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VALIDATION AND OPTIMIZATION OF NUMERICAL SIMULATIONS BY OPTICAL MEASUREMENTS OF TOOLS AND PARTS

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ABSTRACT. *Simulation of forming processes has become an important tool for the current process optimization. It can be supported significantly by modern optical measuring methods based on digital image processing providing full-field information of 3D surface geometry (ATOS) and strain and thickness reduction distributions of formed sheet metal parts (ARGUS). These optical systems have become important tools in industrial tool making and sheet metal forming processes in the last years and together with the simulation of forming they have significant potential for quality improvement and optimization of development time for products and production. As part of complex process chains smooth interfaces to conventional CAD/CAM and numerical simulation systems are of particular importance.*
This paper presents the use of 3D surface geometry data of tools and formed sheet metal parts as input for numerical simulations as well as for the verification of simulations. Furthermore, the digital comparison of measured and simulated strain and thickness reduction distributions is evaluated.

1. INTRODUCTION

The Salzgitter Mannesmann Forschung GmbH (SZMF) is the central research company of the Salzgitter Group. Employing around 300 members of staff active in 6 main departments at the Salzgitter and Duisburg locations, SZMF conducts extensive research and development work revolving around the material steel.

In this way, SZMF is actively supporting customers in their material selection in the early stages of the development process [1]. In these phases, it is important to arrive at a correct assessment of the potentials of individual materials, and predict material and component behaviour by the way of simulation. Therefore SZMF tries to improve constantly their use of material models and simulation tools [2].

GOM develops and distributes optical measuring systems with its main focus on applications like 3D digitizing, 3D coordinate measurements, deformation measurements and quality control. GOM systems are used for product development and for quality assurance, material and component testing. Current developments take care about the need for simulation verification of forming processes.

This paper presents the current possibilities for the verification of forming processes simulations.

2. PROCEDURE OF SIMULATION AND MEASUREMENT

As an example for a validation, a real forming process is used as base for the comparison in the following way:

1. Selection of a part with an existing tool

   The geometry of the tool has to be known exactly for the simulation. Therefore, a complete measurement of the geometry is done with ATOS.
2. Preparing a metal sheet for the forming analysis

   For the forming analysis the dot-grid geometry and position on the sheet is measured with ARGUS.
3. Forming of the parts

   Definition of the blank position at the beginning of the process.

   The sample was formed using a 1000t Diefenbacher press with analytical capabilities at SZMF.
4. Forming analysis of the formed part by ARGUS
5. Comparison with simulation

The following text will describe the measurement techniques, simulation and the process of optimisation by comparing the measurement and the simulation.

3. MEASUREMENT TECHNIQUES

3.1. Basics of Optical 3D Digitizing with ATOS

Optical measuring systems such as the digitizing system ATOS (figure 1) digitize formed components and tool geometries of any size and complexity with high precision and high scanning density very quickly and effectively [3], [4] based on fringe projection (figure 2).

***Figure 1**: ATOS Sensor*

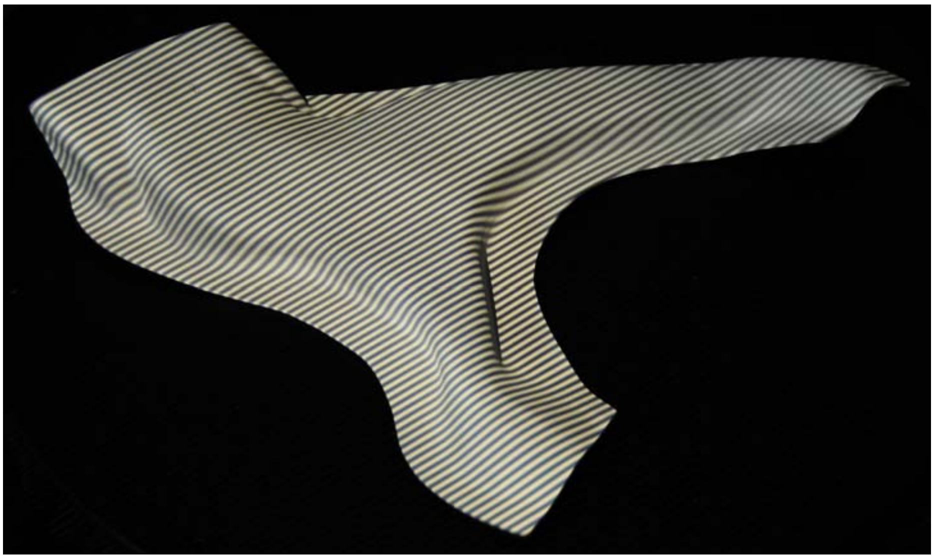


***Figure 2**: Projection of fringe patterns onto the surface of a part*

The measuring results are point clouds in ASCII format and polygon meshes in STL format (Fig. 3). In addition, ATOS outputs the measured trimming and the whole pattern of formed parts as IGES or ASCII data set.

