# SOLVING AN INVERSE PROBLEM CONCERNING THE SHEET METAL BLANK GEOMETRY IN AN INDUSTRIAL APPLICATION TO MINIMIZE THE PROCESSING TIME

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**Abstract.** This paper concerns the optimization of an industrial sheet metal forming process on an automatic panel bender from Salvagnini Maschinenbau GmbH [1] combined with a corner former from an external company. The considered process consists of four steps: (1) The sheet blank is cut out of the raw material. (2) The sheet is bent to 90° on all four sides. (3) The area around the corners is formed into a full corner without welding. (4) Overlapping material at the corners must be cut off. The final product is a box with a precisely defined height and closed corners.
Objective of this work is to develop a simulation framework to find the optimal contour of the sheet blank, so that after bending (step 2) and corner forming (step 3) a perfect geometry is obtained without a final cutting step (4). For the automatic panel bender, a high reliable digital twin already exists [2]. The underlying FEM-model has been extended to simulate the bending process of all 4 sides. Secondly, a further FEM model has been created to represent the corner forming step. With these FEM-models, the process of step (2) and (3) can be simulated. Goal now is to find the optimum shape as an input of step (2) so that the output quality of step (3) does not require an additional step (4).
This inverse problem is solved iteratively: First, we assume a blank contour as initial data. After obtaining the results for bending and corner forming, the sheet blank is adapted. This cycle is repeated until the quality requirements for the corners are achieved. It turns out that with few iterations a suitable result for the industrial application is achieved. The modularized design of the developed simulation framework allows efficient adaptions to the specific requirements.

## 1 INTRODUCTION

Nowadays, the requirements for the production of sheet metal parts in terms of accuracy and manufacturing time are increasing steadily. Accordingly, it is necessary to optimize the manufacturing process more and more. Nowadays, digital twins are used to digitally optimize the development process of machining processes. This can significantly reduce the costs of tool production and material usage because the first designs can be tested on the virtual prototype without having to produce a physical prototype. [3, 4]

In this paper, the optimization of an industrial sheet metal forming process on an automatic panel bender from Salvagnini Maschinenbau GmbH combined with a corner former from an external company, should be discussed. So far, the whole process to produce a metal box includes the following four steps:

1. The sheet blank is cut out of the raw material, e.g. by a laser cutting machine or a punching machine.

2. With the automatic panel bender, the sheet is bent on all four sides to an angle of 90°.

3. The area around the corners is formed into a full corner without additional processes like welding.

4. Overlapping material at the corners must be cut off in an additional production step.

The final product is a box with a precisely defined height and closed corners. The main objective of this work is to develop a simulation framework to find the optimal contour of the sheet blank. This means that after corner forming (3) a perfect geometry is obtained without an additional machining processes, i.e. goal is to eliminate the time-consuming production step (4) of cutting or grinding the edges. For the automatic panel bender, already a high reliable digital twin exists as an outcome of a long-term research project [2]. Thus, the bending process is well known and represented by a simulation model with high precision. The available model has been extended to simulate the bending process at all sides of the part. Secondly, a 3D-Finite Element model has been created to represent the corner forming step.

With these two models, the complete process of steps (2) and (3) is represented: bending all four sides of the part to 90°, and subsequently forming the corners. With this workflow the specific goal is to find the optimum shape as an input of step (2) so that the output quality of step (3) does not require an additional step (4).

The implemented simulation models can be used to determine the shape of the final product based on the selected sheet blank. Iteratively, the solution of the inverse problem is computed. The modularized design of the developed simulation framework allows efficient adaptions to the specific combination of cutting, bending and corner forming machines.

## 2 Basics of the forming process

First, we focus on the material behavior of the sheet. The plastic behavior is specified by the flow curve. As an outcome of an uni-axial tensile test the curve represents the relationship between the true stresses $\sigma$ (Cauchy stress) and the true strains $\varepsilon$ (Hencky strain). In the following, the elastic-plastic behavior is described by the following relations [5]:

- The linear elastic section is defined by Hooke's law

$$\sigma = E\,\varepsilon, \tag{1}$$

  where $E$ is the Young modulus. This relation is valid up to yield stress $\sigma_y$.

