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An overview of Methods for Simulating Sheet Metal Forming with Elastic Dies

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An overview of Methods for Simulating Sheet Metal Forming with Elastic Dies

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Abstract. Sheet metal forming (SMF) simulations are traditionally carried out with rigid active forming surfaces. This means that the elasticity and dynamics of presses and die structures are ignored. The only geometries of the tools included in the simulations are the active forming surfaces. One reason for this simplification is the large amount of computational power that is required to solve finite element (FE) models that incorporates elastic stamping dies. Another reason is the lack of die CAD models before the later stages of stamping projects. Research during the last couple of decades indicated potential large benefits when including elastic dies in SMF simulations. For example, for simulating die try-out or for Digital Twins of presses and dies. Even though the need and potential benefits of elastic dies in simulations are well known it is not yet implemented on a wide scale. The main obstacles have been lacking data on presses and dies, long simulation times, and no standardized implementation in SMF software. This paper presents an overview of existing methods for SMF simulations with elastic dies and discuss their respective benefits and drawbacks. The survey of methods shows that simulation models with elastic tools will be needed for detailed analyses of forming operations and also for purposes like digital twins. On the other hand, simplified and robust models can be developed for non-FEA users to carry out simple one-step compensation of tool surfaces for virtual spotting purposes. The most promising and versatile method from the literature is selected, modified, and demonstrated for industrial sized dies.

1. Introduction

Sheet metal forming (SMF) simulations are traditionally carried out with rigid forming surfaces. This means that the elasticity and dynamics of presses and die structures are ignored. One reason for this simplification is the large amount of computational power that is required to solve finite element (FE) models that incorporates elastic stamping dies and presses. Another reason is the lack of die CAD models before the later stages of stamping projects. Previous research during the last couple of decades indicated large benefits if elastic dies and presses are included in SMF simulations [1-8]. The benefits of simulations with elastic tools are also seen in related manufacturing techniques using dies and presses. Some examples outside SMF are developments of processes and dies in High Pressure Die Casting [9], Thin Profile Extrusions [10], Multi-Point Sandwich Forming [11], Clinching [12], and Forging [13-14]. Even though the need and potential benefits of elastic dies in simulations are well known it is not yet implemented on a wide scale.

The first purpose of this paper is to present an overview of existing methods for SMF simulations with elastic dies and discuss their respective benefits and drawbacks. The survey of methods shows that simulation models with elastic tools will be needed for highly detailed analyses of forming operations, and for purposes like training digital twins. On the other hand, simplified models can be developed for non-FEA users to carry out simple one-step compensation of tool surfaces for virtual spotting purposes.

The second purpose of this paper is to select and demonstrate the most promising method for SMF simulations with elastic dies method from the literature. Modifying the selected method is key to enabling simulations for industrial-sized dies, otherwise it is impossible to solve models of industrial sized stamping dies with a reasonable amount of time and computational power.

The method selected and demonstrated herein has one significant advantage: it can realistically represent both the dynamic and elastic behavior of the cushion and blankholder system. This is further demonstrated in [15]. There are no other existing methods available to represent these behaviors which can have a profound impact on the forming operation.

Models throughout this paper are created in LS-PrePost V4.6.0 and solved with the explicit FE software LS-Dyna R11.1.0 [16]. Keywords and setup of models throughout this paper are referencing this software.

2. Methods for SMF Simulations with Elastic Dies

SMF simulations with elastic tools can be very tedious and time-consuming work. Here, several existing methods are presented and discussed. First, it must be mentioned that forming dies are mounted in presses that have elastic and dynamic behaviors. Predicting die deformations is challenging because it depends on the full press structure which is challenging to include in a FE model. Full representations of presses will result in very large FE models. Presses can however be represented by various measuring and modeling techniques [6, 8, 17-21]. Measuring and characterizing a press cushion is more challenging. It is however easier to model based on CAD data of the cushion structure [22-23]. The elasticity of the blankholder and cushion system can be accurately described by including a model of the press cushion in single action presses or blankholder plates in double action presses.

