Praxis-Orientated Modeling of Tool & Machine Elasticity in Metal Forming Processes

G. Barton$^{1)*}$, C. Barth$^{1)}$, M. Wohlmuth$^{1)}$, H. Schafstall$^{1)}$, M. Tannert$^{2)}$

$^{1)}$ simufact engineering, Tempowerkring 3, 21079 Hamburg / Germany; $^{2)}$ Laboratory for Machine Tools and Production Engineering, RWTH Aachen University, Steinbachstraße 19, 52074 Aachen / Germany

* Corresponding author: E-mail address: gabriel.barton@simufact.de; Tel.: +49 40 790 1620

Abstract

Recent developments incorporated in the commercial FE/FV-simulation software Simufact.forming, which provide fast and user friendly modeling of elasticity effects of the forming machines applied in metal forming processes are presented. Both, the elasticity within the forming dies and the elasticity of the press frame are considered. The elastic deformation of the press is modeled by the relative displacement of the slide and the bed plate perpendicular to the forming direction and their relative inclination caused by tolerances of the bearings and the elastic behavior of the press. These effects are modeled by additional degrees of freedom constrained by non-linear springs assigned to the bedplate. The model is validated by comparison of the simulation results with an upsetting process carried out under laboratory conditions. A simulation of a forging process of industrial relevance is presented. With regard to industrial application the experimental techniques required to determine the elasticity properties of presses are summarized, presenting the work of research groups which provide methods for the measurement of the required properties. Outlooks on simulation models of other metal forming processes using the introduced methodology, and on ongoing efforts to implement dynamic elasticity press models to Simufact.forming conclude this paper.

Keywords: Tools and Dies, Numerical Methods, Elasticity, Nonlinear Finite-Element Method

Introduction

Finite-Element and Finite-Volume simulation programs allow for fast and efficient modeling of metal forming processes typically neglecting the elastic tool behavior.

Even though both, the elasticity within the forming dies and the elasticity of the press are of high significance for deep-drawing and closed die forging operations. This is of particular importance if the resulting forming force is not in the centerline of the press, which is the case for asymmetric geometries. Given that, it is surprising, that only a small fraction of FEM users consider elastic effects during metal forming simulations as reported by Tekkaya (2010). We assume, that either the significance of elastic effects is not yet known to the applicants or the obstacles encountered for elastic simulations are too high.

The development of commercial simulation software for metal forming processes must therefore provide for an user-friendly implementation of elasticity models of the tools and the used forming aggregates. Therefore, preferably models should be implemented, for which the mechanical properties can be easily determined in industrial applications.

State of the Art

The modeling of elastic deformations in bulk and sheet metal forming dies can be easily performed, since the geometry of the dies is essential for the plasticity simulation itself and the Young's modulus required for the simulation of the dies elasticity is a standard mechanical property easily obtained from e.g. the steel manufacturer. Furthermore, it is only required to define the constraint plane of the elastic die in the simulation model. Contrary to this, simulation models incorporating the elasticity of the forming press itself are notedly more sophisticated and still a current research topic being worked on, e.g. in the priority program SPP 1180 funded by the Deutsche Forschungsgemeinschaft.

The elastic deformation of the press can be described by the relative tilting of the ram and the bed plate causing a relative inclination α as shown in **Fig. 1**. Second, a relative displacement of the ram and the bed plate takes place.

Both, the elasticity within the forming dies and the elasticity of the press frame cause deflections, which are of significance for deep-drawing and closed die forging operations. Particularly, if the resulting forming force is not in the centerline of the press, which is the case for asymmetric workpiece geometries. These deformations under load are caused by tolerances of the bearings and the elastic behavior of the press frame and the ram drive system.

