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The advanced forming process model including the elastic effects of the forming press and tool

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This article addresses process, stamping, and manufacturing engineers, as well as tool designers (prototype and series production tools), and press shop planners in the range of metal forming. The paper deals with methods of modelling and simulating the metal forming process and their application in product design, production, and forming process planning. In models usually applied major effects on the forming process are neglected. For instance, the elastic behaviour of presses and die tools is not considered in process and tool planning. Thus, reworking of tools is a consequence of this model oversimplification. The paper illustrates how interactions between forming press, tool and metal forming process can be modelled by enhancing conventional FE models. Several examples demonstrate the information value of the Advanced Forming Process Model (AFPM).

Keywords: *simulation of forming process, digital simulation of behaviour, virtual press, advanced forming process model, AFPM*

1. Introduction

Established as a powerful tool for sheet metal process planning, the Finite-Element-Simulation contributes to product engineering as well as production, process, and tool planning.

Currently applied process models merely consider the sheet metal component and the interface between sheet metal and tool, called workpiece-die interface [1]. Commonly, sheet metal components are described by shell elements with simple constitutive equations. The workpiece-die interface is represented by friction and contact law with constant coefficients. According to the actual state of FE-simulation the forming tool and machine are modelled as rigid i.e. the effect of the forming tool and machine on the forming process is neglected. In reality, both forming tool and machine evidently affect the forming process as required tool rework during the try-out demonstrates. Therefore, the purpose is to minimize time and effort in try-outs by using better simulation methods during the tool planning stage.

If quality and efficiency of metal forming processes are to be controlled already during the planning stage, interactions between subsystems machine, tool, work piece, and forming process need to be included in a complete forming model.

The Advanced Forming Process Model (AFPM) extended by effects of machine and tool is object of research work currently conducted at the “Institute of Machine Tools and Control Engineering” of the TU Dresden. In the following, some results are presented.

2. Ways of Model Advancement

Comprehensive modelling of the forming process demands coupling of subsystems as machine, tool, and work piece influencing the forming process. Principle concepts connecting the FE workpiece model (the common metal forming model) and press model are presented in [4]. Here, coupling variants are to be differentiated according to their way of integration.

- *Offline coupling (non-reactive)* is process characterization within the machine model based on process force progressions. Process force progressions calculated by the workpiece model are loaded from the FEA-environment via ASCII file into the press model [5]. Amongst others, this coupling method is applicable to analyze the operating performance of the machine and to detect the load on assemblies. In [5, 6] the ram deflections of a multi ram press were estimated. In [7] the effects of a tilted ram on the deep drawing process were analyzed.
- *Integrated coupling* is the workpiece model extended by a press model in the FEA-environment. The integrated FE-model realizes direct interaction between the process load and tool position as a result of the press behaviour. The concept describing the press by a reduced structure representing process relevant effects is exemplified in [2, 3].
- *Coupling of discrete models*, the machine effects are depicted in independent press models. Advantageously, the complex influences of the machine behaviour (drive, guidance system, frame, etc. [9]) are modelled in detail by Multi-Body-Simulation (MBS) while the workpiece description is made by FEM. Thus, two simulation tools (MBS and FEM) connected by simulator coupling are to be applied. The simulator coupling organizes the exchange of data and synchronizes the different solution algorithms. A complete forming model by coupling discrete simulation models is exemplified in [8].

To design the forming process, only press behaviour directly affecting the process is relevant. Interactions between assemblies inside the press are less important. Hence, the integrated solution realized in [2, 3] is adequate. Furthermore, applying the integrated approach avoids the independent major problem of coupling different simulation software.

3. AFPM considering elastic press effects

3.1. Relevant static effects

Accuracy defining effects of the press based on its deformation and deflection behaviour are significant to the sheet metal forming process [2]. In standard [10], these effects are determined as accuracy parameters of presses. For the time being, only static effects are to be considered by the model advancement:

- vertical total stiffness c_{totZ},

- horizontal total stiffness c_{totX} and c_{totY},
- resistances against tilt (tilting stiffness) c_{α} and c_{β}.

The resulting stiffness parameters combine all static effects of the press assemblies each regarding to one degree of freedom in the press' coordinate system.

3.2. Press model

In the following, step by step the above mentioned press effects are added to the AFPM. Currently, tool components are handled as rigid bodies as described above. Therefore it is sufficient to define the tool bearing on a rigid ram. A rigid ram takes the advantage of directly applicable principle stiffnesses of the press describing the effects by concentrated parameters. The concentrated stiffnesses are connected to the centre of gravity of the ram as shown in Figure 1a.

