Digital Twins in deep drawing for virtual tool commissioning and inline parameter optimization

Lars Klingel*1, Lars Penter2, Philip Mayer1, Steffen Ihlenfeldt2 and Alexander Verl1

1 Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, 70174 Stuttgart, Germany
2 Institute of Mechatronic Engineering, TU Dresden, 01062 Dresden, Germany

*lars.klingel@isw.uni-stuttgart.de

Abstract. Fluctuating boundary conditions and the highly nonlinear process behavior of deep drawing operations make experience-based selection of suitable control parameters difficult. Nowadays, commissioning deep drawing tools, i.e., die spotting and identification of suitable control parameters for defect-free parts, is conducted on real world try-out presses. Transferring the tools to production machines entails adaption of these initial parameters. Once production is ramped up, any changes to material properties, lubrication and press behavior require continuous manual machine parameter tuning. Virtual tool commissioning and utilizing these simulation models in the production phase to adapt control parameters would reduce time and cost over the entire life cycle of the machine and the tool sets. The virtual representative, which provides services for a plant over several life cycle phases, is also referred to as Digital Twin. In this paper, the authors present a Digital Twin concept for deep drawing presses to predict the state of the system and optimize the control parameters during the production. The integration of all involved subsystems into one system simulation and its efficient calculation is the biggest challenge. The authors combine a virtual commissioning simulation tool with a finite element model to implement all relevant properties of the deep drawing press and the interaction of its subsystems. It is shown, how the idea of a system simulation makes predictions of system parameters specific to a production situation possible, and therefore, can help to select suitable control parameters that leads to a reduction of the error rate in deep drawing.

1. Introduction

Sheet metal forming is characterized by highly automated mass production processes with repetitive motion sequences, high process forces, expensive tool sets and a low margin per part due to high material costs. In order to save resources and costs, achieving zero-defect production is one of the major quests for manufacturing companies. Due to the complexity of the process, deep drawing operations are already extensively optimized. For further improvement, computer models and real-world equipment are combined for precise predictions of the part quality along the life-cycle of the forming tools. Such a system is often referred to as Digital Twin.

The production of large car body parts is conducted on transfer presses or on production lines with several connected presses. Deep drawing is usually the first forming operation in a multi stage process (Figure 1 right). Special deep drawing presses are equipped with die cushions to provide the
blankholder force for large drawing depths. Today’s multi-point die cushions generate local cylinder forces, which then enable local blankholder forces to control material flow into the die cavity. The structure of a single action deep drawing press is shown in Figure 1 on the left.

![Figure 1. Left: single action deep drawing press with die cushion; right: production line of formed metal parts.](image)

Many interacting factors define the final part quality (Figure 2). Due to large forming forces and finite press stiffness, the interactions between process and machine cause significant press and tool deformation which influence the final part properties and are the main reason for manual die spotting during tool commissioning.

Further factors that give reason for tool commissioning are deviations between real and set (simulated in the development phase) values of die cushion forces [1] and uncertainties regarding lubrication, sheet properties and final thickness distribution [2].

![Figure 2. Influences on the deep drawing process, TC – adjustable during tool commissioning, P – adjustable during production.](image)

Currently, tool commissioning is conducted on extra try-out presses and comprises five major steps (Figure 3). The cost share of tool commissioning as part of the tool development process is 31% [3]. Spotted die and blankholder surface as well as identified control parameters are re-evaluated on the actual production press and, if necessary, adapted. The tool set of modern production presses changes every two hours; this additional commissioning procedure takes around five minutes [4].
A complete transformation of tool commissioning into the virtual world would save time and resources. Virtual commissioning became a vital tool for many applications in the field of production engineering. It is a method to detect errors and validate control software in the engineering phase of a production system [5]. In virtual commissioning the control device is connected to a simulation model of the production system [6]. This makes software tests possible before the real machine is set up and provides a safe testing environment where problems which would occur due to the control software, can be found before the machine goes into operation.

