Virtual Tool Commissioning using LS-DYNA Functional Mock-up Interface

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Abstract

The commissioning of forming tools includes the mechanical spotting of the active surfaces and the identification of suitable actuator set values. It represents a time-consuming and expensive step in the tool development process. A major cause for the necessity of this manual die spotting is the elastic compliance of press and die that results in geometric deviations between predicted and produced part geometry as well as the control characteristics and the resulting accuracy of the drives. The interactions between the machine and the forming process can be computed numerically. An integration of simulation models that includes the machine behavior into the tool development process offers potential for time and cost savings for die manufacturers and machine operators.

In this article, a concept for Virtual Commissioning of forming tools is presented. The aim of this concept is to simulate the basic methodology of the die spotting process and the identification of set values on a virtual counterpart of the press. This so-called "Digital Twin" bases on an extended process model that represents the interaction between process, machine and control.

As a suitable approach, the method of cross-platform Co-Simulation by means of a Functional Mock-up Unit (FMU) is used. LS-DYNA is able to generate FMUs and thereby exchange data with other software via Functional Mock-up Interface (FMI). The LS-DYNA plug-in “FMU Manager” supports FMI 2.0 standard.

The coupled simulation model extends the established approaches for the simulation of forming processes (FE-method) with elastic-static machine influences as well as dynamic influences of the drive and die cushion control. Updating the simulation model with real time data allows to predict the optimum tool topology and process parameters for a specific production press.

1 Introduction

Due to the increase of complex forms and functions of sheet metal parts, the process limits for deep drawing forming processes are increasingly exhausted and require the exact determination of set values of the process parameters. Forming simulations based on the finite element (FE) method allow the prediction of these parameters and provide information on the manufacturability of the tool topology [1]. Nevertheless, the commissioning of new forming tools, which includes the finishing of surface geometries and the adjustment of process parameters, on try-out-presses and later on the production press is characterized by a manual iterative trial and error process and is a major time and cost-consuming factor. According to [1] the cost share for this is about 31% of the total lifecycle costs of a forming tool (see Fig. 1).

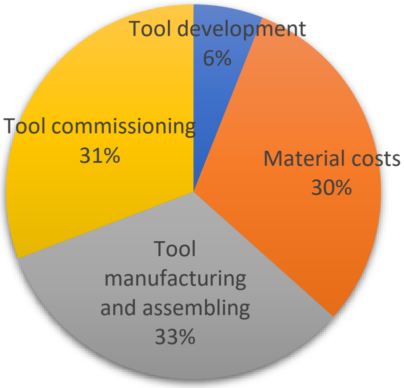


Fig.1: Cost allocation for a forming tool according to [1]

The reason for the manual spotting of the active surfaces and the identification of suitable actuator set values in the tool commissioning process is the neglect of the elastic compliance of press together with the control characteristics of the drives in the FE forming simulation. In following, a first modelling approach using LS-DYNA and the compatible Functional Mock-up Interface (FMI) is presented, which extends the established FE-models for forming simulations with machine influences and dynamic influences of the control system. The Approach combines different sub-models in an extended simulation model and enables a Virtual Commissioning process of deep drawing tools already in the tool development phase. Fig. 2 shows their extension. The extended process model uses information from the CAD surface model and the CAD volume model for the tool construction and describes the interaction between press and die. On this basis, a virtual adaption of the tool geometry and the process parameter is possible, so that the real adaption can already be done with the tool manufacturing. The virtual method has the potential to replace the manual tool commissioning on try-out-presses, which results in time and cost savings for die manufacturers and machine operators.

