Virtual die spotting: Compensation of elastic behavior of forming presses

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Abstract. The rapid change in the automotive industry towards an electrified and digitalized future necessitates companies to shorten product development cycles. To meet customer needs regarding design and quality, the requirements on the production processes are constantly increasing. As additive manufacturing cannot provide large enough batch sizes yet, conventional stamping of car body parts will be the technology in the foreseeable future. The most time-consuming step during the production of stamping dies is the manual spotting during try-out of the tools. To achieve a homogenous pressure distribution on the parts a precise tool closure is necessary. The behavior of the press has huge influence on the tool closure, especially the elastic deformations of ram, bolster and cushion during forming. Current compensation methods are solely based on experience from previous tools. This contribution presents a methodology for designing a virtual die-compensation to account for press machine behavior based on experimentally determined measurement data of the try-out press. The data is used to calibrate FE-substitute-models of ram and bolster. A forming simulation using rigid tools is coupled with structure simulation using elastic tools and machine. By evaluating the deflection of the active surfaces at the bottom dead center of the press, the necessary die-compensation can be determined.

1. Introduction

As product development cycles in automotive industry are getting shorter, while customer needs regarding design and quality are increasing, the requirements on productivity and efficiency during the process chain are growing accordingly. One of the most time-consuming steps during the production of the tools for car body parts is the manual rework in the try-out shop. The authors in [1] amount the manual rework to be 30% of the total cost, for a side frame tool.

There are many different influencing factors on part quality [2] [3]. Besides springback-compensation one of the most important aspects is the tool closure as it affects the surface quality. Primarily, for outer body parts the surface quality is a decisive factor, as even small bumps or sink marks are clearly visible on the painted car. During the stamping process the tools and the machines are elastically deformed because of high loads. These deformations lead to unwanted changes in tool closure at the active surfaces which results in an insufficient pressure distribution on the part. In practice, the pressure distribution is evaluated by applying blue paint on both sides of a blank before
Stamping. After stamping, the areas with high pressures show lighter shade of the blue color, while the areas without pressure have the original shade of the applied color. In an iterative process, the tools are manually adjusted until an even pressure distribution is reached. The changes are in the range of hundredth of millimeters which makes the process as time-consuming as it is.

To reduce the amount of manual rework the active surfaces are being compensated before milling to account for the elastic behavior of tools and machine. Currently, the offset is applied in the middle of the tool and is solely experience based. It ranges from 0.1 to 0.5 mm in the center depending on the part geometry. This compensation is already helping to reduce the rework, but the potential of a simulation-based approach which calculates a machine-specific compensation for every tool is apparent.

The basis for the simulation approach is the measurement of the machines characteristic behavior under load. With the acquired data a simplified FE-model of the machine is calibrated, creating a digital twin of the machine. This model is then used in a coupled stamping simulation, which constantly updates the geometry of the active surfaces during forming based on the elastic deformations of tools and the machine. The resulting changes in the active surfaces can be used to determine the necessary offset to compensate the elastic deformations.

2. Press measurement

To compensate the elastic behavior of a specific stamping press, it is necessary to identify the press-specific characteristics. The most important ones are the applied forces, the deflection behavior of moving bolster, ram and drawing cushion as well as the tilt rigidity of ram and cushion. Different measurement systems have been developed over the last few years [4] [5] [6] [7].

There is a huge variety of stamping presses in different press shops all around the world, all having differences in construction and age. To be able to characterize and compare the presses with minimum effort, a press measuring system called press-fingerprint-tool was developed in cooperation with Fraunhofer Institute for Machine Tools and Forming Technology in 2012. The tool shown in figure 1 allows highly reproducible measurements with minimal setup time. A complete measurement containing various symmetrical and asymmetrical load-cases on the bolster as well as multiple load-cases on the drawing cushion is done in less than eight hours. More than 50 different stamping presses have been characterized so far.

![Figure 1. CAD-model of measuring system: Press-fingerprint-tool [8].](image-url)
The dimensions of the press-fingerprint-tool are 4000 x 2200 mm and 1500 mm in height which is comparable to large car body part tools. Similar to a regular production tool, the upper part is fixed to the mounting surface of the ram and the lower part is fixed to the moving bolster. The tool can either be used to apply forces on the bolster or on the drawing cushion.

To apply forces on the bolster 40 gas pressure springs are filled with nitrogen, the drawing cushion is not active in this case. During the stroke the pins of the upper part come in contact with the springs and compress the gas until the bottom dead center has been reached. Depending on the initial pressure in the springs the total force during the stroke can be controlled. An initial pressure of 130 bar results in a total force of about 11 000 kN. During the stroke multiple different sensors measure the dynamic behavior of the machines. A total of 51 tactile displacement sensors attached to the measuring frames on upper and lower tool are used to measure the deflection of ram and bolster. Four distance measuring laser sensors at the corners measure the tilt between bolster and ram. Load cells in the upper part of the tool are used to evaluate the force distribution at the ram.

