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Research Article

Keywords: Calculation of sweeps, hydroforming, aerodynamic sheet parts, integral geometry

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The inverse task solution for the calculation of sweeps of sheet parts by integral geometry

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Abstract This article deals with the search for a rational semi-finished product for parts of the integral form. Here a variant of the solution of the given problem is described based on the inverse solution of the mathematical problem. The reasons and the nature of the problem occurring in standard approaches to the calculation of the semi-finished product are shown using the example of two parts with aerodynamic curvature. The material and sheet thickness of the components are selected to suit the application. The forming process is also the same as the initial situation. The rational shape of the part can be found using the optimization solution based on the discrepancy of the contours with respect to the sweeps of the dynamic calculation and the CAD model. The new shape of the blank makes it possible to realize the forming process of the parts with minimal deviations from the contour of the 3D model.

Keywords Calculation of sweeps · hydroforming · aerodynamic sheet parts · integral geometry

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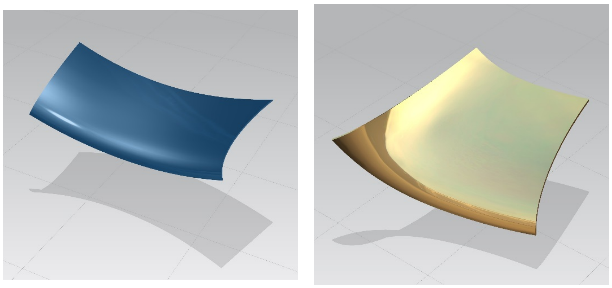
1 Introduction

At present great difficulties in the aircraft construction are caused by the production of parts in the aerodynamic contour of the complex spatial form and the small relative deformations [1, 2]. Some of these parts can be produced by applying bending with superimposed stretch forming or as they say in the aircraft construction "the covering". However, most of these parts are produced by drop hammers. The quality of such parts is very low because of a large number of deformation effects from a hammer [3, 4]. Furthermore, the dimensions of the blank are also considerably larger than the dimensions of the part, which increases the prime cost of the part.

Elastoforming is the most rational production method for such parts. However, using the above-mentioned technology causes a number of problems concerned with the calculation of the exact sweep. This article will show the emerging problems by illustrating the example of two parts and by describing a method of solving these problems by using the solution of the inverse iteration task. Fig. 1 demonstrates parts for modeling with the aerodynamic curvature. The thickness is 1.5 mm. The material of the investigated parts is the aluminum alloy of the Al-Mg-Mn group. The forming process is carried out by hydro-elastoforming [5–11] on a QFC type press by Quintus Technologies with a maximum pressure of 100 MPa.



(a) (b)

Fig. 1: Parts for modeling a) Part 1, overall dimensions: 268 x 116 x 54 mm^3; b) Part 2, overall dimension: 124 x 147 x 50 mm^3

2 Model and results of the inverse formation method

The program complex PAM-STAMP by the French ESI Group is used for technological modeling (license of the Irkutsk National Research Technical University under the state contract No. 159-NRU/EA – 10 of 20.12.2010). The model of the material of blanks has the following dimensions:

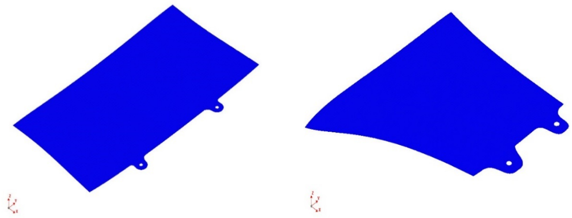
- Young modulus = 72 GPa
- Poisson ratio = 0.32;
- Density = 2.6 kg/mm^3
- Anisotropy factors $r_{0°}$, $r_{45°}$, $r_{90°}$ = 0.5345, 0.8346, 0.5901 [7]
- Plastic part of the current curve is given by the function "Krupkowsky law" with the following form

$$\sigma = K(\varepsilon_0 + \varepsilon_p)^n \tag{1}$$

The constants of the function for the material are as follows: K= 0.65204 GPa, n= 0.2949, ε_0= 0.0045 [8, 11]. The main problem with these kinds of parts (subject to forming of parts by an elastic medium) is the calculation of sweeps. The absence of a flat part on the parts exacerbates this problem. The error at this stage bears the risk that there may not be enough metal in some places of the contour in the part, and that the part may be defective.
Traditionally two methods are used in the calculation of sweeps:

- Geometric method based on the law of constancy regarding areas;
- Simplified method of inverse approach.

The latter consists in the fact that the strain and contact history are taken into account only in the initial and final position of the part, without considering intermediate states. This approach takes into account the properties of the material, but does not take into account the full history of strain and contacts, which is the cause of their errors. To date, the simplified method of inverse approach is considered the most accurate one. Using this method, the sweeps for the selected parts were calculated taking into account the pin holes (Fig. 2).



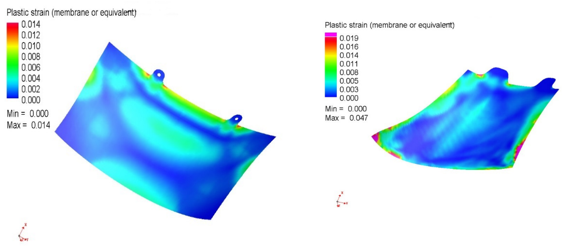
(a) (b)

Fig. 2: Sweeps calculated by means of the simplified method of the inverse approach a) Part 1; b) Part 2

Further testing of the calculated sweeps will include a dynamic calculation of the forming process. Forming was carried out after two transitions:

- 1^{st} transition - forming of the aerodynamic curvature with the rolling machine;
- 2^{nd} transition - forming by the elastic medium to calculate the final form of the part

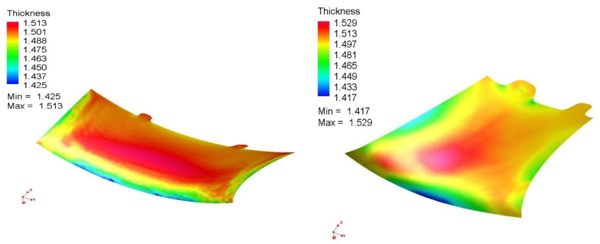
Fig. 3 shows the results from the modeling of the first transition.



(a) (b)

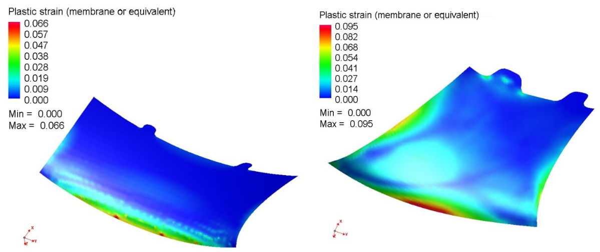
Fig. 3: The results of the 1^{st} transition of forming
a) Part 1, max. strain 1.4 %;
b) Part 2, max. strain 1.9 %

As the results illustrate, the part exhibits low strain (no more than 5 %) after the first transition. The modeling of the forming of the second transition allows obtaining the final form of the part. Fig. 4 and Fig. 5 show the distribution of thickness and strain after the second transition.