The established form of virtual commissioning is the hardware-in-the-loop simulation where a real control device (hardware and software) is connected to the model of the production system with a fieldbus [7]. In this setup, real-time requirements for the simulation arise because the simulation model must provide deterministic calculation results in the cycle time of the real control system and fieldbus. Another configuration for virtual commissioning is the software-in-the-loop simulation where the software is running on an emulated controller and the simulation and control software are synchronized on a virtual time axis [5].

Figure 4 shows virtual commissioning as a phase of a production system’s lifecycle. To build the simulation models, all relevant information has to be integrated such as computer aided design (CAD) models for example. In [8] virtual commissioning simulation models are described as a path to realise the vision of a Digital Twin. This is the reason because virtual commissioning simulations are calculated in real-time, contain lots of different previous artefacts and are available anyways in a modern development process before the real production system goes into operation. In addition to simulation models, Digital Twins contain data of the system and services for the usage of the models and data.
Finite element (FE) forming simulations allow the prediction of the part quality [3] in advance of the actual commissioning and production process [9]. Because forming simulations neither comprise machine influences such as press and tool elasticity, dynamics of hydraulic drives, the behavior of the control device, nor do they update their parameters, the gap between numerical prediction and reality is too large to eradicate real world tryouts and manual adjustments during production [10]. During production, lubrication and sheet properties fluctuate [2], machine properties change over time due to wear and the behaviour of hydraulic system shift due to temperature changes and cause quality problems or even final part defects (Figure 2). These cannot be addressed during tool commissioning and need adjustment while the fabrication process is running, preferably without machine standstill.

A fully adaptive system is needed to achieve a completely error-free production. In literature, such a system is often referred to as Digital Twin [11]. This paper presents an approach to use a system simulation as a base for Digital Twins in deep drawing.

2. Digital Twin of forming process and equipment

In this section a concept for the usage of Digital Twins in deep drawing is presented, which can be subdivided into three steps which are listed in ascending order of complexity: Virtual tool commissioning, inline parameter optimization and online process control. These steps mainly differ in terms of the use case and the real-time requirements of the underlying simulation model, see Figure 5.

2.1. Step 1 - Virtual tool commissioning

Virtual tool commissioning can replace the necessity of try-out presses or complement them for the selection of suitable control parameters in the commissioning phase of deep drawing tools.

Necessary adaptions on the deep drawing tool and the control parameters can be evaluated in the simulation. The main reason for the current usage of try-out presses is the absence of a comprehensive system simulation and fluctuating boundary conditions. A system simulation which combines the machines behaviour and deep drawing process information would be the basis for a Digital Twin as a replacement of try-out presses.

2.2. Step 2 - Inline parameter optimization

Not everything can be tested on a try-out press or on a Digital Twin in the try-out phase. This is because there are chancing parameters in the environment, which have an influence on the deep drawing press. A prominent case is the change of material properties during the production. The variation of forming properties or thickness of the sheet often results in defective parts. To solve this problem, the authors present an approach for an inline parameter optimization in deep drawing, which is shown in Figure 6 with the described use case of changing material properties.
Figure 6. Digital Twin during the production for inline parameter optimization.

The concept requires measurement of the mechanical properties of the metal sheet before deep drawing. Normally the material quality changes if a new coil is used. A way to measure the material properties inline before the sheet is deep drawn are inductive sensors [12]. If the current material, tool and control data is transferred to the Digital Twin, the quality of the future part can be predicted and used by feed forward control algorithms to adapt the control parameters (Option II) or eject the blank because of poor material properties before being processed (Option I). For a continuous improvement of the Digital Twins models and a validation of the control the predicted part can be compared to a measured part in the quality control afterwards.

2.3. Step 3 – Online process control
The application of Digital Twins depends on the accuracy and calculation time of the underlying model. If the model can be calculated in real-time, it could act as an observer for closed-loop control. In [13] this is described as online closed-loop scheme. Because of the highly nonlinear behaviour and difficulty to measure the current state of the sheet during the forming process a model-based observer would allow the design of closed-loop control on parameters such as the sheet thinning. Currently, the computation of FE process models for deep drawing consumes too much time, which makes data driven models necessary for this concept.

