Compensation for tool deformation and expansion in virtual try-outs of hot stamping tools

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Abstract. The mechanical properties of hot-stamped parts strongly depend on the tool’s cooling performance. The cooling rate hinges on sufficient temperature gradients and on an excellent contact conductance between tool and workpiece. A uniform distribution of the contact pressure is the key to an even cooling behaviour, and hence, a homogenous micro structure of the formed part. Elastic deformations of machine and tool components under load are a major influence on the pressure distribution between tool surface and hot-stamped part. This applies to hot and cold forming tools. An additional difficulty in hot stamping are superimposed thermal expansions and contractions of the tool, which also affect the part’s mechanical properties due to their influence on the normal contact pressure. Manual die spotting needs to compensate for all these undesired effects and makes tool try-out a large time and money-consuming factor in the development of hot forming tools. This paper presents methods to transform the spotting of hot forming tools into a virtual production reality in order to reduce manual labour and lower costs. It gives details on the numerical compensation of tool surfaces for elastic tool and machine deformations and for temperature-induced tool expansions and contractions. The authors critically analyse necessary and achievable accuracies of computed surfaces and point out required improvements for the future implementation of virtual try-outs into tool development and manufacturing processes.

1. Direct hot stamping
Direct hot stamping is a hot forming process, which uses the advantage of low forming resistance of special steels at high temperatures and their microstructural transformation towards high strength when quenched above a certain cooling rate. A typical material for hot stamping is 22MnB5 steel. The steel blank is heated above 900 °C for a complete transformation to an austenitic microstructure. Then, the red-hot blank is transferred to the stamping tool and directly formed into its final shape (see Figure 1). Once the tool is closed, the quenching process enables yield strengths up to 1500 MPa due to phase transformations to martensite. To be able to guarantee a martensitic microstructure after quenching is a deciding factor to excellent mechanical properties of conventional hot stamped products. A fact which is even more important for tailored processes to obtain locally adjusted mechanical part properties, such as press hardening with tailored blanks or tailored heating and tailored tempering. Since the formation of martensite depends on the cooling rate of the sheet metal, which depends on the temperature gradient [8] and on the normal contact pressure [2], the punch, die, and workpiece must perfectly fit each other.
2. Try-out of hot forming tools

One way toolmakers approach the try-out of hot stamping tools is to run the process at room temperature and conduct measures known from cold forming such as the application of die spotting ink to identify zones of no or too-high pressure (Figure 1, cycle 1). Based on this information, they remove material from the tools surface and iteratively obtain an even pressure distribution between tool and blank. Since this manual die spotting is conducted with cold blanks and at a significant lower tool temperature than the real process (as shown in Figure 1), there are substantial differences regarding the process conditions:

- The red-hot blank has completely different mechanical properties, which results in dissimilar reaction forces on the tool and machine and entail completely different deformations
- Due to the altered material flow, the final thickness distribution in the formed part changes with elevated temperatures. This also leads to variations in the surface pressure.
- Different thermal states also entail different volumetric dimensions of tool and blank and cause altered tool and machine loads

All these differences combined, cause the necessity for another major try-out cycle for elevated temperature (Figure 1, grey cycle 2). Process temperature is reached after a multitude of forming cycles (up to 100 sheets need to be formed before steady state is established).

Due to a lack of spotting ink for high temperatures, toolmakers of hot forming tools use indirect methods for locating zones of high pressure. One way is thermographic imaging of the part directly after the forming (Figure 2). Local hot spots indicate areas of low or no normal contact pressure since there is only a reduced heat flow in these zones. In conclusion, the toolmaker will manually remove tool material in the colder areas, which correspond to local high spots, and therefore, improve the thermal conductance. In order to take off material from its surface, the tool needs to cool back down to almost room temperature. Die spotting of hot stamping tools takes many iterations and is a large cost factor in the tool development phase. The demand for die spotting is demonstrated on the example of a Fraunhofer IWU press hardening tool (Figure 2). Before die spotting (a), the temperature distribution on the surface of formed part after a 10 second quenching phase had shown unacceptable differences which lead to
inhomogeneous microstructures and cause a large variation of the hardness on the part’s surface and thermal induced deformations. Once the dies were spotted (b), the resulting temperature distribution after 10 seconds of quenching was significantly more homogeneous than before.