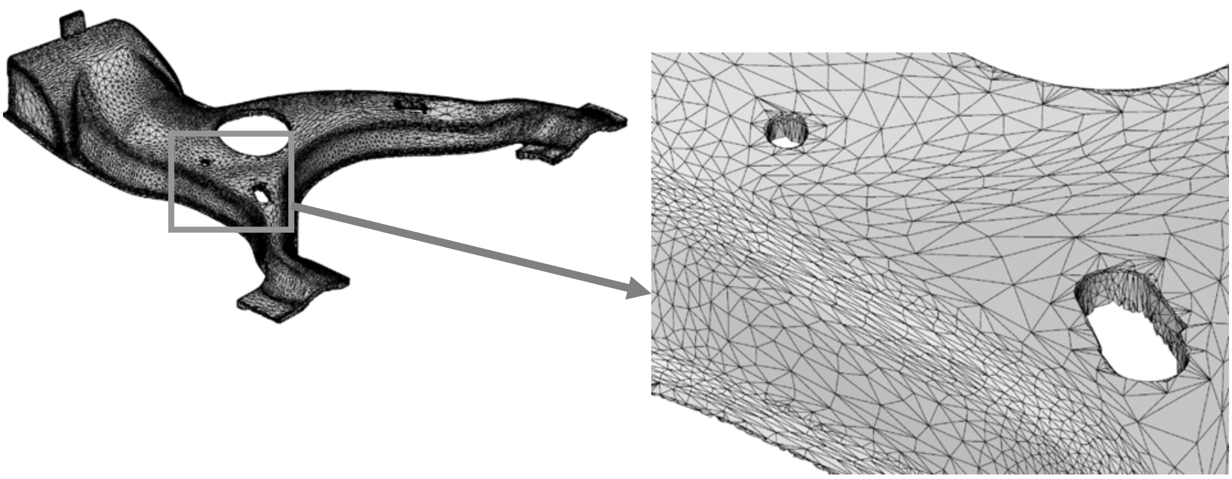


***Figure 3**: Generated polygon mesh for the punch (complete and detail)*

The data is mainly used for

- Surface reconstruction using common CAD systems
- Comparison of measured real geometries with CAD data or with other measured data
- Dimension inspection
- Generation of NC machine data in CAM systems

3.2. Digitizing of the Tool and Definition of FE Starting Geometry

Both sides of the tool are completely digitized by the ATOS system. The result is shown in Figure 4. Based of the slide surface (dark areas) the coordinate systems of both sides of the tool were aligned by transformations and best fit functions to the real working position. Thus the geometry and position of punch, die and blank holder and position adapters are well known. (Figure 5).

