Virtual die spotting: Advanced setup for coupling of forming and structure simulation

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Abstract. Shorter product life cycles and increasing product variety in the automotive industry are leading to increasing pressure on manufacturing of stamping dies for car body parts. A high amount of manual rework is needed to meet product quality, which is one of the main drivers for long production time and high cost. The long-term goal is to meet quality requirements directly after machining of the active tool surfaces to reduce the manual rework needed to a bare minimum. This can only be achieved by taking elastic deformations of tools and press into account during the virtual die making process.

To predict the deflection at the active surfaces during the forming process, a conventional forming simulation with rigid tools is coupled with a structure simulation using elastic tools and press. For the accurate representation of the deflection behaviour of the real press, substitute models of moving bolster and ram are used, which are based on press measurement data. In this paper, different press deformation characteristics are presented, and the viability of the universal FE substitute model is evaluated. Further, advanced settings for the coupled FE simulation are discussed and the simulation results are validated with experimentally determined data.

1. Introduction
As product life cycles in the automotive industry are becoming shorter and product variety is growing, the requirements for cost and time efficient manufacturing of stamping dies are constantly increasing. Furthermore, standards for product quality and part complexity are becoming more demanding. To meet all those demands while securing an economical production, digitalization in the context of industry 4.0 will play an important role in the tool manufacturing process and in the press shop. [1]

One of the main drivers for cost and time during the production process of stamping dies is the manual rework process of the active tool surfaces. To meet the high requirements on quality and dimensional accuracy of the produced parts, the pressure distribution must be homogeneous in all critical areas of the part when the tools are fully closed. The point in time when the tools are fully closed is called bottom dead centre (BDC). While the process forces are constantly growing until reaching the BDC, elastic deformations of press and tools are simultaneously increasing. The result of the elastic deformation is a gap between die and punch which leads to an insufficient pressure distribution on the part. To compensate the deformation during the process, tool surfaces are being cambered before machining and need to be adjusted manually during try-out. [2]
2. Deformation characteristics of forming presses

There are many different approaches on reducing the ramp-up time for stamping dies (e.g. [3], [4], [5]). In this work a universal approach for including the elastic machine behaviour during the tool production process is presented, which is feasible for usage in industrial practice. The prerequisites for this are the standardized measurement of the elastic behaviour of forming presses as well as a universal FE substitute model to represent the machine specific behaviour in the simulation.

2.1. Press measurement

For the standardized characterization of forming presses a specialised measurement system called press fingerprint tool is used. The tool was developed by Volkswagen in cooperation with Fraunhofer Institute for Machine Tools and Forming Technology in 2012. The tool allows the application of symmetrical and asymmetrical load cases with up to 11 MN total force. Multiple tactile displacement sensors as well as laser sensors are used to measure the deflection and tilt of ram and bolster. Load cells are used to identify the force distribution on the ram. Detailed information on the press fingerprint tool is given in [6] and [7]. Furthermore, the usage of the measurement tool as well as the processing of the measurement data is described in [8], [9] and [10].

2.2. Deflection types for bolster and ram

In the scope of this work the deflection behaviour of eight different try-out and production presses is analysed. The selection includes mechanical and hydraulic presses with a total force of 20-25 MN. The geometrical dimension of ram and bolster mounting surfaces are in the range of 4500 × 2400 mm to 4700 × 2500 mm.

Figure 1 shows the measured deflection of different bolsters along x-direction in the middle of the mounting surface. The load of 10 MN is applied symmetrically by the 40 pre-loaded gas pressure springs of the press fingerprint tool which are depicted as black circles in the schematic in the top right corner.

Fig 1. Deflection curves along x-direction of moving bolster mounting surfaces of different try-out and production presses at 10 MN symmetrical load.

The maxima of the shown deflection curves range from 0.34 mm to 0.62 mm. Besides the quantitative deviations the curves also show qualitative differences. To categorise the various types, the
percentage deviation $\Delta \%_{\text{Bolster}}$ between the two middle measurement points $\overline{v}_{\text{middle}}$ and the two adjacent ones $\overline{v}_{\text{adjacent}}$ is calculated:

$$\Delta \%_{\text{Bolster}} = \frac{\overline{v}_{\text{middle}} - \overline{v}_{\text{adjacent}}}{\overline{v}_{\text{adjacent}}} \times 100$$ (1)

Values for $\Delta \%_{\text{Bolster}}$ smaller than 0% are classified as w-profiles (presses A and G), values between 0% and 1% as plateau (presses C and H) and values larger than 1% as parabola (presses B, D, E and F).