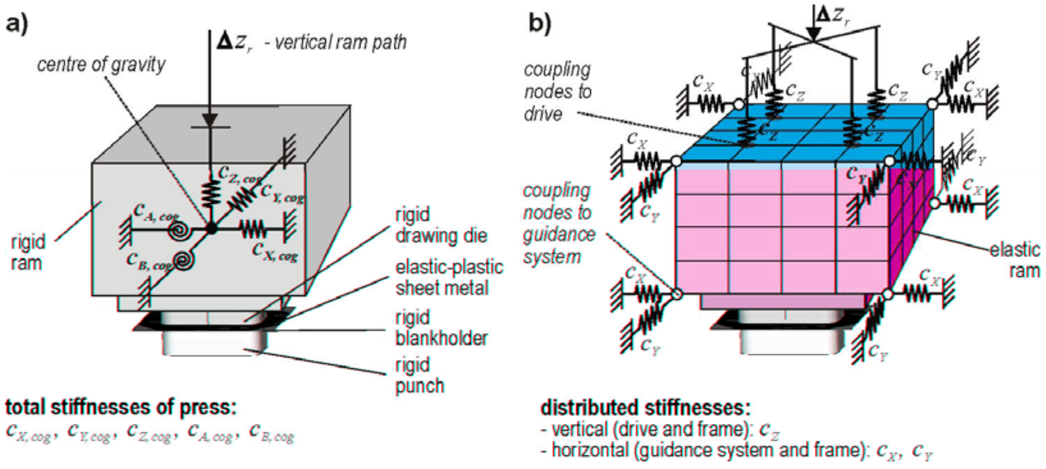


Fig. 1. Advanced Forming Process Model AFPM: a) extended by a press model considering elastic mounting of the rigid ram in the centre of gravity; b) extended by press model separated in drive and guidance springs for the application of an elastic ram (example: O-frame press with 4-point configuration)

Hence, forming process models will be enhanced by elastic tool models demanding elastic embedding in the machine. That implies that the press has to be modelled by an elastic ram and an elastic table of the press. Analogously to real press structures the bearing of the elastic ram in the press is determined by drive and ram guidance.

Figure 1b illustrates the AFPM extended by distributed spring elements. On the corner nodes spring elements in horizontal direction (X- and Y-) and in vertical direction (Z-) according to the drive system are connected to the ram model. Via position and parameterisation of this spring elements the following properties are educible:

- principle stiffnesses of presses,

- drive system (1-, 2-, and 4-point configuration),
- frame stiffness and design (C-frame and O-frame) and structure (frame, ram, table of the press),
- guidance (with and free of clearance).

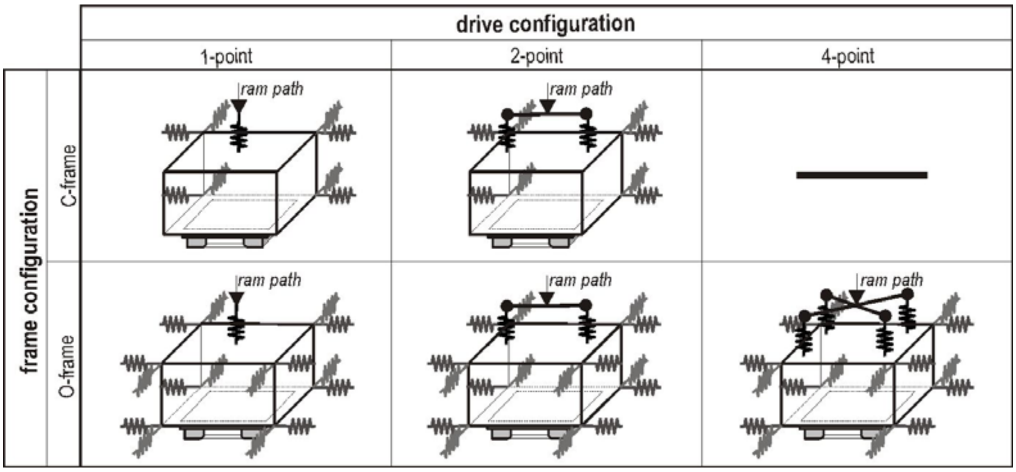


Fig. 2. Scheme of press models for different press structures

Press models for different press structures are charted in Figure 2. The stiffness values of horizontal and vertical spring elements can be obtained by measured values based on [10]. The conversion of tilting stiffnesses c_α, c_β and total vertical stiffness c_{totZ} into spring constants c_X, c_Y and c_Z is carried out using a moment balance system. For this purpose geometrical parameters as ram size and distance between force transmitting drive elements x_{dr} and y_{dr} are necessary. Equations (1–3) exemplify this correlation for an O-frame press with a 4-point configuration.

$$c_x = \frac{c_\alpha - \dfrac{c_{totZ} \cdot x_{dr}^2}{4}}{2 \cdot z_{ram}^2}, \tag{1}$$

$$c_Y = \frac{c_\beta - \dfrac{c_{totZ} \cdot y_{dr}^2}{4}}{2 \cdot z_{ram}^2}, \tag{2}$$

$$c_Z = \frac{c_{totZ}}{4}. \tag{3}$$

3.3. Example "effects of press stiffnesses"

As an example, the AFPM is applied to the following press configurations:

- Model 1: rigid (free of elastic bearings)
- Model 2: O-frame press with 4-point configuration (c_{totZ} = 1250 kN/mm; $c_\alpha = c_\beta$ = 125 MNm) and
- Model 3: C-frame press with 1-point configuration (c_{totZ} = 630 kN/mm; c_α = 45 MNm; c_β = 32 MNm)

The parameters appropriate to a 1000 kN press were obtained from [11]. To get marked effects regarding to tilting an eccentric load case was implemented by eccentric tool positioning.

