Root Cause Analysis of Deep Drawing Processes with Superimposed Low-Frequency Vibrations on Servo-Screw Presses
A Practical Research on Predictability in Simulation

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Abstract: In the area of sheet metal forming, modelling and simulation of deep drawing processes with finite-element analysis are an essential method for an accurate process design and the production engineering of complex parts. The continuous evaluation and qualification of simulation strategies improve the predictability and help to understand complex forming processes. In order to fulfil the constantly growing requirements on product quality and part variety, dimensional accuracy as well as energy and cost efficiency, it is necessary to achieve reasonable forecasting results and optimal parameters. However, the development of enhanced deep drawing techniques supported by vibrations is in general just beginning. Currently, prediction of process parameters as well as the knowledge about effects and coherences of highly dynamic processes with flexible kinematics are insufficient. In this paper, an approach for improvements in simulation of a new technology for deep drawing on servo-screw presses called cushion-ram pulsation is presented. Numerical and experimental model tests in special constructed set-ups have to be performed to determine particular forces. Sensitivity based methods help to identify significant process parameters of complex forming processes with superimposed vibrations. The evaluation of these parameters allows the development of specific meta-models which approximate the behavior in the simulation.

1 INTRODUCTION

In recent years, finite-element analysis (FEA) in simulation has become established as a powerful tool for process design. Also in the field of sheet metal forming, it is an integral part for the development of deep drawing processes and tools. Even in the early design phase, the feasibility of deep-drawing processes can be assessed quite well. In the simulation of forming processes, workpiece properties like stress, deformation and hardening state, wall thickness, dimensional and shape accuracy, indication of failure cases or areas are of particular interest concerning the product requirements, which must be satisfied (Großmann and Neugebauer, 2010). In addition to energy and resource efficiency of forming processes, good component quality is an important competitive factor in sheet metal forming. Therefore, ever higher demands are placed on the dimensional accuracy of formed sheet metal parts, whereby the efficiency of the processes must not be affected. Due to the performance leaps in FEA-tools, the simulation of deep drawing processes with finite-elements has also proved to be an efficient tool for large models with many thousands of degrees of freedom starting from feasibility studies up to the compensation of springback.

Nevertheless, the forecast capability is limited due to the complex, mostly non-linear relationships in deep drawing. The deviations are often caused by the tool development, since not all influences can be considered in the simulation. Especially interactions between the process, tool and machine are only poorly replicable (Denkena and Hollmann, 2013). As a result the final quality of the part can deviate considerably from the simulation result for deep

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drawing processes. An overview of the forecast capability in forming simulation is shown in figure 1, with three groups being distinguished (Roll, 2012).

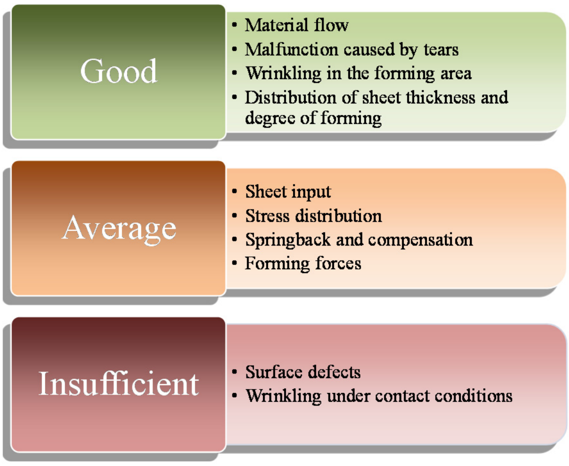

Figure 1: Forecast capability in forming simulation (Roll, 2012).

From figure 1 it becomes clear that surface defects and wrinkles can only be detected poorly due to the complex conditions. This is a particular challenge for innovative technologies with extended process kinematics. In order to fulfil the rising demands and increase the profitability and productivity of forming machines, at a consistent or improved quality of drawn parts, the conventional deep drawing process must be continuously enhanced. An overview of deep drawing techniques with variable motion paths is presented in (Kriechenbauer et al., 2014). There is shown, how superimposed low-frequency vibrations up to 50 Hz can be a new approach to extend forming limits in deep drawing.

One well-known example is the technology of cushion pulsation described in (Fiat, 1994). Positive effects of pulsating blankholder forces, like the reduction of friction forces or the enlargement of the gap between the wrinkling- and the fracture-border, are described in (Doege, 2000). However, optimal process variables of cushion pulsation could neither temporally nor spatially be quantified in a systematic manner yet. An approach for a cylindrical cup through numerical simulation coupled with an optimization technique is presented in (Kitayama et al., 2016). The influence of process parameters from pulsating blankholder forces on drawing depth for a square cup is investigated in (Nezami et al. 2017).