Figure 2. Thermographic pictures of a side sill with hot spots due to insufficient fitting tool a) temperature in formed part after 10 sec quenching time a) before and b) after die spotting.

Two of the main reasons for this extensive tool try-out are mechanical deflections of the press and the tool due to large process forces during quenching and the thermal tool expansions which are not part of the virtual engineering process of the tool’s surfaces.

3. Simulation of hot stamping
The major applications for simulations in hot stamping are the thermal tool design, the thermo-mechanical process simulation and the prediction of the metallurgical transformation [5].

3.1. Simulation chain
Today’s simulation sequence (Figure 3) includes blank heating and its transport to the tool, calculation of the blanks deformation due to gravitational forces, forming and quenching [5].

Figure 3. Today’s simulation chain for hot stamping process design

So far, tool and press deformation as well as thermal expansion of the tool are excluded from this simulation chain, which is one of the reasons for manual die spotting. The following chapters discuss how to implement these properties into the FE process model, how the implementation affects the simulation results, and how to integrate them into the tool development process.

3.2. Elastic deformations in process simulations
Since the implementation of elastic tool and press deformations will entail significant increases in computation time, the simulation strategy needs to be as efficient as possible (Figure 4). Because the blank shows only little residence during the actual forming, the forces acting on the equipment are relatively low and it can be considered as rigid. Once upper and lower die touch, the pressure on the formed part increases (quenching phase 1), which causes the real tool and press to deform. Due to process-machine interactions, these deformations affect the surface pressure between tool and
workpiece, and hence, influence its cooling rate. For that reason, the tool model switches into elastic mode for the initial quenching phase. Since the acting press force remains the same over the course of the quenching process, the deformation of the tool and the press will not change. It is a fair assumption, that the tool can now be considered as rigid again. Therefore, the deformed tool surface mesh from simulation stage b) is mapped on the thermo-mechanical process model in simulation stage c). This procedure saves a significant amount of computation time. It still needs to be quantified how much the volumetric change from austenite to martensite effects the local surface pressure distribution (please refer to chapter 6: challenges for future applications).

![Diagram](image)

**Figure 4:** Time efficient strategy for computing tool elasticity during hot stamping.

Hot stamping dies are usually designed for hydraulic presses with die cushion (Figure 5 a). Since the friction coefficient between hot steel and the tool surfaces during hot stamping is high (µ > 0.4 [4]) and the material’s hardening exponent low, toolmakers usually rely on spacers for fixed gaps between blankholder and die surface rather than directly applying a blankholder force. That way, the die cushion of the press needs to generate enough force to ensure that the spacers touch the opposite side. The same principle applies to the tool’s punch and die to accomplish a fixed die clearance.

![Diagram](image)

**Figure 5.** a) CAD model of hot stamping tool; b) FE-Modell with elastic tools and press table.

Punch and die are usually equipped with cooling channels. The experimental tool was designed for a single action press with die cushion (Figure 5 b). Since the hot metal has a high friction value and the material’s yield stress is very low, there is a fixed gap between die and blankholder to ensure an easy material flow into the cavity. Spacers separate die and punch as well. The height of the spacers is adjusted during tool try-out to tune the pressure distribution. Punch and die are equipped with cooling channels to guarantee a thermal steady state.
In order to reduce simulation time for this principle investigation, a 40 mm slice of the tooling was modeled. For further reduction of computation time, the tool surface was modeled with fine shell elements and tied to coarsely meshed volume elements, which represent the tool structure. Since this method was separately suggested for both thermal [6] and elastic [3] simulations, it was applied in the thermo-mechanical quenching simulation (Figure 6). In order to deform realistically, the FE punch sits on an elastic surrogate model of the press table with a thickness of 400 mm (Figure 6). Now, it is possible to calculate the influence of the elastic tool deformation on the actual heat flow from workpiece to tooling. For further details on the simulation model, please refer to [7]

Figure 6. Rigid and elastic tool model.