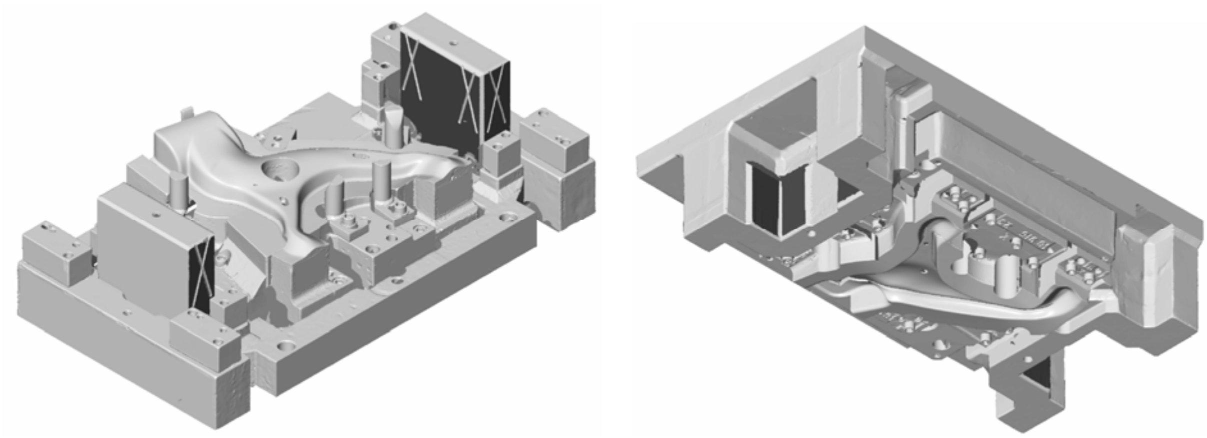


***Figure 4**. Digitization result: Complete geometry of both sides of a forming tool (Slide surfaces are dark)*

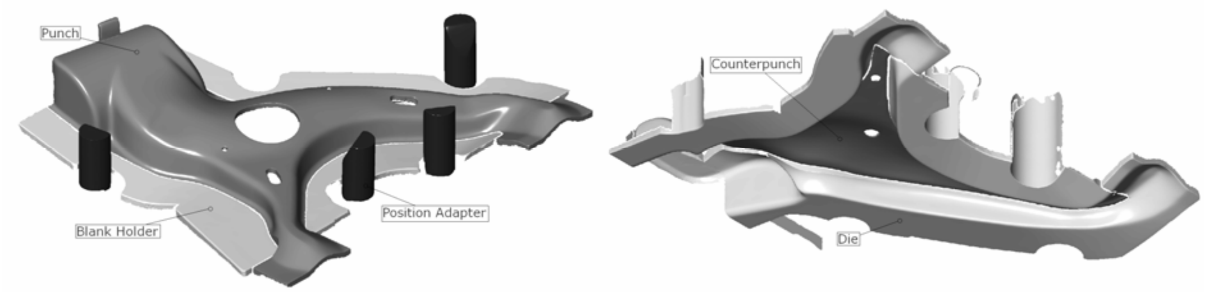


***Figure 5.** Geometry and position of Punch, Blank Holder and Position Adapter (left) and Die and Counterpuch (right)*

3.3. Forming Analysis by ARGUS

ARGUS is a modern measuring solution for forming analysis on formed metal sheet parts [5]. Circular dots are applied to the original sheet metal with a regular spacing of typically 1 mm to 5 mm prior to the forming process. For this purpose, mainly structures are used that were created by electrochemical etching, laser marking or printing. These dots follow the deformation of the part during the forming process and are maintained even in case of large relative movement between the sheet metal and the tool. The center of these dots is the reference for determining the coordinates and for the following deformation analysis.

After the forming the shaped component (figure 6) is recorded with a digital camera from various views [6] (figure 7).

Photogrammetric algorithms use these images to determine the 3D coordinates of the dots on the sheet metal. Thus, the entire surface of the shaped sheet metal is described according to the density of the etched structure.

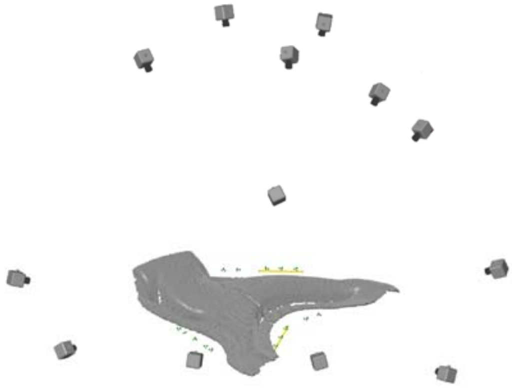


Figure 6. *Example for a shaped metal sheet after the forming process (left side)*
Figure 7. *Different camera positions during the ARGUS measurement (right side)*

In this mesh each 2x2 point field is compared to the original geometry and the corresponding surface strain tensor in space is determined. As a result e.g. the major and minor strain (Fig.8 and 9) and the thickness reduction of the sheet metal are available as surface information. The thickness reduction is directly calculated from the major and minor strain assuming a constant volume.

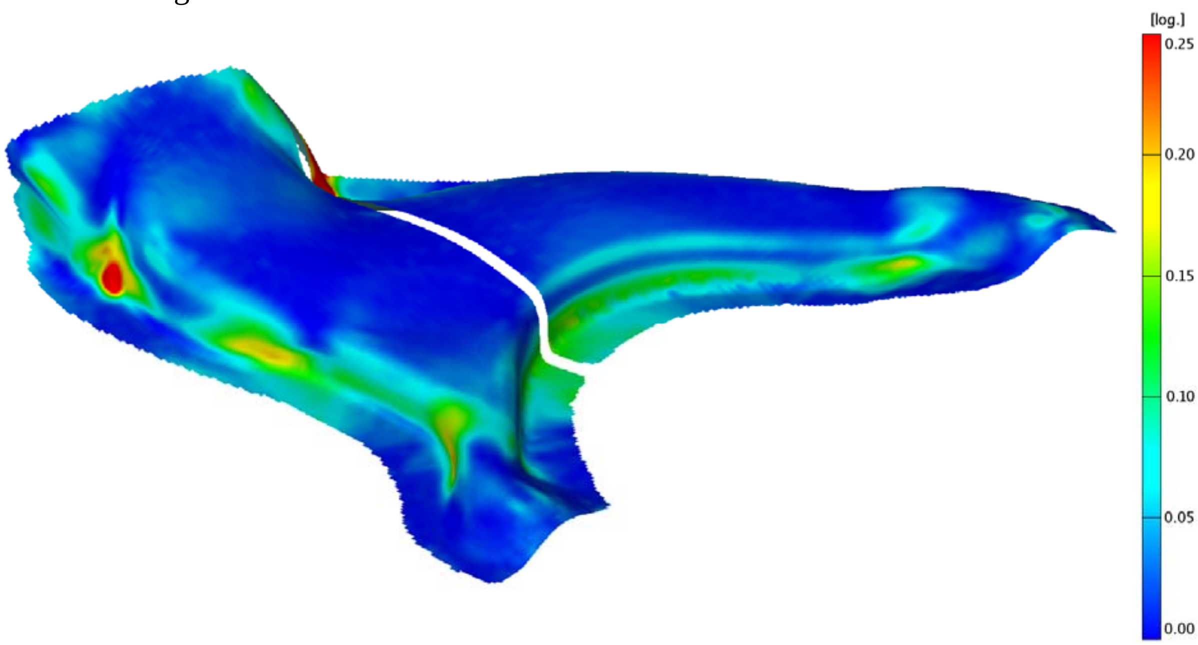


Figure 8: *Major strain distribution*

The forming limit diagram compares the major and minor strain with given material characteristics (figure 10) and the distance to the FLC is shown in figure 11. Thus, the forming process can directly be evaluated with respect to the material limits.