Another example of a highly dynamic deep drawing process is the cushion-ram pulsation on servo-screw presses (Kriechenbauer et al., 2014). The development of electromechanical servo-screw presses constitutes a significant progress for deep drawing with superimposed low-frequency vibrations and opens new potential in sheet metal forming. The direct driven system is characterized by outstanding dynamical axis features, high stiffness and the transferability of high forces. Due to flexible controlling options, it is possible to realize variable motion paths with ram and cushion even in workpiece contact during forming process. The cushion-ram pulsation extends forming limits (Kriechenbauer et al., 2014). However, this new approach has been investigated in an almost exclusively phenomenological way and the design of the process is only supported by empirical methods.

In (Neugebauer et al., 2012), progress has been made in the simulation of low frequency vibrations during deep-drawing processes on servo-screw presses. New methods have been developed to improve the predictability of process simulation by considering the quasi-static interaction between process and machine in (Drossel et al., 2013). Despite the improvements, it has not yet been possible to reproduce the component quality with sufficient accuracy due to extensive wrinkling phenomena.

In particular, for the simulation of the cushion-ram pulsation, new methods have to be developed in order to be able to predict the formation of wrinkles more accurately and to take into account quality-determining influences during the process adjustment with superimposed low-frequency vibrations. Furthermore the prognosis of optimal process parameters is insufficient. So far there are no corresponding assessment bases. In addition to basic questions about process design, the root causes of the technological effects are largely unexplained. Fundamental research is needed in order to ensure the prognosis accuracy of deep drawing techniques with superimposed low-frequency vibrations on servo-screw presses.

Consequently, the main goal of the following paper is to give a contribution for improvements in simulation and design of deep drawing processes supported by vibrations, with cushion-ram pulsation as an example. This technology is described in the next section. Subsequently, a novel method for the determination and assessment of single force components is presented. This approach will be used to enable a comparison between conventional deep drawing, cushion pulsation as well as cushion-ram pulsation and to understand effects and coherences of complex forming processes. Afterwards, special developed test setups for experimental model tests and preliminary results are presented. Finally a summary and outlook of future work is provided.

2 DEEP DRAWING WITH SUPERIMPOSED LOW-FREQUENCY VIBRATIONS

In the area of sheet metal forming low- as well as high-frequency excitation mechanisms can be used to generate different kind of vibrations. Typical vibration amplitudes are in the millimeter range at frequencies lower than 50 Hz (Klose and Bräunlich, 2000) and in the micrometer range at high frequencies above 1 kHz (Siegert and Ulmer, 2001). Usually superposition of vibrations in the tool takes place with a magnetostrictive, piezoelectric, electro-mechanic, or hydraulic excitation. The vibrations favor tribological conditions between tool and sheet. As a result the friction force is reduced. Further positive effects of forming techniques supported by vibrations are extended process limits, saving of lubricant, higher drawing ratios as well as the reduction of drawing steps and cracks (Mauermann, 2010).

Deep drawing techniques with superimposed vibrations are highly dependent on the properties of the forming machines used. In the past, mainly hydraulic systems were used for this purpose. However, modern servo-screw presses enable vibrations in the sub millimeter range at frequencies up to 50 Hz without additional actuators (Kriechenbauer et al., 2014). Advantages of these systems are high drive stiffness and dynamics as a result of the axial powertrain arrangement. In addition rapid changes of direction and quick load cycles are feasible in ram as well as in cushion due to high jerk values and great accelerations (Neugebauer et al., 2012).

The special drawing technique on servo-screw presses with synchronized motion paths of ram and cushion, called cushion ram pulsation is in focus of the investigations. This technique is a position-controlled process with additional holding times for the ram. The synchronized motion paths of cushion and ram consists of sinusoidal cycles. The sequence and corresponding parameters for an individual cycle are illustrated in figure 2. One single cycle is divided into two process steps. The cushion moves away from the stationary ram during dwell time in the first step. As a result the distance between the sheet and the blankholder grows and the flange gap opens. After dwell time the ram moves down to draw the part in a small step. Due to the open flange gap only low friction and compression forces occur in the drawing radius and in the flange. However the opened flange gap enables a disadvantageous formation of wrinkles too. Subsequently in step two the ram is stopped during the holding time and the cushion moves against the stationary ram. That results in an increase of surface pressure and wrinkles in the flange will be reduced. Thereby the cycle is completed and can be repeated as required with possible different parameters.