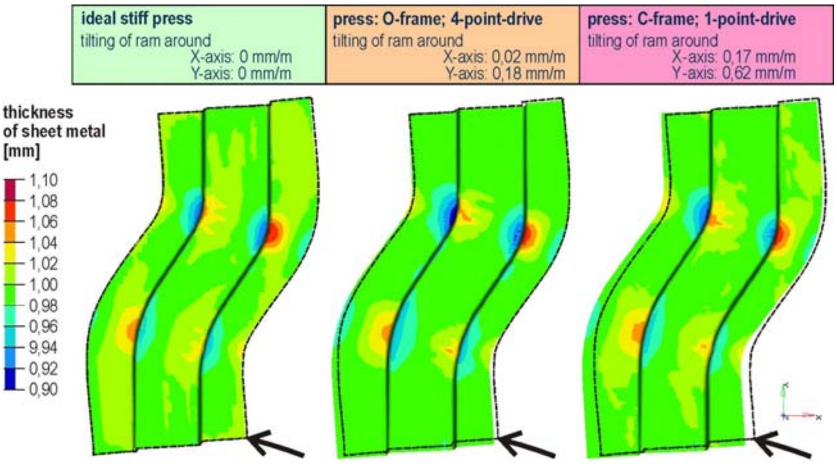


Fig. 3. Thickness distribution and sheet metal flow at a drawing depth of 40 mm for the "S-Rail"

The computer simulation refers to single action presses with hydraulic die cushion. The blankholder force defined as constant in stroke is represented by a constant distributed load applied on the blankholder surface. The simulation results (LS-DYNA) shown in Figure 3 illustrate the increasing effect of ram tilting to sheet metal flow and thickness as a consequence of an eccentric process load (tool assembled 200 mm eccentric in X-direction) and press stiffness. The effect to the material flow is clearly recognizable. This behaviour is justifiable by the asymmetric distributed compression at the contact area in the flange.

3.4. Example "compensation of press effects"

The example demonstrates the feasibility to realize the tool tryout in Virtual Reality. Previous, ram tilting was calculated under process load. The effect of ram tilting can be compensated by an inclined tool installation.

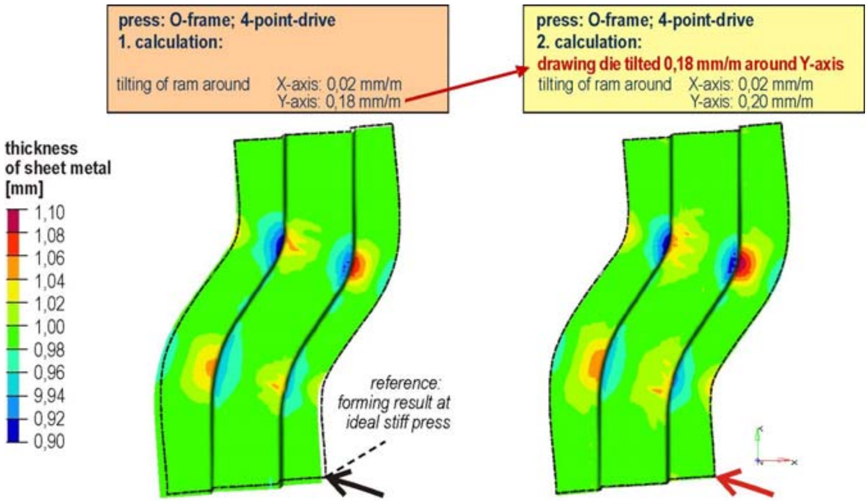


Fig. 4. Compensation of press effects (ram tilting) by inclined die installation (thickness distribution and sheet metal flow at a drawing depth of 40 mm for the "S-Rail" part)

Figure 4 displays the simulation results. On the left, the sheet metal flow in case of a straight assembled tool is illustrated. In comparison with the ideal press (free of tilting) the machine effect is in evidence. The result on the right side verifies that the variation of sheet metal flow caused by ram tilting was compensated by inclined tool installation.

4. AFPM extended by elastic die cushion effects

4.1. Relevant static die cushion effects

An elementary influence on contact and friction conditions at the interface between die and blankholder results of the blankholder. According to the usual practise, in the AFPM describe above the blankholder is represented by a constant distributed load on the blankholder surface. But in reality the distributed load on the blankholder surface results from the equilibrium between process load variable in time and place, blankholder deflection and deformation, respectively. Demonstrating this essential effect on drawn parts in the forming simulations demands the extension of the model by the deformation and deflection of the blankholder. First preparatory works for advanced research studies planned in [12] led to the following approach.

4.2. Die cushion model

The blankholder shape under process load depends on its elastic properties. Its location is determined by elastic properties of:

- the press (drive, blankholder ram, ram guidance, frame) in case of double action press or
- the die cushion (drive, die cushion plate, guidance) in case of a single action press and
- the tool guidance.

To model the blankholder bearing in case of a double action press the prefixed press models are applicable. In order to realize the blankholder bearing of a die cushion the model structures were successively developed, first to apply rigid and then elastic blank holders [9].