Analogues to the bolster, Figure 2 shows the measured deflection of the ram along x-direction in the middle of the mounting surface. The applied force is again 10 MN.

![Figure 2. Deflection curves along x-direction of ram mounting surfaces of different try-out and production presses at 10 MN symmetrical load.](image)

For the ram mounting surface the measured maxima in the deflection vary between 0.19 mm and 0.36 mm. The characterization of the different ram deflection types uses a similar calculation method as the bolster:

$$\Delta \%_{\text{Ram}} = \frac{\overline{v}_{\text{middle}} - \overline{v}_{\text{adjacent}}}{\overline{v}_{\text{adjacent}}} \times 100$$ (2)

Evaluating the values for $\Delta \%_{\text{Ram}}$ leads to the deflection types m-profile (presses A, B, D, E and G), plateau (press H) and parabola (presses C and F).

The shown deflection curves in Figure 1 and 2 illustrate the variety in the elastic behaviour of different presses. In general, ram shows a smaller deflection compared to bolster, which can be explained by the construction differences in the support structure. While bolsters are normally only supported on the edges, rams can have multiple reinforcement ribs in the centre of the mounting surface.

To evaluate the overall elastic behaviour of a press the combination of bolster and ram is important. For a simplified approximation of the expected tool closure for a given load case, the deflection maxima
of bolster and ram can be added up. A press with a stiff ram but soft bolster can theoretically have a similar tool closure as a press with soft ram but stiff bolster. However, the geometrical accuracy of the produced part will be different between the two.

If possible, in industrial practice try-out presses and production presses should be combined in a way that both quantitative deflection as well as deformation characteristic are matching.

3. FE-substitute model of press bolster and ram
To be able to include the measured elastic behaviour of the presses in the virtual tool development process, a universal FE substitute model for bolster and ram is developed. For an efficient usage in industrial practice, the models need to be as simple as possible. This is achieved by using a combination of shell and spring elements. At the same time, the models must be able to reproduce all the identified deflection types of ram and bolster. The modelling approach is explained in detail in [9], [10] and [11].

3.1. Capability of the press substitute model
To validate the capability of the FE substitute model, three presses with different characteristics are chosen. Figure 3 shows the measured deflection curves of presses B (parabola), C (plateau) and A (w-profile) as grey lines. In comparison to Figure 1, the measured values have been adjusted by the displacement of the measuring frame of the press fingerprint tool (explained in [9] and [10]). The dashed black curves depict the deflection of the respective machine specific FE substitute models. All three models show a very precise match with the measurement data.

![Figure 3](image-url)

**Figure 3.** Simulation result of bolster parameter optimisation for three different deflection types in x-direction at 10 MN symmetrical load.

Analogues to the bolster substitute model, the ram model is validated with three characteristic press deformation types as well. In Figure 4 the measured deflection curves of press C (parabola), H (plateau) and E (m-profile) are illustrated as grey lines. As with the bolster, the measured values are adjusted by the displacement of the measuring frame. The simulation results of the respective substitute models are depicted as dashed black lines. The deviations between simulation and measurement are extremely small for all three types, which makes the developed substitute model feasible for application in practice.
4. Coupling of forming and structure simulation

To include the machine elastic behaviour in the forming simulation, two separate simulations are coupled. The forming process is simulated in PAM-STAMP with rigid tools while parallel to that the elastic deformations of the press and the tools are simulated in a structural simulation in PAM-CRASH. During the calculation, the contact forces at the tools in the forming simulation are transferred to the structural simulation, which returns the displacements of the nodes at the active surfaces of the tools. The number of exchanges is controlled by the coupling interval $\Delta t$. The coupled simulation approach is explained in more detail in [8].

