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# Umformtechnik -
# Ein Wirtschaftszweig mit Potential

Herausgegeben von Prof. Dr.-Ing. B.-A. Behrens

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# Simulation and Optimization of Metal Forming Processes-New Applications and Challenges

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## 1 Introduction

The main goals of process simulation in manufacturing are to reduce manufacturing/part development time and cost and increase quality and productivity /1/. For this purpose FE-Simulation, coupled with optimization routines, are being used as a design tool to estimate optimum process parameters such as blank holder force /2/, preform blank geometry /3/ in stamping, internal pressure versus axial feed relation in tube hydroforming /4/, preform/billet geometry in forging /5/, /6/, /7/. Thus, it is possible to obtain a defect free part for a given die geometry. However, the process sequence (die geometry in each stage) in metal forming is still decided based on past experience and modified by trial and error simulations. Currently new methods are being developed to automate the process sequence design in metal forming process using FE simulation to further reduce the process development time and cost /7/.

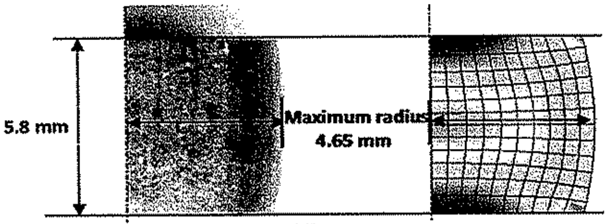
## 2 Determination of reliable input parameters for process modeling

The accuracy of FE process simulation depends on the reliable input data namely, a) CAD data of the die geometry, b) speed and force characteristics of the press used for forming, c) flow stress of the deforming material as a function of strain, strain rate and temperature in the range relevant to the process being analyzed, and d) friction characteristics at the interface between the deforming material and the die.

## 2.1 Material properties

### 2.1.1 Forging – Cylinder compression test

In the cylinder compression test, barreling is often observed at the center plane of the cylindrical test specimen due to the friction at the die-specimen interface, (Figure 1). Therefore, in order to accurately determine the material properties, it is necessary to account for the friction involved in the test. In the ERC/NSM, test results namely, a) upset load versus stroke and b) shape of the billet at the end of forming are used in the FE simulation-based inverse analysis technique to estimate the flow stress that compensates for friction at the billet – die interface /8/. The material properties and the interface friction conditions in the FE simulation are then varied iteratively to match the load versus stroke curve and barreling observed in the FE simulation with experiment (Figure 1) /8/.



$\sigma = 795.7\ \varepsilon^{0.15}$ Mpa

friction factor m = 0.15

**Figure 1: Comparison of deformed shape in the compression test from FE simulation and experiment for the optimized material parameters**

## 2.1.2 Stamping and Sheet Hydroforming -Viscous Pressure Bulge (VPB) test

In sheet forming, material properties obtained from tensile test are not adequate for process simulation because a) stress conditions in stamping/ sheet hydroforming are often biaxial compared to uniaxial in the tensile test, and b) the maximum effective strain achievable in the tensile test is relatively small because of local necking. Therefore, the bulge test (Viscous Pressure Bulge test, VPB test) is preferred in order to determine the properties of sheet materials used in stamping/sheet hydroforming process simulation.

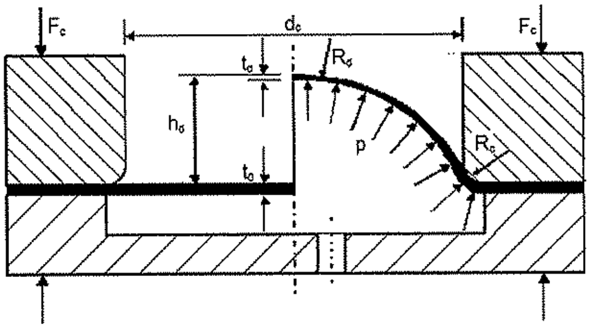


**Figure 2: Schematic of the VPB tooling and the specimen after and before burst in the VPB test.**

Figure 2 shows the schematic of the bulge test where the sheet clamped at the edges is bulged freely by the viscous pressure until it bursts. The measured dome height and pressure are used as an input to the inverse analysis using FE simulation to determine the flow stress of the material /9/. The burst dome height is a good indicator of the formability of the material (The higher burst dome height the better formability). Also, the burst dome height can be used as an indicator/ design specification to check the quality of the incoming material to the stamping plant /9/. A similar bulge test has also been developed to evaluate the properties of tubular materials /10/.