The die cushion model for an elastic blankholder is shown in Figure 5. The stiffnesses of die cushion drive, guidance, pressure pin, and pin guidance are represented by substitutional springs. This spring elements are arranged on the coupling nodes of the elastic blankholder as they are in the real structure. The stiffness of the spring element was parameterized according to [13].

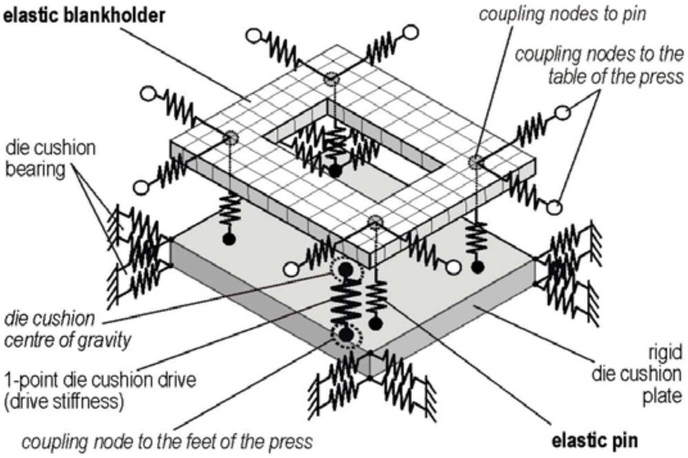


Fig. 5. Model structure of the die cushion for applying an elastic blank holder

4.3. Example “effect of die cushion bearing stiffness”

The example visualizes how die cushion and blankholder affect the deep drawing process of a rectangular tub. The process models 1 to 3 of the previous example were extended by an elastic die cushion bearing.

The simulation results of the process models with integrated die cushion model are shown in Figure 6. It illustrates sheet thickness and flow in forming process models with different levels of abstraction. For comparison, in Figure 6 the conventional forming process model (rigid machine, tool, and die cushion model) is displayed. Due to a constant distributed load across the contact surface the tub possesses a symmetric sheet thickness distribution and a symmetric sheet metal flow. In contrast, applying the AFPMs the eccentric tool location results in ram tilting (see Figure 6b) or in ram and blankholder tilting (see Figure 6c), respectively. Tilting leads to asymmetric thickness distribution and asymmetric sheet metal flow. In this example, the effect of the blankholder deflection to the drawn part is stronger than the tilting of the ram.