Since the punch in the model deforms under quenching load, the surface pressure between punch and die reduces and entails a lower thermal conductance. The consequences are visible in the part temperature. Not only is there a difference in the final part temperature, but also the temperature gradient (cooling rate) is lower in the process model with elastic punch compared to the process model with rigid punch (Figure 7). Since the microstructural transformation depends on the cooling rate, there is a significant risk of predicting incorrect part properties with rigid tool surfaces.

Figure 7. Temperature in the part during quenching phase 2: left: part center, right: part radius

4. Thermal expansion

Since mechanical die spotting requires manual labor, the tool must cool down well below steady state process temperature to be accessible for the worker. This temperature difference yields in a thermal expansion of both the upper and lower die (Figure 8). The regular strategy to compensate for this
geometrical change in the shop floor is to adjust the surfaces iteratively based on information of the resulting part temperature after quenching.

**Figure 8.** Influence of tool expansion on part shape and mechanical properties.

The simulation shows, that the contact pressure between tool surface and quenched part increases with the tool temperature (Figure 9). The contact pressure rises until the reaction force exceeds the set load of the press, the tool would lift and the spacers would not touch anymore.

**Figure 9.** Influence of thermal expansion on the contact pressure between die and blank.

In the example, the temperature difference is only 25 K. The tool expands by 20 µm in Z direction, which causes a contact pressure growth by 30 MPa in the flat middle area of the part. According to Figure 9, the thermal contact conductance coefficient would multiply by 4. Based on this simulation, the toolmaker would need to remove a significant amount of material on the upper and lower die to guarantee the correct closing behavior under process temperature.

The simplification of rigid tool and machine parts obviously causes a larger increase of contact pressure than observed in reality. The next steps are to complete the model with all thermal boundary conditions such as cooling channels and heat transfer from active tool elements to all attached elements and the environment.

5. Compensation

5.1. Workflow

Future goal is to compensate for mechanical deformations and for thermal induced chances of the tool geometry before the physical production of the tool, and hence, reduce try-out cycles and overall try-out time. In order to do so with a minimum of computation power, the workflow (Figure 10) starts with a process simulation with rigid tools and a steady state temperature distribution. The first phase of quenching will be simulated with elastic tools and mounting plates; the steady state temperature field will be mapped on the tool structure. Now, the tool’s surfaces are embossed by the amount of deformation under quenching load. The last step of the compensation method is to compute the contraction of the tool and prepare the geometrical data for machining.
5.2. Example
In order to show the difference between compensated tool surface and conventionally engineered surface, we ran the simulation sequence for both surfaces and compared the part temperature and microstructure after 5 seconds into quenching. The results suggest two major effects. First, due to a lower overall contact pressure, the cooling of the part is significantly slower for the adjusted surface. Second, a more even distribution of pressure on the surface (Figure 11) leads to a more homogeneous temperature in the part.

6. Challenges for future application
The key to the compensation of thermo-mechanical deformations is an accurate geometrical representation of the tool surface. Automatic mesh generation with geometrical error limitation is standard in most pre-processing software. Due to a large variety of mathematical surface descriptions, the transfer of the actual state of the tool surface to the process simulation and vice versa is complicated. As of now, we cannot guarantee that small surface adjustments conducted in the process simulation will affect the real process due to many necessary data transformations from FEA to CAD to CAM to the surface finish.

Because of the pressure dependent heat transfer, hot stamping simulation models require a correct computation of the interface pressure. However, the surface pressure of FE models shows a strong dependency on the individual mesh size (Figure 12), the element type and the contact formulation.
Figure 12. Element size influences pressure distribution.

To address these problems, alternative methods like NURBS-based finite elements must be investigated in future research and compared to real pressure distributions. The digitalization of the interface pressure between tool and formed is another major challenge for model evaluation, and therefore, for a high model quality. Practical approaches like histogram-based analysis of spotting ink on adjusted tool surfaces [1] will be investigated.

Additional effects on the surface pressure might result from the volumetric change due to phase transformations. Future work at the IWM will focus on efficiently compute this interactive effect and how to implement this into the tool design process.

Further challenges will be the efficient handling of complex surfaces and structures and of multifaceted tool set-ups with cooling channels, insolation, surrounding equipment and their influence on the temperature distribution in the tool and the formed part.

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