(a) (b)

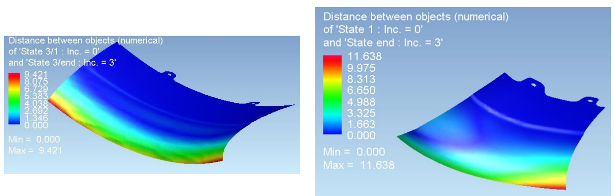
Fig. 4: Distribution of thickness after the 2nd transition
a) Part 1, min. thickness – 1.425 mm;
b) Part 2, min. thickness – 1.417 mm



(a) (b)

Fig. 5: Distribution of strain after the 2nd transition a) Part 1, max. strain 6.6 %;
b) Part 2, max. strain 9.5 %

The calculation results show that the parts have a large elastic response after forming due to the low strain [1] (Fig. 6).



(a) (b)

Fig. 6: Distribution of the spring back after the 2nd transition
a) Part 1, max. distance – 9.421 mm;
b) Part 2, max. distance – 11.638 mm

According to the results of the calculation, laying the part contour from the CAD model over the form taken from the sweep in the CAE system can show large differences that indicate the impossibility of using the simplified method of the inverse approach to calculate the final form of the sweeps. Fig. 7 and Fig. 8 show discrepancy of contours of the 1st and 2nd parts.

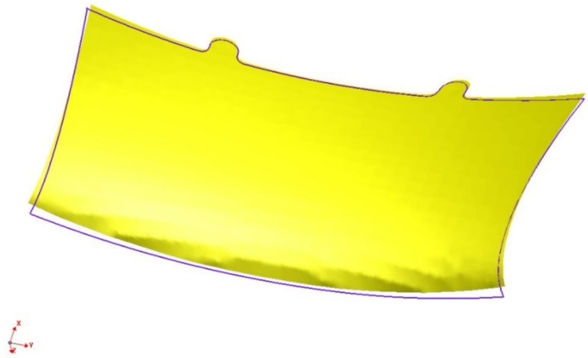


Fig. 7: The discrepancy results with the contour of part 1

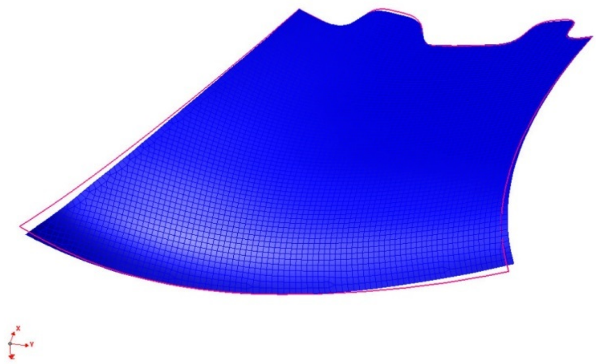


Fig. 8: The discrepancy results with the contour of part 2

3 Numerical and physical benchmark

Having received such a situation under the real conditions of production, the plant begins to adjust the initial blank based on measurements of discrepancy of contours. However, due to the complexity of the input data and measurements on integral surfaces, the corrections are quite inaccurate, which leads to a large number of iterations when searching for the correct blank. Thus, this causes an increase in the processing cost of the part because each unsuccessful iteration of the approximation results in scrap.
However, this new approach offers a solution. This solution of the mathematical problem is called the solution

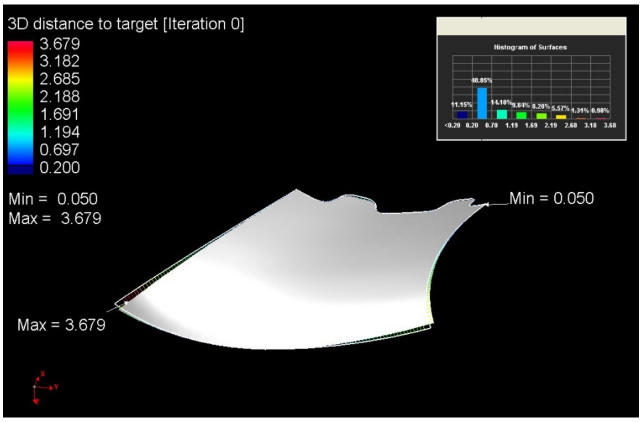


Fig. 10: Results from the solution optimizer for part 2

of the inverse task. The purpose of this process is to eliminate the human factor and all the iterations to find a solution that is transferred to a virtual environment. The calculation comprising a scan calculated by a simplified method of the inverse approach is well suited for zero iteration.
Using the program complex PAM-STAMP solved the problem of the algorithm task regarding the optimization problem based on which an inverse decision can be made. To begin with, using the optimizer type solver allowed the detection of the part contour deviations in the CAE system and the part contour from the finite element model (Fig. 9 and Fig. 10).

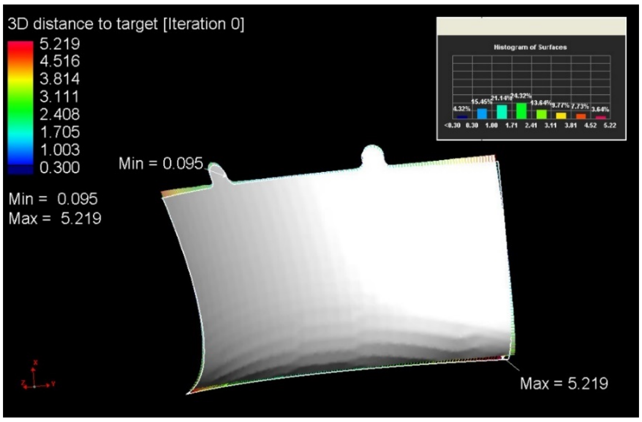


Fig. 9: Results from the solution optimizer for part 1

From the results of the work of the solution optimizer it follows that the deviation gradient is transferred to a flat blank, which is modified taking into account the discrepancy of contours. Next, the formation and again the comparison and calculation of the contour deviations take place. Iteration by iteration (step by step) reduces contour deviation. As a result, after four iterations for the first part (Fig. 11) and two iterations for the second (Fig. 12) were found sweeps allowing to get parts with minimal differences in contours.

