calculated in AutoForm R3.1. The total binder force and the coordinates of the force application point are implemented in AutoForm with the function *Columns (User def.)*. In case of the presented part, the eccentricity in y-direction can be neglected because of symmetry.

PROCESS WINDOWS

Finding a suitable operating point in the field of simulation design is often challenging. Many parameters, such as binder forces, force distributions, blank size and position are influencing the process distinctively. In many cases it is unclear how strong a specific parameter is influencing the determined quality criteria, especially when taking multiple design parameters into account. In process engineering the simulation parameters are first changed iteratively, which is strongly depending on the user's understanding of the process behaviour. Thus, the quality of the outcome and the required time for iterative optimisation correlates with the experience of the process engineer.

For more complex and larger car body shell parts, for example sidewall frames, the process parameters are optimised based on variant simulations. Depending on the number of independent variation parameters, the simulations are calculated based on a design of experiment. Then, for each detected quality criterion a metamodel can be evaluated, which allows to analyse the influences and sensitivities of the varied parameters on the specific quality criterion. Moreover, in the current state of the art different process windows can be displayed, such as one- and two-dimensional process windows based on conservative minimum/maximum analysis, convex hulls and multi-dimensional hypercubes parallel to the axes. For each of these simplification methods some information gets lost [4] [5].

For the trunk lid in this work four design parameters are optimised over 30 simulations: The total binder force, the x-coordinate of the force application point (to allow different force distributions), the force on the die inlet and the x-coordinate of the blank position. The die inlet is preventing skid impact lines. Because of the symmetry of the part, the y-coordinates of the forces and of the blank position stay constant. After simulating in AutoForm the simulation results are imported in Matlab. For each defined quality criterion a metamodel is evaluated and validated with the *leave-one-out cross validation*. The used types of metamodels are based on the *Response Surface Methodology*, *Kriging method* or *Radial Basis Functions*. The polynomial degree is limited to a quadratic base model without interaction coefficients. Each metamodel is limited by an upper or lower limit, e.g. *Max. Failure* in AutoForm (ratio between the simulated major strain and the major strain from FLC for a given minor strain [7]) at 0.8. By keeping the die inlet force and the coordinates of blank position constant at a predefined value, the contour lines of the metamodels can then be projected in the plane of the remaining parameters "total binder force – force distribution" (see Figure 2b).

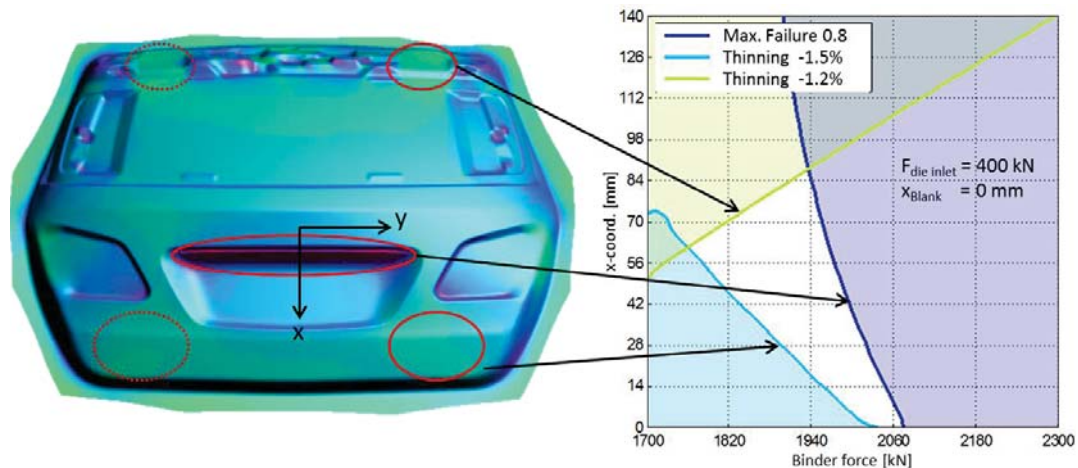


Figure 2: Definition of quality criteria (a) and their process limit in the process window (b)

The light-blue and light-green coloured regions in Figure 2b illustrate the parameter combinations, where the corresponding quality criterion regarding stretching is limiting the process. In the dark-blue region the *Max. Failure*-criterion exceeds the predefined limit of risk of splits. The remaining white triangle represents the valid process window. It shows the amount of force necessary to avoid insufficient stretching and the optimal force application point for which all of the predefined quality criteria are fulfilled. In the shown process window above this point lies around 1900 kN and 56 mm.