All calculated values can be displayed in colour on the 3D contour as sections or as form limit diagrams. Short, precise and complete information on the shaping process is available by simply rotating the 3D contour. In addition, all calculated values and the respective 3D coordinates can be exported in user-defined ASCII files and imported into other post processors. If it is required to provide the results in the CAD coordinate system of the component, ARGUS can carry out coordinate transformations.

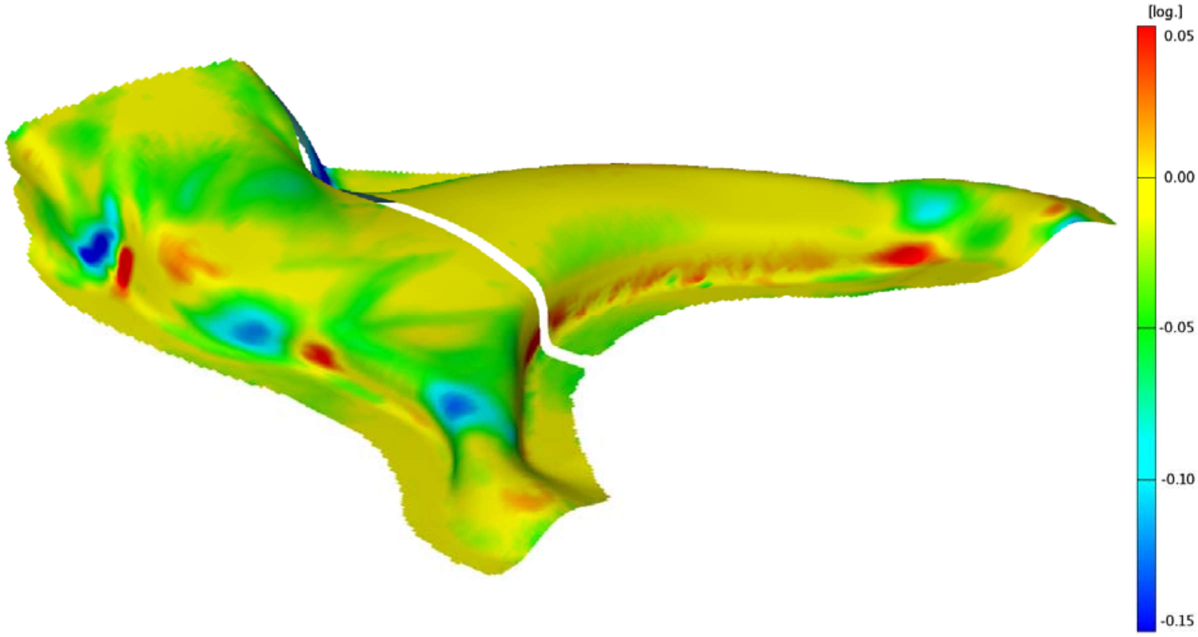
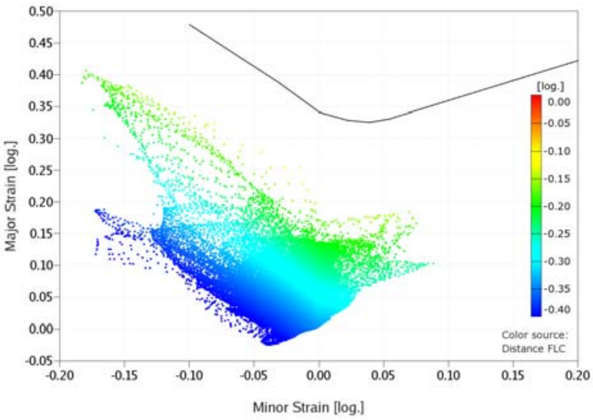


Figure 9: *Minor strain distribution*



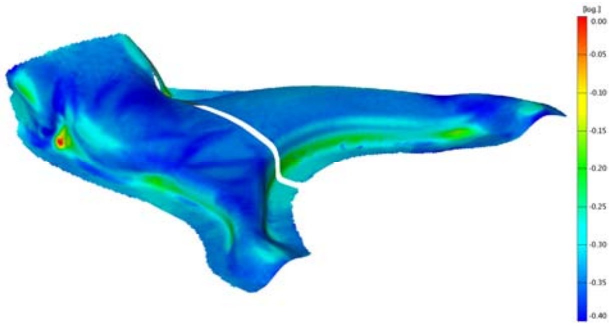


Figure 10: *Forming limit diagram inclusive measured strain values*
Figure 11: *Distance values from FLC*

The recording principle of the system allows for flexible adaptation of the measurement to various applications. A minimum of three views is required for measuring. As the individual views are recorded successively with a single camera, the system can be used for simple and for very complex parts as well as for small and large measuring volumes. As during the photogrammetric calculation the system is calibrated automatically, no other preparations of the system are needed except for adjusting the lenses to the desired measuring volume. Based on this procedure the accuracy of the geometry for an ARGUS measurement reaches the high accuracy level from photogrammetric measurements for the 3D coordinates in space.

