Chapter 18
Consideration of the Machine Influence on Multistage Sheet Metal Forming Processes

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Abstract. Metal forming processes are highly affected by the properties of the forming machine. In multistage processes, the force path curve of each stage is influenced by the surrounding stages. This research focuses on the interaction between the forming machine and multistage processes with respect to the quality of the workpiece. The accuracy of the numerical results could be increased by coupling the process simulation with the machine simulation. Further influencing factors, such as different friction conditions during forming and the elasticity of the tool, were considered in the simulation. In addition, the thermal properties of the press were investigated and considered in the machine simulation. Hence, a better correlation between the numerical results and the experiment could be achieved.

18.1 Introduction

Metal forming processes, such as deep drawing, place high demands on the properties of the forming machine. Even slight scatters or inaccuracies in the ram motion can lead to imperfections of the workpiece. The characteristic deformation of the forming machine and the tool system under load has a crucial influence on the result. To simulate forming processes, the use of the finite elements method (FEM), where local influences on the process (e. g. the lubrication or inhomogeneous material properties) can be included in the simulation, is state of the art. Influences between the machine and the forming process have not been taken into account yet. In metal forming simulations, an ideal rigid forming machine is assumed. Thus, differences between simulation and reality occur. Hence, for many applications it is not possible to manufacture parts with the required accuracy right from the beginning so tools have to be set up for each machine in a try-out phase.

In order to reduce the start-up time for new metal forming tools it is necessary to consider the properties of the forming machine in the FE process simulation. Different approaches for a coupled simulation to consider the interaction between forming machine and forming process are known. A classification is drawn between offline-coupling, model integration and co-simulation.

In offline-coupling, the process simulation and the machine simulation are calculated separately. After calculating the process, the resulting force path curve is

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transferred into the machine simulation as input data for a new calculation. Subsequently, the correction of the ram movement as a result of the machine simulation serves as a boundary condition for the FEM simulation, if a new calculation by the two models is performed by means of an iterative loop. In several loops, an approximation to the real workpiece dimensions can be achieved [1]. The most important advantage of offline coupled simulations is that both simulations are implemented in their common software environment. Due to this, both simulations can benefit from the tools, which are available in the typical software environment. The disadvantage of this approach is the fact that no dynamic interaction can be simulated and that the calculation time increases due to the repeated calculation.

An approach, where the machine and the forming process are simulated in a common simulation environment, is called model integration [2, 3]. In [4], the machine structure was reduced and integrated into the FEM process model by means of elasticity conditions. The tilt and the vertical deflection as well as the deformation of the die cushion and the ram were taken into consideration by means of spring elements. This approach resulted in an improvement of the accuracy of the forming simulation. However, if the machine properties and the drive control are examined, this method is limited.

In co-simulation two independent, sufficiently detailed models for the forming machine and the forming process, which exist in different simulation environments, are used [5, 6]. These models exchange data after each time-step. Thus, it is possible to consider dynamic influences within the simulation, which occur during the forming process. In [7], a coupled simulation for bulk metal forming processes was realized. Due to the consideration of the machine properties the accuracy of the forming simulation could be increased. Furthermore, the results of the forming simulation were compared using machine models with different degrees of detail. Even with the least detailed machine model the simulation results of the workpiece dimensions could be approximated to reality by means of a co-simulation in comparison to a separate process simulation.

Within this project, an offline-coupling was implemented. The machine model is based on a phenomenological approach. The process simulation is modeled in a classic FEM environment. The simulation of single processes is state of the art. This project deals with the simulation of multistage processes, where interactions between each stage have to be considered additionally.

18.2 Machine

Experimental investigations were carried out on a high-speed press with a space rod drive (fig. 18.1). The advantage of a space rod drive is the independent adjustment of the ram position and the length of the stroke. The connection rods of a conventional mechanical press can only be moved in two directions. The connection rods of a space rod drive have one more degree of freedom. Thus, the kinematics of the press result in a slower course of motion shortly before reaching the bottom dead centre (bdc). This is especially advantageous for deep drawing processes. The bdc marks the reversal point of the ram.

Nominal force	630 kN
Stroke rate range	40-200 min^{-1}
Stroke adjustment	15-80 mm
Bolster plate clamping surface	750*400 mm
Ram clamping surface	750*310 mm
Max. tool mounting height	315 mm
Max. sheet metal width	200 mm

Fig. 18.1 High-speed press Wanzke STA63

18.2.1 Approach

The method to describe the elastic properties of forming machines is based on the results of experimental tests using a phenomenological approach. The deflections of the forming machine under process load are measured and reproduced using an elasticity matrix with variable elements as machine model. The required information for the model is provided by means of a single measurement of the press, based on a static press measurement similar to the standard DIN 55189 [8]. Due to this fact the model is applicable for many metal forming machines after carrying out this measurement.