3. Concept and implementation of the model
The concept and its implementation in the following chapter address the first two steps of chapter 2. The main focus of this work is the Digital Twins underlaying simulation model. Which is implemented in form of a co-simulation. First the concept of the co-simulation is shown which combines the machine and process behaviour. Afterwards the used application example is introduced and the used simulation tools as well as a schematic physical diagram of the model is shown.

3.1. Concept for the co-simulation environment of the Digital Twin
For the realization of the Digital Twin, a detailed model of the system which includes the machine and process is needed. In this work the system simulation is implemented in form of a co-simulation. In Figure 7 the blue parts represent the parts of the machine simulation, which is calculated in a virtual commissioning tool. The forming part on the right in the middle is calculated in an FE tool. Those simulations are coupled during the runtime with the functional mock-up interface [14]. The system boundaries and resulting coupling signals can be found in Figure 7.
Virtual commissioning simulation tools provide a connection to control devices. This makes it possible to transfer current control parameters to the machine simulation. In case of step 2, the measured data from the real press can be transferred to the simulation model additionally. The simulation model provides a predicted part quality to the control which allows simulation-based control functionalities.

3.2. Application example and simulation setup
A hydraulic deep drawing press which is located at the Institute of Mechatronic Engineering at the TU Dresden served as example machine. This press features a hydraulic slide with a maximum force of 2500 kN and a 4-point hydraulic cushion with a maximum force of 1000 kN.

The preliminary work of TU Dresden is the basis for the implementation of the simulation model [10][15]. As an example part a rectangular pan is used.

The co-simulation employs ISG-virtuos for the simulation of the machine (see Figure 8, right top) and LS-DYNA for simulating the forming process (see Figure 8, right bottom). These simulation tools are coupled with the functional mock-up interface which comprises the interface signals shown in Figure 7. For a detailed description of the ISG-virtuos coupling with LS-SYNA refer to [16]. The left side of Figure 8 shows the physical abstraction of the system’s elasticity and dynamic in ISG-virtuos and the system boundaries to LS-DYNA. A virtual CNC controller which is integrated into the system simulation generates the input trajectory, which is shown in the diagram (red arrow). From the perspective of virtual commissioning this setup is called software-in-the-loop configuration.

In a software-in-the-loop simulation the communication between the model of the plant and the control is synchronized on a virtual time axis. The simulation in ISG-virtuos is running with a step size of 1ms. LS-DYNA uses a variable step size and is not real-time capable. The co-simulation is slowed down by the FE simulation and the functional mock-up interface, which uses TCP/IP for the data transfer.

Figure 7. Structure of the control coupled co-simulation environment.
4. Results
In this chapter the authors show how the simulation can be used for a prediction of the part quality, which is necessary for virtual tool commissioning and inline parameter optimization.

The part quality is measured by the maximum sheet thinning with the target to get close to 20% but not to exceed it, which leads to a hardened sheet on the one side and avoidance of cracks on the other side. In Figure 9 there is shown the distribution of the sheet thinning with the changing parameters strength coefficient and input sheet thickness for a static blankholder force. In the bottom part of Figure 9 a parameter study is shown for the steel DC04 with the same varying material properties and with three different blankholder forces. In each graph the other material property is constant. The values and the variation of the parameters are based on DIN EN 10130 [17] and DIN EN 10140 [18]. The parameter variation which is depending on the input material can be measured before the sheet is deep drawn in the press. In the parameter study the characteristic curves for varying blankholder forces are shown. During virtual tool commissioning and inline parameter optimization those plots can be calculated after boundary parameters changed, like a new input sheet with different material properties. With this calculation the blankholder force which leads to a maximum sheet thinning close to 20% can be chosen. In Figure 9 in the left diagram there is shown how the simulation can be used to determine a suitable blankholder force. In this example the current blankholder force is 100 kN and current strength coefficient is 480 MPa (P₀ in Figure 9). With changing material, the strength coefficient changes from 480 to 440 MPa. It shows that the combination of a strength coefficient of 440 MPa with a blankholder force of 100 kN leads to a sheet thinning over 20% (P₁ in Figure 9). To solve this problem a different blankholder force has to be chosen, which sets the operating point under the critical sheet thinning again (solid arrow).
5. Conclusion
In this paper the vision of Digital Twins in deep drawing was introduced. A concept was presented which would allow the rollout of Digital Twins into the production process of formed metal sheets. Those three steps are virtual tool commissioning, inline parameter optimization and online process control. In this paper a co-simulation environment was designed and implemented with an example application, which could be applied on the first two steps. It was shown how the simulation could be used to detect errors in parts simulatively. In a next step this model should be validated with data from the real plant. A problem is that the process simulation is to slow, to achieve a real-time capable co-simulation which is necessary for the online process control. This is why other approaches like data driven simulations should be evaluated, this should be a focus of further research in the field of Digital Twins in deep drawing. Finally, the Digital Twin based control system should be evaluated on a deep drawing press, to validate if the usage of Digital Twins can actually increase the part quality and decrease the error rate.