During deep drawing operations, high tensile stresses in the part frame usually lead to fractures, which frequently occur in the punch radius. For cushion-ram pulsation, drawing progress with opened flange gap in the first step represents a process similar to deep drawing without blankholder, whereby local tensile stresses in the frame are reduced and critical loads are shifted to higher drawing ratios. In conventional deep drawing, formation of wrinkles is prevented with the blankholder and high friction forces must also be

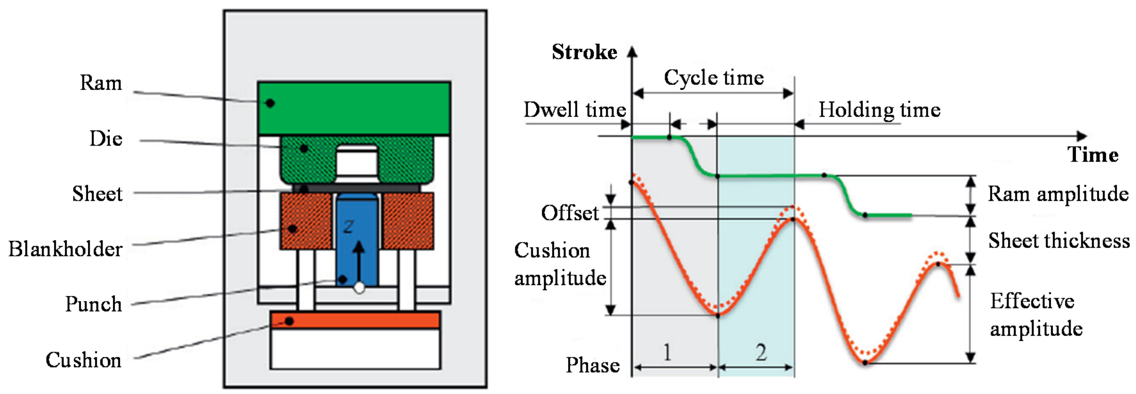

Figure 2: Process parameters for cushion-ram pulsation (Neugebauer et al., 2012).

considered. As a result the total force introduced via the punch during drawing progress is always lower in cushion-ram pulsation than in conventional deep drawing (Neugebauer et al., 2012). In the second step there is no progress in drawing. Consequently no tensile stress relevant for breakdown affects the edge. Due to the technological separation of drawing progress and reduction of wrinkles, larger drawing depths can be achieved, which is a technical benefit of the cushion-ram pulsation.

Elastic deformations of press machine and tool systems have to be compensated by specific parameter settings. A negative offset or die closing force is proposed in (Neugebauer et al., 2012). The formation of wrinkles depends on the limited ram and cushion amplitudes. In order to achieve high productivity it is necessary to decrease amplitudes and to increase frequency. Usual amplitudes are settled in the sub millimeter range.

3 NOVEL METHOD FOR THE SEPARATION OF FORMING FORCE

In this section, a novel method for identifying the root causes of extended forming limits is described. First of all, the total force required for forming is divided into the individual terms for buckling, bending and friction, similar to (Siebel and Beisswänger, 1955) and (Pankin, 1961). The necessary spatial resolution distinguishes between flange and die radius. In both areas buckling, bending and friction processes take place. The last step is a time distinction for the discontinuous processes like cushion pulsation or cushion-ram-pulsation. A phase with low surface pressure and a phase with high surface pressure exist there.

With the three force components for buckling, bending and friction in the two areas of die radius and flange for the three methods and an additional phase I and II for cushion pulsation and cushion-ram pulsation respectively, there are 30 individual force components, which are summarized in table 1.

In order to determine the individual force components, experimental and numerical tests are planned. In this way, a better calibration of the finite-element calculations and a fundamental evaluation possibility of deep drawing with superimposed low-frequency vibrations should be realized.

For the investigation a modular part series illustrated in figure 3 is used. The round sheet is virtually divided into four parts A1 to A4. Subsequently, straight stripes are inserted, resulting in a square sheet with round corners of a defined radius. The inserted stripes form a cross sheet. Due to the decomposition of the square cup, the influence of buckling in the corner regions of the square sheet is eliminated, thus only bending and friction forces act. When the round cup is drawn, all three force components take place. Together with the cross cup, the total forming force for the square cup is obtained. In this configuration it is possible to examine individual force components in isolation from each other.