4. SIMULATION OF THE FORMING PROCESS

4.1. Basic Simulation

For the simulation of the forming process the FE-solver LS-Dyna was chosen. This multipurpose solver can easily be coupled with external macros and parameter optimisers [7].

The first simulation step was performed as a standard job. The following parameter where used:

- Element type: shell type 16 (full integrated Belytschko-Lin-Tsay) [8]
- Adaptive remeshing
  The elements had a length from about 1mm in the refined zones. All edges could be represented with a good accuracy and element quality.
- Blank holder force 1000 kN (was taken from the press data)
- All tools were rigid and constrained in their rotational and in the adequate translational degrees of freedom. This keeps the results close to a standard job and minimizes the calculation time. For further investigation the tools might be modelled with elastic behaviour by using solid elements.

4.2. Material Data

The forming tool was trained for the use of S355MC with 2.5mm thickness. This grade was also applied to the simulation. The mechanical properties of the S355MC blanks were measured at SZMF in comply with the SEP 1240 (PuD-S) [9]. Thus all material parameters for the use of Mat36 (Barlat 89) were given.

4.3. Mesh Based on ATOS

It is common to use a FE-mesh based on a CAD-geometry to perform a forming simulation. In this investigation the STL-mesh from the real tool measured by ATOS was used. In ATOS the amount of data was reduced by local thinning in plane areas and high scanning density in areas with small radii . The high quality of this data allows a direct use for the FE calculation without additional reverse engineering. This avoids a loss of accuracy based on in-between stages.

In deep drawing simulation it is common to use a contact algorithm based on Lagrange multiplier for all travel controlled tools. This method achieves very accurate contact behaviour. The shells follow the exact tool geometry and the movement of the tool. Unfortunately this method causes local areas with high pressure peaks. This is undesired on force-controlled tools such as the blank holder. In these cases the penalty method achieves more realistic results. In this investigation an unsmooth surface was used. The Lagrange multiplier method would have caused many local pressure peaks on the small rises of the surfaces. Therefore the penalty method was chosen for all contacts which caused the best results.

4.4. Comparison of Simulation and Measurement

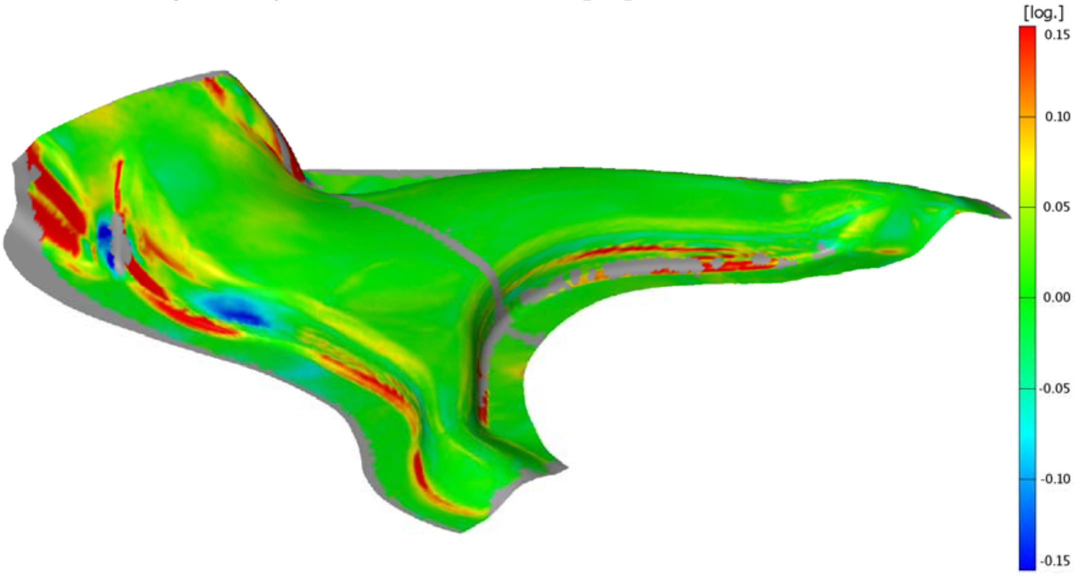
The comparison of the results from simulation and the ARGUS measurements were done in a special FE-compare-module from GOM. In this module, the selected result values (geometry, 3D displacements, strains) can directly be compared and the differences can be shown as full-field information. Therefore, the following steps were done:

- Import result data file of the FE-solver LS-Dyna into the compare module
- Import measurement data into compare module
- Transformation of measurement data to the coordinate system of the FE for:
  - unformed flat sheet
  - formed part