The relative total shift between the ram and the bolster plate results from deformations of the connection rods, the ram guide, the press frame, the bolster plate and the ram as well as the partially non-linear elastical characteristics of bearings and guidances. This leads to a shift of the position of the bottom dead centre. The deformations of the press components, except the ram and the bolster plate, can be summed up as deflection of the ram in relation to the bolster plate including the tilting. The deflection and the tilting are first calculated in the machine simulation assuming a rigid bolster plate and ram. The relative total shift is calculated in a further step by superposing the deflection with the deformation of the bolster plate and the ram (Fig. 18.2). For employing the principle of superposition it has to be assumed that superposed loads cause summable deformations. This principle is applicable as long as there is a linear correlation between the loads and the resulting deformations [9]. This approval is valid for very stiff bodies as the ram and the bolster plate.

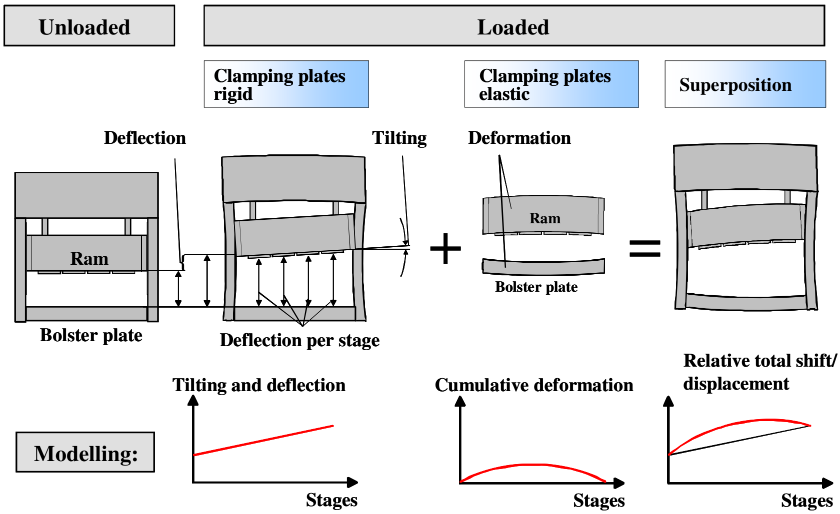

Fig. 18.2 Superposition of deflection and deformation

The number of stages of multistage forming processes is an adjustable parameter in the machine model. A load at a single stage not only causes a shift at the stage itself but also at all other stages.

18.2.2 The Parameterization of the Machine Simulation

18.2.2.1 Press Measurement

The machine model requires the properties of the press as input data. In order to provide these data it is necessary to determine the properties under a defined load. The measurement procedure is based on a static press measurement similar to DIN 55189. Therefore, a load is applied between the ram and the bolster plate via a hydraulic cylinder. The hydraulic cylinder is placed at the position, where the stages will be mounted. The total shift of the press is determined at the positions of the stages by means of displacement transducers. Fig. 18.3 shows the measurement setup of the press for a three-stage process, where the first stage is loaded.

Stage 1 is loaded first. The shift due to the load occurring at the stage itself and at the other stages is recorded. Afterwards, the procedure for the second and the third stage is executed in the same way.

The results of each measurement are path-force curves of the ram at each stage. These are the input data for the machine model, which describe the properties of the press. Fig. 18.4 exemplarily illustrates the total shift at stage 1 in relation to the position of the application of load. The figure shows that a load at stage 1 causes the highest total shift at stage 1, whereas a load at stage 2 of the same amplitude causes a smaller total shift at stage 1. Correspondingly, a load at stage 3 causes an even smaller total shift at stage 1. By means of this data the influences of the stages are described. These influences decrease with an increasing distance to the related stage.