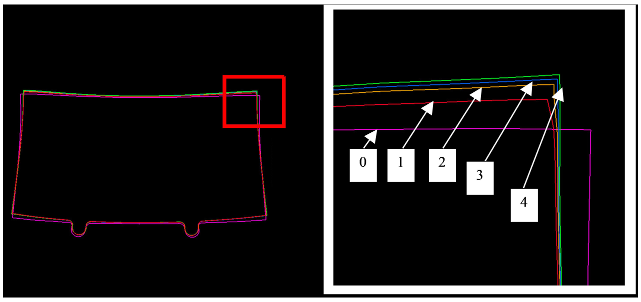


Fig. 11: Contours calculated resulting from the inverse task solution for the part 1

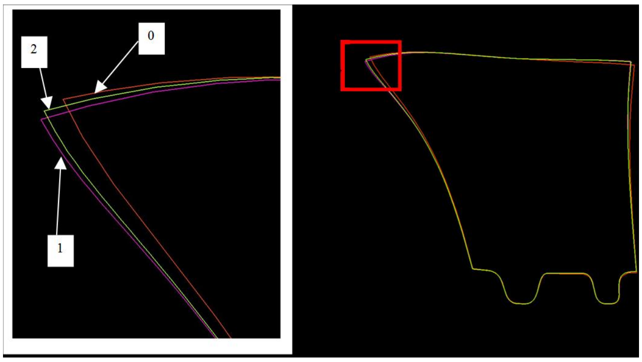


Fig. 12: Contours calculated resulting from the inverse task solution for the part 2

As a result, after solving the inverse task concerned with the optimization of the contour of the sweep, it is possible to get the form of the part which differs from the contour of the CAD model by less than 0.11 mm, that indicates that the part has the contour tolerance (Fig. 13 and Fig. 14).

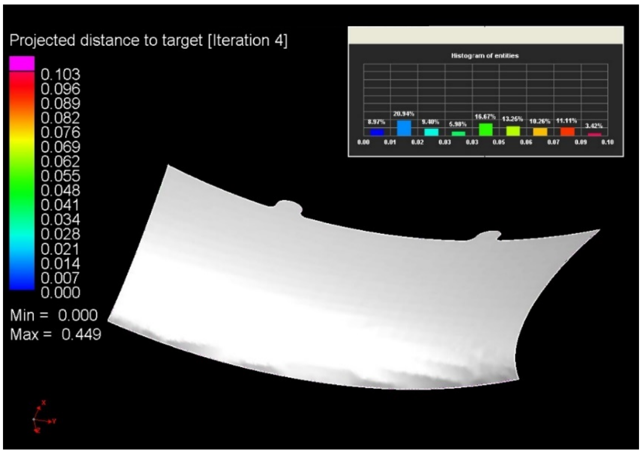


Fig. 13: Results from the solution optimizer for part 1 after the 4th iteration of the inverse task solution

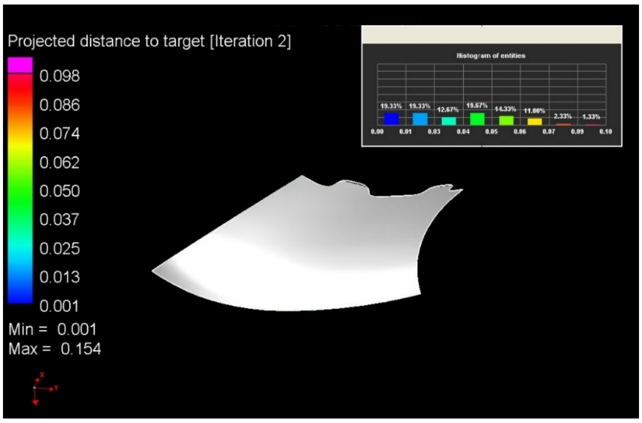


Fig. 14: Results from the solution optimizer for part 2 after the 2nd iteration of the inverse task solution

4 Conclusion

A method has been developed and proposed to solve a complex optimization problem associated with the adjustment of the sweep of the parts of the integral form, based on the solution of the inverse mathematical task. Based on the modeling results the real experiments were performed. The full-scale experiment was carried out on the press of the Swedish company "Avure Technologies" Model: QFC-1,2x3-1000 (Fig. 15).

Fig. 15: Type QFC-1.2x3-1000 forming press

The cycle time of the forming on the QFC-1,2x3-1000 press is typically one to three minutes. This depends on the size of the press, the shape of the die and the pressure. The main features of the QFC-1,2x3-1000 press are as follows:

- table size width / length – 1200 mm / 3000 mm;
- height of the working area – 200 mm;
- maximum pressure – 100 MPa.

A set of tools made of chipboard type BA GOST RUS 20966-75 is used for forming (Fig. 16). The forming of the parts is done with the help of a punch and the clamp. Holes are made in the punch and in the clamp for the pins to position the sheets and to guide the clamp. The sheet to be formed is positioned on the punch with the help of the pins and fixed by the clamping. The clamp also performs the function of forming the part. The lower surface of the clamp is the same distance from the punch as the thickness of the sheet.

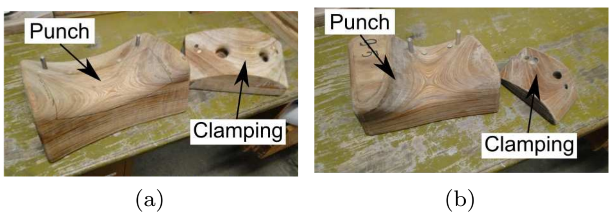


Fig. 16: Forming tools used for a) Part 1; b) Part 2

The parts were formed on the specially made tools according to the calculated semi-finished products and the results were compared with the calculation results and confirmed(Fig. 17).

(a) (b)

Fig. 17: Parts resulting from real experiments a) Part 1; b) Part 2

This method makes it possible to exclude iterations of test sweeps on the press which do not correspond to the contour of the parts. In addition, it also excludes the human factor in the measurement of contour deviations. These facts make it possible to reduce the processing costs of parts and their manufacturing costs.

Authors' contributions V. Mironenko: modelling and optimization, experiment, writing; D. Elovenko: modelling and optimization, interpretation, writing; A. Graf: writing-original draft preparation, review and editing; V. Kräusel: review and editing; C. Ledovskikh: modelling and optimization, interpretation, writing

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Data availability Input data and research data can be provided by the corresponding author upon reasonable request.

Declarations

Ethics approval (include appropriate approvals or waivers) Not applicable.

Consent to participate (include appropriate statements) Not applicable.

Consent for publication (include appropriate statements) Not applicable.

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix 1

The output of the optimisation is the FEM calculation of the manufacturing process as described above (Fig. 6). Then the OPTIMIZER programme is started. The first step is to approximate the detail contour obtained from the calculation in the CAE program (decimated by 1 point with chord error tolerance = 0.05) and eliminate a double point in the detail contour (adjusted by 1 double point) to smooth the spline and eliminate errors. The next step is to divide the contour into equal segments (resampled with maximum length = 2.19312) (Fig. 18 - yellow colour).

```
=====================================================
OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration : 0
=====================================================
Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%
```

Fig. 18: Start of the OPTIMIZER programme

Then OPTIMIZER generates a deviation gradient with a step given in maximum length = 2.19312 between the detailed contour from the CAD model and the detailed contour obtained by finite element analysis (FEA). The results of this part of the programme are shown in Fig. 9. In a programme listing, the data is written as the mean value of the maximum and minimum circle deviation (Fig. 18 - green colour). Finally, the programme gives a value for the detail contour from the CAD model that matches the detail contour obtained by FEA in percentage, and this parameter is "proportion under max.distance" (in this case it is equal to 4.32% to 0 iteration) (Fig. 18). Then the programme takes 0 iteration (i.e. performed FEA of the formation) as the best iteration, gives the message that the optimisation goal has not been achieved (matching of contours of more than 90% with a maximum deviation of less than 0.11 mm. for this case) (Fig. 19 - turquoise colour) and starts to modify the existing workpiece contour (Fig. 19 - purple colour) by gradients of deviations obtained earlier (Fig. 18 - green colour). When changing the contour, the finite element mesh of the workpiece is also rebuilt.

```
=====================================================
OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration : 0
=====================================================
Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%
Best iteration is 0
Writing iteration analysis to file
Target not reached, new iteration 1 will be built
Building new iteration 1
Loading first stage setup '01_stamp0'
Building new outline(s)
Replacing previous blank outline(s) with modified one(s)
Blank mesh will be updated at solver start, not meshing it now
Writing iteration input file allowing restart from this iteration
Saving new iteration 1
```