2.1. Discretization with solid elements

Discretization of the entire die and press structure with solid elements is not a viable way for forming analyses on an industrial scale. This approach uses brute force by adding an enormous number of solid elements to achieve a high resolution of the forming surfaces. This makes the models computationally costly [5-7, 22]. Further, they require access to die CAD data with updated forming surface geometries throughout stamping die project. However, this technique can be used on small er dies to study the influence of the elastic forming tools [1, 4]. The important first steps in method development and motivation for using elastic tools were taken with this method.

2.2. Uncoupled FE models

In [24] a method was implemented of first carrying out a structural FE-simulation of the forming tools in the FE software ABAQUS. The simulation was based on scanning data of existing forming dies past die try-out. The die surfaces and elastic tool parts were loaded with forming forces before exporting geometries to the SMF simulation software AutoForm. The method consists of pressing the die parts against each other, also used in [25], in structural simulation software. Then transferring the deformed die shapes to the forming surfaces in AutoForm. The use of sub-modeling in ABAQUS was recommended to transfer the deformed shapes. This approach showed in [24] that die deformations can have a large influence on the forming process, even though the resulting die deformations are frozen at a single point in time. Die deformations and dynamics throughout the press stroke are not included in the simulation. Manually running two or more software and transferring data between them is not desired.

Uncoupled models are not fully suited for SMF simulations with elastic tools, even though they were used to demonstrate the influence of elastic dies on the forming operation. The method can be good enough to get a sense of how much die surface compensation is needed for virtual spotting.

2.3. Reduction techniques for DOFs

In [4] and [7], different methods for reducing the degrees of freedom (DOF) in tool structures are presented. The first method is called static condensation, or super elements, and is available in most finite element codes. Parts of the model are presolved, then only nodes on forming surfaces and other contact areas are retained. Static condensation is shown in [4] to not be a viable way for the reduction of sheet metal forming simulations. The method is only suitable when the retained degrees of freedom are on the order of a magnitude smaller than the initial amount of degrees of freedom. In SMF simulations a very large amount of segments have to be retained on the forming surfaces.

A second method suggested in [4] is deformable rigid bodies, or modal method, where the deformation of the structure is estimated by a linear combination of so-called modes. For a cross die, presented in [4], this approach is increasing the solver time only by a few percent when deformable tools are added to the forming simulation. The method needs presolving which adds extra steps during the implementation of the model. So, unless the solving for modes and model setup is easy and simplified for the FE user, the methods presented in the following sections might be more suited for SMF simulations with elastic dies. However, Industry 4.0, Machine Learning, Digital Twins, etc. are areas that are growing fast. There, a large amount of data is needed for the data-driven models. FE models might need to be continuously running to give stamping plants decision support. For this, reducing the number of DOFs might be valuable and worth the extra effort.

2.4. Coupled FE models

In [6, 26-29], the forming simulation based on the geometry of the active surface of the die is performed in PAM-Stamp. Then a separate elastic structural simulation model of the die, punch, and blankholder was created. Contact forces from the forming simulation were used to estimate the displacements in a structural FE-model, then sending back updated surfaces for continuing the forming operation. This exchange of contact forces and displacements between forming simulation and structural simulation is performed through coupling steps in the simulation.

This method yields sound and realistic results that are confirmed in real try-out conditions. Especially if it is coupled with realistic estimations of press behavior based on experimental measurements [27]. To estimate a sound structural behavior and avoid unrealistic oscillations in tool deformations the coupling steps between the forming model and the structural model must be performed with high frequency.