When the drawing cushion is measured, the gas pressure springs are not active. Instead, the cushion is in its highest position and lifts 44 pins in the lower part of the tool. During the stroke these pins are pushed down by the upper tool. The load cells in the upper plate measure the cushion force. As described before, displacement and laser sensors are active. Additional position sensors attached to pins at the four corners of the tool measure the height and the tilt between cushion and bolster.

For this contribution, a hydraulic try-out-press with a maximum force of 25 000 kN was chosen for the virtual compensation. In the current state, the substitute model focuses on the behavior of bolster and ram. The measured deflection curves for the examined press are shown in figure 2. For reasons of simplicity only the sensors along the bisecting lines are displayed. Maximum displacement for a total load of 10 000 kN amounts to 0.4 mm on the bolster and to 0.27 mm on the ram.

![Figure 2](image_url)

**Figure 2.** Measured deflection at ram and bolster compared to the resulting deflection of the calibrated FE-substitute model for a symmetrical load of 10 000 kN.
3. Substitute modelling

A range of different approaches on considering the elastic behavior of presses have been presented before. The author in [5] compares the accuracy of analytical model and full CAD-model with measured deflection behavior. A full CAD-model is also used in [9], [10], [11] and [12] to simulate the machine influence. The author in [13] presents simplified substitute models for presses which use segmented shells with varying thickness and Young’s moduli. In [14], deformable rigid bodies are used to describe the deflection of tools and presses.

The focus of the modelling approach presented in this paper lies on a universal applicability and a minimal calculation time. This is necessary in regard to the huge number of different presses. For many machines the CAD-data or technical drawings are not available. Measuring the construction by hand is not an option as many parts of the structure are not easily accessible. In the scope of this project, detailed information on the structure is not required. The system boundaries are the mounting surfaces of ram and bolster. The deflection behavior at these surfaces can be measured by the press-fingerprint-tool with little effort and thus be used for the calibration of the FE-models.

For the setup of the models Altair HyperMesh™ and LS-PrePost® have been used. Both mounting surfaces have been represented by shell elements whose thicknesses correspond to the real mounting plates. Young’s modulus is 200 000 N/mm². The models are supported by groups of linear-elastic springs, whose free ends are fixed. The stiffness values of the springs are calibrated during parameter optimization in LS-OPT®/LS-DYNA® where the measured deflection is used as the target. In this way, a machine-specific substitute model can be generated for any measured press.

To minimize the modelling effort, the process is partly automated. Length, breadth and element size are given as input parameters to a Tcl-script which generates the meshed models with all springs, sets and boundary conditions.

Figure 3 shows the FE-substitute models of bolster and ram with the respective spring assemblies. Further, the simplified FE-model of the press-fingerprint-tool is displayed with its upper and lower part. The shown deflection on the mounting surfaces is the result of parameter optimizations of ram and bolster for a load of 10 000 kN. The parameter optimization is explained in more detail in [15].

![Figure 3. FE-substitute models of ram and bolster with section cut of press-fingerprint-tool model. Resultant displacement of calibrated model for total load of 10 000 kN.](image-url)
The resulting deflection behavior of ram and bolster is shown in figure 2 in the previous chapter. Overall, the simulation results are very close to the measured values. The highest deviation of about 0.02 mm occurs in the center of the ram. The mean square error is 0.0038 mm² for the 24 target values at the bolster and is 0.0069 mm² for the 27 target figures at the ram. Since the measured deflection shows a linear behavior for different forces, the model is viable for any load.

As the substitute models of ram and bolster are used for the coupled simulation in Visual-Crash PAM 14.1, a verification simulation is performed to ensure that the deflection behavior is identical for the calibrated stiffness values of the springs.

4. Coupled simulation
The numerical representation of the elastic behavior of press machine components into the process simulation can be done in different ways. The authors in [16] categorize these methods into offline coupling, integrated coupling and coupling of discrete models. The tools designed with each of these can vary significantly as each of them has a different balance between the calculation time and the accuracy of the results. A good compromise on inclusion of the elastic behavior of the tools and the calculation time can be achieved using the coupling of discrete models.

The implementation of the chosen coupling method requires two different simulations to be set. One with rigid tools to simulate the forming process which is referred to as forming simulation and the other with elastic tools to simulate the elastic behavior of the tools which is referred to as structural simulation. There is a discrete transfer of data between the two simulations at an interval called the coupling interval. At the beginning of each coupling interval, the forming simulation imports the newly deformed tool geometry from structural simulation and exports the forces occurring on the tools at the end of the coupling interval. This exported force data is then used by the structural simulation to calculate further deformation in the tool geometry. This deformation is then imported by the forming simulation and its tool geometries are updated and used for calculations in the next coupling interval. Hence, the coupling interval controls the balance between the tool design quality and the calculation time.

The process simulation setup used is similar to the standard rigid tool stamping simulation, with gravity, closing and forming stages, except that the tool geometry is regularly updated during the simulation run. This means that the tools even in this setup are made up of single layered rigid mesh. The structural simulation, on the other hand, consists of volumetric tools. The exchange of data is therefore confined to the entities directly included in the active surfaces of the tools. The exchanged data is mapped by interpolation in case, the meshes on both setups do not match.