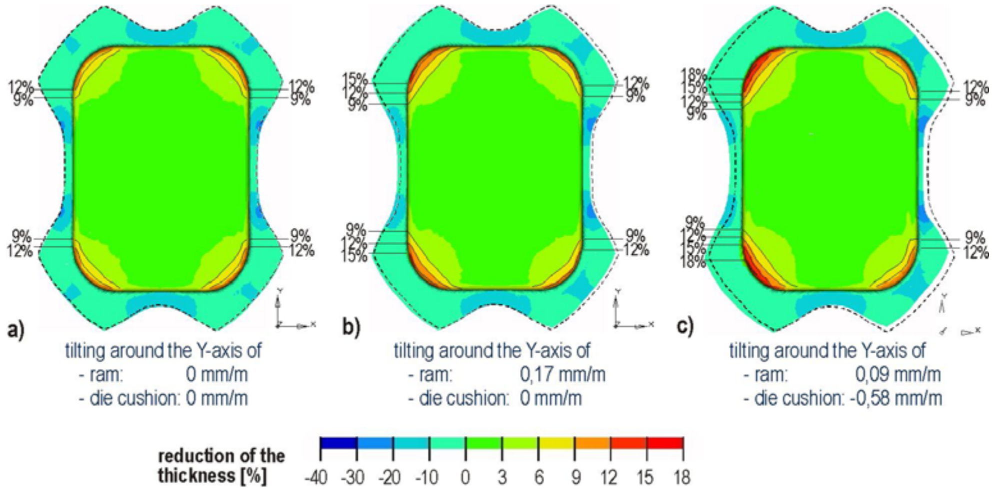


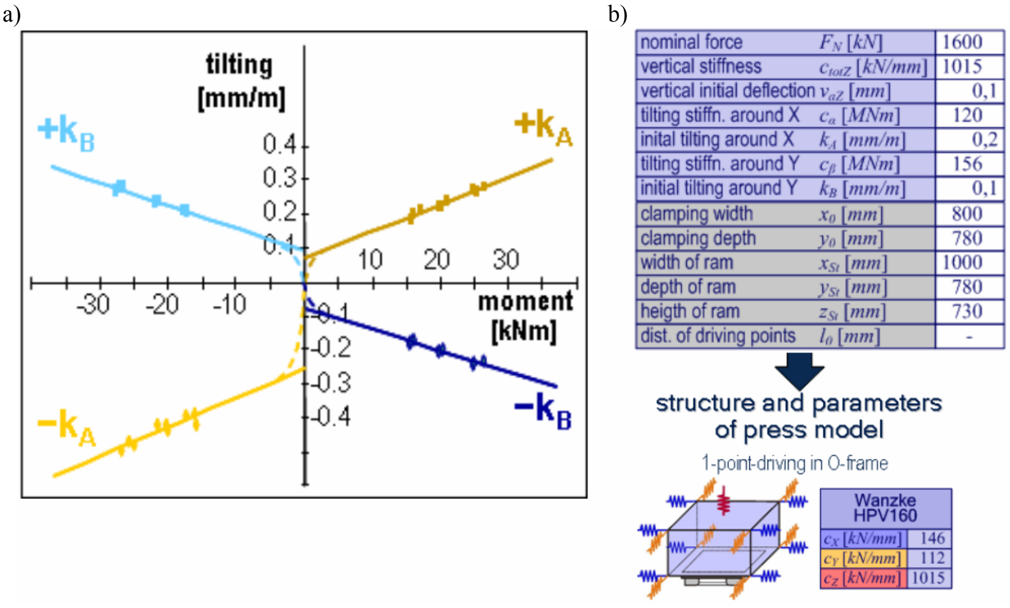
Fig. 6. Sheet thickness reduction and material flow, O-frame press with 1-point configuration: a) rigid press and tool, rigidly supported die cushion, b) elastic press, rigidly supported die cushion, rigid tool, c) elastic press, elastically supported die cushion, rigid tool

The deformations and surface pressures on the blank-holder according to the results in Figure 6 show different distributions corresponding to the interactions between the die cushion, machine and process and justify the sheet metal flow as shown. In all calculations the resulting blankholder force was the same.

5. Experimental verification

5.1. Experimental equipment

In order to verify the modelling concept with experiments the single action hydraulic press Wanzke HPV 160 is available at the IWM. Initially, the static tilting and stiffness behaviour of the press is determined by inducing a defined moment with the press testing equipment. The diagram shown in Figure 7a displays the tilting behaviour of the ram around the X- and Y-axis. These characteristic tilting curves result in the tilting stiffness c_α, and c_β as well as in the vertical total stiffness c_{totZ}. These values are converted into the stiffness parameters of the horizontal and vertical spring elements c_X, c_Y and c_Z of the FE model for an O-frame press with a 1-point driving system.



nominal force	F_N [kN]	1600
vertical stiffness	c_{totZ} [kN/mm]	1015
vertical initial deflection	v_{aZ} [mm]	0,1
tilting stiffn. around X	c_α [MNm]	120
inital tilting around X	k_A [mm/m]	0,2
tilting stiffn. around Y	c_β [MNm]	156
initial tilting around Y	k_B [mm/m]	0,1
clamping width	x_0 [mm]	800
clamping depth	y_0 [mm]	780
width of ram	x_{St} [mm]	1000
depth of ram	y_{St} [mm]	780
heigth of ram	z_{St} [mm]	730
dist. of driving points	l_0 [mm]	-

Wanzke HPV160	
c_X [kN/mm]	146
c_Y [kN/mm]	112
c_Z [kN/mm]	1015

Fig. 7. Press characteristics of Wanzke HPV 160: a) tilting around X-axis (k_A) and Y-axis (k_B), b) structure and parameters of the press model

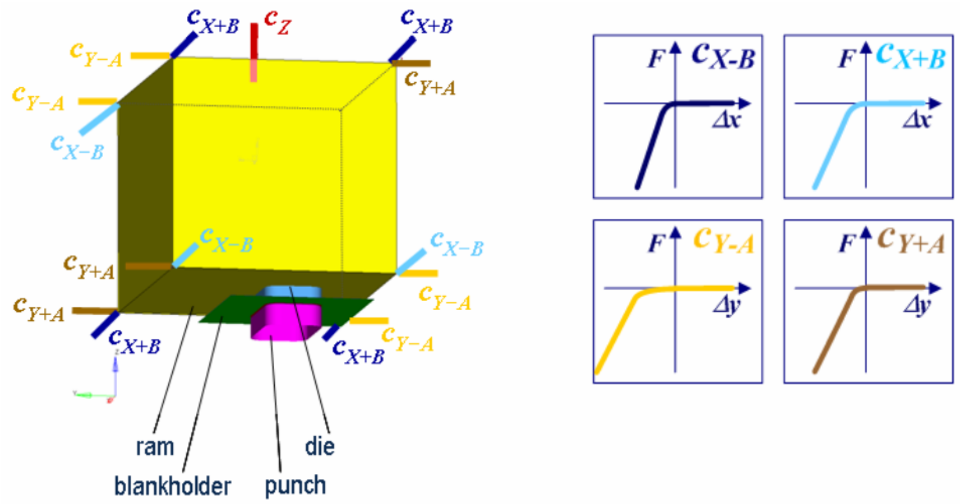


Fig. 8. Press model Wanzke HPV 160 with non-linear compression springs

Since the approach to use linear-elastic springs does not correspond with the real tilting and stiffness behaviour of the experimental press the press model is refined with non-linear spring characteristics. In order to consider the tilting behaviour, which is dependent on the direction of the rotation, only non-linear compression springs are attached to the corner nodes of the ram (as clarified in Figure 8).

The rectangular tub shown in Figure 11 is selected as specimen for the experimental verification. The stiffness properties of the experimental tool are modified by implementing disc springs in the die to be able to vary the total stiffnesses in the press-tool system (Figure 9).