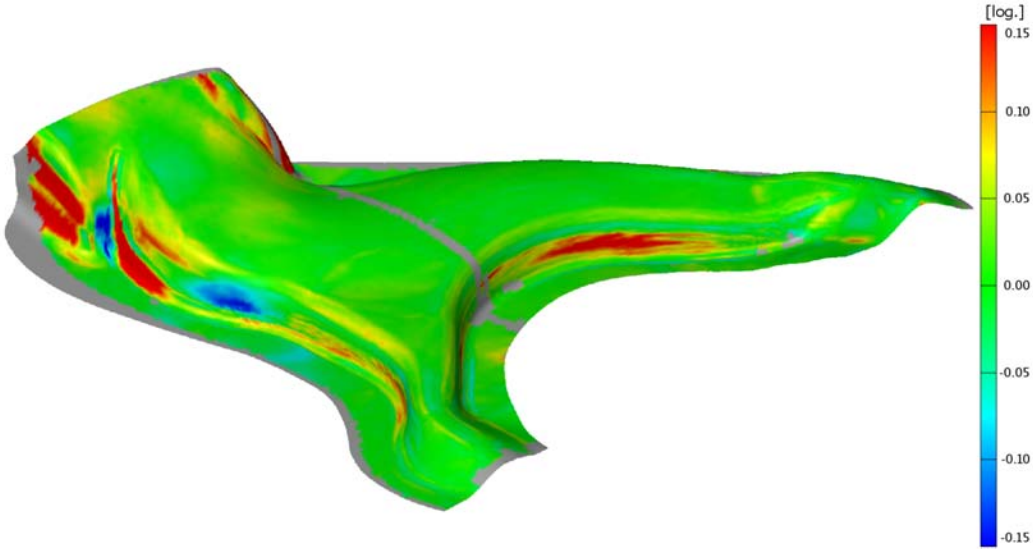
  Multiple different transformation functionalities are available in the compare module. In this case, the coordinate system and the positions for the measurement

of the unformed metal sheet were fitted by border information and RPS registration against the borderlines of the initial simulation.
The measurement of the formed part was transformed using the best-fit method into the simulation result. For this, only the central area of the formed part is used (so this area is defined to be close to zero for the geometry comparison in figure 16).

- Generation of comparison points
  The meshes (FE and measurement) have not the same node positions. For a comparison with the result values one of the meshes has to be remeshed, to have equal node positions. Here the FE-mesh was used as master and the measurement mesh was remeshed by using bi-linear interpolation for node position and result values based on the neighbouring nodes.
- Comparison of
  - result values (strains and displacements)
  - geometry (deviation as distance perpendicular to the mesh)



Major true strain deviation on outer surface



Major true strain deviation of concave sides

Figure 12: *Comparison of measurement and first simulation step (Colour definition: Deviation of simulation to measurement)*

Regarding the results during different steps of iteration it could be observed, that the strains on the convex formed side of the specimen fit better to the measurements than on the other (concave) side. Thus the progress of iteration of the simulation was validated based on the comparison of the deviation of the convex surface areas as shown in figures 12 and 13.

4.5. Iteration of Simulation Parameters

During this investigation some parameters were varied to achieve a better fit with the experimental results. The parameters were all chosen to achieve a more or less global improvement and they were varied in common ranges. In this first stage of result comparison a more complex or automated variation was omitted.
First the friction behaviour was investigated. It was set to 0.125 which is a common value for oiled steel. During the real forming of the samples the tool was well lubricated. Therefore the friction coefficient was decreased. In general, this adjustment achieved a better draw-in. Especial in the zones parallel to the drawing direction the strain distribution differed more than expected. That was minimised by the use of a different extrapolation of the measured flow curve. The improved flow curve has more work hardening behaviour.

The result of the first simulation in comparison to the measurement is shown in figure 12. Large deviation can be found e.g. on the left side (large red area). The major strain was to high calculated. It can be recognized, that the border of simulation (outer border of the dark grey area, figure 15) shows large deviation from the borders of the measured specimen (different draw-in).

It was assumed, that the sheet in the beginning was clamped between blank holder and die without disturbance. Regarding the curved surface of blank holder and its contact area in the die, a free form bending occurs before the clamping. A more detailed analysis of the contact area of clamping shows, that the measured position on both sides does not fit very well. The blank holder was not measured (and is not shown in figures 4 and 5) in the real working position. For the simulation, a movement perfect parallel to the measured position was assumed.