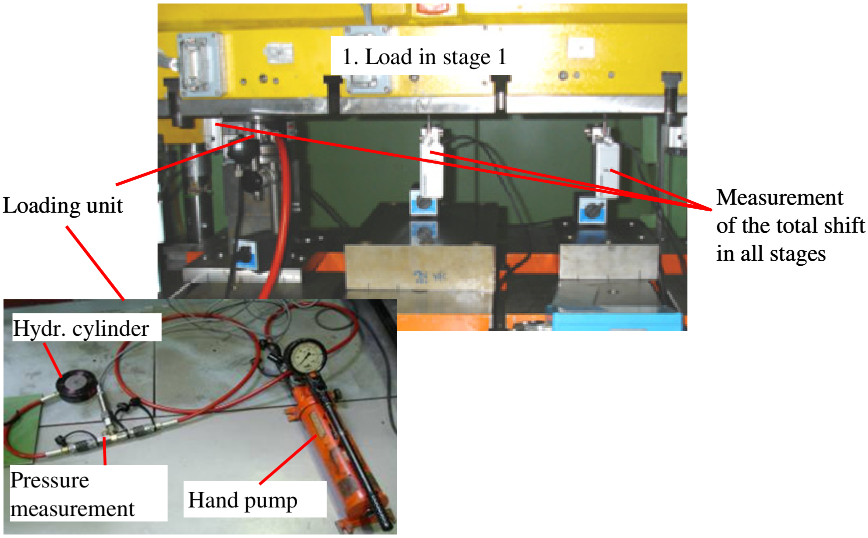

Fig. 18.3 Measurement setup

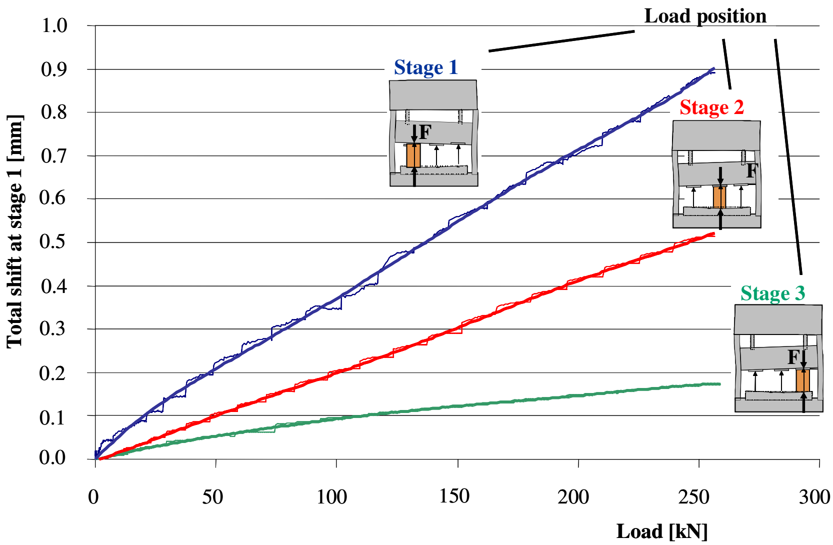

Fig. 18.4 Total shift at stage 1 dependent on a load at stage 1, stage 2 and stage 3

18.2.2.2 Investigation of the Temperature-Influence

During the start-up period of a metal forming production line, temperature changes arise on the components of the press as well as on the metal forming tools. Changes in the temperature of the press components have an influence on the properties of the press and therefore on the quality of the manufactured products. To predict such effects by means of a coupled simulation it is essential to extend the machine model with respect to temperature effects. Hence, the influence on the static properties of the press due to changes of the temperature was examined. It could be shown that the position of the bdc is affected by temperature changes.

To determine the temperature curve of the press, temperature measurements were executed during the operating time of the press up to a nearly steady thermal condition. Apart from the temperature curve of the press, its influence on process parameters, such as forming force and the position of the bottom dead centre, was investigated. In order to quantify and consider the thermal influence in the machine model, parts were formed after different operating intervals and the force path curve of these metal forming processes was captured for the different thermal conditions at each operating interval. Therefore, piezo-electric load cells were integrated into the tool stages and thermocouples were applied to relevant press components (Fig. 18.5). According to Fig. 18.5, for a permanent number of strokes of 90 rpm the system reaches a nearly steady thermal condition after eight hours of operation.