- The plastic domain is described by the formulation of Hollomon [6]

$$\sigma = a\,\varepsilon^n, \tag{2}$$

  which is a very good representation of the plastic behavior, as it is experimentally shown in [7] for the material DC01, which is widely used on the considered machines. In Eq. (2), $a$ is the strength coefficient and $n$ the hardening exponent. These parameters depend on the specific material and are determined by tensile tests. The plastic part of the strain $\varepsilon_p$, then is $\varepsilon_p = \varepsilon - \sigma/E$. Finally, the elastoplastic material behaviour is represented by the following equation:

$$\sigma = \begin{cases} E\,\varepsilon & \sigma \leq \sigma_y \\ a\,\varepsilon^n & \sigma > \sigma_y \end{cases}. \tag{3}$$

- Anistropy also plays an important role in this forming process, especially it has an influence on the geometry of the edges. Anisotropy can be described by the Lankford parameters $r_0$ and $r_{90}$ [8]. To determine these parameters a tensile test in longitudinal (0°) and transversal (90°) direction, reletated to the rolling direction, must be performed. With the use of Hill's yield criterion [9] in conjunction with the Lankford coefficients, anisotropy can be fully described according to [10].

To get a better understanding of the process, the main operating principles of the bending operation and corner forming are described in the following. A cross-sectional view of the bending process is shown in Figure 1. The initial sheet (after punching) is shown in Figure 2. First, the sheet is clamped between the upper and lower clamping tools with a predefined clamping force $F_c$. Secondly, the sheet is bent with the help of the bending tool, which has two degrees of freedom allowing any motion in the cross-sectional plane (x,y). The specific trajectory depends on the sheet thickness, the material, the bending angle and the relative position of the bending tool to the sheet, and is obtained by the digital twin of the bending machine, [2]. This operation will be executed on all four sides of the sheet (Figure 2).

In Figures 3 and 4, the corner forming process is schematically shown. For a better view, the cross-section and the top view is shown. The sheet is clamped between the upper and lower clamping tools. By moving the roller downwards the corner area of the sheet is formed to the final corner. Note, that the corner area does not have a bending angle of 90° after the bending process, as will be shown by the simulation results in next section. This task has to be done with the cornerformer. The counterholder plow serves as a "guide" for the sheet. This part is necessary to prevent the sheet from overlapping during the corner forming.

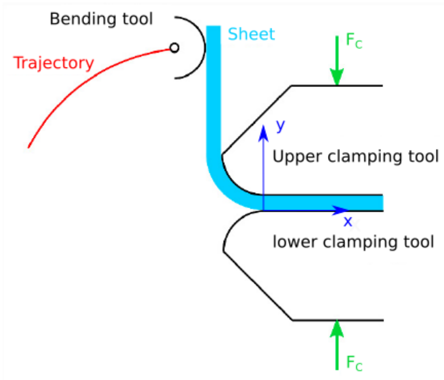


**Figure 1**: Bending process

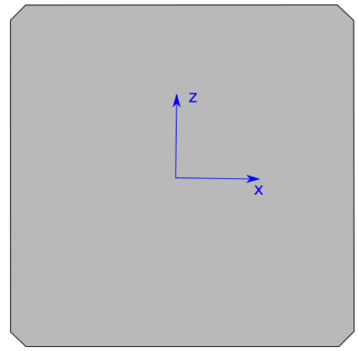


**Figure 2**: Sheet metal contour

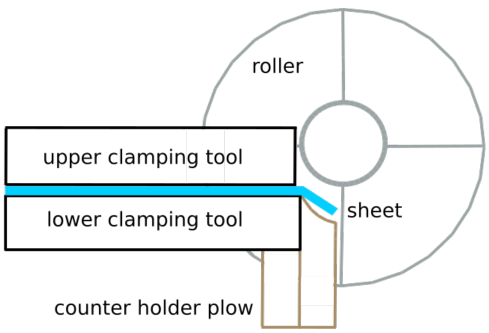


**Figure 3**: Crossview of the cornerformer

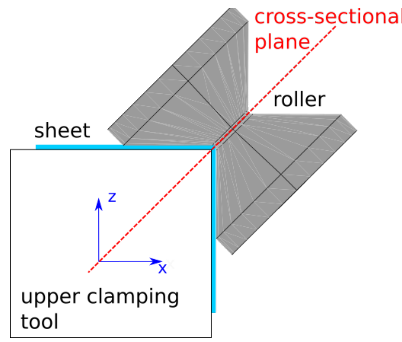


**Figure 4**: Top view of the cornerformer

## 3 SIMULATION MODELS

Before dealing with the solution of the inverse problem, the structure of the simulation models is explained. The process is represented by the following two models:

- Bending Process (Salvagnini Automatic Panel Bender)
- Corner Forming (Third party Cornerformer)

As Finite Element Software Abaqus is used. Main focus is to ensure that the deformation and stress state of the sheet is represented accurately. Since an iterative solution strategy is applied, the simulations have to run several times. Therefore, shell elements are used for the sheet metal, because with the latter the simulation time can be reduced significantly compared to 3D solid elements. To analyse the behaviour and the accuracy of this element type, a preliminary study was performed on a simplified model. This study builds on the results of [11], in which the behavior of shell elements and continuum elements was investigated.