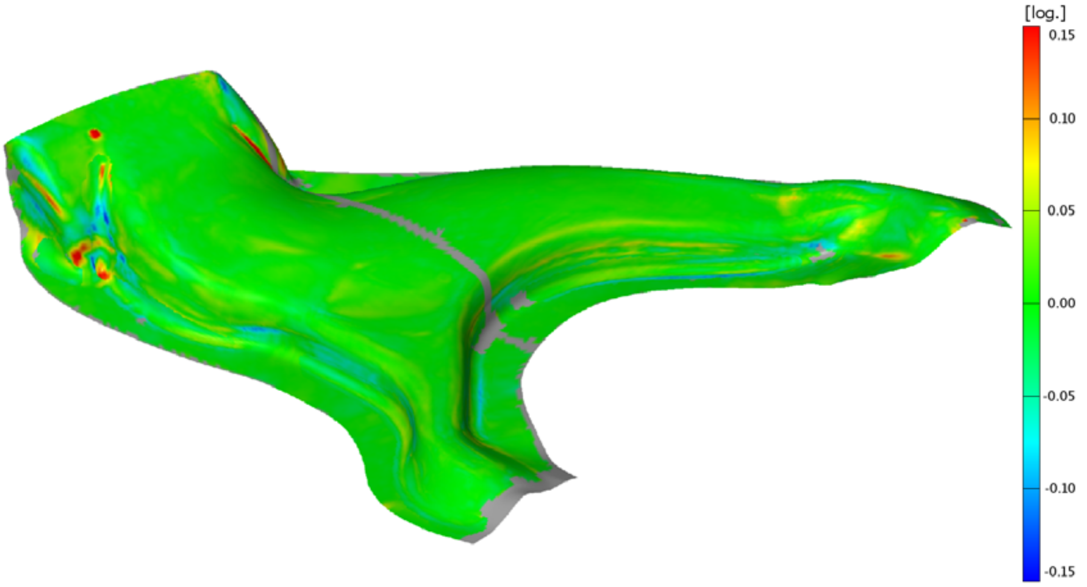


Figure 13: *Major true strain deviation after some different steps of optimisation (Colour definition: Deviation of simulation to measurement)*

Regarding the elasticity and the unknown clamping position additional degrees of freedom were added to the simulation procedure. A free rotation in two axis perpendicular to the drawing direction was enabled. Altogether these adjustments produced a good compliance of the strains (figure 14) and draw-in (figure 16).

The measured ARGUS grid reflects very well the position of the real border of the part (figure 16 left). In the image of the first simulation (figure 16 middle) the border of the dark area (simulation mesh) has a large distance to the real (ARGUS measured) border. The draw-in of the simulation is too low.

For the last simulation step (figure 16 right) the draw in of the simulation fits well to the real situation (only small dark area visible).

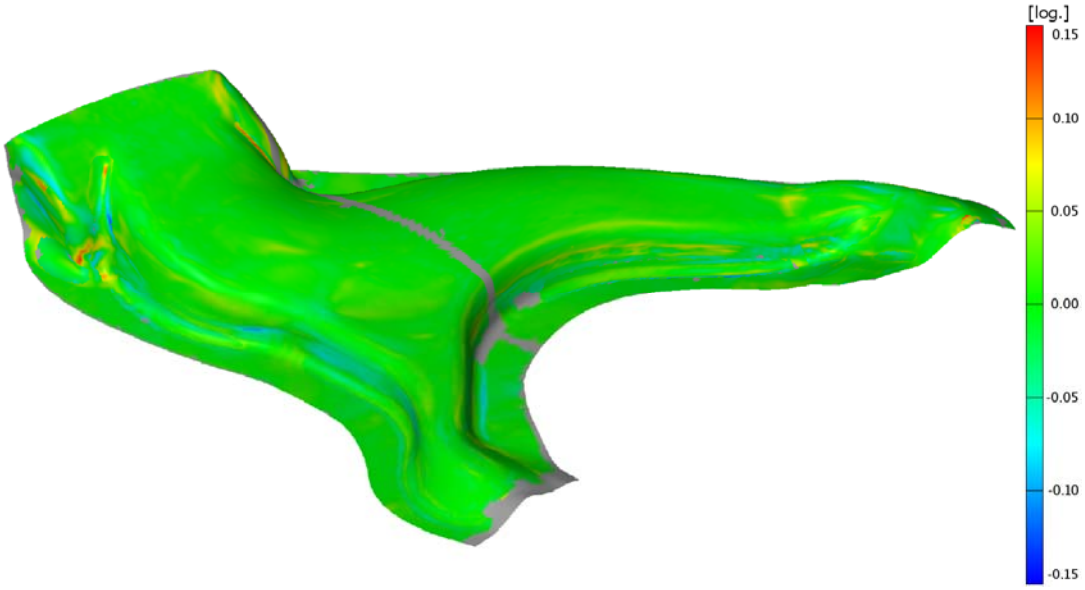


Figure 14: *Major true strain deviation after optimisation (Colour definition: Deviation of simulation to measurement)*