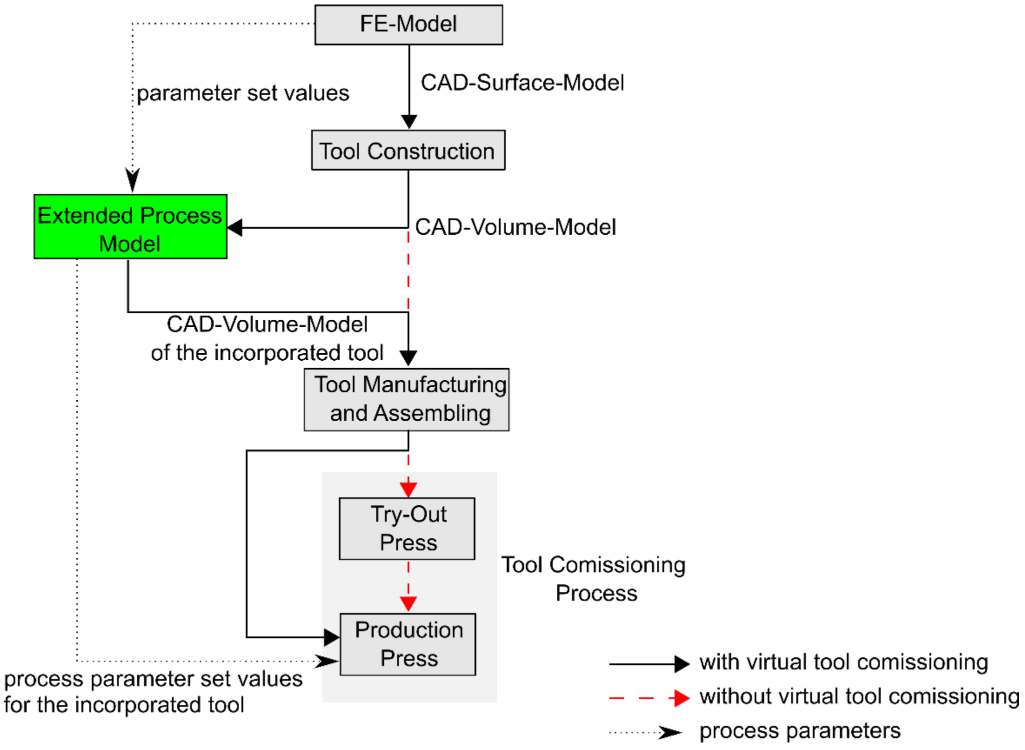


Fig.2: Expanded development process for forming tools

2 State of the Art

2.1 State of the Art

Deep Drawing and Tool Commissioning

Deep drawing of sheet metal parts is a forming process in which the sheet metal blank is formed under a combination of tensile and compressive load. A deep drawing tool normally consists of a punch, die and blank holder. Mechanical or hydraulic presses are used to generate the needed forming forces. Sheet metal parts with complex geometries, like car body parts, can be produced in multistage forming processes on multiple press units and tools arranged in sequence. For a first approach, the focus on this work will be on a single-stage forming process on a single-action press, as shown in Fig. 3.

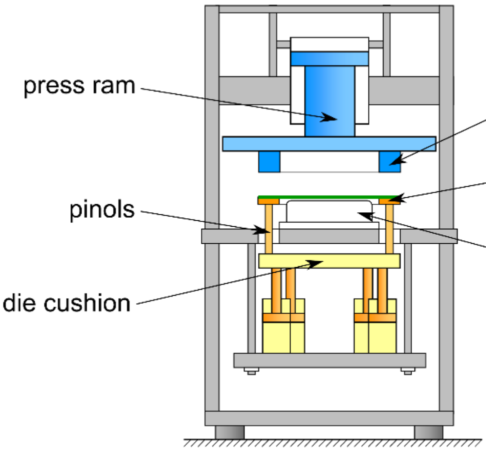


Fig.3: Single-action press with deep drawing tool

The quality of the deep drawn part depends on many factors. A detailed overview of influencing factors can be found in [2]. An overview of the essential variables, which affect the forming process, can be seen in Fig. 4. The consideration and compensation of machine influences is not yet taken into account for the development process of a forming tool. The elastic compliance of press and die can lead to ram tilting under off-center loads [3], elastic deformation of the die cushion plate [4] as well as elastic deformation of the press table and ram [5]. This can result in defects at the work piece as well as damage to the forming tool surfaces. An incorrectly adjusted blank holder force can also lead to deep drawing errors like wrinkles or cracks. The manual tool commissioning tries to compensate the machine influences with mechanical spotting of the active surfaces and the identification of suitable actuator set values. Due to the inaccessibility of normal production presses, special try-out presses are used. The manual spotting of the free tool surfaces is repeated in an iterative process with the goal to achieve a homogeneous pressure distribution between blank, blank holder and die. Therefore the whole process can be divided into several steps and a detailed overview can be seen in [1].

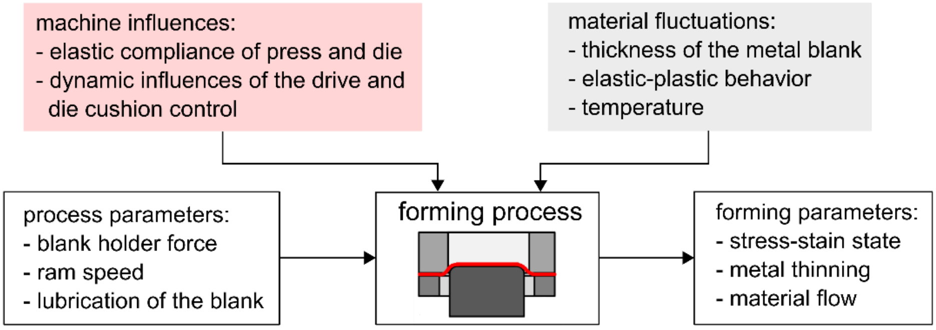


Fig.4: Influences on the forming process

Even during series production, fluctuations in the material properties of the blank, wear-related changes in accuracy or changing tool temperature can lead to defects, if no adjustment of the production parameters takes place. A real-time capable extended process model, the so-called “Digital Twin”, which can be updated with actual machine data, offers the possibility to predict the changing process parameters.