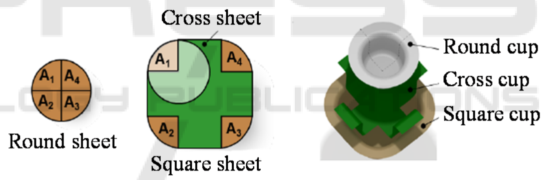

Figure 3: Composition of modular part series.

To ensure that the part geometries complement each other in a completely modular way, the remaining geometry elements are not changed. In addition it is necessary to observe preferably constant and comparable boundary conditions. This

Table 1: Individual force components for deep drawing (DD), cushion pulsation (CP) and cushion-ram pulsation (CRP).

Technology		Total force	Kind of force					
			Buckling		Bending		Friction	
			Die radius	Flange	Die radius	Flange	Die radius	Flange
DD		F	$F_{Bu\text{-}D}$	$F_{Bu\text{-}F}$	$F_{Be\text{-}D}$	$F_{Be\text{-}F}$	$F_{F\text{-}D}$	$F_{F\text{-}F}$
CP	phase I	F_{CPI}	$F_{CPI\text{-}Bu\text{-}D}$	$F_{CPI\text{-}Bu\text{-}F}$	$F_{CPI\text{-}Be\text{-}D}$	$F_{CPI\text{-}Be\text{-}F}$	$F_{CPI\text{-}F\text{-}D}$	$F_{CPI\text{-}F\text{-}F}$
	phase II	F_{CPII}	$F_{CPII\text{-}Bu\text{-}D}$	$F_{CPII\text{-}Bu\text{-}F}$	$F_{CPII\text{-}Be\text{-}D}$	$F_{CPII\text{-}Be\text{-}F}$	$F_{CPII\text{-}F\text{-}D}$	$F_{CPII\text{-}F\text{-}F}$
CRP	phase I	F_{CRPI}	$F_{CRPI\text{-}Bu\text{-}D}$	$F_{CRPI\text{-}Bu\text{-}F}$	$F_{CRPI\text{-}Be\text{-}D}$	$F_{CRPI\text{-}Be\text{-}F}$	$F_{CRPI\text{-}F\text{-}D}$	$F_{CRPI\text{-}F\text{-}F}$
	phase II	F_{CRPII}	$F_{CRPII\text{-}Bu\text{-}D}$	$F_{CRPII\text{-}Bu\text{-}F}$	$F_{CRPII\text{-}Be\text{-}D}$	$F_{CRPII\text{-}Be\text{-}F}$	$F_{CRPII\text{-}F\text{-}D}$	$F_{CRPII\text{-}F\text{-}F}$

means that for cushion pulsation and cushion-ram-pulsation, suitable averages must be used as reference values for the vibration-superimposed process variables. Furthermore the demountability of the square cup must be demonstrated for deep-drawing processes with extended process kinematics on basis of the experimentally measured force components.

A more detailed differentiation requires additional model tests, which emulate forming conditions. Further individual force components are determined in stripe drawing tests corresponding to (Netsch, 1994) and wedge drawing tests, which are also used for the measurement of friction coefficients. These model tests are illustrated in figure 4.

The friction force in the die radius is different from those in the flange, due to different surface pressures. Therefore the influence of friction for the two areas is examined separately. Friction forces in the flange are measured with the stripe drawing test in the plane. The friction coefficient is used in the forming simulation with finite-elements for a corresponding material combination and normal force. The bending forces occurring in the die radius are determined in tests with a moveable cylindric deflection roll. Subsequently the friction forces in the die radius can be calculated from tests with a fixed radius. Buckling forces can only be isolated experimentally in the flange area, since bending also takes place in the die radius and a metrological resolution of the force components is not possible.

The force component in the flange may be investigated using the wedge tensile test. In order to recreate the conditions of the cylindrical cup the stripe drawing tests are built with appropriately shaped deflection roller and die radius.

However, influences from the surrounding material areas cannot be taken into account in these experimental model tests. Frictional losses on the wedge surfaces also influence the result. In order to quantify these effects, simulation models for the stripe drawing tests with idealized boundary conditions are created and validated. Force components, which cannot be measured in experiments, must be numerically calculated and evaluated.