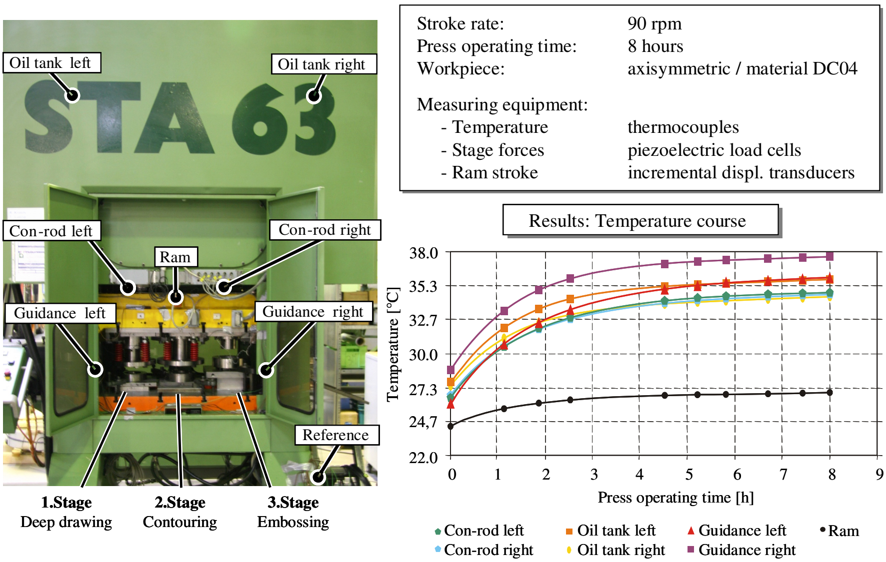

Fig. 18.5 Experimental setup and temperature curve

In order to provide a general comparison between the force-time curve and the temperature-time curve, the temperature of the right connection rod is shown in Figure 18.6. The right connection rod has a direct influence on the embossing stage as the process force at the embossing stage is mainly transferred by the right connection rod. Between the temperature-time curve at the right connection rod and the curve of the embossing force at different operating times correlations can be identified. Both measurement curves have a high gradient at the beginning, which decreases with time. Thus, the curves converge towards a certain steady state. This is related to the fact that the punch not only forms the sheet metal but it also pushes against the bottom of the die. Thus, the force at stage 3 increases as the expansion of the connection rod leads to a higher force on the bottom of the die, which possesses a high stiffness and a correlation can be seen (Fig. 18.6, bottom right).The values of the process force at different operating times at the deep drawing stage and at the contouring stage do not change with the measured increase of temperature (Fig. 18.6). These values mainly depend on the material characteristics of the sheet metal. The increase of the temperature for the deep drawing stage and the contouring stage results in a shift of the bdc since the dies are open in forming direction. As a consequence, the forming path increases and affects the workpiece geometry.

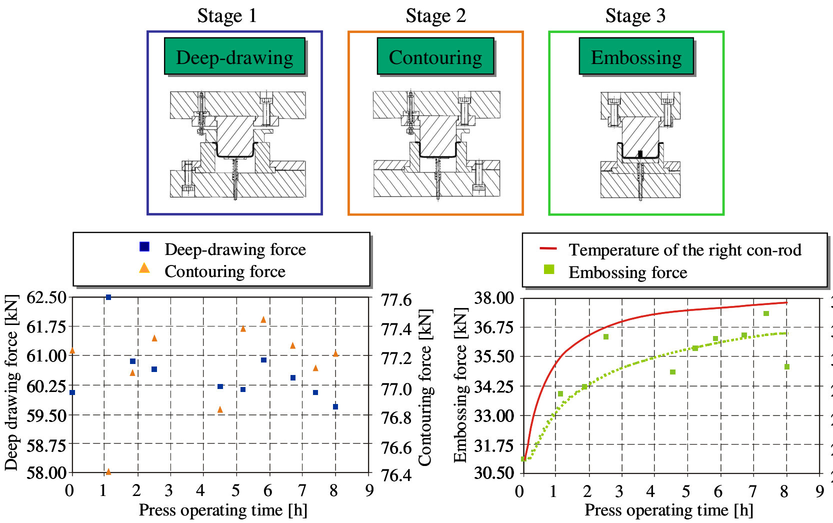

Fig. 18.6 Maximum forces at the forming stages with increasing operating time

The differences of the position of the bdc due to the increase of the temperature of the press can be measured by means of displacement transducers. The changes of the bdc are affected by the expansion of the press components due to the increased temperatures. The initial condition of the "cold" operating state is taken as a reference. The difference between the bdc and the reference bdc defines the total shift caused by changes in the temperature profile of the machine. Fig. 18.7 illustrates the position of the bdc with respect to the operating time for the stages deep drawing, contouring and embossing. It was measured by incremental displacement transducers.

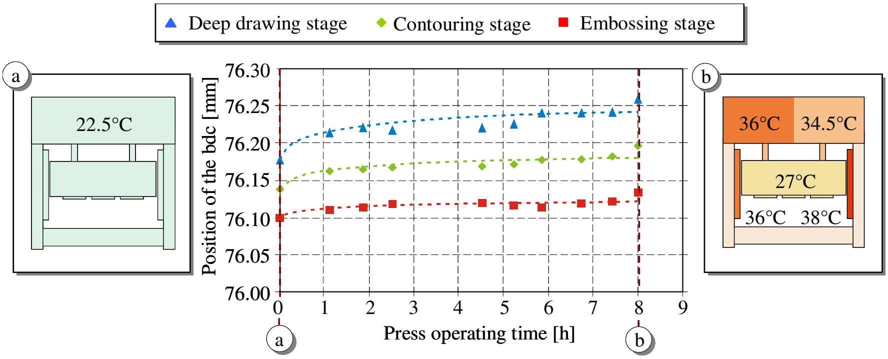

Fig. 18.7 Development of the shift of the bottom dead centre (bdc) related to the operating time of the press