Virtual Commissioning

Virtual Commissioning (VC) is a method to detect errors and validate the control software in the engineering phase of a machine or plant [6] or develope the control software in advance with the help of a simulation model. To realize a VC, a real control system is connected to a simulation model of the component, machine or plant [7], as shown in Fig. 5. From the control system's point of view, there is no difference in this setup between the real production system and the model.
VC can save both time and money in the engineering phase of a production system. The time savings result primarily from the fact that the control software can be developed and tested on the simulation model at an early stage, when the real plant is not yet assembled. This results in a cost advantage, since the real commissioning can be started with a higher degree of control software maturity.

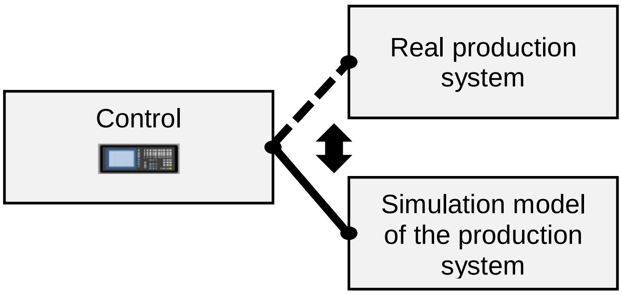


Fig.5: Idea of virtual commissioning

The established form of VC is the Hardware-in-the-Loop Simulation (HiLS) where real control systems (hardware and software) are used and connected to the model of the machine via a fieldbus [8]. Due to this setup, hard real-time requirements arise for the simulation. Because the simulation model must provide deterministic calculation results in the cycle time of the real control system and fieldbus.

Co-Simulation

Nowadays, a variety of specific modelling and simulation tools exist, but most of them are used independently. In most cases, only one physical discipline such as mechanics or electrics is covered [9]. To represent an entire production system, multi-physical simulation becomes necessary, which is only possible through the interaction of specialized tools.
There are different interpretations of the term Co-Simulation. On one hand, there is the coupling of modelling tools and on the other hand, from an information technology point of view, there is the coupling of simulation tasks. Scheifele investigates Co-Simulation for the application in VC and defines Co-Simulation as the coupling of simulation tasks [10]. That does not exclude, but rather is the basis for coupling simulation tools.
By distributing a simulation over several tasks, not only the execution of several modelling tools in different step sizes in the form of a multi-rate simulation is possible, but also the software-side prerequisite for the calculation on multi-core processors is created.
There are some proprietary formats but also independent standards to exchange models between simulation tools or to couple simulation tools. The most widely used standard is the Functional Mock-up Interface (FMI) [11]. This standard defines the methods to couple simulation tools or exchange models via so-called Functional Mock-up Units (FMUs). The FMI defines two different approaches, the so-called model exchange and Co-Simulation [11]. In both cases the FMI contains an executable DLL and a model description in XML format. An FMU for model exchange only contains the simulation model and the DLL but the equations are solved by the master tool that imports the FMU. The Co-Simulation approach always uses the solver of the tool which was used for modelling. It is possible to export a stand-alone

FMU with the model and solver, which can be used without further notice of the modelling tool. Some simulation tools like LS-DYNA support the Co-Simulation with tool coupling, where the master tool and simulation tool for modelling must run parallel. The red arrows in Fig. 6 represent the standardized functions of the FMI and the black arrow can be any communication protocol.

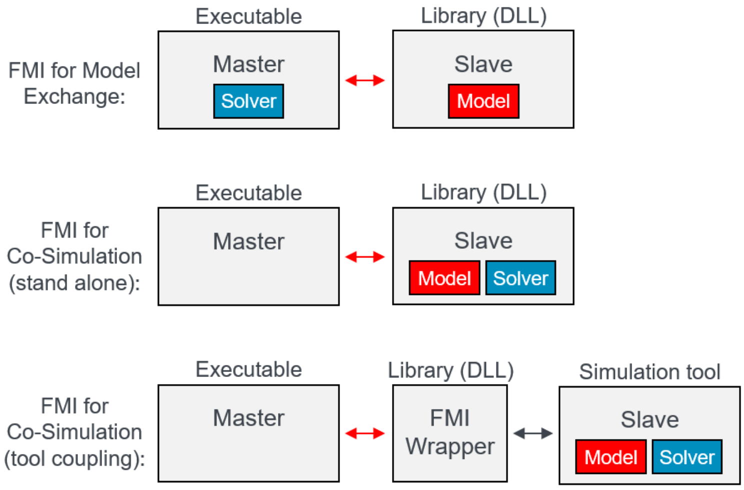


Fig.6: Main design ideas of FMI [11]

Independent of the FMI standard, different approaches were already made to Co-Simulate with LS-DYNA and other domain-specific software solutions to expand the deep drawing simulation [12]. The so-called “Simulator coupling” uses a C++ coupling interface to exchange simulation data between LS-DYNA and other software solutions for every loop. For this purpose, the restart function of LS-DYNA was used, which results in a heavily increasing calculation time. The further development of the method using a shared-memory for the data exchange resulted in a drastic reduction of the calculation time. Nevertheless, the calculation time needed for the computation of coupled simulation model is more than double compared to a FE-process model without machine interaction [13].