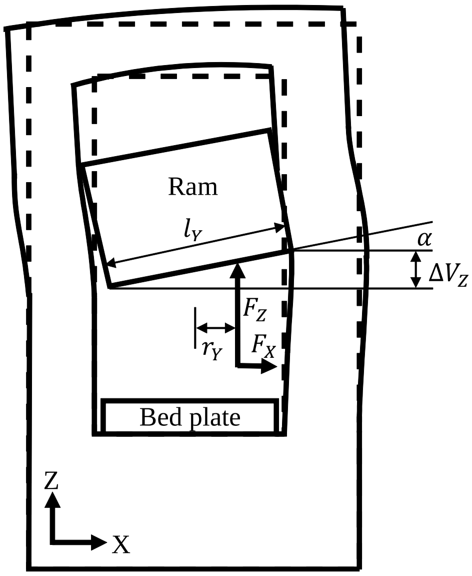


Figure 1. Tilting of the ram if loaded eccentrically according to Doege and Behrens (2006)

The relative displacement and tilting are described as a function of the unbalanced forming forces and subsequently resulting moments acting on the ram and bed plate.

The measurements of these elasticity effects under static loads are standardized for mechanical and hydraulic sheet metal forming presses by the German standard DIN 55189.

Several approaches to model the metal forming process coupled with the machine behavior have been published.

Puchhala et al. (2009) utilizes two separate program instances for the modeling of the plasticity problem and the tool elasticity of rolling processes. Contact stresses and the elastic tool deformations are interchanged between both programs at predefined time steps. This approach allows to reduce the number of iterations for the elastic bodies and to cease continuing the elasticity simulation if steady state conditions are reached. However, only a fraction of metal forming processes reach steady state conditions. This approach models the elasticity effects within tools, but does not add further degrees of freedom caused by elasticity effects of the machines.

A more comprehensive approach for bulk metal forming processes has been realized by Schapp (2008) connecting two simulation models, one modeling the metal forming process itself using the commercial software Forge2005, the other, GekoSim which is a development of the author's institution. GekoSim is reading the force loads acting on the tools from the plasticity simulation, calculates the non-linear elastic machine behavior and returns the calculated tilting and displacement of the tools to the plasticity simulation.

It is simulating the static elasticity behavior of the entire forming press using an implemented analytical model. Optionally, it can be connected to a third software to carry out a Multi-Body simulation considering dynamic effects. If processes with multiple forming stages in one press are to be simulated Brecher et al. (2008) developed an extended approach of this method which allows simulating the plasticity behavior of each stage individually and combines the individually simulated forces to compute the elastic press deflection. This method is faster than simulating all forming stages in one plasticity model. Furthermore, at least for the bulk metal forming processes investigated by Brecher et al. (2010), it is sufficient to consider the static non-linear elastic machine behavior (neglecting dynamic effects) for a high quality of the simulation results.

For sheet metal forming processes Großmann et al. (2008, 2009) have developed a simulation model which models the forming die, the blank holder and the ram as elastic bodies. The tilting and displacement of the ram and the blank holder are modeled by elastic springs. At every corner of each elastic tool for each degree of freedom an individual spring is assigned.

Bogon et al. (2010) developed an simplified model for fast and efficient simulation of elasticity effects of the die and bed plate in sheet metal forming processes and its tilting and displacement.

Measurement systems for elastic machine properties. Simulation models are only as precise as the input data describing the modeled properties and do therefore require as precise as possible measurements. A number of authors have investigated methods for the experimental determination of elastic machine properties.

Behrens and Javadi (2007) have developed a mechanical measurement system for fast and cost effective determination of static elastic machine properties for sheet metal forming processes according to DIN 55189.

Schapp et al. (2006) have developed an optical measuring method to investigate elastic machine deformations using a laser tracker combined with an in-house developed visualization system of the measured deformations. The advantage of this system over mechanic measurements is the possibility to carry out measurements under static and dynamic loads.

Simulation Model

We are convinced, that implementing the static elasticity behavior of bulk metal forming presses properties measured in accordance to the standard DIN 55189 by attaching tools to non-linear elastic springs as suggested by Schapp (2008) is the most efficient way to simulate tool elasticity effects in bulk metal forming simulations without increasing the modeling complexity so much, that potential users will be discouraged from applying it. We have provided a user friendly implementation of this approach directly into the commercial simulation software Simufact.forming.