## 2.1.3 Surface properties – Indentation test

When a forming operation involves non uniform input material that has undergone several stages of forming followed by heat treatment and machining, the material properties are not uniform and regular test methods cannot be used. At ERC/NSM, the indentation test, generally used to measure the hardness of the material, is also used to estimate local flow stress of the material near the surface, Figure 3. During the test, the load versus stroke is measured continuously. The measured data is used as an input to the FE simulation-based inverse analysis technique to estimate the flow stress of the material (Figure 3) /11/.

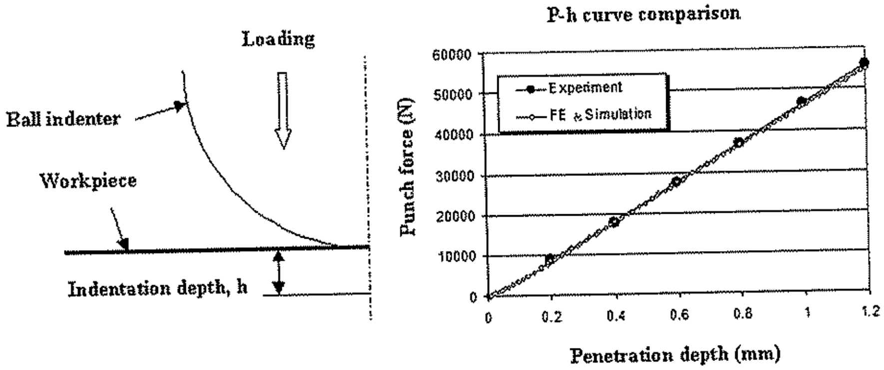


**Figure 3: Schematic of the indentation test along with a comparison of the indentation load stroke curve from FE simulation and experiment for the optimized material parameters and interface friction conditions.**

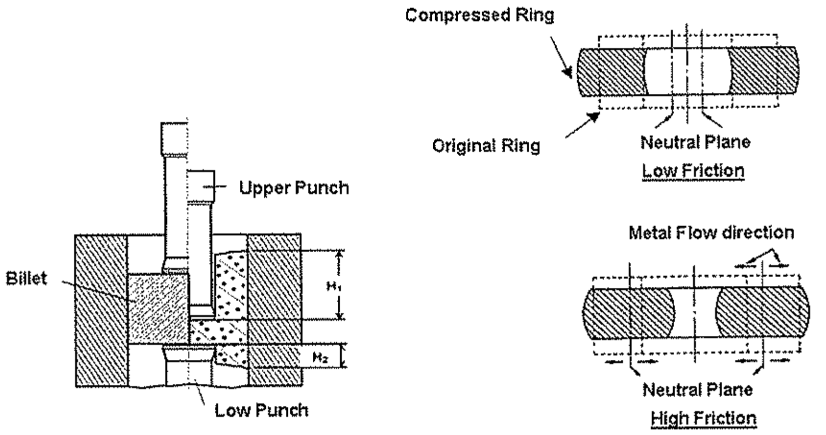
## 2.2 Interface friction conditions

### 2.2.1 Forging (Ring Compression and Double-cup Extrusion Tests)

In forging, the ring compression and double cup extrusion tests are commonly used to evaluate and to estimate friction factor (m) of the lubricants and coatings. The choice of the test depends on the contact pressure and surface expansion in the process that is being studied. The double cup extrusion test is used to evaluate lubricants in processes that involve high contact pressures and surface expansion (Figure 4a) whereas the well known ring compression test (Figure 4b) is mainly used to test lubricants in cold heading and hot forging. The friction factor of the lubricant is obtained by matching the deformed geometry, namely, a) the inner diameter expansion in ring compression test, and b) the cup height ratio in double cup extrusion test, with the calibration curves that are generated through FE-Simulations of the test /12/.