4.1. Advanced setup

A conventional forming simulation is normally controlled by the press stroke. With all rigid tools, the simulation is set up to end when the tools are fully closed. Because of the elastic deformation of press and tools in the coupled simulation, the tools are not fully closed when the design stroke is reached. Depending on the produced part and the occurring forming forces, the gap between punch and die can be several tenth of millimetres in the design BDC. This makes a validation of the pressure distribution and the geometrical accuracy of the part unfeasible.

The gap results from a combination of two effects. First effect is the global offset of the punch and die, which results from the deflection of the ram and bolster mounting surfaces. It can be counteracted with additional movement of the die beyond the design stroke length. Second effect is the local elastic deformation at the active surfaces of punch and die. Those deformations can only be compensated by cambering the active surfaces in advance.

In Figure 5 the effect of the two described countermeasures is visualised by means of the occurring forming forces of a 0.7 mm thick steel side frame. In this case, the simulation end is time-based, and the movement of the die is controlled by means of a velocity curve. To increase the number of coupling steps in the later part of the simulation, the die velocity is slowed down at roughly 0.06 s simulation time.
The Figure 5 shows the forming forces of the conventional reference simulation with rigid tools and CAD-surfaces without any camber or other manipulations in light grey. In the BDC at 0.0992 s, the die reaches 13.6 MN force while the punch force amounts to 9.4 MN.

In comparison to that, the coupled simulation with elastic tools and press is depicted as dark grey lines in Figure 5. In the design BDC at 0.0992 s the die and punch forces are about 1.2 MN lower than the reference values. The velocity curve is extended, so that the die keeps moving in 0.1 mm steps. As the tools are getting closer, the forces are gradually increasing. In the last step at about 0.14 s simulation time, the force shows a bigger jump, which indicates a pinching of the blank between punch and die.

With the additional stroke the global offset of the tools can be counteracted, however the tools will still not be fully closed because of the local deformations in the active surfaces. To achieve that, a simulation with cambered active surfaces and additional pressure areas, which are also used for the milling of the tools in practice, is carried out. The resulting forces are presented as black lines in Figure 5. Starting at 0.065 s simulation time, the forces of the coupled simulation with milling data are slightly higher than the ones from the coupled simulation with CAD-data but still lower than the reference forces. When reaching an additional stroke length of +0.3 mm, the die force reaches 13.5 MN and the punch force 9.3 MN, which is close to the reference values. In the following steps at +0.4 and +0.5 mm the forces are jumping, which again is resulting from pinching of the part.

![Figure 5. Comparison of forces from PAM-STAMP simulation of the side frame with CAD data surfaces for rigid and elastic tools as well as milling data active surfaces with elastic tools.](image)

**Figure 5.** Comparison of forces from PAM-STAMP simulation of the side frame with CAD data surfaces for rigid and elastic tools as well as milling data active surfaces with elastic tools.

5. **Experimental validation**

To validate the simulation with extended stroke length, the approach is compared with experimental data. Therefore, the distance between punch and die in the BDC is measured. This is done with the help of lead strips. Multiple holes are being drilled into a produced part at critical areas. Afterwards the part is placed in the tool and 1 mm thick lead strips are positioned in the holes. The press is closed with the same force used for the forming of the part which leads to a compression of the lead strips. After opening the tools, the thickness of lead strips can be measured. The part with drilled holes as well as the measured values of the lead strips are presented in the top left corner of Figure 6.

![Diagram](image)
Figure 6. Experimental and numerical determination of distance between die and punch surfaces at the BDC (experiment) and at +0.3 mm additional stroke (simulation) for the side frame tool.

For the validation, the distance between punch and die at different additional stroke lengths is evaluated in the simulation. In Figure 6 the distance at +0.3 mm stroke length is illustrated as well as the 26 measurement points used in the experiment. The averaged deviation between experiment and simulation is lowest at +0.3 mm stroke length with 0.035 mm, which confirms the assumption from analysing the forces in section 4. All distance values from experiment and simulation as well as the resulting deviations are listed in Table A1 in the appendix.

6. Outlook
In this paper, the capability of ram and bolster substitute models to reproduce all identified press characteristics was approved. The development of a universal FE substitute model for the drawing-cushion based of press fingerprint tool measurement data is part of an ongoing research project. Further, the advanced coupled simulation was successfully validated with experimental data.