4 EXPERIMENT AND SIMULATION

In this section, first experimental and simulative results from the conducted stripe drawing test are presented. The experimental determination of single force components requires the design of special test setups. The experimental assembly for stripe and wedge drawing tests as well as the constructed fixture with the plane tool are illustrated in figure 5.

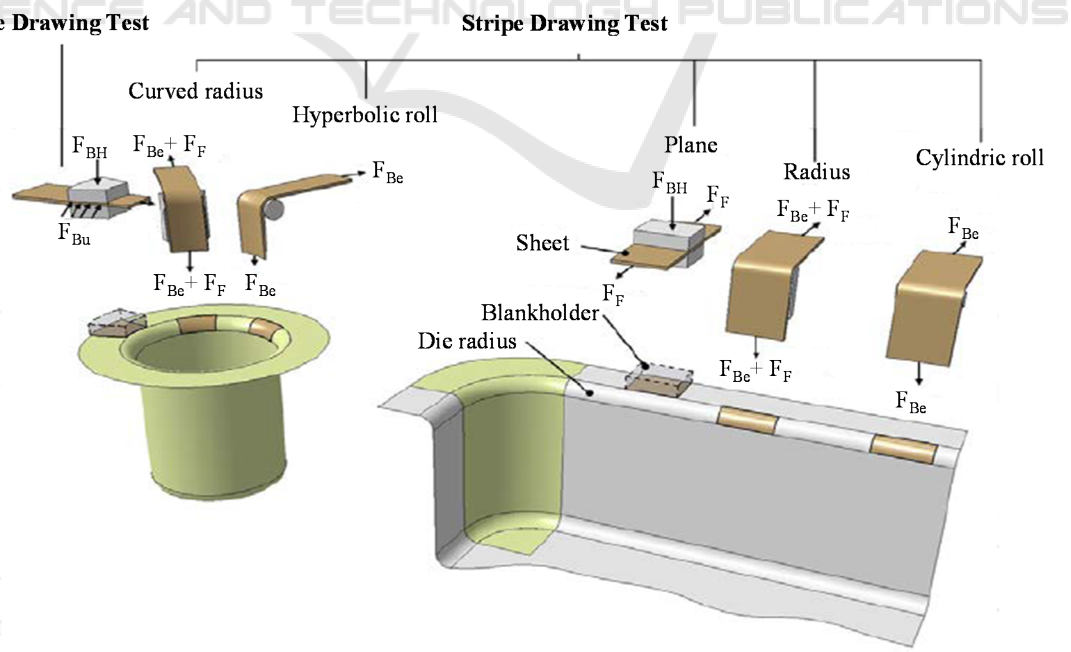

Figure 4: Stripe and wedge drawing tests for the determination of individual force components: left modified model tests for the round cup, right stripe drawing tests for the square cup (Netsch, 1994).

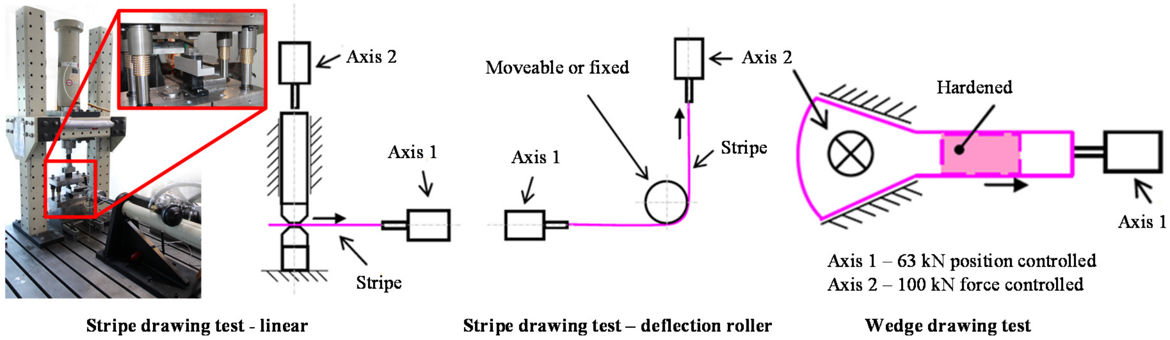

Figure 5: Experimental assembly for stripe and wedge drawing tests.