2.2 Deficits of the State of the Art

The finishing of surface geometries and the adjustment of process parameters during the tool commissioning process is still standard in industry and represents a time-consuming and cost-intensive work step. The reason for this is that the FE-models used during the tool development process are not capable of mapping interactions between machine and the forming process. In addition, there is a lack of suitable simulation methods to reproduce the manual tool commissioning process.

The Method of VC has also not yet been used in forming technology. A main reason for this is that the calculation time for FE-models is normally too long and does not meet the real-time requirements in interaction with the real control system. The use of the extended process model as a Digital Twin offers the possibility to adapt the process parameters based on real-time data.

3 Concepts and used Tools

3.1 Concept

The aim of this work is the development of a simulation environment for VC of deep drawing tools based on an extended process model. To achieve this, a Co-Simulation environment via the FMI 2.0 standard between LS-DYNA and ISG-virtuos, a simulation platform for VC, is used. The combination of these domain-specific software solutions enables the use of deep drawing simulation models in LS-DYNA for real-time applications in machine control systems. This Digital Twin offers the possibility for online-optimization and the adaption of the process parameters with changing boundary conditions during production and can contribute to a more stable and accurate process in forming technology. For a first approach, the consideration of machine influences to the forming process is limited to the die cushion

system. A model expansion to consider the elastic compliance of press and die will be discussed in future works.
The simulation environment should be able to simulate a series of strokes together with changing process and environmental parameters between the strokes. To achieve this, the following methods are used for Co-Simulation: Dynamic parameters that change during the forming process are exchanged via FMI. Parameters, that can be assumed to change only between strokes, are written directly into the LS-DYNA keyword file (k-file), a simple text file that contains all keyword inputs. The communication with LS-RUN over the windows shell allows to restart the LS-DYNA solver. On this way, several strokes in a row with different parameter sets and different process set values can be simulated. The concept for the stroke-to-stroke simulation can be seen in Fig. 7.

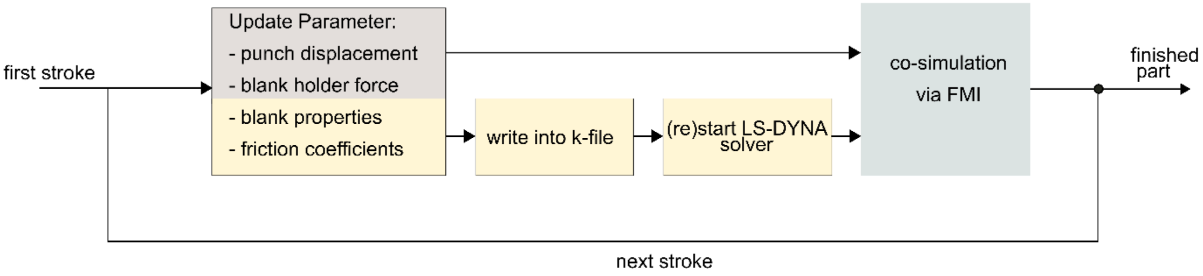


Fig. 7: Concept for stroke-to-stroke simulation

For Co-Simulation, the following sub-models are implemented in the ISG-virtuos software environment:

- **Displacement of the punch**: The displacement of the punch can be implemented in LS-DYNA via the keyword `*BOUNDARY_PRESCRIBED_MOTION_RIGID` as a boundary condition. For this purpose, a time-velocity curve is normally specified. The definition of this curve is done in the environment of ISG-virtuos by differentiating the desired time-displacement curve. At each time step, the corresponding values are then transferred via FMI.
- **Specification of the blank holder force**: The blank holder force is calculated using a simplified model of the die cushion drive and an associated model for force control. The resulting force value is send via FMI to LS-DYNA for each time step, where the boundary condition is implemented via the `*LOAD_RIGID_BODY` keyword.
- **Calculation of friction coefficients**: Friction between the blank and the free surfaces of the forming tool can be reduced by a film of lubricant applied to the blank surface. For this purpose, the lubrication model provides a correlation between the amount of lubricant applied to the blank and the resulting friction coefficient. It is assumed that the friction conditions only change between strokes. The new friction coefficient is therefore written directly into the k-file.
- **Fluctuation of material properties**: It is assumed that material parameters of different blanks only change between strokes, so that new values are directly written into the k-file.

An overview of the concept is shown in Fig. 8. For describing the characteristics of friction on lubricated surfaces Stribeck curves are used, which give the relationship between the contact pressure, sliding velocity, kinematic viscosity of the lubricant and the resulting friction coefficient [14]. Such a model is not implemented yet, but the interface is already available. The resulting nodal displacements for selected nodes are also exchanged via FMU and can be displayed in ISG-virtuos during the simulation.