Fig. 18.7 shows that the shift of the bdc of all three stages is similar and converges exponentially with time. The highest gradients of the shift curve in position of the bdc occur during the start-up period of the press. As the operation time increases the gradients of the shift curve in position of the bdc decrease until a nearly steady thermal condition is reached. This result corresponds to the temperature measurements at the press components (Fig. 18.5). Thus, for each stage a shift of the position of the bdc in forming direction occurs and converges towards a certain value with increased operating time.

Differences in the position of the bdc between initial condition at the start-up and the steady thermal condition of the press after eight hours occur at all three stages. At the deep drawing stage, the difference is 0.08 mm, 0.05 mm at the contouring stage and 0.03 mm at the embossing stage. Although these differences mainly result from the temperature increase they also depend on the process. The differences in the shift of the position of each bdc in relation to the position of the bdc in “cold condition” are 0.1 % (deep drawing), 0.06 % (contouring), 0.04 % (embossing). Thus, for the machine model a temperature coefficient of 0.04 % for the steady thermal condition of the press was implemented. This value improves the accuracy of the simulation of the press for all investigated processes by use of the minimal requirements for the embossing stage. Therefore, no further settings are required by the user.

18.3 Modeling of a Three-Stage Process

For the experiments, a modular tool set for a three-stage forming process was designed. The three single tools contain forming processes, which are common in multistage sheet metal forming: these are deep drawing, contouring and embossing (Fig. 18.8). For the deep drawing stage and the contouring stage spring-actuated blank holders are applied. For the final forming of the part all forming stages have to be run through. Every single stage causes a characteristic force path curve. If several individual tools are mounted under one ram, the curves change for each stage since the press deforms and the single stage gets influenced due to

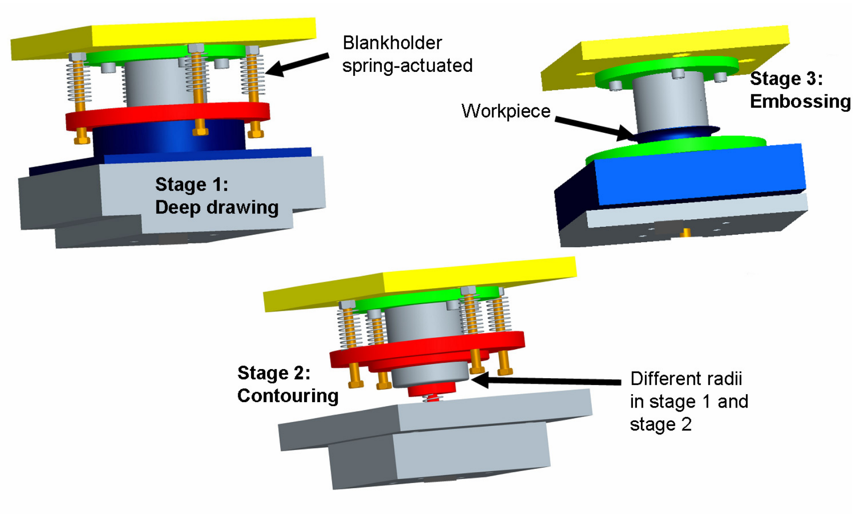

Fig. 18.8 Design of the examined forming stages deep drawing, contouring and embossing

forces of other stages, which are applied simultaneously. The stages can be mounted into the press and operated individually as well as together.

The design of the three-stage tool system was supported by a process simulation. Therefore, simulation models based on the CAD data of the tools were generated and numerical experiments by means of the finite elements method were executed. Fig. 18.9 illustrates the three simulation models for the forming stages deep drawing, contouring and embossing.