One possible drawback of this method could be the modeling of the cushion and blankholder in single action presses. The deformations of the tools and press parts are calculated in an implicit structural model where boundary conditions are needed on any structure to prevent rigid body movements from causing divergence in the solver. In a realistic case where the cushion is not in contact with its guiding rails, only a mapped pressure on the top and point force underneath are loading the cushion structure. In [6], the bottom surfaces of all the cushion pins are constrained in all directions when deformations are calculated; it is mentioned in [27] that work is ongoing to create a universal substitute model for the cushion system based on experimental measurements. These limitations in blankholder modeling limit the use of this modeling technique e.g., robustness analysis, digital twins, and process control applications. There, blankholder forces, deformations, shimming, tilting, etc. are very important parameters and need to be realistically modeled.

2.5. Shell elements connected to solid elements

In [7] the idea is raised that the tool geometry probably does not have to be resolved by a very fine mesh to estimate the global tool deformations. On the other hand, the forming surfaces need a fine resolution. It is therefore suggested to, in one simulation model, connect shells representing the forming surfaces to a solid element mesh of the die structure. An example is demonstrated by simulating the forming of an s-rail geometry where the forming surfaces are connected to the tool structure by tied offset contacts in LS-Dyna.

3. Selecting and modifying a method for SMF simulations with elastic dies on industrial-sized dies.

Reduced FE models, described in chapter 2.3, is highly dependent on the model from which it is originally reduced. It also requires extra preprocessing and solving steps before the model is completed. The method is best suited when solver time is critical, e.g., large robustness analyses or for building digital twins. But even then, the model could be too slow, metamodeling is needed for production control when responses are needed within minutes or even seconds.

	Simulation of small forming dies, eg. lab tools.	Feasibility simulations in car projects.	Robustness simulations.	Virtual Spotting and Die Tryout	Use the model for inline process control (Digital Twin)	COMMENT
Simulations with rigid dies. (Current Industrial and Academic standard)	OK if die deformations can be ignored.	Die elasticity is ignored in the early phases of feasibility.	Missing effects of elastic deformations.	Missing effects of elastic deformations.	Missing effects of elastic deformations.	Only reliable when the influence of elastic deformations can be ignored.
Solid elements for tool discretization. (Chapter 2.1)	Fast enough for small dies.	No CAD data of solids early in SMF projects.	Requires too much computational power	Requires too much computational power	Requires too much computational power	Theoretically the most accurate model. Limited by computational power for simulations of larger dies.
Uncoupled FE models. (Chapter 2.2)	Not required, the method in chapter 2.1 is OK.	No CAD data of solids early in SMF projects.	No deformations during the stroke.	OK for one-step spotting, but the methods below are more advanced and reliable.	No deformations during the stroke.	The method is missing dynamic effects and continuous deformations of the die. The method was however a valuable step on the path toward the methods described in Chapters 2.3-2.5.
Reduced FE models. (Chapter 2.3)	Not required, the method in chapter 2.1 is OK.	No CAD data of solids early in SMF projects.	Highly dependent on the reduced original FE-model.	Highly dependent on the reduced original FE-model.	Highly dependent on the reduced original FE-model.	Will be important when the simulation time is very critical, but the properties of the model will depend on the model on which it is based.
Coupled FE models. (Chapter 2.4)	Not required, the method in chapter 2.1 is OK.	No CAD data of solids early in SMF projects.	Limited in blankholder and cushion modeling.	Reliable for punch and matrix deformations.	Limited in blankholder and cushion modeling.	Fully elastic SMF simulations. There are currently unresolved limitations of blankholder and cushion modeling. This limits the use to blankholder spotting, robustness simulations, and digital twins.
Shell elements connected to solid elements. (Chapter 2.5)	Not required, the method in chapter 2.1 is OK.	No CAD data of solids early in SMF projects.	Reliable, might require long simulation times for robustness analyses.	Includes all important dynamic and elastic effects.	Reliable predictions, powerful if it can be used as a basis for metamodels.	Fully elastic SMF simulations. Reliably represents elastic press and die deformations and dynamics.

Table 1. Comparison of identified models for sheet metal forming simulations with elastic dies.