### 2.2.2 Stamping

In stamping, the sheet metal slides under the action of normal pressure under the blank holder region while at the die and punch corner radius it under goes bending followed by stretching. A test developed to evaluate lubricants for stamping should emulate these conditions to accurately estimate the friction coefficients of the lubricants. At the ERC/NSM the deep drawing test and modified limiting dome height test are used to a) estimate the friction coefficient (m) of the lubricant used, and b) evaluate commercially available lubricants for use in production.



a) Double cup extrusion test (DCET)

b) Ring compression test (RCT)

**Figure 4: Lubricant evaluation tests for cold and hot forging processes.**

## Deep Drawing Test for Stamping Lubricant Evaluation

The deep drawing process itself can be used as a test to evaluate the performance of the lubricant, Figure 5. This test emulates the interface condition that exists in production, both in the flange and in the punch. In this test, circular cups are drawn from a blank of fixed draw ratio but with different blank holder force until they fracture. The largest blank holder force that can be used to draw the cup without failure indicates the performance of the lubricant. The higher is the blank holder force, the better is the performance of the lubricant in the test. Also, a large punch force indicates bad performance of the lubricant /13/. Several lubricants were evaluated using this test, Figure 6. Among the tested lubricants, lubricant B gave the best performance. Test measurements, namely punch force, draw-in of material in the flange; cup wall thinning can be used along with FE simulation of the test to quantitatively estimate the coefficient of friction for the lubricant used in the test /13/.

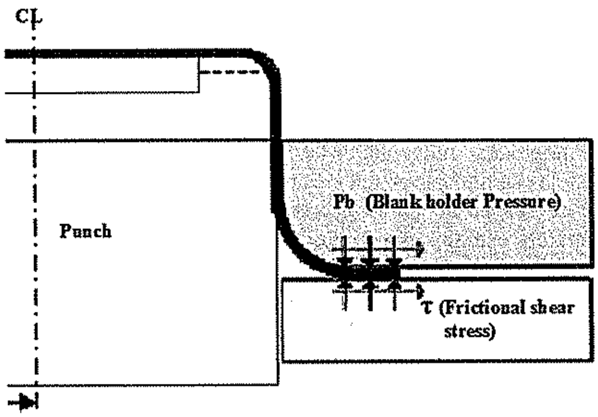


**Figure 5: Schematic of the deep drawing test for lubricant evaluation /13/.**

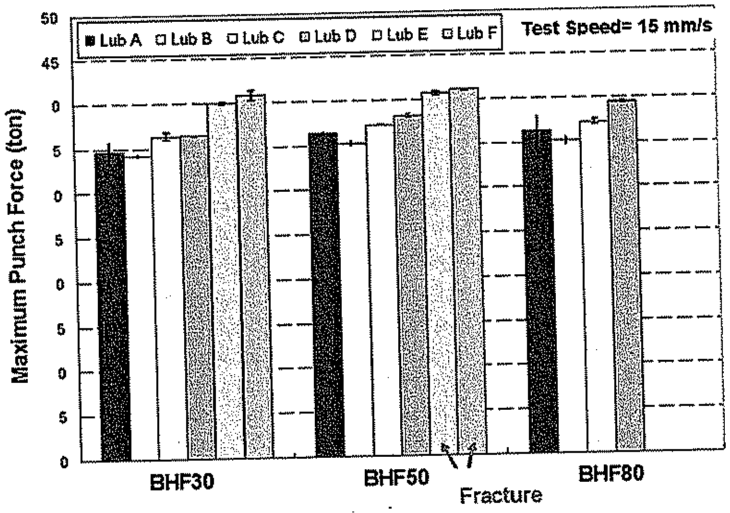


**Figure 6: Example ranking of the lubricants in the deep drawing test based on the maximum blank holder force (in tons) that can be applied to successfully draw a cup of 152.4 mm diameter /13/.**

## Modified limiting dome height test

In this test, a circular blank with a circular hole at the center, held at its edges, is being stretched against a hemispherical punch as shown in Figure 7. The diameter of the hole in the blank before and after the test is measured. Change in the diameter indicates the lubricity of the lubricant, Figure 7. Large change in diameter indicates the lubricant performed better allowing more material flow from center to the periphery. The friction coefficient (m) is obtained by conducting FE simulation of the test with different friction coefficients (m) and matching the diameter of the hole at the end of the test obtained from the simulation with the experiment /14/.