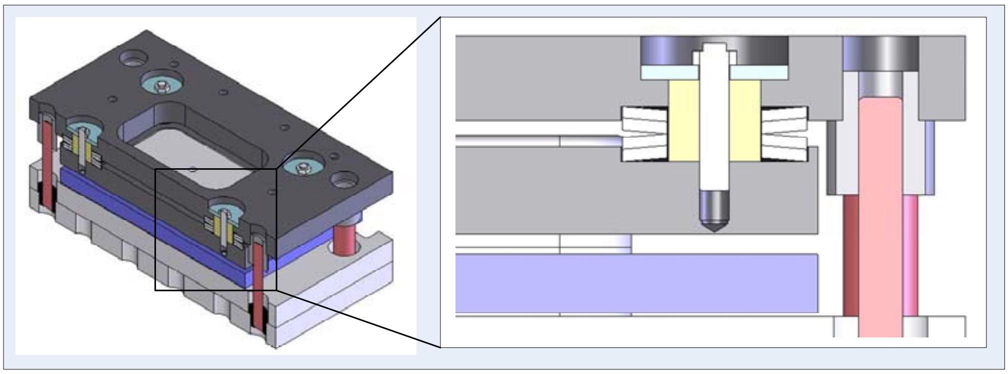


Fig. 9. Modification of the total stiffness and the tilting stiffnesses in the experimental tool by variable disc springs

5.2. Advanced forming process model of the experimental equipment

Initially, in the FE simulation setup with non-linear springs, the blank holder is rigid but is allowed to tilt. In the simulation a different tilting behaviour due to an asymmetrical tool installation in the press is observed, but no correlations with the deep drawing failures in the experiment are found. Therefore, it is necessary to setup a more comprehensive forming process model (Figure 10) in LS-DYNA, which considers the elastic properties of the press HPV 160 containing the die cushion, forming tool, and disc springs.

Since the die cushion of the experimental press is not guided but attached to the cushion cylinder only, an analogous substitute spring model is applied. The layout of the blankholder springs is derived from the properties of the die guidance. The values to parameterize the stiffnesses are obtained from the literature [13]. Due to performance and stability reasons (mass scaling, damping) the relative tool movement is realized by driving the punch (which is fixed in space in reality) instead of driving the ram.

5.3. Comparison of simulation and experiment

The performance of the advanced process model is demonstrated by integrating a specific disc spring setup in the experimental tool. The bearing of the die on the variable disc springs allows for adjustment of different total stiffnesses within the press-tool system. Figure 11 shows an asymmetrical loading case.

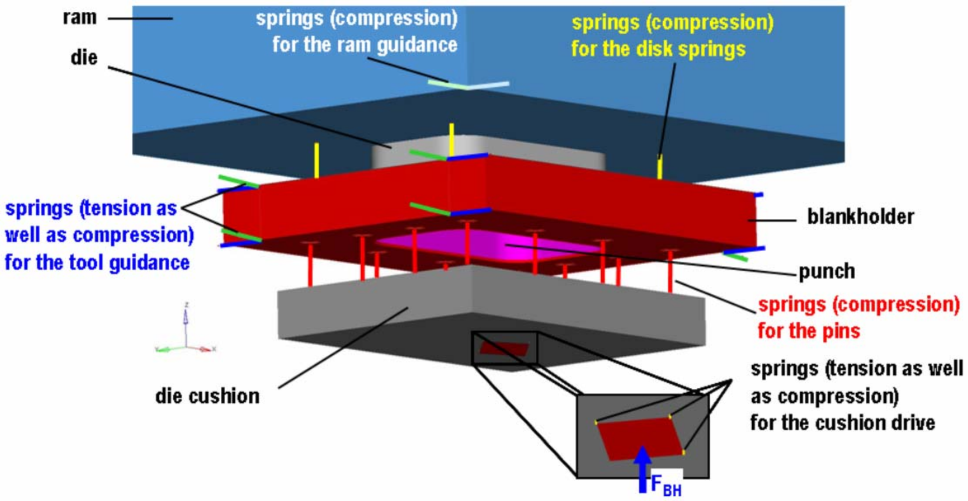


Fig. 10. Forming process model considering the elastic properties of press HPV 160

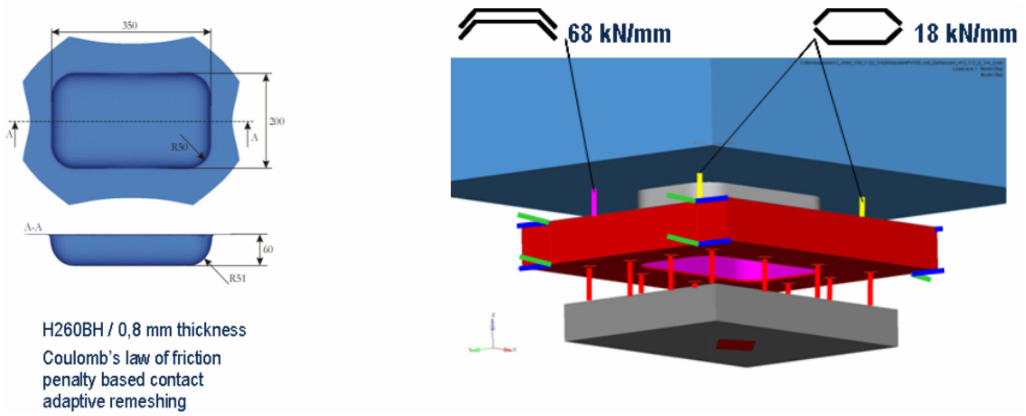


Fig. 11. The specimen and the asymmetrical load case selected for the verification

The draw-in and the thickness distribution of the drawn cup are measured for different blankholder forces. The drawing failures (such as wrinkles and cracks) and their point of origin are identified.