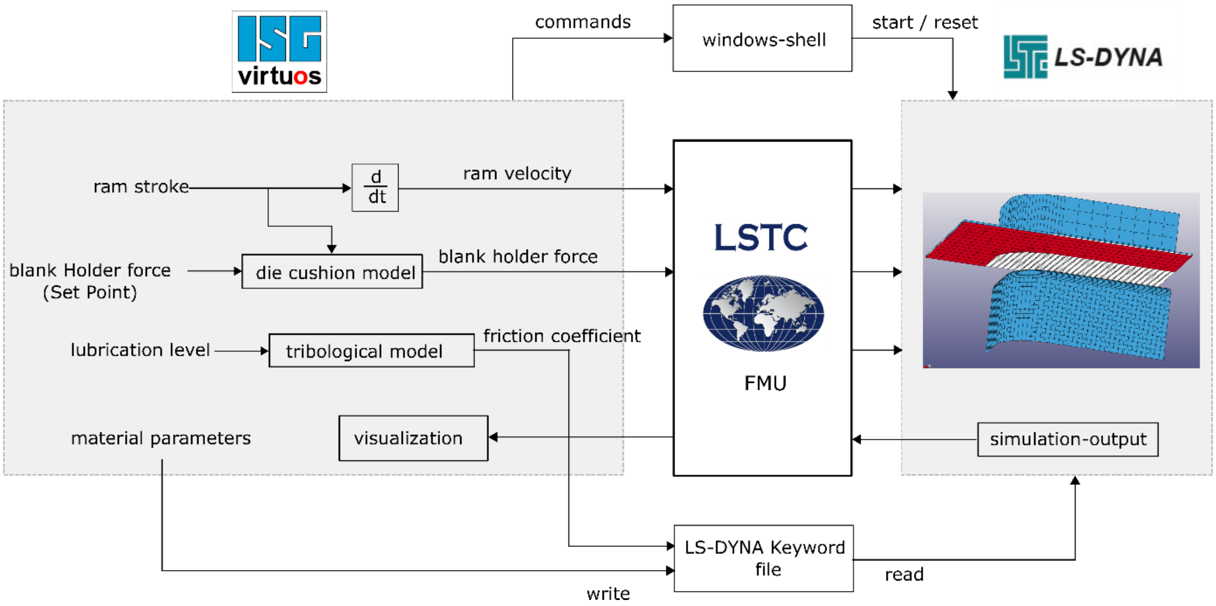


Fig.8: Co-Simulation environment between LS-DYNA and ISG-virtuos

3.2 Used tools

LS-DYNA

LS-DYNA is a universal finite element solver for the analysis of static and dynamic behavior of structures under large deformations [15]. For deep drawing, the explicit time integration code is used. The FMI Manager Kit is an additional plugin and provides the support to the 2.0 FMI standard together with LS-DYNA R12.0.0 [16].

ISG-virtuos

The simulation tool ISG-virtuos is a real-time simulation platform that is mainly used for VC. The tool goes back to the scientific investigations of Pritschow and Röck [8]. On this basis, further libraries were added, for example in order to be able to simulate the intralogistic material flow [17]. Furthermore, ISG-virtuos offers the possibility to perform a real-time Co-Simulation. Currently, several Windows tasks can be coupled with up to four real-time tasks that are executed in TwinCAT.

3.3 Test Setup

All the models described are based on a real test setup available at the Institute of mechatronic Engineering at TU Dresden and are shown in Fig. 9. The hydraulic deep drawing press features a hydraulic ram with a maximum force of 2500 kN and a hydraulic die cushion with a maximum force of 1000 kN. As an experimental tool a deep drawing tool for the production of rectangular pan is used.
The test setup has already been the subject of several research projects ([18], [12], [13]) and a deep knowledge is already available regarding the modelling and parameterization of the different components.

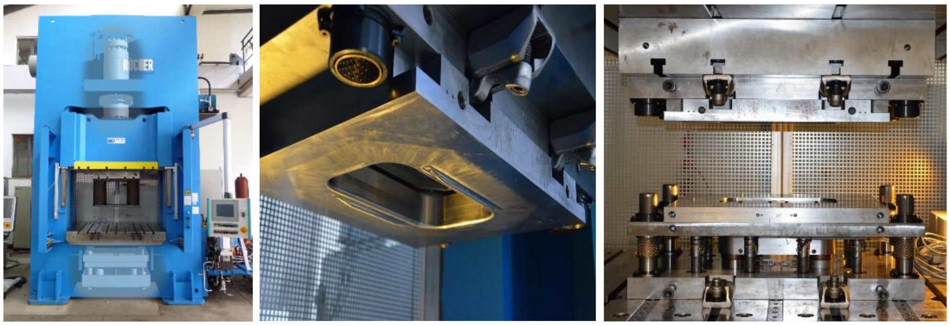


Fig.9: Test setup: a) hydraulic press, b) die, c) complete forming tool

4 Results and Conclusion

4.1 Modelling of tool and press

The FE-model of the forming process includes the blank, blank holder, punch and die of the forming tool and can be seen in Fig. 10 (left). For the deep drawing analysis rigid tool surfaces and stiff press properties are assumed. The blank has an initial thickness of 1 mm and was modeled with 4-node shell elements. The reference model with 52.000 nodes, activated adaptive remeshing and the Barlat yield criterion (**`*MAT_-3-PARAMETER_-BARLAT`**) is computation time-consuming. To match the requirements of a HiLS, a reduction of the model complexity is necessary. Taking advantage of the symmetry, only a quarter of the reference geometry has to be mapped. Nodes on the symmetry lines have to be constrained with the **`*BOUNDARY_SPC_SET`** keyword. A finely resolved mesh and adaptive remeshing is additionally dispensed with. The reduced model has around 5000 nodes and can be seen in Fig. 10 (right).