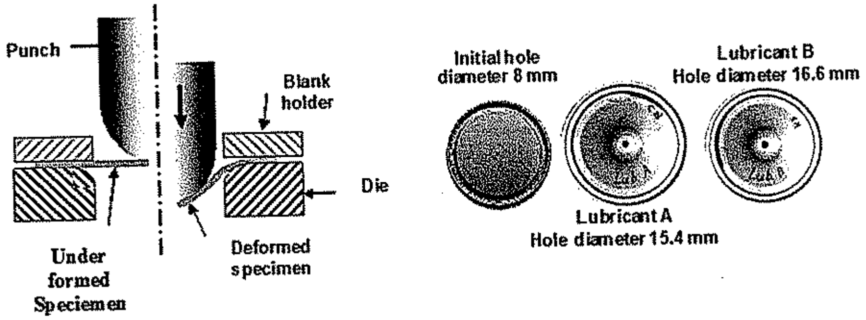


**Figure 7: Schematic of the modified limiting dome height test along with samples before and after testing.**

# 3 Process modeling for precision forming

## 3.1 Forging

### 3.1.1 Case study - Orbital forming

Orbital forming is an incremental forming process used for forging axisymmetric and near axisymmetric parts, Figure 8. In orbital forming the tool inclined to the axis of the work piece rotates and moves in axial direction to deform the workpiece at the small contact area. Incremental deformation mode and less contact area in orbital forming reduces the axial load necessary for forming a part, compared to a regular forging operation.

Orbital forming is also used for precise assembly of the inner race of the bearing to the wheel spindle in an automobile. FE simulation of the orbital forming process of spindle bearing assembly is being conducted in DEFORM 3D to design a robust assembly process. Through FE simulations, the influence of various process parameters such as axial feed, tool axis angle, etc., on the residual stress in the bearing inner race of the assembly, deformed geometry of the spindle, and the axial load that the assembly can withstand is being studied. The predicted load required for forming, the deformed geometry of the spindle and the residual stress were found to agree with the experiments /15/.

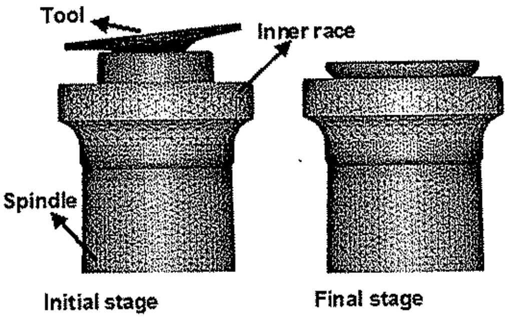


**Figure 8: FE model for orbital forming of spindle bearing assembly**

### 3.1.2 Case study - Microforming

Forming at micro-scale is currently being investigated at various research institutions. A micro-scale coining process for manufacturing a surgical slit knife was designed using FE simulations. FE simulation of coining processes was conducted using DEFORM-3D™. In the manufacturing process of the knife, the incoming perform wire is initially flattened, annealed and then coined. Figure 9 shows the FE model of the initial preform and the formed part at the end of the coining process. FE simulations were conducted to optimize the tool geometry to form the part of desired shape and with minimum tool stresses. The designed tool geometry was successfully used in production to coin this part /16/.