Coupled FE models, described in chapter 2.4, is a full working model for SMF simulations with elastic dies. The models are solved within a reasonable time and seem to yield good accuracy for virtual spotting of punch and matrix. There is however one identified drawback of the model: the blankholder and the cushion system will not be realistically constrained. This is because the blankholder and cushion need to be artificially constrained to avoid rigid body motions when blankholder deformations are calculated. This happens because the deformations are calculated in a separate FE model where they should be loaded solely by forces from the blank and the cushion cylinders. In theory, this will work, but the slightest numerical imbalance will cause rigid body motions and non-convergence of the FE-model. This is solved by artificially locking nodes on the blankholder and/or cushion solids, often the bottom of the cushion pins restricting deformations and rotations.

The preferred method by the authors is a method originally proposed by Haufe et al. in [7] where a shell mesh is coupled to a solid structural mesh. This idea to include both forming and structural behavior in the same model seems very attractive, both from a preprocessing and a solver perspective. This method has none of the previously mentioned drawbacks of extra preprocessing steps or numerical issues during solving. However, in its´ current form it is impossible to solve models on an industrial scale. Important modifications of the method to enable this is presented in this paper.

Since 2015, research within Swedish and international research projects is developing methods for SMF simulations with elastic dies [4, 22, 30] where this simulation method is further adopted in LS-Dyna. The goal has been to define a method that makes it possible to include all desired parts in a single FE-model. The model shall be solved continuously, with realistic boundary conditions, without any mapping or simplifications between different codes of FE-models. Modeling should also be quick and easy, and geometries fast to update. The simulations presented in subsequent chapters of this paper are based on this approach. The models were found to be relatively straightforward to set up in LS-Dyna, but when it was implemented for industrial-sized dies and simulations some further modifications and considerations were needed that are presented in this chapter. When applying the method to larger body panels it was discovered that the solver cost for the contact algorithm is large. A major issue in running forming models in an explicit code with elastic tools is the dynamic behavior of the large and heavy mass scaled die parts. Density is therefore artificially reduced to minimize the dynamic oscillations while keeping the structural stiffness intact. It is also important to distribute the model in a smart way across the computing cores during the solving process.

Based on literature and the previous discussion, table 1 compares methods identified for SMF simulations with elastic dies.

3.1. NULL material for forming surfaces

Forming surfaces in an FE model needs a fine resolution, which will generate a lot of very small solid elements if only solid elements are used. The meshing becomes complicated and solver times extremely long. The solution proposed by Haufe et.al. [7] is to cover a coarse solid mesh with a finer shell mesh. A flexible and nimble way to utilize this strategy is to cover a solid mesh with *MAT_NULL shell elements [16], which is a material lacking any mechanical properties. It will act as an infinitely thin blank covering the coarse solid elements and representing the active forming surfaces, not influencing time steps and mass scaling. During design iterations, this method enables the same solid mesh to be used repeatedly while only swapping out the forming surfaces.

The shell elements representing the forming surfaces are connected to the solid elements in the die structure by a tied contact with offset. The contact type for connecting the shell elements to the solid structure is *CONTACT_TIED_NODES_TO_SURFACE_CONSTRAINED_OFFSET [16].

Two contact parameters are critical in ensuring that the NULL elements are tied to the solid structure [30]: The depth of the contact search shall be large enough so that each node finds a solid element segment to follow, this can be adjusted by setting negative values for the SST/MST parameter on the contact card. PARMAX should also be used to extend the contact segments in the segment-based projection. Otherwise, there is a risk that some nodes will not find a contact segment on the solid.