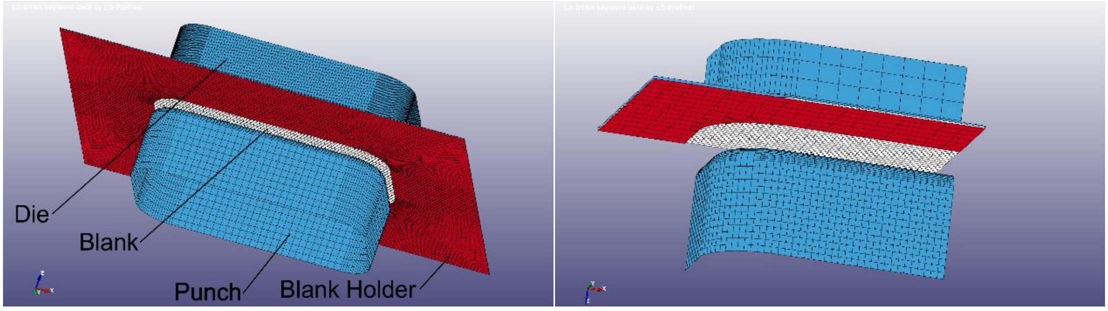
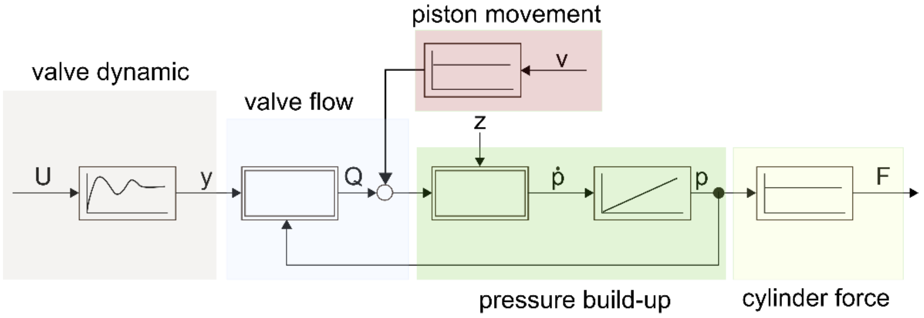


Fig.10: LS-DYNA process model: Left: reference model; Right: optimized model

For mapping the elastic-plastic behavior the material card **`*MAT_POWER_LAW_PLASTICITY_TITLE`** is used, which does not consider anisotropic behavior but is less time consuming. All the changes result in a significantly reduced computing time. To compare the performance of the reference model and the optimized model, both were run on a computer with an AMD Ryzen 1800x processor with 8 cores. With the use of all cores and the MPP solver, the reference model needs a computing time of 23 minutes, the optimized model only 7 seconds.
To visualize the kinematics of press and forming tool during the forming process, the respective CAD models were implemented in ISG-virtuos, as shown in Fig. 11.

Fig.11: Visualized simulation model of the press in ISG-virtuos

The hydraulic die cushion is modeled with block based transfer functions in ISG-virtuos. For this approach, a simplified model is used, which is described in [19] (see Fig. 12). The force set point for the die cushion cylinders in controlled by a feed-forward-control system. The model calculates the resulting cylinder force.



U ... voltage applied to the control valve
y ... control valve position
Q ... control valve volume flow
z ... cylinder position

v ... cylinder velocity
p ... cylinder pressure
F ... resulting cylinder force

Fig.12: Block based model of the hydraulic die cushion. From [19].

The simplified die cushion model is able to represent the force control of a die cushion cylinder when the die is closed. In this condition, it can be assumed that the displacement of the blank holder as well as the displacement of the die cushion plate is equal to the displacement of the press ram.

4.2 Coupling LS-DYNA and ISG-virtuos

For the coupling of ISG-virtuos and LS-DYNA custom model blocks implemented in C++ are used. The block library and the modelling surface is shown in Fig. 13. The “K File”-block is used between strokes to update the k-file with new values for material parameters or the lubrication level. For every stroke the simulation in LS-DYNA has to be started from ISG-virtuos which can be done with the “LS Run”-block. That block makes it possible to start LS-Run with the current k-file through the use of the windows shell. During the simulation in LS-DYNA, which means during a stroke, the dynamic data like blank holder force as an input for LS-DYNA or the material flow as an output of LS-DYNA are exchanged through the FMIimport block, which is an implementation for the import of FMUs. All those blocks are custom developments for the presented simulation environment.