### 3.1.3 Improvement of Material Utilization in Hot Forging

In hot forging with flash a considerable amount of input material may be lost into flash. Material costs constitute a major chunk of the finished part cost besides labor thus presenting the opportunity of huge cost savings if volume losses in flash can be reduced. In order to maximize the material savings it is necessary to:

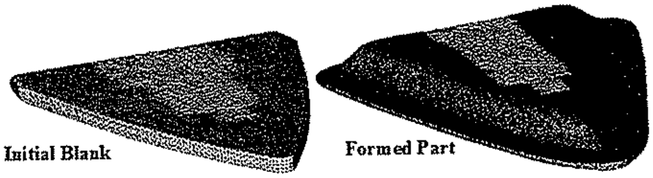


**Figure 9: Microforming of cutting blades (Blank thickness = 0.1 mm Final blade thickness = 0.01 mm)**

- Identify the optimum shape and size of the preform with the best possible material distribution to obtain complete cavity filling without defects.
- Modify the flash design of blocker & finisher die to minimize the loss of material into flash.

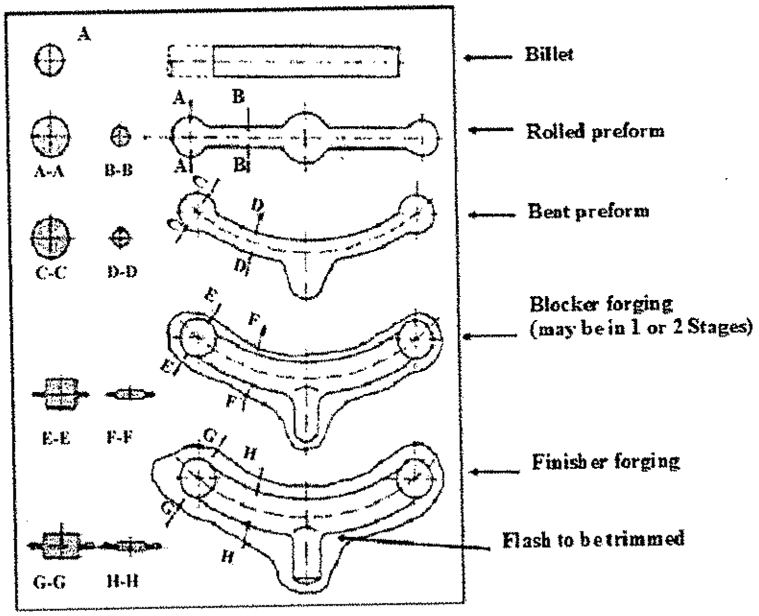


**Figure 10: Illustration of the hot forging sequence for upper control arms using an example part /17/.**

A study was conducted for a tier one aluminum forging supplier to optimize the preform and die (blocker and finisher) designs, forging temperatures as well as flash dimensions (Figure 10).

A combination of 2D and 3D simulations were used to design the optimum reducer rolled preform and the blocker die geometries. The 2D simulations were used under the assumption of plane strain metal flow, whereas, the geometrically complex sections required the use of 3D FEA for those local regions (Figure 11). Final validation (Figure 12) of design changes was conducted with 3D FEA of the forging and rolling operations.

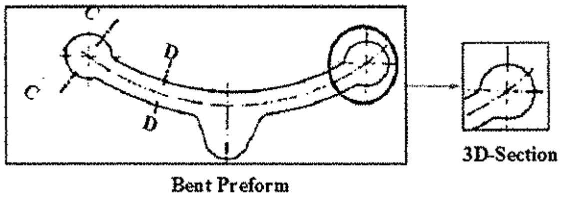
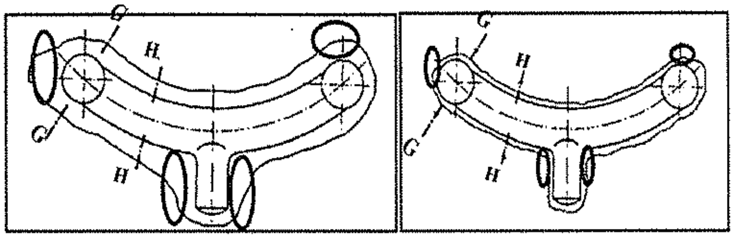


**Figure 11: FE simulation of geometrically complex 3D sections.**



Original Finisher Forging

Final Forging with Reduced Flash

**Figure 12: Final validation of the die and preform design with 3D FE analysis.**

Based upon FE simulation results the material yield was increased by 15 % with only preform optimization i.e. the incoming forging stock and reducer rolling operation were optimized to improve the material yield with the existing dies. These design recommendations were implemented on the shop-floor. A potential improvement of a further 3-4 % was expected upon completion of the blocker design study. Thus, an FE simulation based design study improved the material yield by approximately 19 % in hot forging of a high volume automotive component.