Fig. 19: The creation of a new flat sheet contour

Furthermore, the system saves a new modified version of the workpiece in a file of the FEA and designates it as iteration 1 (Fig. 20 - brown-green colour).

```
==========================================================
OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration  : 0
==========================================================
Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%
Best iteration is 0
Writing iteration analysis to file
Target not reached, new iteration 1 will be built
Building new iteration 1
Loading first stage setup '01_stamp0'
Building new outline(s)
Replacing previous blank outline(s) with modified one(s)
Blank mesh will be updated at solver start, not meshing it now
Writing iteration input file allowing restart from this iteration
Saving new iteration 1
Iteration 1 set as current
Running solver for iteration 1
Launching solver starting from stage '01_stamp0'
Solver successfully launched
```

Fig. 20: Creation of a new iteration

Then, under the tag "Waiting for start of stage", certain steps of the forming are started with a modified workpiece. The calculation progress of each forming step is tracked under the tag "Calculation of stage". After finishing the calculation process of forming, the procedure of approximation and division into segments of the contour of the part obtained from the modified workpiece is performed as described earlier and then compared with the contour of the part from the CAD model (see Fig. 18 - yellow and green colour). At the end of the first iteration, the programme gives the value of the percentage in which the contour of the part from the CAD model coincides with the detailed contour obtained by FEA and this parameter "Proportion under max. distance" (in this case it is equal to 41.69 % after 1 iteration, i.e. the optimisation process is running correctly and the size of the coincidence contours is growing). Then the steps are repeated again to modify the circle with the deviations and create a new iteration. The calculation process continues until the given calculation criteria are reached (in this case it is a coincidence of the contours of more than 90% with a maximum deviation of less than 0.11 mm). At the end of the 4th iteration OPTIMIZER obtains the value of the maximum deviation 0.103 and the percentage of coincidence of the contours 92.66% (Fig. 21) OPTIMIZER writes that the optimisation goal has been achieved and concludes the work (Fig. 21). A similar optimisation calculation was carried out for the second part.

```
Checking results of iteration 4
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.18319
Computing measures between result and target
Computing measures statistics
Average distance is 0.026
Maximal distance is 0.103
Minimal distance is 0.005
Proportion below max. distance is 92.66%
Best iteration is 4
Writing iteration analysis to file

Target is reached at iteration 4, stopping iterations (Сообщение достижении цели оптимизации с заданными критериями)

Optimizer normal termination (Сообщение о успешном окончании оптимизации)
```

Fig. 21: The end of optimisation

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Figures

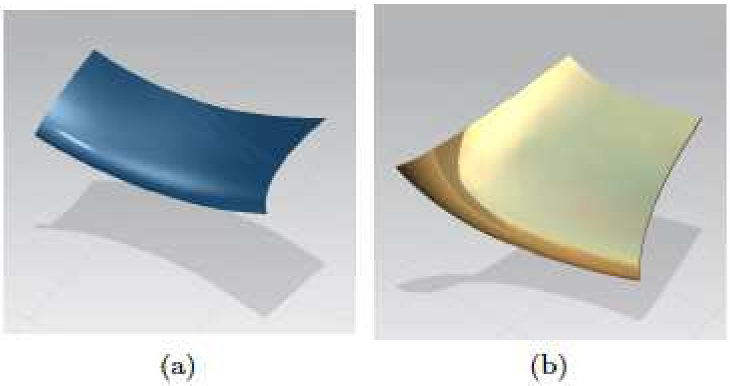


Figure 1

Parts for modeling a) Part 1, overall dimensions: 268 x 116 x 54 mm3; b) Part 2, overall dimension: 124 x 147 x 50 mm3

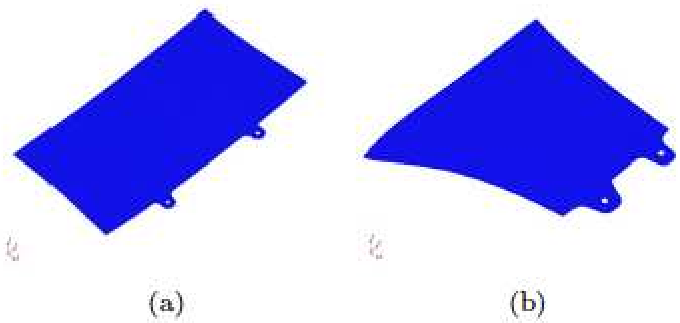
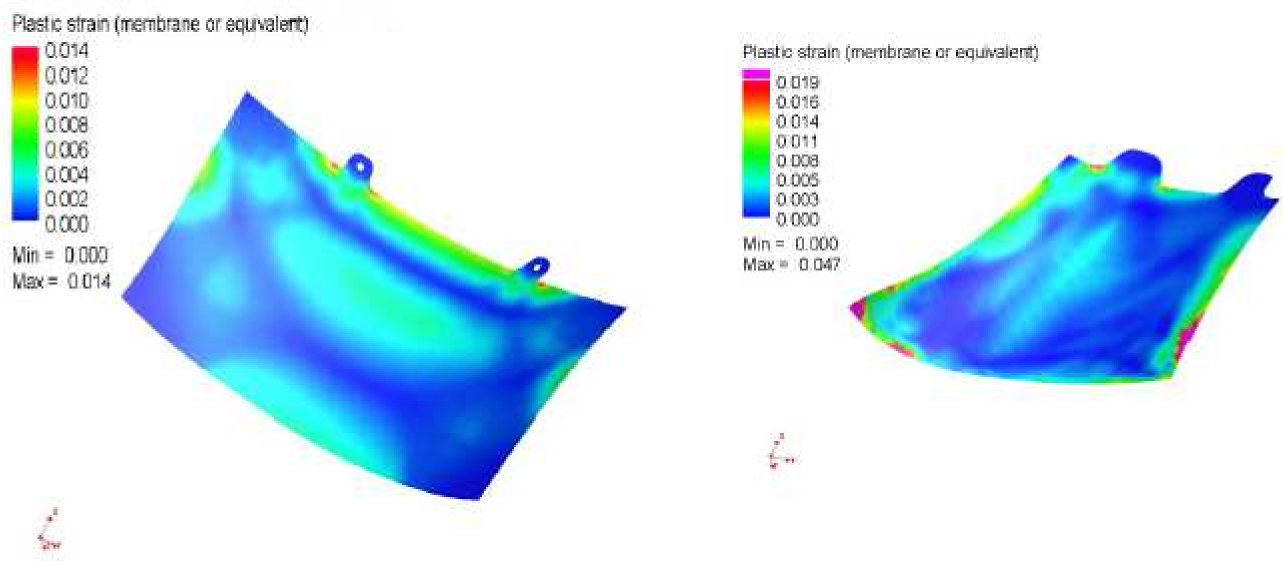