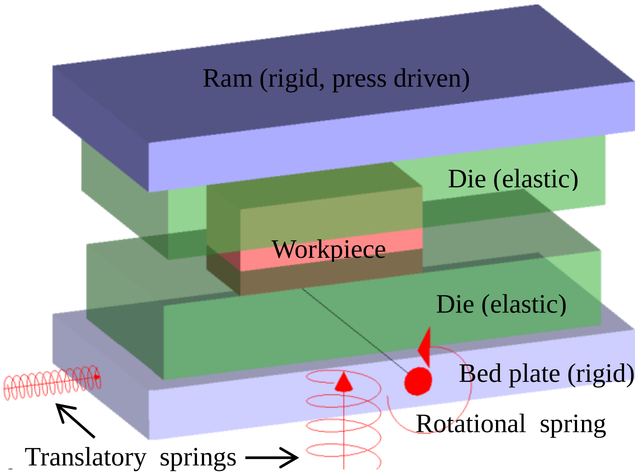


Figure 2. Principle of the developed simulation model

In our simulation model, shown in **Fig. 2**, the bed plate and the ram are modeled as rigid bodies. The ram is actuated translatory by the press kinematic. All elasticity effects of the machine are represented by the rigid body motion of the bed plate, which is for this reason assigned two additional translational and one rotational degree of freedom each limited by non-linear translatory or rotational spring. The bed plate instead of the ram was chosen to model the elasticity behavior to be able to postprocess the displacements due to the elasticity of to the machine independent of the machine's forging kinematic. Dynamic elasticity effects of the machine are neglected.

Each one translatory spring is used to represent:

– Elastic displacement in z-direction due to force F_z

– Elastic displacement in x-direction due to force F_x

One rotational spring is used to represent:

– Elastic rotation around the y-axis due to the eccentricity of force F_z

If required, the displacement in the y-direction and the rotations around the x- and z-axis could be added in the same manner as well. These springs must be attached to rigid bodies. Therefore, the elasticity behavior of the dies itself is modeled by elastic dies, which are glued to the rigid bed plate or ram. The workpiece is deformed between these elastic dies.

To verify the functionality and the precision of the simulated results of our model the upsetting of a ring was simulated as shown in **Fig. 3**. modeling the upsetting process thoroughly documented and studied by Schapp (2008). We have used the Finite-Element solver of Simufact.forming 10.0 for this study.

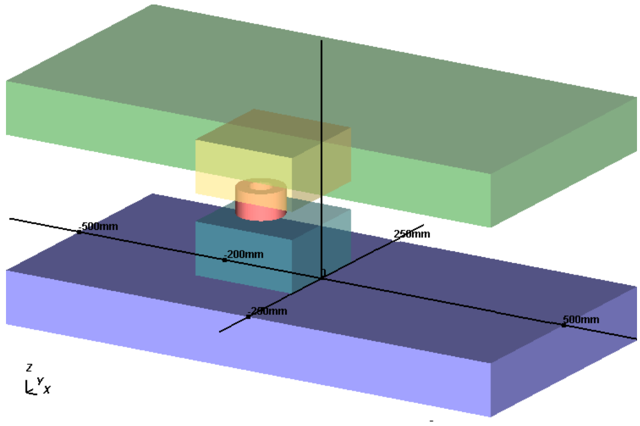
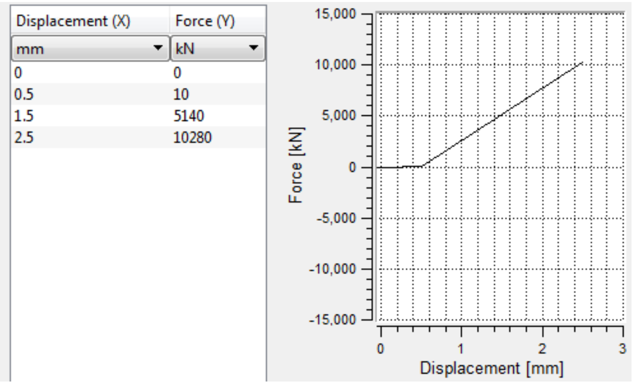


Figure 3. Simulation model of ring upsetting process

A ring manufactured from Steel St52-3 (material number 1.0570) was upset at room temperature (30°C) from 50 mm to 34 mm height using a Hasenclever VER 630 crank press operated at a speed of 130 rev/min. The ring's initial outer diameter is 90 mm, its inner diameter is 45 mm.