### 3.1.4 Prediction and Improvement of Die Life in Warm and Hot Forging

This ongoing study sponsored by the Forging Industry Educational and Research Foundation (FIERF), aims to reduce die wear in warm and hot forging through application of proprietary hot-work tool steels and ceramic-based materials through combination of computational analysis and shop floor experimentation. As part of this initiative, guidelines will be developed for a) die design under hot and warm forging conditions, and b) selection of optimum lubrication systems for increased die life. The goals of this study will be achieved through detailed FE simulation-based design and analysis followed by shop-floor validation through active cooperation with a number of FIA member companies. A number of example parts were selected for analysis of die-workpiece interface conditions and die design using extensive FE simulation. In each case the entire forging stroke was simulated using production process parameters and measured data to track the temperature variation and distribution in the dies (Figure 13):

- Die chill time i.e. the time spent by the billet on the bottom die until contact with the top die.
- Deformation or forging time i.e. the time from start of deformation until bottom dead center (BDC).

- Dwell time i.e. the time until part removal/ejection.
- Cooling time i.e. the lubrication spray time and the dwell time until the next billet is placed on the die.

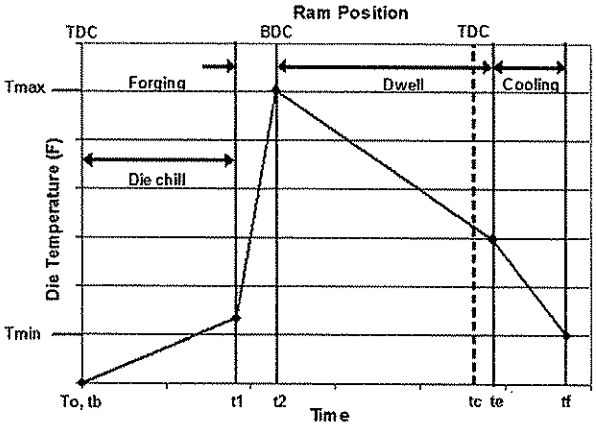


**Figure 13: Die temperature cycle for a typical forging process in a mechanical press**

Candidate die materials were selected based upon their material properties (hot hardness, thermal fatigue resistance, etc.) and the failure mechanism observed in the production process. Die design modifications were made to reduce overall contact time and relative sliding where possible. Additionally, design methodologies for shrink-fitted dies (ceramic/ carbide inserts) are being developed in order to retain compressive stress in spite of thermal expansion. Selected die materials along with new die designs were then tried out under normal production conditions.

## 3.2 Stamping

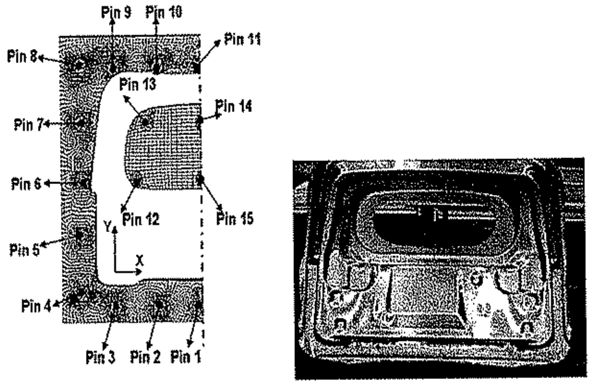
### 3.2.1 Case study - Determination of preform blank shape and slot shape

Net shape stamping of an optimal blank that after forming conforms to the desired shape of the final product would reduce post forming operation such as trimming, piercing etc., thereby reducing the manufacturing cost and scrap rate. In this study, (FE) analysis using PAMSTAMP-2000™ was used to determine the optimal slot shape in the initial blank for a sample part. Thus, the initial blank with optimal slot shape could be formed to give the final part that has the design dimensions. Figure 14 shows the final formed blank obtained at the tryout using the predicted input blank. The formed part matched well with the design dimensions /18/.