So far, the primary focus of the coupled simulation approach in industrial practice was the design of compensation measures to reduce manual rework during try-out. The potential for improving prediction accuracy of the forming simulation regarding part quality is currently analysed in an internal project. First results show a significant difference between conventional forming simulation and the coupled approach.

To further improve the advanced coupled simulation, a pinch test can be used as stop criteria as it can be difficult, to determine the correct additional stroke length manually. However, pinching of the elements might be intended to a certain degree, so that a simple pinch test stop criterion could be too sensitive. The potential of pinch test as stop criterion in combination with thick shell elements should be examined in future work.

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### Appendix

**Table A1.** Measured distances between die and punch surfaces from experiment and coupled simulation with milling data.

| Measurement points | Experiment [mm] | Coupled simulation with additional stroke [mm] |
|--------------------|-----------------|-----------------------------------------------|
|                    | BDC             | +0.1  | +0.2  | +0.3  | +0.4  | +0.5  |
| 1                  | 0.70            | 1.001 | 0.914 | 0.829 | 0.750 | 0.688 | 0.669 |
| 2                  | 0.70            | 0.989 | 0.902 | 0.816 | 0.738 | 0.678 | 0.660 |
| 3                  | 0.67            | 0.970 | 0.882 | 0.796 | 0.718 | 0.661 | 0.647 |
| 4                  | 0.73            | 0.982 | 0.897 | 0.814 | 0.745 | 0.700 | 0.695 |
| 5                  | 0.76            | 1.037 | 0.949 | 0.864 | 0.788 | 0.735 | 0.721 |
| 6                  | 0.74            | 0.968 | 0.883 | 0.802 | 0.732 | 0.689 | 0.684 |
| 7                  | 0.70            | 0.803 | 0.733 | 0.668 | 0.626 | 0.604 | 0.610 |
| 8                  | 0.59            | 0.711 | 0.637 | 0.568 | 0.521 | 0.493 | 0.495 |
| 9                  | 0.70            | 0.955 | 0.869 | 0.786 | 0.714 | 0.660 | 0.648 |
| 10                 | 0.66            | 0.815 | 0.737 | 0.663 | 0.606 | 0.576 | 0.582 |
| 11                 | 0.68            | 0.933 | 0.846 | 0.760 | 0.685 | 0.635 | 0.629 |
| 12                 | 0.65            | 0.813 | 0.734 | 0.659 | 0.602 | 0.575 | 0.583 |
| 13                 | 0.68            | 0.926 | 0.838 | 0.753 | 0.677 | 0.631 | 0.627 |
| 14                 | 0.68            | 0.945 | 0.857 | 0.772 | 0.698 | 0.642 | 0.628 |
| 15                 | 0.69            | 0.937 | 0.854 | 0.772 | 0.692 | 0.624 | 0.591 |
| 16                 | 0.69            | 0.940 | 0.856 | 0.774 | 0.694 | 0.627 | 0.597 |
| 17                 | 0.69            | 0.958 | 0.874 | 0.790 | 0.709 | 0.639 | 0.603 |
| 18                 | 0.70            | 0.973 | 0.889 | 0.805 | 0.723 | 0.650 | 0.607 |
| 19                 | 0.66            | 0.959 | 0.872 | 0.786 | 0.701 | 0.631 | 0.589 |
| 20                 | 0.70            | 0.924 | 0.844 | 0.766 | 0.698 | 0.647 | 0.632 |
| 21                 | 0.80            | 1.079 | 0.994 | 0.911 | 0.836 | 0.779 | 0.760 |
| 22                 | 0.68            | 0.902 | 0.826 | 0.751 | 0.683 | 0.629 | 0.606 |
| 23                 | 0.71            | 1.064 | 0.979 | 0.895 | 0.816 | 0.749 | 0.714 |
| 24                 | 0.67            | 1.034 | 0.946 | 0.859 | 0.776 | 0.706 | 0.663 |
| 25                 | 0.74            | 0.895 | 0.822 | 0.750 | 0.682 | 0.630 | 0.602 |
| 26                 | 0.68            | 0.951 | 0.865 | 0.781 | 0.705 | 0.645 | 0.627 |

Average deviation: 0.247 0.163 0.086 0.035 0.049 0.061
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