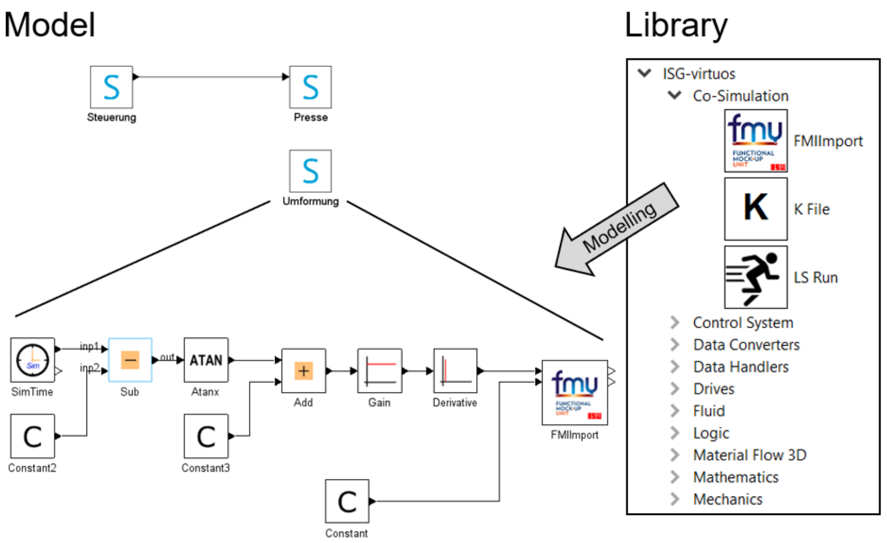


Fig.13: Modelling Surface in ISG-virtuos

4.3 Results

A comparison of the optimized model with the reference model should show his accuracy. For this purpose, the same boundary conditions are used for both simulations. A constant blank holder force of 100 kN and a punch displacement of 60 mm with constant velocity are specified. For the comparison, the displacement of the nodes 1309 and 1312 of the optimized model is considered (see Fig. 15 right). Both are located on the edge of the blank and have a constrained displacement due to the symmetry condition. In the reference model, the nodes 593 and 25 can be regarded as equivalent. For the comparison, the simulation times were normalized to a value of 1. The resulting curves are shown in Fig. 14. The maximum displacements of the nodes 593 and 1309 are 48.4 mm and 47.1 mm. The difference is 1.3 mm. The maximum displacements of the nodes 25 and 1312 are 33.9 mm and 32.3 mm, which makes a difference of 1.6 mm. The differences are thus only very slight.

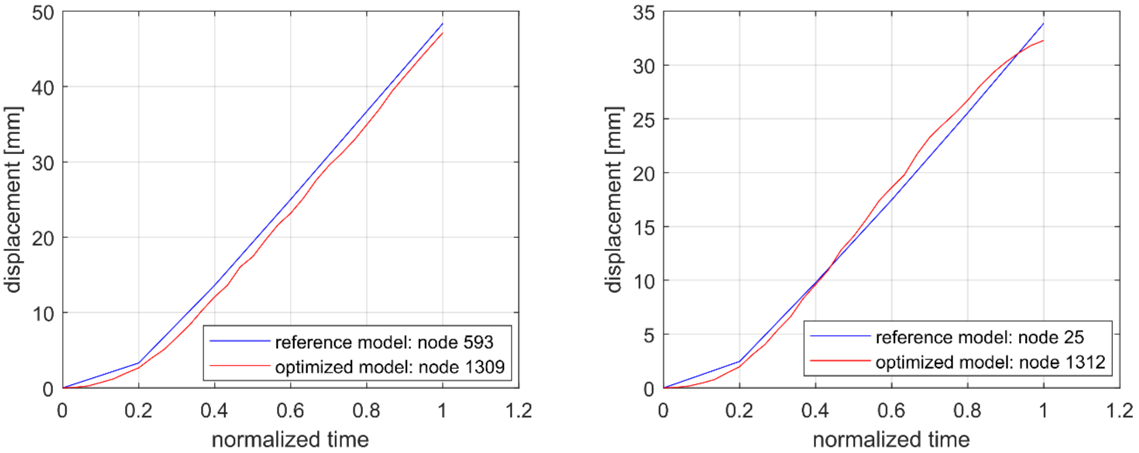


Fig.14: Comparison of the optimized model with the reference model

For an initial experiment with the extended model, the use of a laser triangulation measurement system was virtually mapped. The sensors are attached to the side surfaces of the blank holder. The displacement of the edge of the blank in the direction of the laser beam is measured. For the virtual mapping of the measurement process, the displacement of the nodes 1309 and 1312 can therefore be considered as output signals of the two sensors (see Fig. 15).