### 3.1 Comparsion of shell and hexahedral elements

In this preliminary study, for the sheet shell elements of type S4R are compared to hexahedral elements C3D8R. The accuracy of the shell elements is verified with a test model, in which simplified tools are used to reduce the computational time: A cylinder is used as a bending tool, and cuboids as upper and lower clamping tools. The sheet under consideration has a thickness of 1.5 mm and a start distance of 10 mm between sheet and clamping is used. Figure 5 shows the simulation results of the test models. For a better overview the upper clamping tool is not shown in this representation. Both, the stress amplitude and the stress distribution are almost identical. The maximum stress amplitude for the model with hexahedral elements is 377 MPa and 376.6 MPa for the shell elements. Based on the test model, it can be shown that very similar results are obtained with both element types. However, when using shell elements, the simulation time reduces by 9.6 h compared to the original duration of 12.3 h. This results in a reduction of 78%. Furthermore, the number of elements of the plate is reduced from 211,000 to 80,000.

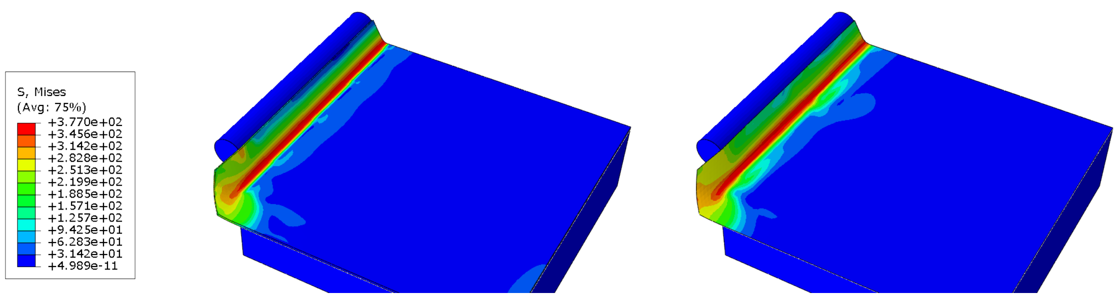


**Figure 5**: Comparison of hexahedral elements (l.) and shell elements (r.)

Because of the good coincidence with the 3D continuum elements and the better computational performance, shell elements are used to represent the sheet.

### 3.2 Bending process

The basic procedure of the bending process has already been explained in section 2. Here, the simulation model as shown in Figure 6 is discussed. Only the essential components are included in the model. Furthermore, a quasi-static analysis is performed, not taking into account inertial forces because they are negligibly low in this process.

Besides the correct specification of the trajectory and the material behaviour, an appropriate contact model is essential for an accurate result. "Surface-To-Surface" contact according to [12] is used for all contact pairs. It turned out that the model is very sensitive to the selection of contact properties. Finally, hard contact has been chosen for the contacts which involve the guide of the bending tool, not allowing any penetration of the bodies. Due to numerical reasons, exponential soft contact is used for the contacts which involve the sheet metal blank allowing penetration exponentially depending on the contact pressure.

Figure 7 shows the simulation result for the sheet after applying the bending steps on all four sides. It can be seen that the corner areas are not bent to 90°. Note, that this is not possible just by bending the sides separately. To generate this specific shape of the corners a special geometry of the bending tools is need. Thus, the result for this pre-bent sheet is passed to the corner former simulation model.