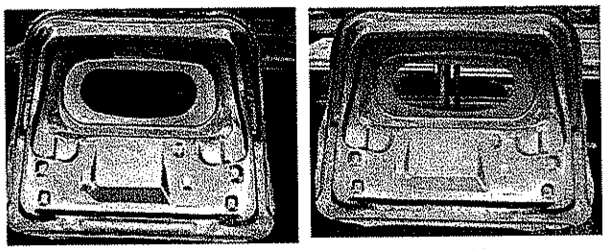
**Figure 14: Slot shape and the outer boundary in the formed blank using the predicted input blank boundary and slot shape**

### 3.2.2 Case study - Programming a multipoint cushion system

Modern presses are equipped with multi-point cushion (MPC) systems that allow the blank holder force (BHF) to vary with location and during the stroke. Also, dies built with nitrogen cylinders to provide the blank holder force, allow the option of using nitrogen cylinders with a different pressure on each cylinder, thereby varying the blank holder force with location. However, this capability is under utilized currently in production because a) it is difficult to estimate the BHF that should be applied by each cushion/nitrogen cylinder and b) conventional steel sheets can be formed with the existing method of constant blank holder force. Increase in the complexity of the parts and emphasis to use lightweight materials with low formability require the use of multi-point cushion capabilities to better control the material flow and expand the processing window.



a) Pin layout for the selected part. b) A6111-T4 , t = 1 mm



c) DP500 , t=0.8 mm d) BH210 , t=0.8 mm

**Figure 15: Optimum blank holder force, variable in space and constant in time (predicted by optimization for forming the lift-gate from three different materials) /19/**

As part of a USCAR project, an optimization technique was developed coupled with FE codes to estimate the blank holder force that is variable in space and constant in stroke. The developed software was used to predict the blank holder force required to form a full size automotive panel (Lift-gate – inner) from three different materials (aluminum alloy A6111-T4, t = 1.0 mm, BH210, t = 0.8 mm and DP500 t = 0.8 mm). An example of BHF profiles estimated for A611-T4 material is shown in Figure 15. It should be noted that the part could be formed from A6111-T4 with varying BHF which otherwise is not feasible with conventional constant blank holder force /19/.

### 3.2.3 Case study – Design of progressive/transfer die sequence

Integration of design experience with simulation facilitates the design of a robust process sequence and considerably reduces physical tryouts and die-development costs. In this case study, in cooperation with a commercial stamping company, a process sequence was designed for a sample part, using extensive FE analysis (Figure 16). The main objective in progressive-die-sequence design is to estimate:

- the number of forming stages;
- the tool geometry for each stage (punch/die diameter, punch-corner and die-corner radii);
- the draw depth in each forming stage;
- the blank holder force for each stage.

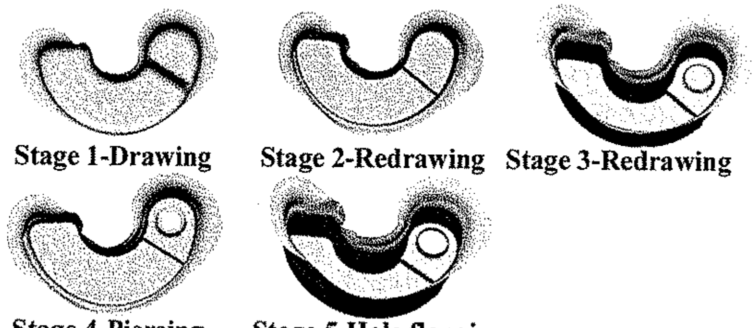

Stage 1-Drawing
Stage 2-Redrawing
Stage 3-Redrawing
Stage 4-Piercing
Stage 5-Hole flanging

**Figure 16: Schematic of the designed progressive die sequence for forming a complex part**

The existing design was improved through FE simulation to reduce the potential for failure in the formed part (excessive thinning and wrinkling). The estimated final sequence to form the part is shown in Figure 16 before final trimming. Also, the blank shape was estimated to reduce thinning and excessive scrap material. The predicted thinning distribution at the final step is shown in Figure 17. Maximum thinning was less than 30 % and no wrinkling was observed.