In the simulation setup the blank is meshed with shell elements, the blank material H260BH is described by the anisotropic model HILL3R and adaptive net refinement is applied. The tribological conditions are described by the Coulomb's law of friction and a penalty based contact algorithm.

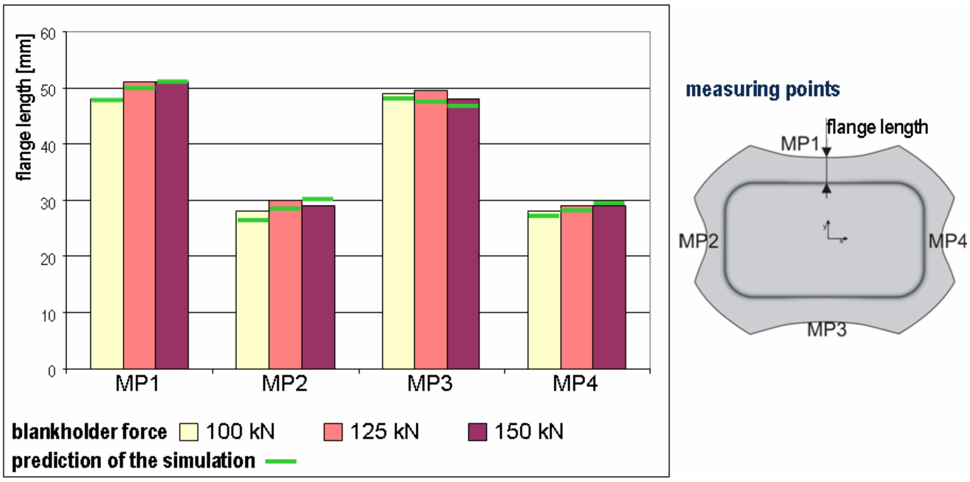


Fig. 12. Comparison between the results of the simulation and the experiment – length of the remaining flange at different blankholder forces

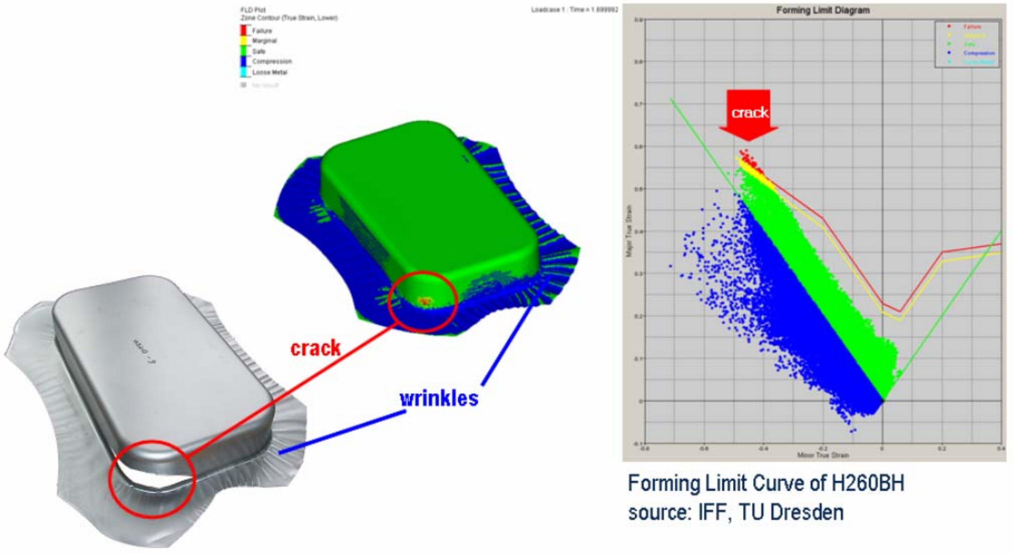


Fig. 13. Comparison between the results of the simulation and the experiment – analysis of the drawing failures using a FLC

The prediction of the simulation matches well to the experimental results as illustrated by the draw-in at the four edges of the remaining flange in Figure 12. Furthermore, the prediction of the wrinkles and cracks using a forming limit curve are confirmed by the experimental results (see Figure 13).

6. Conclusion and Outlook

Based on conventional process modelling in FE systems and analysis of the relevant effects of the press, tool, and die cushion on the forming process an advanced modelling method is developed.

The simulation results obtained by applying the AFPM and a conventional model of forming process (without elastic press, tool, and die cushion effects) are compared. The comparison shows, that the relevant static effects of the press, tool and die cushion on the forming process can be visualised by the advanced process model.