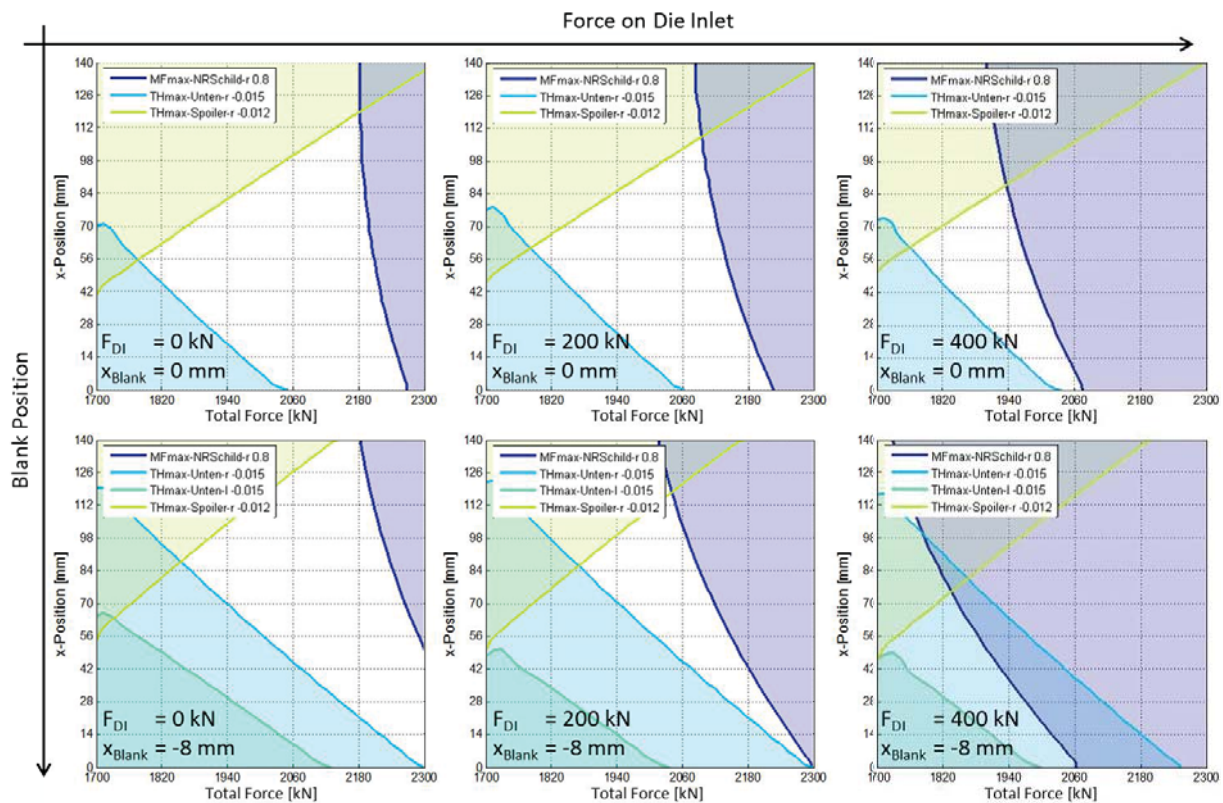


Figure 3: Set of process windows with different parameter settings

By repeating this method for different die inlet forces and blank positions a set of different process windows can be created (see Figure 3). The process windows in the upper row have a constant blank position at the nominal value of 0 mm and in the lower row of minus 8 mm. Considering the windows column by column the die inlet force stays constant at 0, 200 and 400 kN respectively. It becomes obvious, that the die inlet force does not influence the stretching

at all, whereas the failure criterion is affected significantly. The higher the die inlet force is, the smaller the process window gets, which means the robustness could be influenced negatively. On the other hand the die inlet avoids skid impact lines. Therefore a suitable compromise needs to be found, which reduced the skid impact lines to a minimum but keeps the process in a safe zone.