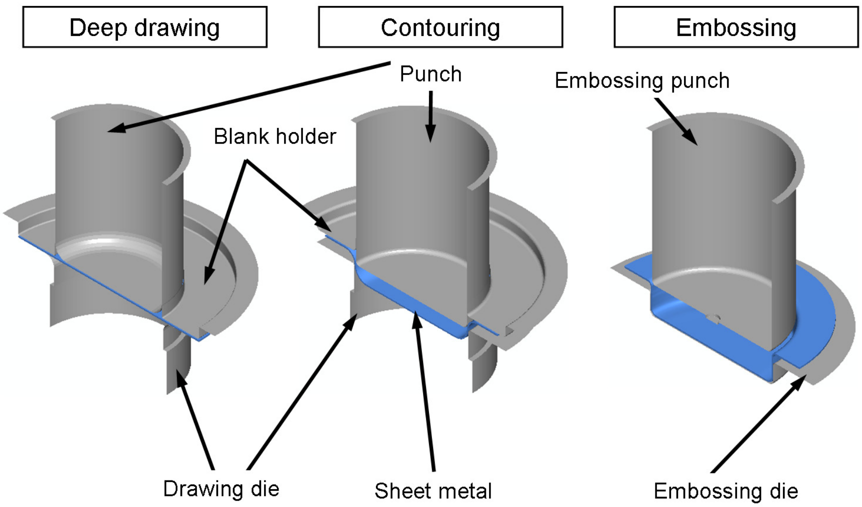

Fig. 18.9 Finite elements models of the three forming stages

The tools are designed to form sheet metals with a thickness of 1.0 mm. The results of the simulation show that this design leads to the required utilization of 80 % of the nominal press force, if a DC 04 deep drawing steel is used. Within the simulation, the friction was set to a constant value of $\mu = 0.16$. In the progression of the project, a new friction law to consider the dependency of the friction on the smoothing pressure and the contact pressure was applied.

In a further step, the drawing die was modeled elastically. The deep drawing stage is illustrated in Fig. 18.10. The punch and the blank holder were still modeled with rigid shell elements. Only the die was modeled with elastically-solid elements to prevent an increasing simulation time. The elastic properties of the die were taken into account in order to simulate the varying local contact conditions. This allows an accurate calculation of the contact pressure.

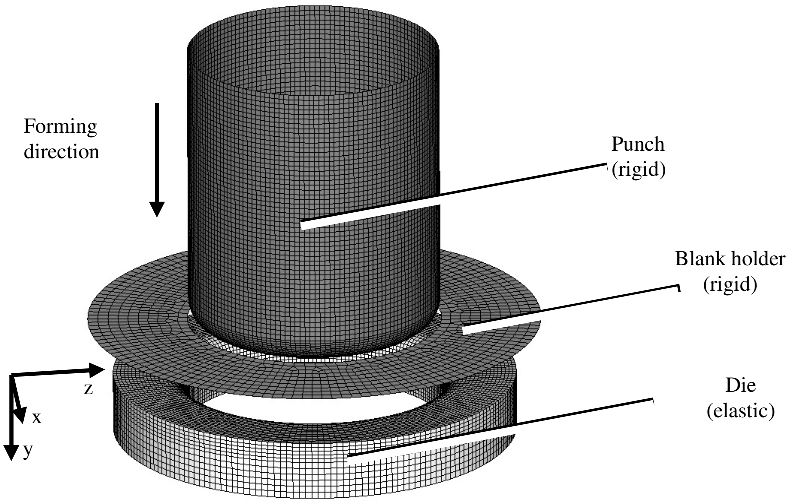

Fig. 18.10 Finite elements model of the deep drawing stage with the elastic die

For an improved description of the friction between the tool and the workpiece during a sheet metal forming process the evolution of the surface conditions of the workpiece has to be considered. The influence of the changing surface topology on friction conditions has to be included in the FE simulation. The contact pressure leads to a smoothing of the surface topology. The smoothed surface results in a reduced friction coefficient. For this reason, a concept for the description of a technical surface structure was used [11]. A workpiece with different smoothed regions is shown in Fig. 18.11.

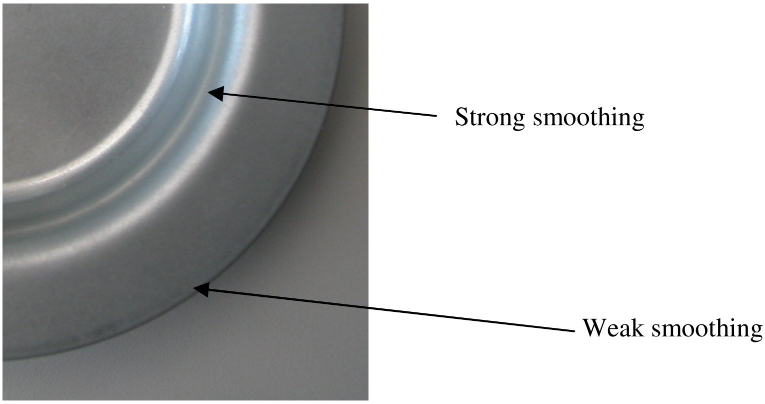

Fig. 18.11 Drawn cup with different degree of smoothed regions

A friction law $\mu = (P_E, P_K)$, where the friction coefficient μ is a function of the smoothing pressure P_E and the contact pressure $P_{K,}$ is implemented in ABAQUS/Explicit via a user subroutine. This friction law considers the local surface pressure as well as the transformation history of the sheet metal surface.