By using an example of a rectangular tub drawing tool and the associated experimental equipment it is shown that the simulation results match the experimental o.

A complete forming process model is available to consider different configurations of presses and die cushions in the process planning stage. Thus, the effort in the tool try-out and the ramp-up can be reduced by using the FE simulation.

The current research works have following main objectives:

- systematic development of models for various die cushions,
- extension of the AFPM by the tool guidance and analysis of effects on the forming process,
- applying practicable methods to reduce large FEA-tool models to handle tool models as elastic bodies,
- including of kinematic and dynamic behaviour.

References

[1] Roll K., Wiegand K.: *Eine Möglichkeit zur Berücksichtigung der Werkzeugelastizität bei der Blechformsimulation*, “Neuere Entwicklungen in der Blechumformung” Leinefelden-Echterdingen (Stuttgart), MAT INFO Werkstoff-Informationsgesellschaft mbH, Frankfurt, 2006.

[2] Großmann K., Hardtmann A., Wiemer H.: *Simulation des Blechumformprozesses unter Berücksichtigung des statischen Verhaltens der Pressmaschine*, *Simulation of the sheet metal forming process considering the static behaviour of the press*, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 101, No. 10, 2006, pp. 600–605.

[3] Großmann K., Wiemer H., Hardtmann A., Penter L.: *Stand der Simulation von Umformprozessen mit den elastischen Einflüssen aus Maschine und Werkzeug*, Tagungsband T 27 des EFB-Kolloquiums „Neue Wege zum wirtschaftlichen Leichtbau“ in Fellbach, EFB, Hannover, 2007, pp. 185–198.

[4] Großmann K., Wiemer H.: *Maschine, Werkzeug und Prozess – ein ganzheitliches System*, “6. Sächsische Fachtagung Umformtechnik”, Dresden, 1999.

[5] Großmann K., Wiemer H., Thoms V., Schirmacher F.: *Modellierung des Blechumformprozesses in der Anlagensimulation auf Grundlage von Ergebnissen der FEM-Prozeßsimulation*, EFB-Forschungsbericht, No. 178, EFB Hannover, 2001.

[6] Großmann K., Wiemer H.: *Simulation of the Process Influencing Behaviour of Forming Machines*, Steel research international 76, Verlag Stahleisen GmbH Düsseldorf, No. 2/3, 2005, pp. 205–210.

[7] Schirmacher F., Wiemer H.: *Kopplung von Prozess- und Anlagensimulation – ein wesentlicher Teilschritt auf dem Weg zum „Virtuellen Umformen“*, Tagungsband T 21 des EFB-Kolloquiums „Prozessoptimierung in der Blechverarbeitung“ in Fellbach, EFB Hannover, 2001, pp. 11.1–11.18.

[8] Brecher C., Schapp L., Paepenmüller F.: *Gekoppelte Simulation von Presse und Massivumformprozess*, Werkstattstechnik online Jahrgang, 96, 2006, pp. 7/8.

[9] Wiemer H.: *Stand und Möglichkeiten der Systemsimulation von mechanischen Pressmaschinen*, *State and Potentials of Forming Press Simulation*, Dissertation, TU Dresden, 2004.

[10] N.N.: *German Standard. Deutsche Normschrift DIN 55189: Ermittlung von Kennwerten für Pressen der Blechverarbeitung bei statischer Belastung*, Beuth Verlag Berlin, 1988.

[11] N.N.: *German Standard. VDI-Richtlinie VDI 3145: Pressen zum Kaltmassivumformen. Blatt 1: Mechanische und hydraulische Pressen*, VDI-Verlag Düsseldorf, 1985.

[12] Großmann K., Hardtmann A., Wiemer H.: *Entwicklung und Bewertung von Simulationstechnologien für die Blechumformung unter Berücksichtigung der Wechselwirkungen zwischen Maschine-Werkzeug und Prozess-Werkstück*, laufendes Vorhaben der DFG im SPP, pp. 1180.

[13] Pahl K.J.: *Elastische Wechselwirkungen im Ziehapparat einfach wirkender Pressen*, VDI Verlag, Düsseldorf, 1994.

Zaawansowany model procesu kształtowania plastycznego uwzględniający sprężyste odkształcenie prasy i narzędzie

Artykuł dotyczy procesów tłoczenia i kierowany jest do inżynierów produkcji, jak również projektantów procesów i narzędzi (ich prototypów i produkcji seryjnej narzędzi). Publikacja ukazuje metody modelowania i symulacji procesów kształtowania plastycznego metalu i ich zastosowania w projektowaniu produktu i produkcji. W zwykle stosowanych modelach procesów kształtowania efekty sprężyste są pomijane. Na przykład sprężyste zachowanie pras i matryc nie są brane pod uwagę podczas projektowania narzędzi, powoduje to ich częste przerabianie już w trakcie procesu rzeczywistego. Artykuł ilustruje jak wzajemne relacje między prasą, matrycą i procesem kształtowania plastycznego mogą zostać zamodelowane poprzez ulepszanie konwencjonalnych modeli MES. Zostało to zademonstrowane na kilku przykładach.