Figure 2

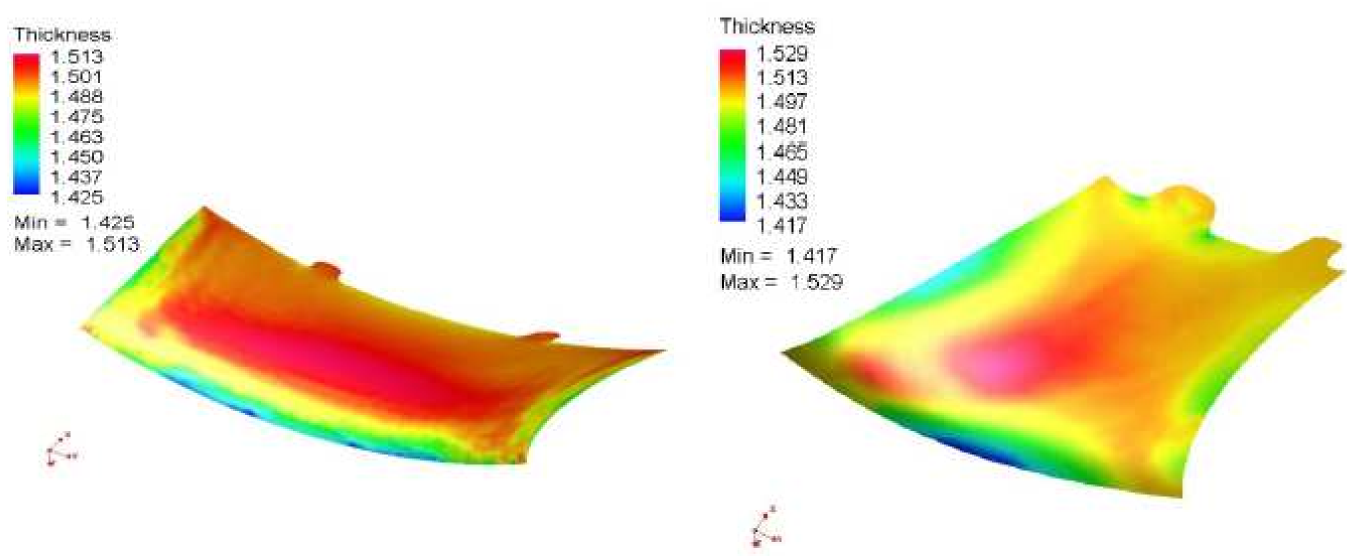
Sweeps calculated by means of the simplied method of the inverse approach a) Part 1; b) Part 2



(a) (b)

Figure 3

The results of the 1st transition of forming a) Part 1, max. strain 1.4 %; b) Part 2, max. strain 1.9 %



(a) (b)

Figure 4

Distribution of thickness after the 2nd transition a) Part 1, min. thickness - 1.425 mm; b) Part 2, min. thickness - 1.417 mm

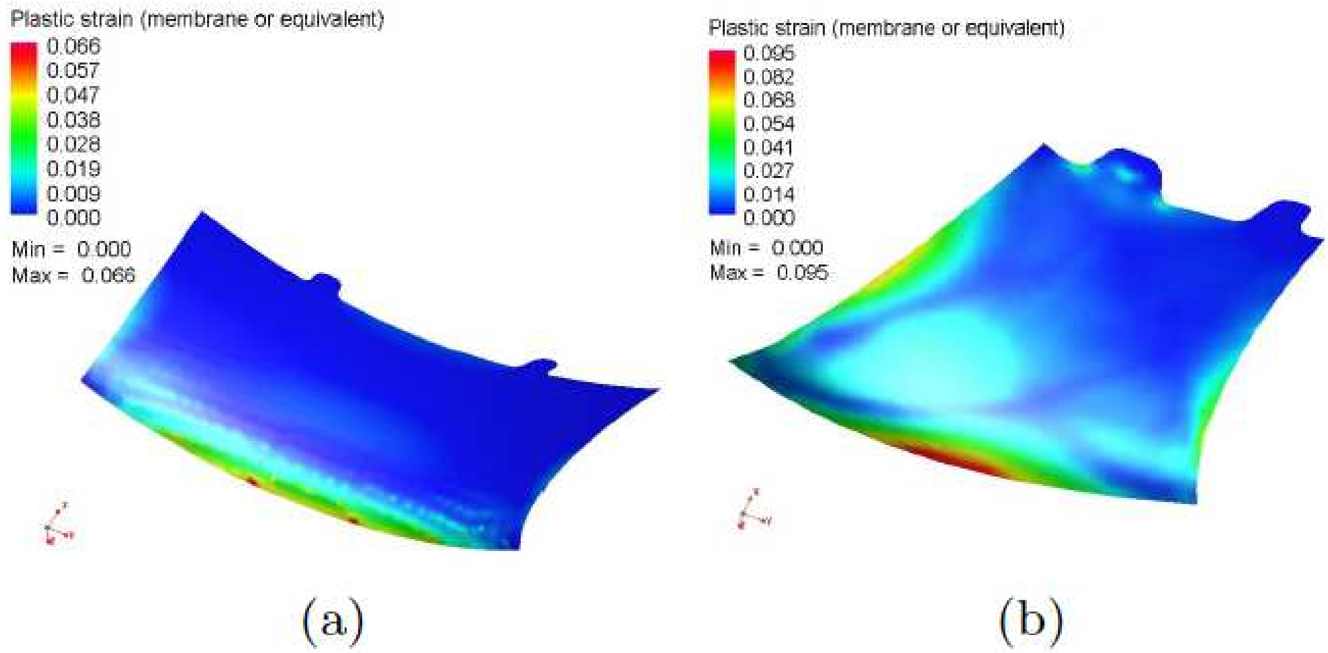


Figure 5

Distribution of strain after the 2nd transition a) Part 1, max. strain 6.6 %; b) Part 2, max. strain 9.5 %