Acknowledgements
This work was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation DFG) within the project 438646126.
References

[1] Helmke M, Majer H, Thanassakis A 2016 Improvement of hydraulic control quality for deep drawing presses through retrofit 10th International Fluid Power Conference

[2] Purr S, Moelzl K, Meinhardt J, Merklein M 2016 Das Presswerk 4.0 – Data Mining zur Vermeidung von Qualitätsproblemen bei der Herstellung von Karosseriebauteilen 36. EFB-Kolloquiums Blechverarbeitung

[3] Birkert A, Haage S, Straub M 2013 Umformtechnische Herstellung komplexer Karosserieteile Springer-Verlag Berlin Heidelberg

[4] Hummelsberger R, Meinhardt, J, Grossenbacher K, Kreissl S 2016 Strategische Ausrichtung der Presswerke der BMW Group 36. EFB-Kolloquium Blechverarbeitung

[5] VDI 2018 Virtuelle Inbetriebnahme VDI 3693 Blatt2

[6] Röck S 2007 Echtzeitsimulation von Produktionsanlagen mit realen Steuerungssystemen Stuttgart Jost-Jetter Verlag

[7] Pritschow G, Röck S 2004 Hardware in the Loop Simulation of Machine Tools CIRP Annals 53 Issue 1 pages 295-298

[8] VDMA 2021 Leitfaden Virtuelle Inbetriebnahme: Handlungsempfehlungen zum wirtschaftlichen Einstieg

[9] Penter L 2016 Qualifizierung von FE-Prozessmodellen zur Inbetriebnahme von Karosserieziehwerkzeugen TU Dresden dissertation.

[10] Schulze T, Weber J, Großmann K, Penter L, Schenke C 2015 Hydraulic die cushions in deep drawing presses – analysis and optimization using coupled simulation Proceedings of the ASME/BATH 2015 Symposium on Fluid Power & Motion Control

[11] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W 2018 Digital Twin in manufacturing: A categorial literature review and classification IFAC PapersOnLine

[12] Bäume T 2019 Prozessregelungen durch piezoelektrisch erweiterte Umformwerkzeuge Technische Universität Chemnitz Dissertation

[13] Allwood J.M, Duncan S.R, Cao J, Groche P, Hiert G, Kinsey B, Kuboki T, Liewald M, Sterzing A, Tekkaya A.E 2016 Closed-loop control of product properties in metal forming CIRP Annals 65 Issue 2 Pages 573-596

[14] Blochwitz T, Otter M, Åkesson J, Arnold M, Clauß C, Elmqvist H, Friedrich M, Junghanns A, Mauss J, Neumerkel D, Olsson H, Viel A 2012 Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models 9th International Modelica Conference

[15] Schulze T, Weber J 2017 Model Based System Identification for Hydraulic Deep Drawing Presses The 15th Scandinavian International Conference on Fluid Power

[16] Heiland S, Klingel L, Penter L, Jaensch F, Schenke C, Ihlenfeldt S, Verl A 2021 Virtual tool commissioning using LS-DYNA functional mock-up interface 13th European LS-DYNA Conference 2021 Ulm

[17] DIN EN 10130 2006 Kaltgewalzte Flacherzeugnisse aus weichen Stählen zum Kaltumformen - Technische Lieferbedingungen

[18] DIN EN 10130 2006 Kaltband – Grenzmaße und Formtoleranzen