The ring is formed between two elastic dies, which are each 200 mm wide and deep and are 100 mm high. It is made from HSS steel with a Young's Modulus of 210000 MPa. The centerline of the ring is parallel to the z-axis and is eccentrically positioned x= -125 mm off the press center. An initial gap of 2 mm is left between the ring and the upper die. The friction between the ring and the dies is described by Coulomb friction with μ=0.1 limited by plastic shear friction with m=0.2.

The press stiffness for translation due to the press elasticity was determined by Schapp (2008) to 695 kN/mm in x-direction (without bearing clearance) and 5140 kN/mm in z-direction with 0.5 mm bearing clearance. **Fig. 4**. shows the press characteristics for deflection in z-direction which have been input to Simufact.forming as a table.

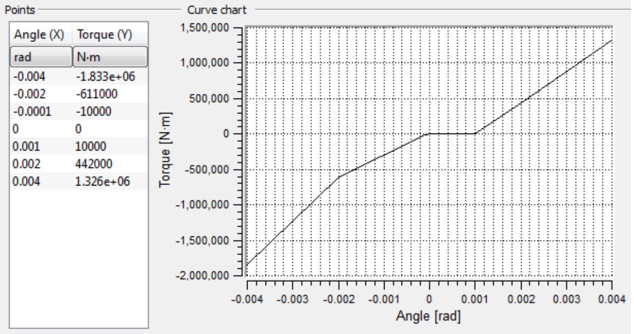


Displacement (X)	Force (Y)
mm	kN
0	0
0.5	10
1.5	5140
2.5	10280

Figure 4. Properties of bed plate deflection along z-axis

The press stiffness for rotation of the bed plate due to the press elasticity around the y-axis (negative direction) is 611 kNm/(mm/m) with a bearing clearance of 0.1 mm/m as shown in **Fig. 5**. Different behavior depending on the direction can be considered.

Both, the upsetting and the backstroke to release the workpiece are simulated.



Angle (X)	Torque (Y)
rad	N·m
-0.004	-1.833e+06
-0.002	-611000
-0.0001	-10000
0	0
0.001	10000
0.002	442000
0.004	1.326e+06

Figure 5. Properties of bed plate rotation around y-axis

Simulation Results

The simulated force required for the ring upsetting process is plotted in **Fig. 6** as a function of the press stroke. There was no averaging applied to plot the forces. Nonetheless, the simulated forces are smooth which is an indicator for the high numerical stability of the solver resulting in an stable contact situation.

The upsetting forces, cause the bed plate to translate vertically in negative z-direction and to rotate in negative direction around the y-axis. The vertical translation is shown in **Fig. 7**. These simulated values coincide with the values simulated by Schapp (2008). For a stroke of 6 mm he simulated a vertical translation of 1.1 mm, our model predicts 1.05 mm. For a stroke of 18 mm he simulated 1.45 mm, which is exactly met by our model. The measurement on the press showed a displacement of 1.6 mm for a stroke of 18 mm, which is 10% higher than simulated.