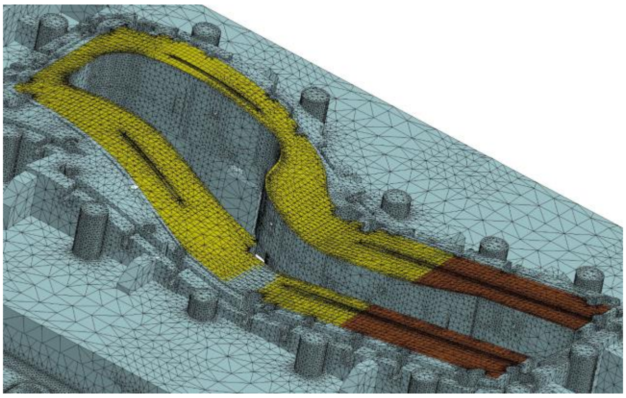

Figure 1. Example of a solid blankholder covered with NULL elements

3.2. Reduced density of solid parts

Explicit SMF simulations are conducted with very high velocities, often in the range of 500-2000 mm/s. This will lead to very large dynamic effects if large elastic bodies are used in the models to represent elastic stamping dies. The elastic bodies would start to bounce against each other and vibrate a lot during the simulation, see figure 2. One solution to this issue is to run the simulations with small velocities that will reduce mass scaling but lead to very long simulation times.

Another way is to artificially lower the density of the elastic bodies, this allows for the simulations to run at velocities normally used in SMF simulations but with small dynamic effects, still maintaining a physically sound representation of the elastic response. Figure 2 depicts the movement of the ram driving the blankholder with normal density and mass scaling, and when the density of blankholder parts is reduced by a factor of 100. The blankholder is closing with 2000 mm/s, thereafter, applying a blankholder force of 1900 kN.

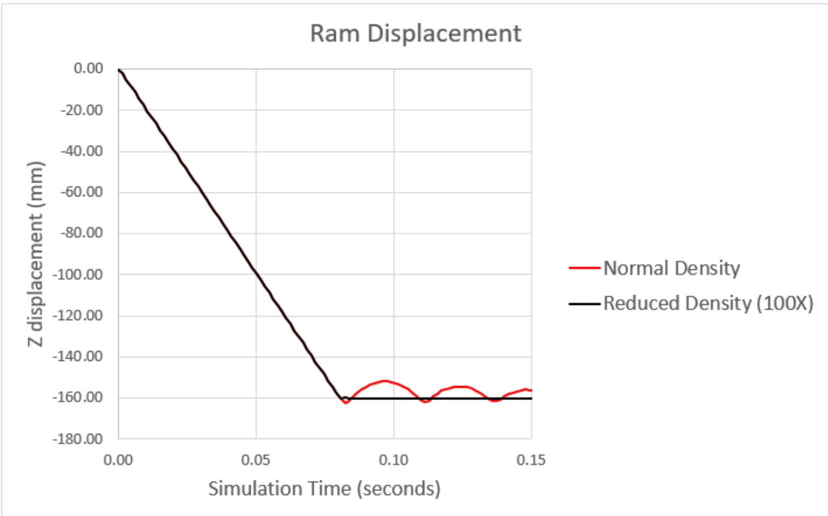

Figure 2. Ram displacement for blankholder with normal and reduced density.

3.3. Model Decomposition

An important aspect when solving SMF models with elastic dies is the decomposition of the models. Decomposition distributes the model across cores on the cluster that is solving the model. Here it is important to select a method that distributes the calculations for elements, material, and contacts as

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evenly as possible across the cores. A bad decomposition can lead to a few cores doing a lot of calculations while others are idle. Poor ways of performing the decomposition are e.g., to divide the model along the x, y, or z-axis in the model. Decomposition along the height of a tool is illustrated in figure 3A below. This can lead to most contact calculations, and elastoplastic material calculations are carried out on very few cores. Meanwhile, most of the cores quickly carry out the calculations for the elastic elements in the tool structure and then sit idle. An attractive way of performing decomposition for SMF simulations with elastic dies is *CONTROL_MPP_DECOMPOSITION_CONTACT_DISTRIBUTE which distributes the model across the cores based on contact interfaces selected by the user. It is recommended to use the contact interface between the blank and the die which will yield a good distribution based on the large number of elements in this interface, this is shown in figure 3B. Using *CONTROL_MPP_DECOMPOSITION_CONTACT_DISTRIBUTE decreases the simulation time by approximately one third for the presented model, from 3 to 2 hours.