By moving the blank out of the nominal position about 8 mm in spoiler direction, the process boundary of the stretching in the lower part region moves upward right. This can be explained by the fact that less material is in contact with the lower binder region and consequently the material is held back less. To counteract this, the force in the near binder region should be increased, either by moving the force application point in positive x-direction (redistribution of binder force) or by raising the global binder force. Both of these measures are intended to increase the corresponding retention force on the blank. In general the movement of the blank position out of its nominal value does not enhance the size of process window. Indeed the process window is even getting smaller. Actually, with an eccentric blank position and a maximal die inlet force of 400 kN, no binder force and force distribution combination can fulfil all required limit values of the quality criteria, which means no process window would be available for this parameter combination.

CONCLUSION AND OUTLOOK

The presented methodological approach allows to visualize two-dimensional process windows as a function of two variation parameters containing predefined quality criteria. By changing additional parameters gradually and showing the resulting process windows in rows (third parameter) and column by column (fourth parameter), four-dimensional process windows can be illustrated. On one hand the changing of the size of the process window can be seen at one glance, on the other hand the individual effects of the process design or noise variables on the quality criteria can be observed. Thus this way of illustrating process boundaries provides a spatial feeling about the process window. Moreover the process behaviour of a complex part can easily be visualized and the process understanding can be enhanced. The illustrated process windows have been compared with the real tryout steps that have been done on the presented tool. As far as a comparison is possible, a very good accordance of the tendency between the virtual tryout and the real behaviour of the part could be determined [8].

Skid impact lines and sink marks cannot be predicted very well. Therefore novel result variables should be developed, in order to improve the prediction accuracy.

Furthermore the methodological approach can also be used for draw-in regions. Each draw-in measuring point can be defined as a normal quality criterion and limited by a boundary value. Based on the calculated metamodels an inline feedback control can be realised [6].

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REFERENCES

- [1] D. Hortig. *Experiences with the Robustness of sheet metal forming processes*. Forming Technology Forum 2011, Proceedings, Zürich, 2011.
- [2] P. Hora, J. Heingärtner, N. Manopulo, L. Tong. *On the way from an Ideal Virtual Process to the Modelling of the Real Stochastic*. Forming Technology Forum 2011, Proceedings, Zürich, 2011
- [3] D. Harsch, J. Heingärtner, D. Hortig, P. Hora. *Virtual tryout planning in automotive industry based on simulation metamodels*. The International Deep Drawing Research Group, Proceedings, 2016
- [4] C. Annen. *Entwicklung einer neuen Methode zur Ermittlung und Visualisierung von robusten Prozessfenstern in der Blechumformung*. Diss. ETH Nr. 20573, ISBN 978-3-906031-35-4, 2012.
- [5] N. Stander, W. Roux, T. Goel, T. Eggleston, and K. Craig. *LS-OPT User's Manual*. Livermore Software Technology Corporation, pp. 9-11, 2009.
- [6] P. Fischer, D. Harsch, J. Heingärtner, Y. Renkci, P. Hora. *Inline feedback control for deep drawing applications*. The International Deep Drawing Research Group, Proceedings, 2016
- [7] AutoForm. *Helpviewer 11.5.4*. AutoForm Engineering GmbH, Version AutoForm R3.1, 2011.
- [8] N. Schelhammer, Mercedes-Benz Cars Operation – Press line 3 & 4 (TF/PW4), Sindelfingen; *Private communications*, 2014.