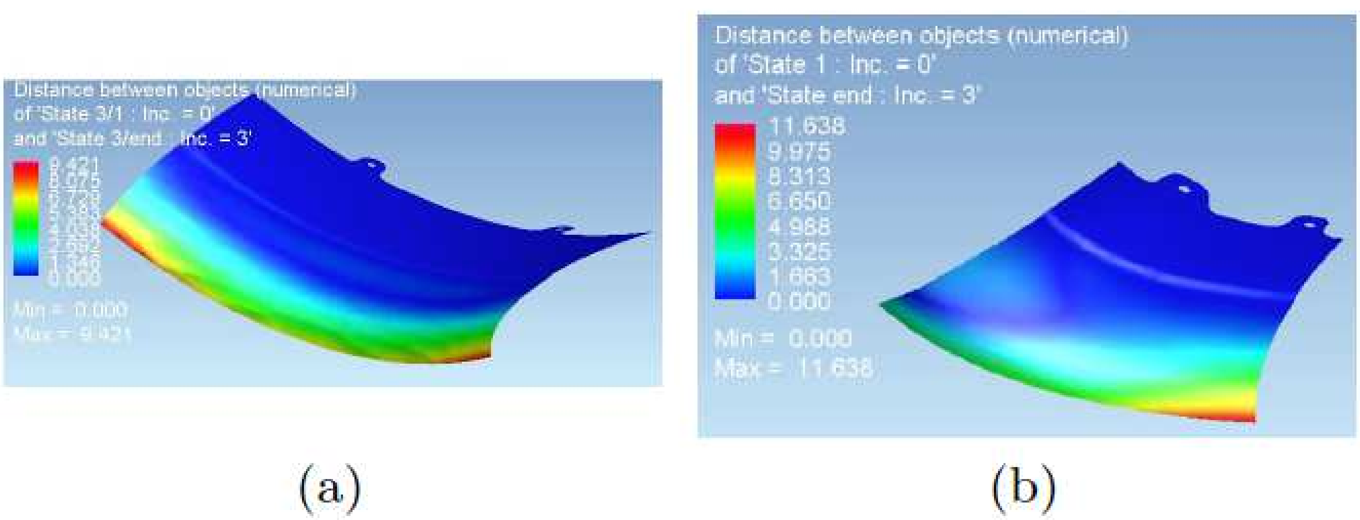


Figure 6

Distribution of the spring back after the 2nd transition a) Part 1, max. distance - 9.421 mm; b) Part 2, max. distance - 11.638 mm