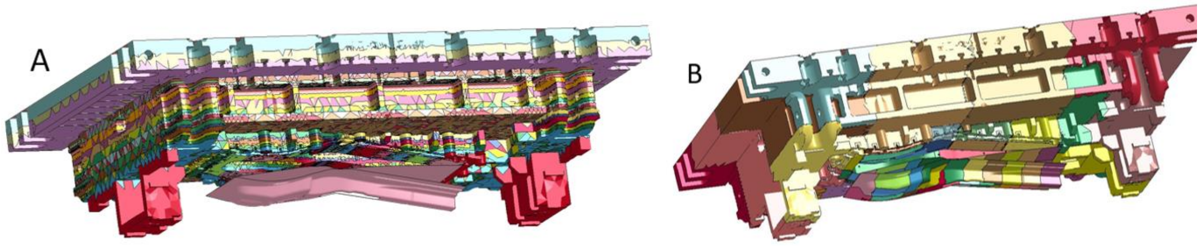

Figure 3. A: Decomposition along the height of the die, for 24 cores. Each core represented by a color. B: Decomposition by contact interface between die and blank.

3.4. Scaling analysis

Standard forming analyses in LS-Dyna with rigid tools are normally conducted with 4-8 cores for most car body parts. Simulations with elastic tools are found to benefit from more cores. For the specific part simulated in this example an optimum number of cores seems to be around 20. All simulations here are run with 24 cores, unless other specified. A comparison is therefore done with the rigid die simulation using 24 cores. The result can be seen in figure 4. A normal simulation with rigid dies takes <1 hour. Adding elastic tools increases the simulation time by a couple of hours.

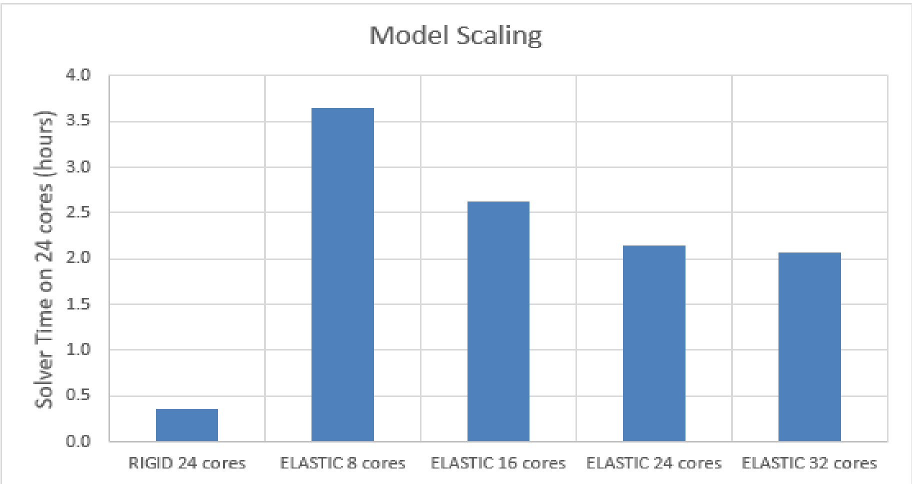

Figure 4. Scaling of FE model. The number of hours required to solve the presented model is plotted versus the number of cores.

3.5. Summary of methods for short simulation times
For a fast and nimble modeling approach, it is efficient to use a coarse solid mesh for the tool structure together with NULL shell elements representing the forming surfaces. If templates are created for LS-PrePost it takes <1 hour in LS-PrePost to set up forming simulations with elastic dies. It is only the meshes, together with material parameters, forces, and velocity curves that need to be replaced.

There is basically just one major difference in preprocessing compared to standard simulations with elastic dies: preparation and meshing of the die solids. For a full-sized stamping die this will take at least an hour to complete. The authors found the possibilities of meshing within the CAD software Catia V5 to be very efficient in meshing the die structures for use in LS-PrePost. It is very important to have standardized and parameterized CAD files for an efficient work flow. For example, it is not desired to include every small drilling hole in the die structure in the meshed die body. There can be hundreds of them in each forming die and removing them individually would be very time consuming and tedious. It is key to have a CAD model where it is possible to deactivate groups of features with a few clicks in the CAD software. This is fortunately common practice in the car industry today.