The difference in contact pressure at the contact surface leads to a different component smoothing. The high pressures at the die radius (Fig. 18.12) contribute to different friction conditions during the forming process.

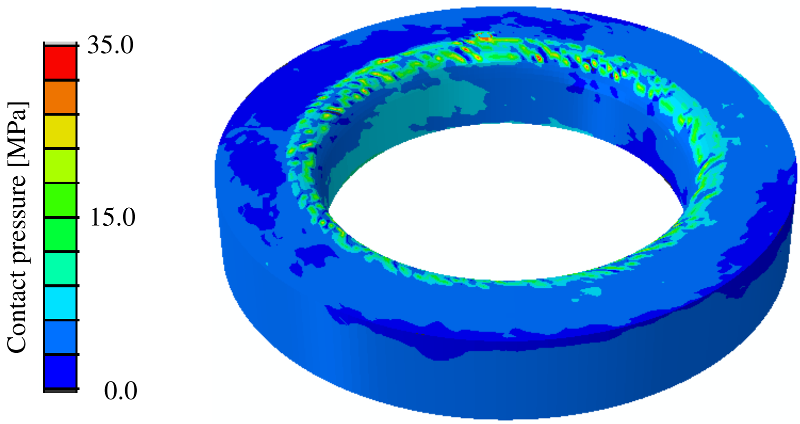

Fig. 18.12 Contact pressure distribution at the die

18.4 Coupling of the Machine Simulation and the Process Simulation

The "offline-coupling" method mentioned above was applied to couple the machine simulation and the process simulation. The two simulation environments run sequentially and the entire cycle iterates. Fig. 18.13 illustrates the progression of the coupled simulation between the process simulation in ABAQUS and the machine simulation in Matlab.

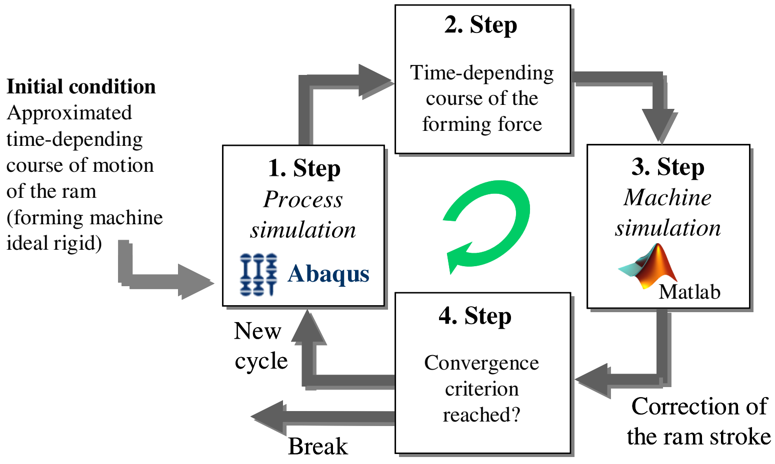

Fig. 18.13 Progression of the coupled simulation

A cycle of the coupled simulation contains four sequentially running steps. The ram motion at each stage, which is necessary for the required part depth assuming an ideal rigid press, serves at first as boundary condition for the process simulation. The process simulation calculates each forming stage one by one and then provides the related coordinates for the nodes of the mesh of the tool punch, the applied node forces and the related forming times in a text file (ASCII format). The text file with the information about the force-time curves of the punch is sent to the machine simulation in Matlab in a second step. By means of this input data the relative shift between the bolster plate and the ram can be determined by the machine simulation. The output of the machine simulation consists of way-time curves for the process simulation, considering the deflection and the deformation of the machine components. This result is then sent back to the process simulation and serves as new input data for the process simulation. This process is repeated until a certain convergence criterion is reached. The convergence criterion consists of the comparison of the difference between the forming paths of two succeeded iterations. This value was set to 0.01 mm. Fig. 18.14 illustrates a simulation, where the convergence criterion was reached after three iteration cycles.