4.1. Forming simulation
The setting up of the simulation has been done in PAM-Stamp 2018.1. The tools of the process simulation of an outer side frame part have been built based on the geometry of the active surface of the die. The blank material is high formability steel for drawing with 0.7 mm thickness. Geometrical drawbeads have been used in order to ensure proper mapping of the process forces. An optimal value of friction coefficient in regard to part quality and draw-in has been found out to be 0.05.

4.2. Structural simulation
The structural simulation has been set up in Visual-Crash PAM 14.1. The set up consists of volumetric models of punch, punch casing, die, die casing as well as outer and inner blank holders. All these tools have been assigned elastic plastic solid material behavior. The punch casing is supported by the substitute model of the press table. Similarly, the die casing is supported by the substitute model of the ram mounting surface. Both the press table and ram mounting surface are modelled with shell elements and have been assigned elastic shell material behavior. The contact between the press table and punch casing pair and the ram mounting surface and the die casing pair has been modelled with implicit small sliding contact. All the translational and rotational degrees of freedom of all the free nodes of the springs have been constrained. Also, all the nodes on the bottom surfaces of the pins supporting the blank holders are completely constrained.
4.3. Coupling
As process forces during the forming stage form the major part of the total forces occurring, the coupling has been done only during the forming stage. This is achieved by using the XMX-interface introduced in PAM-Stamp 2018.1. The active surfaces of the process tools have been selected on both the simulations. For a successful coupling, the corresponding active surfaces should initially be within the tolerance enabling a good mapping of the exchanged data.

The forming simulation is set to run on time reference during forming stage and a coupling interval of 1 ms has been used. With a total simulation time of 0.078 s, this leads to 78 coupling steps over the stamping process. More coupling steps lead to an increased calculation time whereas less coupling steps result in a lower accuracy. Figure 4 shows the principle of the coupling between forming and structural simulation.

![Coupling principle](image)

**Figure 4.** Exchange of contact forces and displacements between (a) forming simulation and (b) structural simulation.

5. Results
The coupling strategy described in the previous section gives an opportunity to estimate the actual geometry of the tools under the process forces and also the actual distribution of the contacts pressures on the blank. Figure 5 shows the deformation occurring on the punch, blank holders and die surfaces at the end state of the process simulation. Maximum deformation values on the punch and die respectively occur at rear wheel and B-pillar regions with a magnitude of 0.309 mm and 0.130 mm.

![Deformation](image)

**Figure 5.** Z-Displacement for (a) punch and blank holders and (b) die.
The significance of these deformations becomes apparent by evaluating the increase in the relative gap between the deformed tools. At the rear wheel the distance between punch and die is about 1.1 mm which is 150% of the initial blank thickness. This results in the changes in the contact pressures thus leading to insufficient stretching in some areas of the part. Figure 6 demonstrates the contact pressure distribution in the standard non-coupled rigid tool simulation and the coupled simulation. The blue areas show a contact pressure greater than 0.2 MPa, corresponding to the blue paint in practice. The loss of contact between the tools and the blank is clearly evident from the increased gray regions in the coupled result. Especially in the areas with the highest tool deformation, like the rear wheel and the lower part of the doors, the differences are clearly visible. The results show the significance of the influence of machine elasticity on the product quality and also give an opportunity to analyze the continuous changes in the process pressure distribution.

Figure 6. Contact pressure greater than 0.2 MPa at the blank in bottom dead center (a) for standard non-coupled simulation and (b) for coupled simulation with elastic tools and machine.

The coupling strategy presented above leads to the opening of several ways to fasten up the rework on the tool try-out presses. The total elastic deformation of the tools can be calculated by comparing the initial and the final position of each of the nodes on the active surface. This elastic deformation can be compensated along its own vector by introducing a factor k. The value of this factor can be optimized by using the product geometry as the target function. The compensated geometry can be used for milling of the active surfaces. Further, the tool structure can be adjusted, to reduce the elastic deformations in critical areas.

Considering the advantages of the coupling strategy, the feasibility of its implementation depends on the computational costs. When using 16 cores, the standard uncoupled simulation took 17.5 h while the coupled simulation took 27.5 h. Although, the coupled simulation takes approximately 50% more time than the standard simulation, the total time and money required for the rework of the tools can be significantly reduced, which makes the presented method economically viable.

6. Summary and future work
In this contribution, a coupling strategy with great potential to include the elastic behavior of press machines in the tool design process has been discussed. Its feasibility in the application to large sized car body parts makes it a stand out method. The results of the method are close to practical experience. In addition, it provides a great insight into most of the process characteristics. This helps to understand the influence of different factors on the process and can lead to better tool design practices.

As future work, the dynamic changes in the process forces and pressure distribution can be analyzed and reliable practices to overcome some of those unwanted changes can be developed. Also, various parameters, like the coupling interval, need further adjustment, to minimize calculation time.
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