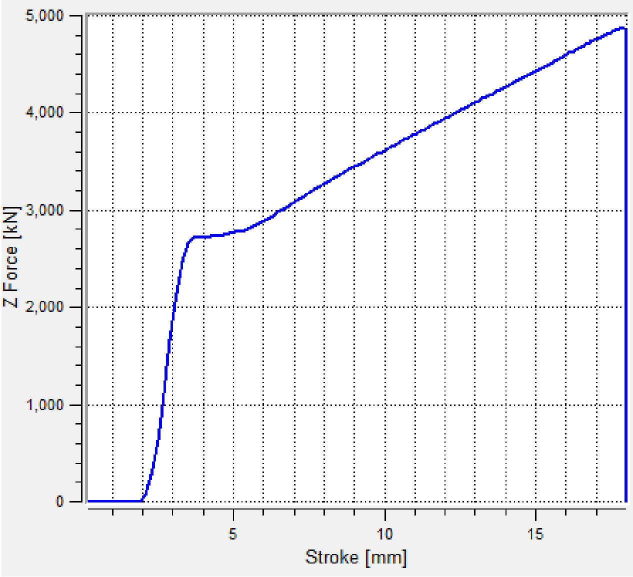


Figure 6. Simulated upsetting force

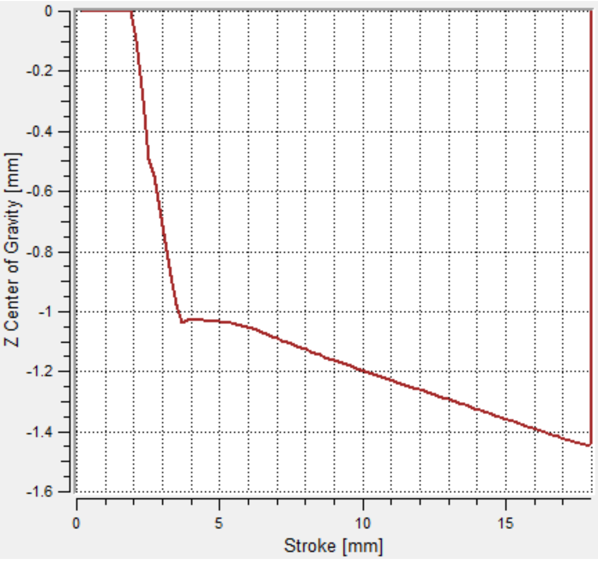


Figure 7. Simulated vertical bed plate translation

The simulated bed plate rotation is compared to results of Schapp (2008) in **Table 1.** Unfortunately only one measurement is available for comparison with the experiments.

Table 1. Bed plate rotation

Stroke [mm]	Simufact.forming [mm/m]	GekoSim (analytical model) [mm/m]	Measurement [mm/m]
3	1.5	1.7	n.a.
6	1.8	2.0	n.a.
12	2.1	2.4	n.a.
18	2.4	2.7	2.5

The ring has not been deformed to the final height of 34 mm, due to the elasticity effects of the crank press and the dies which both have been considered in the simulation model. Instead as shown in **Fig. 8**, the final height is 35.8 mm at the right hand side of the ring (which is closer to the center line of the press) and 36.1 mm on the left hand side. This is 1.8 mm, respectively 2.1 mm higher than if not considering the elasticity. 1.45 mm of these values are due to the vertical deflection of the press, 0.15 mm due to elastic die deformation and 0.2 mm on the right hand side of the ring to 0.5 mm (on the left hand side) due to the bed plate rotation.

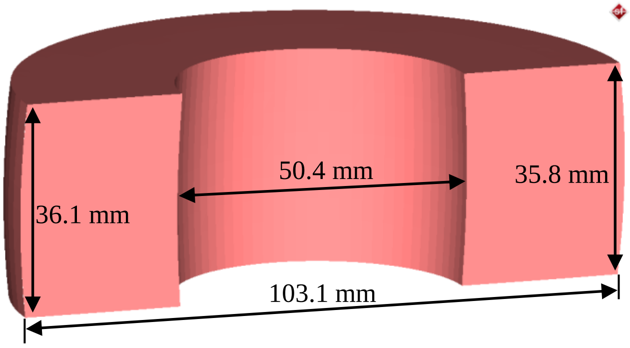


Figure 8. Simulated ring geometry (stroke 18 mm)

Finally, the simulated stresses in the workpiece and the dies are shown in **Fig. 9** for a stroke of 18 mm.