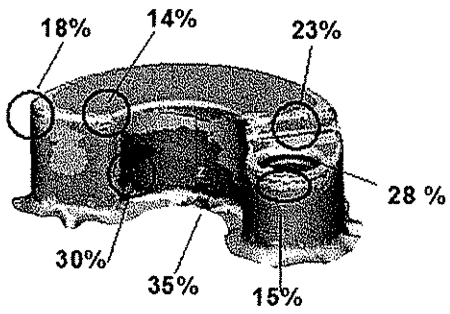
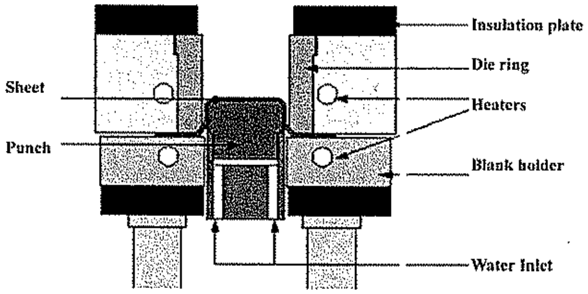


**Figure 17: Thinning distributions in the final formed part predicted by FE simulation using optimum initial blank geometry.**

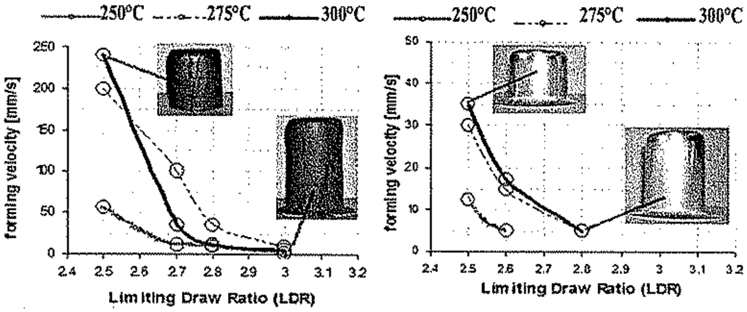
### 3.2.4 Case study - Warm sheet forming of magnesium and aluminum alloys

A study was conducted, in co-operation with Aida-America, to investigate deep drawing of a magnesium alloy, an aluminum alloy and austenitic stainless steel at elevated temperature. Figure 18a shows the schematic of the round cup tooling used for this study. Die and blank holder can be heated up to 300° C using cartridge heaters, while the punch can be cooled by water circulation /20/.

In the experiments, the sheet was heated in the tooling and then formed at different speeds using a servo motor driven press that allows infinite degree of freedom to control the ram motion and speed. Experimental results for aluminum alloy AL5754-O and Mg alloy AZ31B-O sheet materials are summarized in Figure 18b and c. Maximum draw ratio of 3.0 can be obtained at elevated temperature of 300° C with maximum forming speed (ram velocity) of 2 mm/sec and 5 mm/sec for AZ31B and AL5754-O sheet material, respectively /20/.



a) Schematic of the warm deep drawing tooling used for the experiments (courtesy Aida-America)



b) Magnesium alloy - AZ31B

c) Aluminum alloy – 5754-O

**Figure 18: Limiting Draw Ratio versus forming velocity at different forming temperatures for (a) Magnesium alloy AZ31B-O (b) Aluminum alloy 5754-O /20/.**

## 4 Concluding remarks

Process modeling through FE simulation is an essential tool in modern metal forming to reduce the development cost and time. Continuous development of FE software for metal forming has increased its scope to cover a large range of metal forming processes including warm sheet forming and metal cutting. In this paper an overview is given on the application of FE simulation for industrially relevant practical problems to a) improve the existing manufacturing process, b) estimate optimum process parameters and c) design of process sequence, in the areas of forging stamping, and hydroforming. Despite advances in the technology, reliable input parameters hold the key to successful application of FE simulation for process modeling. Thus, in addition to simulation capability, it is necessary to have methods for accurately determining the important input parameters such as a) mechanical properties of the deforming material and b) interface friction conditions.

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