Artificially reducing the density of the elastic tool parts is the single most important step for reducing simulation times. This singlehandedly makes it possible to reduce the simulations time to a few hours using 10-20 cores. This should be compared to simulation times of tens of hours using hundreds of cores as in [23]. Selecting a reliable decomposition method, and a good number of cores, can then further cut the simulation times by more than 50% [22, 30].

Depending on the desired level of detail in the simulation it is also possible to save time by selecting less detailed material models, fewer integration points in the shell elements, a lower frequency of updates in the contact algorithms, etc. Reducing the detail level in the blank and contacts will still yield very similar results for the tool deformations, even if the response of the blank becomes less detailed. However, it is the described meshing technique, distribution across cores, and density reduction of the tools that mainly influences the simulation time. So, there are no limitations to reach the same accuracy for the blank as in simulations with rigid surfaces.

The focus of this modeling is to describe the global deformations of the die structures. The accuracy of describing these deformations is sufficient due to a large number of elements across the die structures resolving these deformations. However, these models should not be used for studying the effect of local deformations within the die. This is due to the underlying die structure being meshed with a coarse mesh that is not capturing these small deformations, for example inside the draw beads.

4. Conclusion
None of the existing methods in the literature for SMF with elastic dies are fully mature for simulations of industrial sized dies. Either they are missing important features or are too simplified. Or, as for the method presented in this paper, the method is promising but computationally very demanding and requires several modifications to become feasible for use in industry and academia. Important modifications of the selected method in an explicit FE code are to artificially reduce the density of the die solids, and distribute the model in an efficient way across the solver cores. The scaling of mass is not the common mass scaling used in explicit FE codes. Here, the mass of the die solids is reduced by a factor of 100. This cancels unrealistic dynamic effects arising from high velocities in explicit FE simulations. The scaling is still preserving the elastic behavior of the solid structures.

After modifications, the selected method for SMF with elastic dies is deemed to be fast, robust, and powerful in the sense that it provides an easy way for modeling. The method consists of using explicit time integration where the tool parts are meshed with a coarse solid mesh. The forming surfaces are then modeled with a finer shell mesh and attached to the coarse tool mesh by tie contacts with offset, originally proposed by Haufe et al. in [7].

It is easy to update the model by replacing separate parts such as die solids or forming surfaces.

Die deformations are calculated continuously throughout the simulation in one single model.

There is an increase in preprocessing and simulation time compared to using rigid tools, but industrial dies can now be modeled within an hour and solved within a working day.

One of the main criteria in favor of the selected approach is that it can realistically model the blankholder and cushion system in single action presses. This is very important for realistic results and there is no known solution for this if other methods are used. However, the elasticity of the bolster and ram needs to be represented reliably. Methods to measure and represent the bolster and ram have therefore been suggested in the literature. The existing methods all seem promising and will hopefully converge to a standard method within the SMF industry and academia.

The proposed method for SMF simulations with elastic dies can also act as a base model for robustness analyses or digital twins. Carrying out a robustness analysis, through parameter study, is feasible with the current method. It might be worth the effort to reduce the model by the model reduction techniques presented in chapter 2.3. But the most important argument for using these models in parameter studies is that elastic tools can yield a very different result compared to simulations with rigid forming surfaces, exemplified by the model in chapter 4.2.

A close topic of parameter studies is to create digital twins for inline production control where decisions are needed in seconds. In this case, it is needed to build meta-models that represent the behavior of the real production system. An interesting approach is to combine twins based on data and twins based on numerical models into hybrid twins [31, 32].

Models are now available for reliable virtual tryout and production support. The next frontier in the research area of SMF with elastic dies is probably related to topics such as digital factories controlled and monitored by smart digital systems.

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