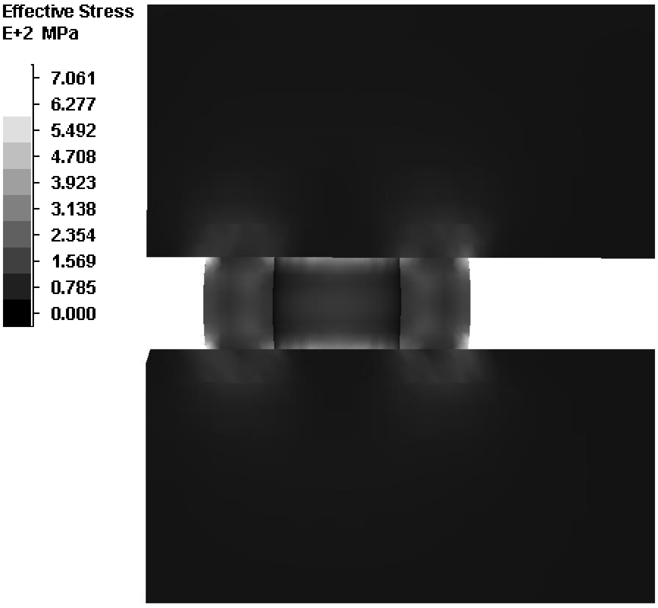


Figure 9. Simulated equivalent stresses of ring and dies

The workpiece was modeled with 6048 Hex elements, the two deformable dies with each 1070 Hex elements. The computing time for the presented model was 36 minutes using an Intel Core i7 CPU Q840 @ 1.87 GHz. The computational cost is increased only by 2 % if the translations and rotations due to the machine elasticity are considered.

Application of the presented model for industrial forging processes. The presented model has been used to simulate a hot forging process of an support arm made from aluminum AlMgSi1 alloy which is shown in **Fig. 10** using the same press as for the ring upsetting simulation. The part has an length of 660 mm. The simulated translation of the lower die is presented in **Fig. 11**. The rotation of the lower die is shown in **Table 2**.

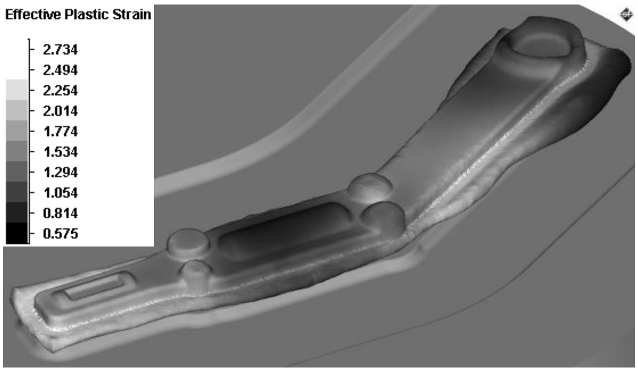


Figure 10. Simulation model of support arm

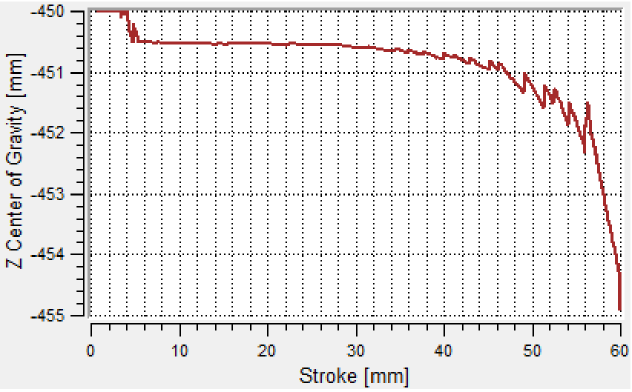


Figure 11. Simulated vertical translation of lower die

Table 2. Rotation of lower die around y-axis

Stroke [mm]	Simulated die rotation [mm/m]
5	0.10
9	0.14
15	0.24
25	0.19
35	0.26
40	0.35
45	0.46
50	0.94
55	0.88
60	0.40

The simulated support arm is asymmetric and causes unbalanced forces in the crank press which result in unparalleled dies. The maximum unparallelity for the given length of the forged part is 0.65 mm. Whereas the vertical translation of the dies is 3 mm.

Discussion

Simulating the elastic behavior of metal forming presses increases the accuracy of the metal forming simulation in respect to the product geometry.

The instabilities sometimes encountered when elasticity effects are modeled with separate programs at the beginning of the forming process, where small changes in die loads result in an large machine displacement which then can lead to an unstable contact situation are effectively avoided in our simulation model.

No additional program is required, which limits the training requirements maintenance effort to a minimum. The additional computing time for the simulation of the machine's elastic translations and rotations is barely increased.

The press characteristics required for this simulation approach can be determined by a number of standardized techniques as described above. Additionally to these techniques, it should be possible to determine the elastic press characteristics from measurements of the geometry of the formed parts and the measured upsetting forces. An inverse analysis by means of simulation could then be used to describe the elastic machine behavior.