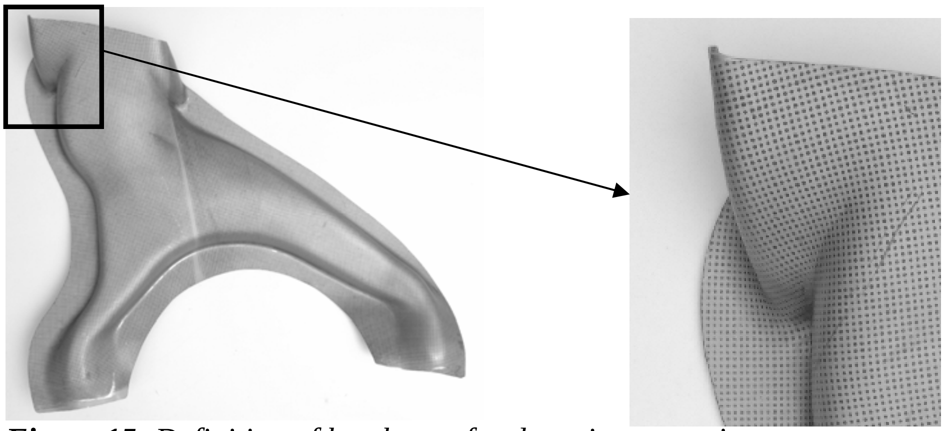
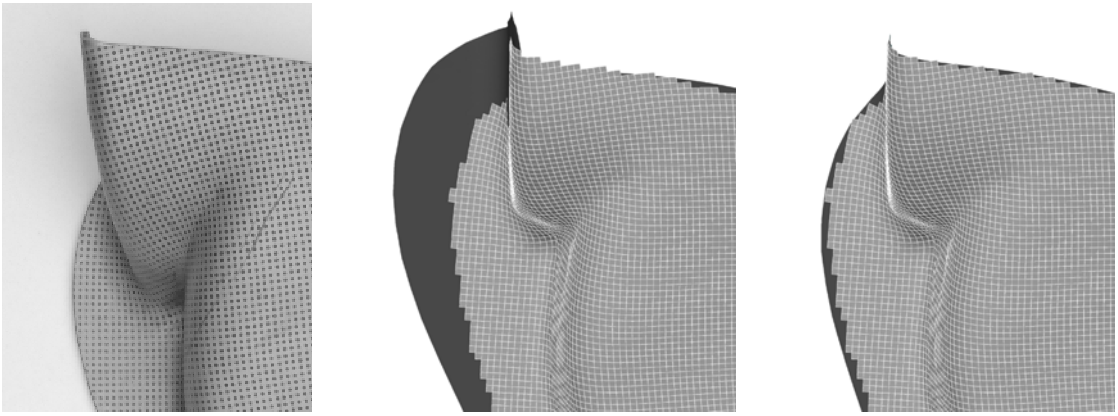


Figure 15: *Definition of local area for draw-in comparison*

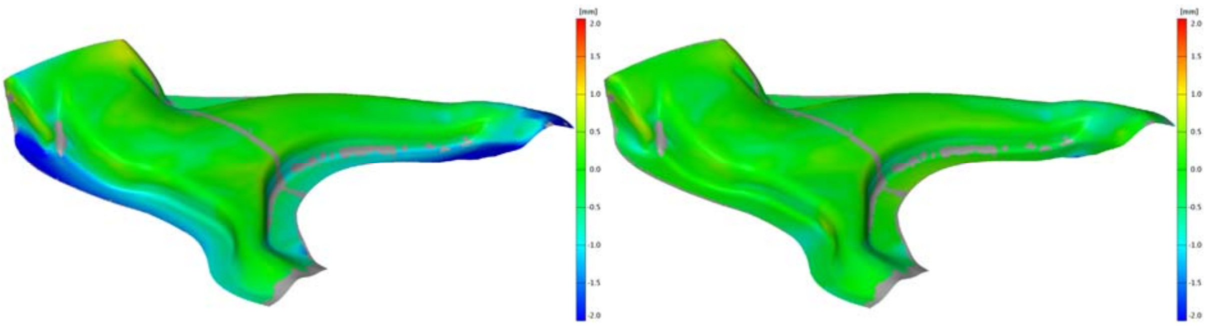


area of measurement image *first simulation* *final result*

Figure 16: *Draw-in differences of a local area, simulation geometry (dark) overlaid with ARGUS measurement grid*

4.6. Comparison of Geometry and Springback

To allow a comparison of the geometry the simulated part had to be in the same mechanical condition as the real part. Therefore after the forming simulation a springback simulation had to be performed. The springback behaviour was controlled and adjusted by the use of different values for the Young’s Modulus [10]. Herewith it was possible to reach a good geometric correlation of the flanges (figure 17).



without springback simulation *with springback simulation*

Figure 17: *Deviation of geometry (Deviation of simulation to measurement)*

5. CONCLUSIONS

The described procedure shows the direct numerical comparison of forming simulations with experimental forming analysis (ARGUS) on basis of differences of full-field strain and shape information. This comparison enables an easy full-field comparison between simulation and measurement results (strains, geometry and displacements) and a complete validation of the actual iteration step of the simulation.

Regarding the results during different steps of iteration it could be observed, that the strains on the convex formed side of the specimen fit better to the measurements than on the other (concave) side. This might show the limits of the combination of the used computation model (shell elements) and parameters for the selected application with a material thickness of 2.5mm. Further investigations will show if e.g. solid elements are more useful.

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