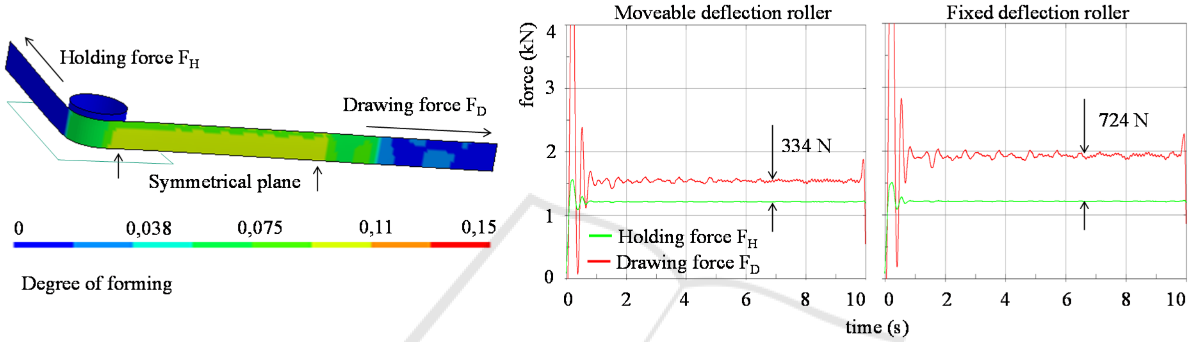

Figure 6: Simulation results from stripe drawing tests with movable and fixed deflection roller.

This setup consists of two servo-hydraulic axes. The system enables the simultaneous and highly dynamic control of several axes. The horizontally arranged axis is used for the position controlled feed while the vertically arranged axis creates the normal forces. Force and distance measurement takes place directly on the axes. The tool sets for different model tests are flexible interchangeable and all tests can be carried out in the experimental assembly. In addition, the developed system can be used to superimpose vibrations like in cushion pulsation and cushion-ram-pulsation. An interrupted feed with variable motion paths is possible, besides constant and pulsating force transmission. Furthermore a transition from low to high surface pressure as well as a change between sliding and static friction when stopping can be generated. During wedge drawing tests the friction losses are kept as low as possible by appropriate design and technological measures on the wedge surfaces. This is realized by freely rotating wheels. Here, buckling forces at the wedge surfaces and the friction force at the blankholder are measured.

Simulation models for the method of single force components are set up in the first step additionally to the experimental investigations. The models describe the stripe drawing tests and the wedge drawing test with finite elements. The main goal of the simulation is to achieve a good replication of the real experiments. Simulation results from stripe drawing tests with movable and fixed deflection roller for the determination of the friction and bending forces in the radius are illustrated in figure 6. Due to the influence of friction, the drawing force with fixed deflection roller is higher. A comparison between averaged values of measured and simulated force components in preliminary investigations of stripe drawing tests with fixed and moveable deflection roller show good agreement (table 2). From this it can be concluded, that the used simulation models are suitable for recreating experimental model tests.

Table 2: Comparison between averaged values of measured and simulated force components for stripe drawing tests with fixed and moveable deflection roller.

Simulation results	Measurement results	Deviation Δ [%]
$F_{Be} = 334$ N	$F_{Be} = 370$ N	$\Delta_{Be} = 9.73$
$F_{Be}+F_F = 724$ N	$F_{Be}+F_F = 753$ N	$\Delta_{Be+F} = 3.85$

5 CONCLUSIONS

In this paper, current research results in evaluation of simulation strategies for deep drawing processes with superimposed low-frequency vibrations on servo-screw presses are presented. A method for the determination and assessment of single force components was developed to enable a comparison between conventional deep drawing, cushion pulsation and cushion-ram pulsation. In addition special test setups required for experimental investigations as well as corresponding simulation models were designed. A good agreement of the results has been achieved in preliminary investigations. The simulation models can be used to determine further components of total deep drawing force.

The core idea of the research project is the evaluation and improvement of simulation strategies for deep drawing technologies with variable motion paths on servo-screw presses. For this reason, in the next step, the single force components of cushion pulsation and cushion ram pulsation have to be investigated in experimental and numerical tests. Subsequently experimentally determined parameters are numerically evaluated. Then they can be used as a boundary condition in the process simulation. Furthermore, process parameters with low impact have to be identified and eliminated in a sensitivity analysis. The individual sensitivities are determined using a DoE (Design of Experiments) method known from statistical experimental design. The sensitivity analysis yields a meta-model that characterizes the relationship between the input and output variables. This will result in an efficient simulation model, which is quantitatively secured. In future investigations, the individual force components, which were not accessible in a direct force measurement experiment or falsified by experimental constraints, will be determined from the validated models.

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DFG Deutsche Forschungsgemeinschaft

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