Modeling of machine elasticity effects in other processes. This approach to simulate the elastic machine behavior is not limited to upsetting processes. The springs and local degrees of freedom as used for the upsetting press simulation can be combined in a modular way to be applied for the simulation of elastic rolls in rolling and ring-rolling processes as shown in **Fig. 12**. In this model, the center part of the mandrel is modeled as an elastic body. The upper and lower bearing stud are modeled as rigid bodies which are glued to the elastic roll. Local degrees of freedom allow both studs to rotate around all three axes. The movement of the lower stud is constrained in x- and z-direction, where as the upper stud is only constrained in x-direction. The feed in y-direction is defined by a press-kinematic acting on both studs.

This ensures a realistic representation of the bearings, which allow the mandrel to rotate around its axis and allows for a realistic bending line as well as for a vertical movement of the upper stud. Nonlinear springs can be added to simulate the behavior of the mandrel bearings.

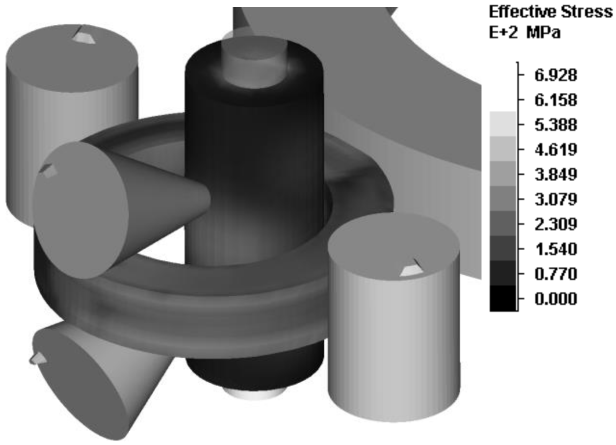


Figure 12. Elastic mandrel in ring-rolling simulation

For cogging and radial forging applications the presented approach can be used to model a more realistic manipulator behavior giving way to the work piece elongation in the workpiece longitudinal direction during a blow. See **Fig. 13**.

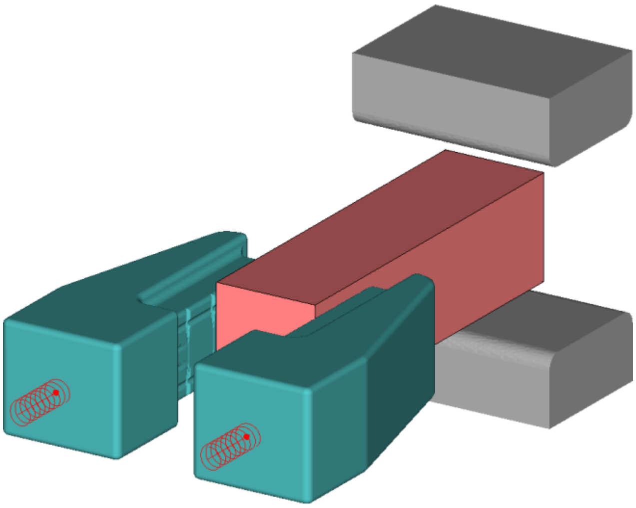


Figure 13. Elastic manipulator in cogging simulation

Outlook on future developments. Future enhancements of Simufact.forming target the implementation of interfaces to the external "GekoSim" machine model for the simulation of dynamic press/machine behavior. This will also allow for a fast simulation of the elasticity behavior of presses, in which several stages of a part are pressed at once.

The accuracy of the implemented model shall be studied when used for sheet metal forming applications.

Another development target is the implementation of segment-to-segment contact algorithms to smooth the simulated contact stresses and increase the numerical stability when simulating processes with elastic tools touching each other, e.g. in models of 4-high and more complex rolling mills.

Conclusion

The implementation of recent developments to model tool elasticity effects in to the commercial special purpose Finite-Element / Finite-Volume simulation software Simufact.forming was shown. The implemented functionalities for the modeling of elastic machine properties have been demonstrated for an upsetting process and validated by comparison of the simulation results with an upsetting process carried out in laboratory conditions and well documented by literature.

These enhancements allow for user-friendly modeling of various elasticity effects of metal forming machines in addition to elastic tools.

In the case of forging presses the required input data can be derived from several standardized measurement techniques.

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