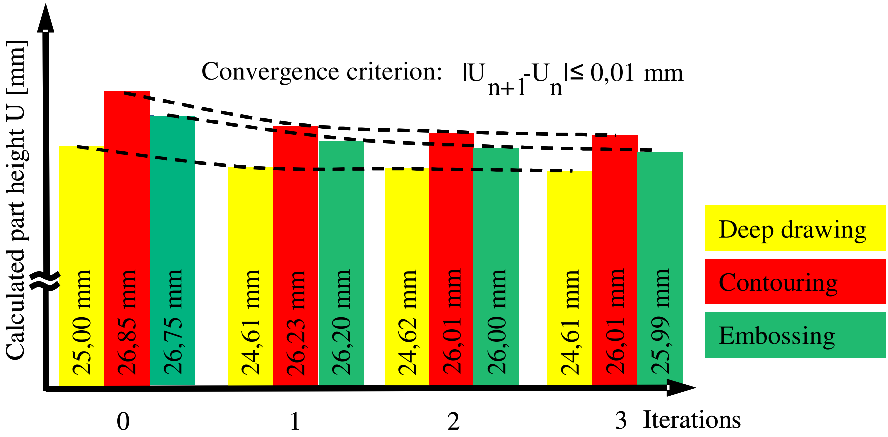

Fig. 18.14 Results after each iteration cycle of a coupled simulation

The data exchange is executed by means of a Matlab function and an external, self-running file. The calculation time of the coupled simulation with ABAQUS 6.7 and Matlab on an Intel Xeon 3.4 GHz processor with 2 GB RAM takes about 20 hours including the enhancements mentioned above (friction model, elastic die model, temperature factor) of the enhanced coupled simulation.

18.5 Validation of the Coupled Simulation

In order to verify the results of the coupled enhanced simulation they were compared with experimental results (Fig. 18.15) and the results of the previous coupled simulation regarding geometrical properties (Table 18.1). In contrast to to the previous simulation, the enhanced coupled simulation considers the elastic die, the improved friction law and the temperature influence of the machine. The results of the previous coupled simulation model are presented in [12].

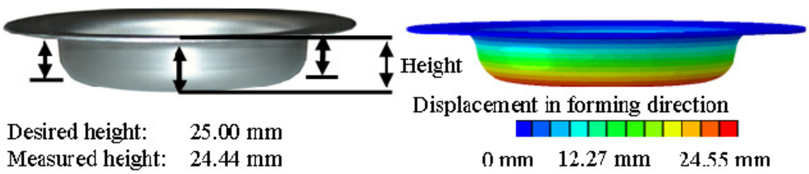

Fig. 18.15 Experimental and simulated height of the part after the deep drawing stage

The height of the formed parts was measured with the optical measurement system GOM ATOS II. In Table I, the results are compared and it is shown that the results of the coupled enhanced simulation could be improved in comparison with the enhanced decoupled and the previous coupled simulation. Using an elastic tool model, an improved friction law and the temperature factor leads to a more realistic simulation but the simulation time is more than six times higher than the previous coupled simulation.

Table 18.1 Comparison of the experimental and the simulated results

–	– *Simulation time* – *[min]*	– *Part height* – *[mm]*		
–	–	– Stage1	– Stage2	– Stage3
– Experiment	–	– 24.44	– 25.92	– 25.86
– Previous coupled simulation	– 170	– 24.61	– 26.01	– 25.99
– Decoupled enhanced simulation	– 390	– 24.90	– 26.10	– 26.10
– Coupled enhanced simulation	– 1240	– 24.55	– 25.98	– 25.92

18.6 Conclusion

The numerical simulation of forming processes is an established method for the analysis of common metal forming processes. By this method, the interactions between the process and the machine are not taken into consideration. Within the experiments in the frameworks of this project it was shown that the machine has an impact on the process and that this impact also affects the geometry and the quality of the manufactured parts.

By means of the described coupling of the process simulation with a machine simulation it became possible to take into consideration the influences of the machine. These influences mainly result in the shift of the bottom dead centre caused by the deformation and the deflection of the ram as well as the tilting of the ram. To improve the accuracy of the dimensions of the simulated workpieces these influences have to be considered in the boundary conditions of the process simulation. Therefore, an offline-coupling was used and validated by the results of experimental data. It was shown that by means of this offline-coupling the simulation results approached the real geometrical dimensions of the workpieces.

With an increasing degree of detail of the models and an enhancement by further influencing parameters, more realistic results with a higher compliance were reached. However, these lead to higher calculation times and to the necessity of further computing resources. It could be shown that the total shift of the bottom dead centre for the analyzed workpiece is less than 1 mm. Particularly the thermal influence of the machine on the process is very small. The differences of the position of the bottom dead centre concerning a change in the temperature profile of the machine range around a few hundredths of a millimeter.

Due to the fact that the influence of a forming machine on a forming process is nominal, the coupled simulation has especially advantages for the tool set-up in forming machines for tools including embossing processes. The tolerances of the height of an embossing punch are often limited to hundredths of a millimeter.

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