Figure 7

The discrepancy results with the contour of part 1

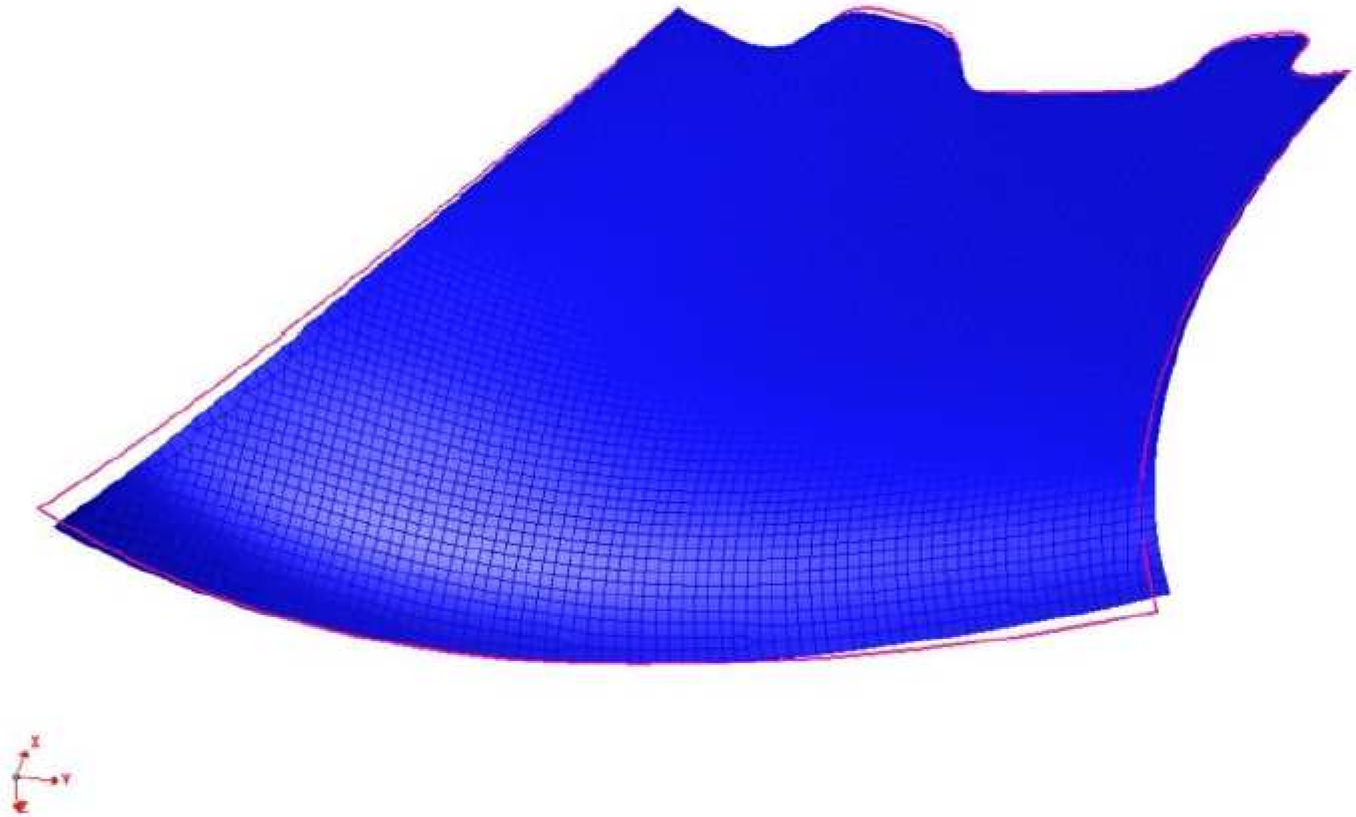


Figure 8

The discrepancy results with the contour of part 2

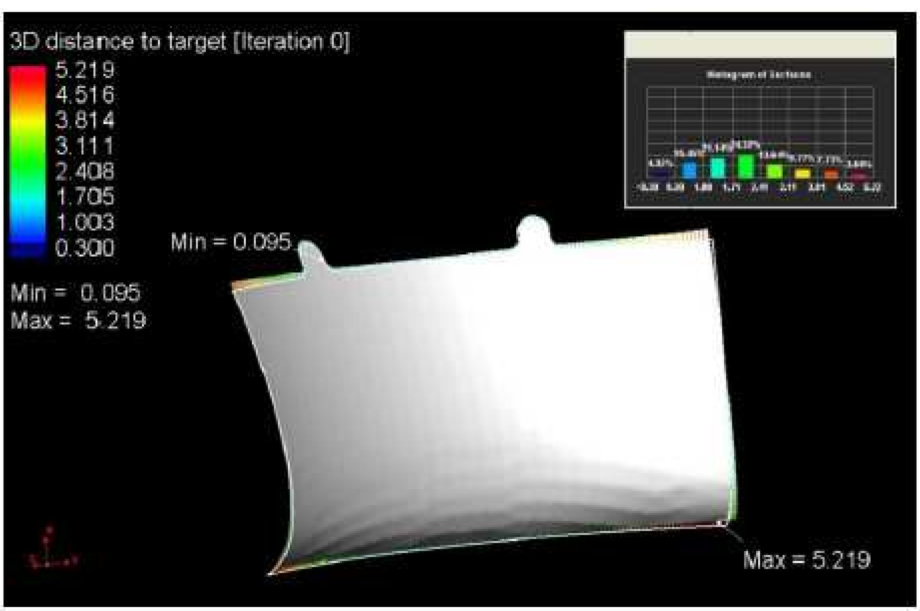


Figure 9

Results from the solution optimizer for part 1

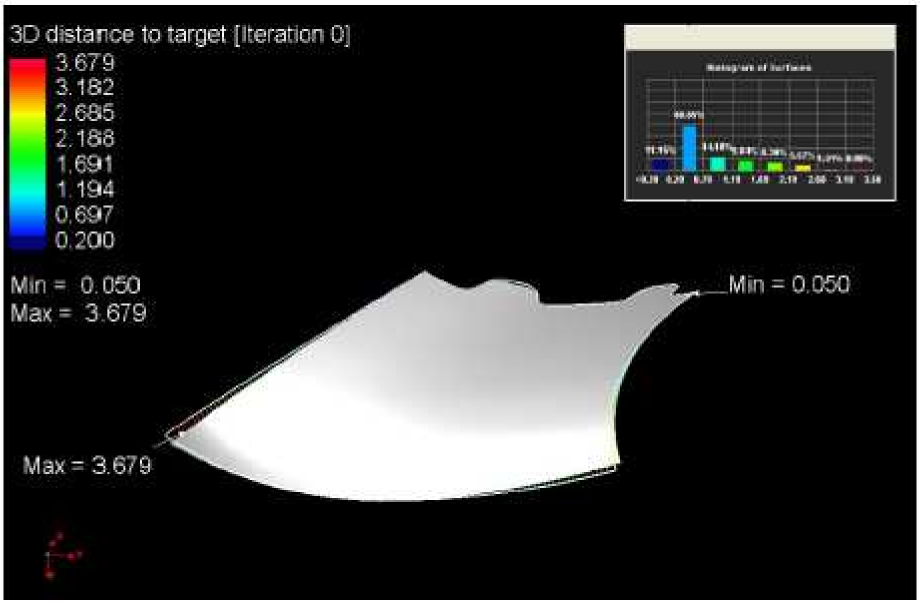


Figure 10

Results from the solution optimizer for part 2

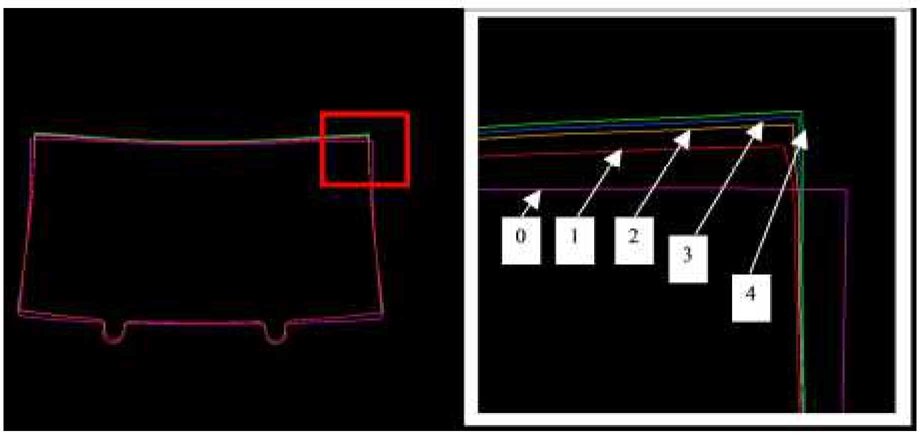


Figure 11

Contours calculated resulting from the inverse task solution for the part 1

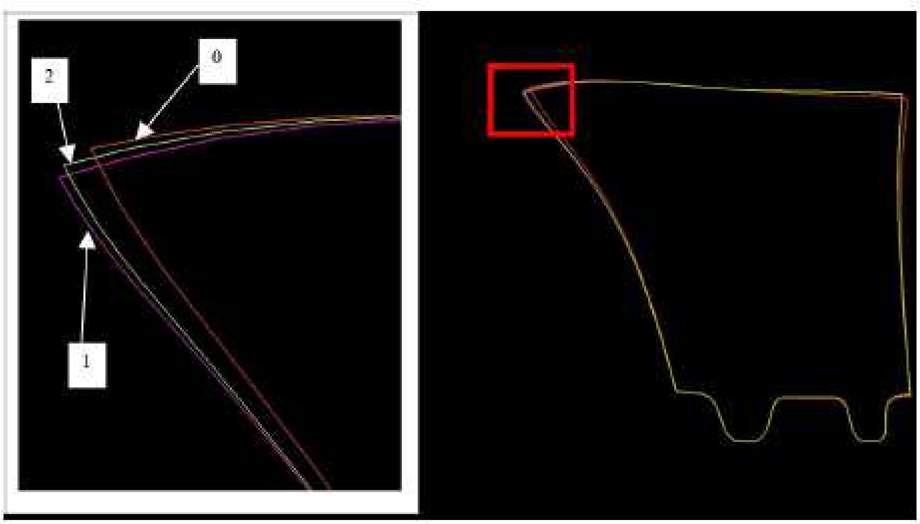


Figure 12

Contours calculated resulting from the inverse task solution for the part 2

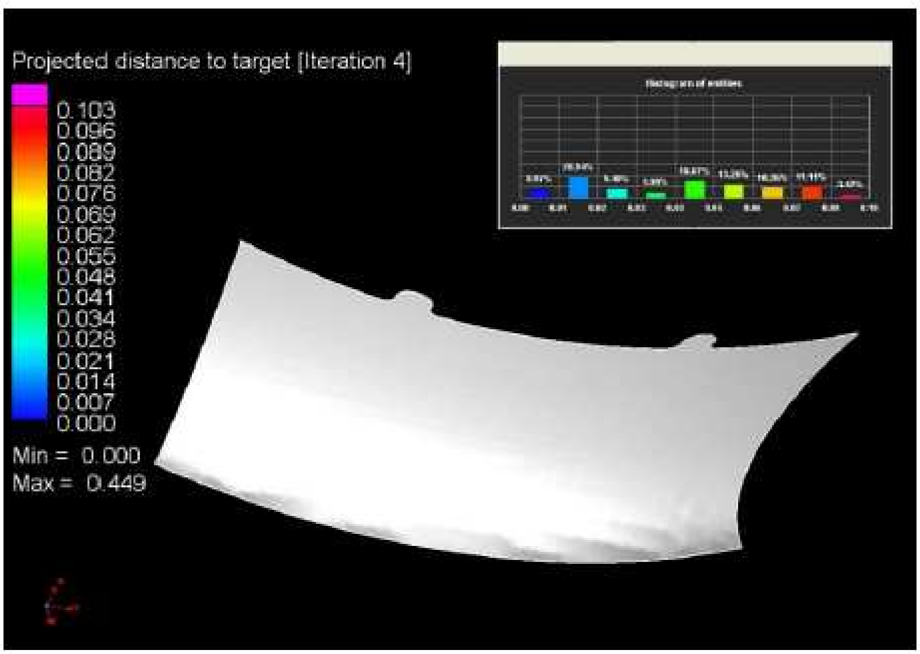


Figure 13

Results from the solution optimizer for part 1 after the 4th iteration of the inverse task solution