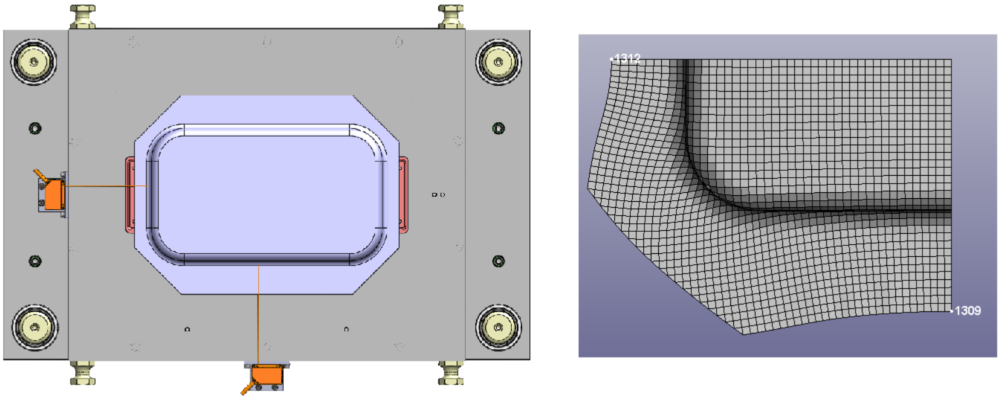


Fig.15: Virtual mapping of a laser triangulation measurement system

The simulation results are shown in Fig. 16. The above graphs show the curves for the hydraulic cylinder position and speed. It descends with a constant speed. The displacement is equal to the punch displacement in the simulation. This results in a drawing depth of approximately 70 mm.
The graph in the center shows the resulting blank holder force over the time. To improve the command response and to avoid overshoot, a pilot control was implemented. The actual value thus converges asymptotically to the set-point value of 100 kN.

The lower graph shows the displacement of node 1309 in x-direction and the displacement of node 1312 in y-direction. The resulting displacements at the end of the forming process are approximately 55 mm and 37 mm.

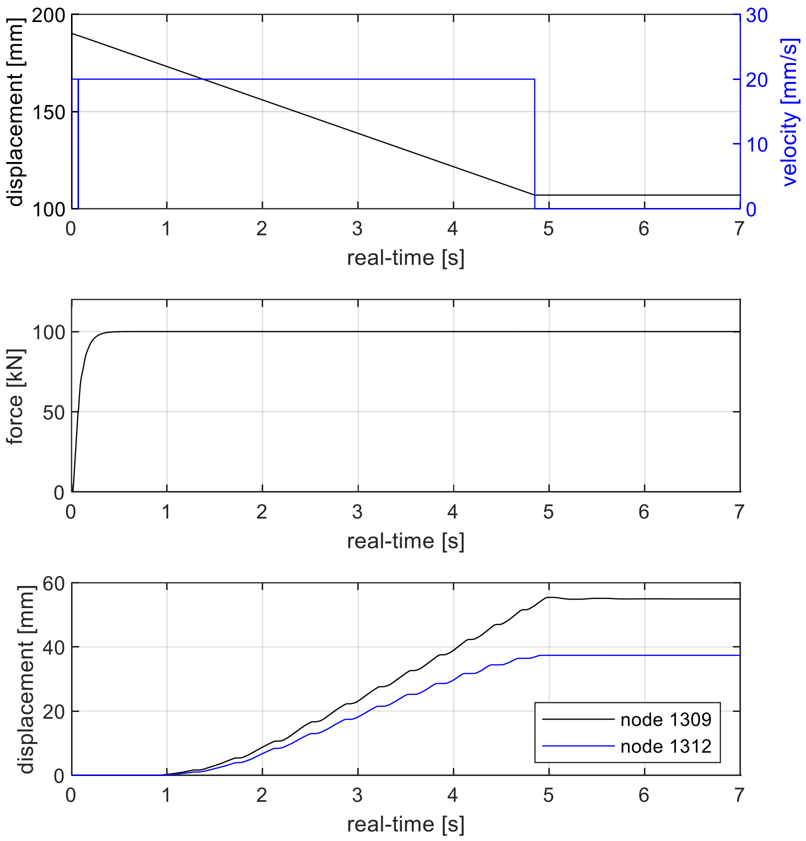


Fig.16: simulation results: Above: cylinder displacement and velocity; Center: blank holder force; Below: displacements of the nodes 1309 and 1312 in x and y direction

To investigate the real-time capability of the model, the needed simulation time was compared with the time needed for the real process. The time needed for one stroke for the real tool is around two seconds. Therefore, the Simulation model is 3.5 times slower than the real process. This means that it would not be possible to adapt the process parameters during the forming process, but it could take place between the strokes.

5 Conclusion and outlook

In the presented investigation a Co-Simulation environment between LS-DYNA and ISG-virtuos, a software for VC, was developed. This environment is to be used as a basis for the implementation of an extended process model and offers the possibility of a direct coupling to a real control system. In this way, it is possible to use the extended process model as a “Digital Twin” for the online optimization of forming processes and the use of real-time data as an input.

At the present time, only influences by the die cushion are considered. For reproducing the manual tool commissioning process, a simulation model of the whole process-machine interaction is necessary. Therefore the existing model must be extended to include further machine influences, in particular the elastic compliance of press and die.

Another important aspect is the real-time capability of the models to use them in HiLS. By reducing the model complexity, the computation time required for the process model used could be reduced significantly. However, further optimization is required for a use of the models as a Digital Twin. The Application of model order reduction techniques can reduce the computational effort. In addition, data-driven models based on simulation data are the subject of further investigations.

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