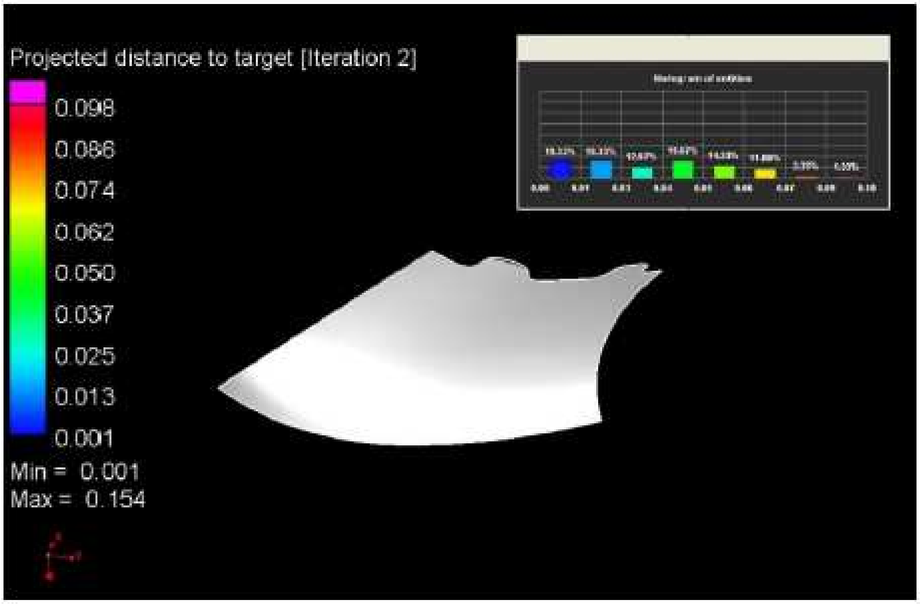


Figure 14

Results from the solution optimizer for part 2 after the 2nd iteration of the inverse task solution

Figure 15

Type QFC-1.2x3-1000 forming press

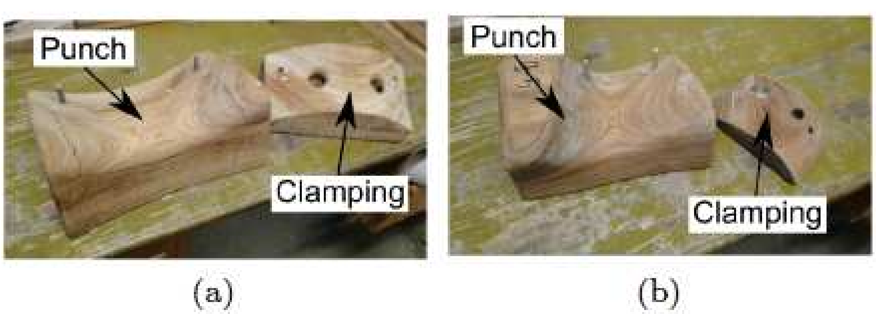
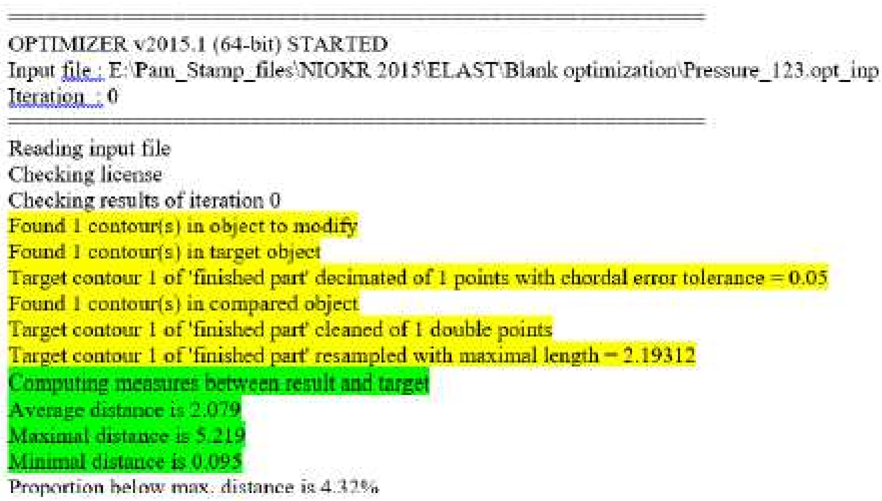


Figure 16

Forming tools used for a) Part 1; b) Part 2

Figure 17

Parts resulting from real experiments a) Part 1; b) Part 2



OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration : 0

Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%

Figure 18

Start of the OPTIMIZER programme

```
========================================================
OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration : 0
========================================================
Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%
Best iteration is 0
Writing iteration analysis to file
Target not reached, new iteration 1 will be built
Building new iteration 1
Loading first stage setup '01_stamp0'
Building new outline(s)
Replacing previous blank outline(s) with modified one(s)
Blank mesh will be updated at solver start, not meshing it now
Writing iteration input file allowing restart from this iteration
Saving new iteration 1
```

Figure 19

The creation of a new at sheet contour

```
========================================================
OPTIMIZER v2015.1 (64-bit) STARTED
Input file : E:\Pam_Stamp_files\NIOKR 2015\ELAST\Blank optimization\Pressure_123.opt_inp
Iteration : 0
========================================================
Reading input file
Checking license
Checking results of iteration 0
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.19312
Computing measures between result and target
Average distance is 2.079
Maximal distance is 5.219
Minimal distance is 0.095
Proportion below max. distance is 4.32%
Best iteration is 0
Writing iteration analysis to file
Target not reached, new iteration 1 will be built
Building new iteration 1
Loading first stage setup '01_stamp0'
Building new outline(s)
Replacing previous blank outline(s) with modified one(s)
Blank mesh will be updated at solver start, not meshing it now
Writing iteration input file allowing restart from this iteration
Saving new iteration 1
Iteration 1 set as current
Running solver for iteration 1
Launching solver starting from stage '01_stamp0'
Solver successfully launched
```

Figure 20

Creation of a new iteration

Checking results of iteration 4
Found 1 contour(s) in object to modify
Found 1 contour(s) in target object
Target contour 1 of 'finished part' decimated of 1 points with chordal error tolerance = 0.05
Found 1 contour(s) in compared object
Target contour 1 of 'finished part' cleaned of 1 double points
Target contour 1 of 'finished part' resampled with maximal length = 2.18319
Computing measures between result and target
Computing measures statistics
Average distance is 0.026
Maximal distance is 0.103
Minimal distance is 0.005
Proportion below max. distance is 92.66%
Best iteration is 4
Writing iteration analysis to file

Target is reached at iteration 4, stopping iterations (Сообщение достиженни цели оптимизации с заданными критериями)

Optimizer normal termination (Сообщение о успешном окончании оптимизации)

Figure 21

The end of optimisation