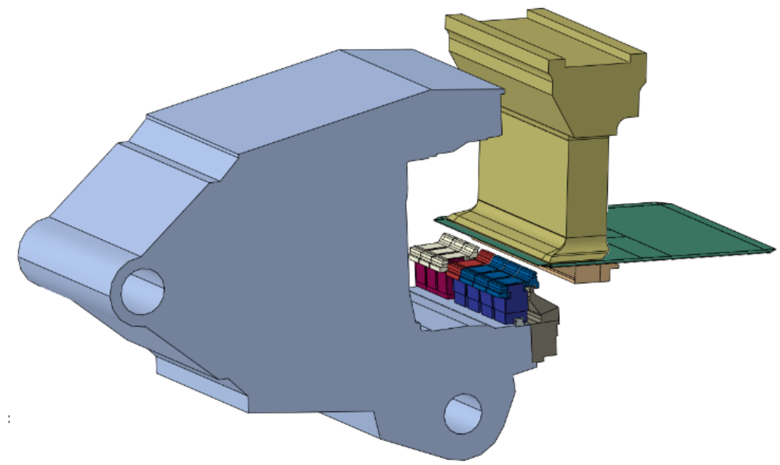

**Figure 6**: Simulation model: Bending process

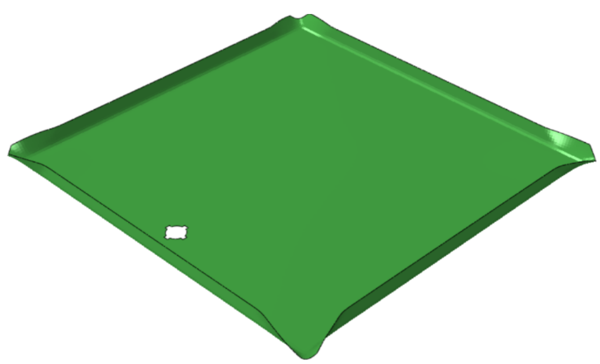

**Figure 7**: Sheet after bending

### 3.3 Cornerformer

The principle of the cornerformer is shown in Figures 3 and 4, and the simulation model in Figure 8. Note, that in this representation the corner to be processed is hidden by the roller. In the simulation model, the machine components of the cornerformer are simplified and generalized because it is not a product of Salvagnini. The geometries of the components can be adapted to the special requirements of the particular application. The investigation presented here is primarily intended to show the feasibility of the optimization of the complete workflow. As mentioned before, in this process step the corner area is formed into a fully finished corner. Since the sheet tends to wrinkle during forming, a counterholder plow is required. After fixing the sheet between the upper and lower clamping tool, the roller moves down to form the corner.

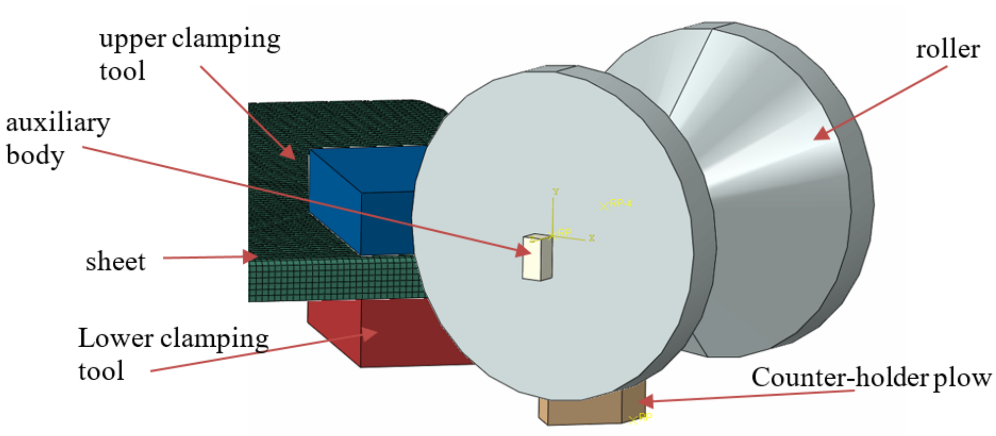


**Figure 8**: Simulation model of the cornerformer

A specific feature in this model is the roller bearing. Since the roller does not only perform a linear motion downwards, but also a horizontal displacement due to elastic deformation of the machine. To represent this behavior in the model, the centers of the roller side surfaces are punctually connected with an auxiliary body as shown in Figure 8. Due to the vertical translation of the auxiliary bodies, the roller moves down. Additionally, the connection between the roller and the auxiliary body allows the roller to rotate. Due to the elasticity of the auxiliary bodies, there is a compliance in the roller bearing, which allows the roller to move horizontally. By the geometry and the Young modulus of the auxiliary bodies, this compliance can be adjusted. Thus, the contact pressure of the roll can also be controlled. The bearing of the counterholder plow is a combination of a linear guide and a spring. The linear guide allows the plow to move vertically only, and the spring stiffness can be used to adjust the resistance against this movement. The spring stiffness can be used to control the influence of the counterholder plow on the forming process.

The deformed sheet from the simulation of the bending process (Figure 7) is used as input for corner forming. Therefore, the sheet must be imported into the cornerformer simulation, which was done as an "orphan mesh". The orphan mesh is characterized by the fact that any information about the exact geometry (CAD) is lost, i.e. it is only represented by the Finite Elements. The big advantage is that the deformations and stresses are also imported. For this purpose, a "Predefined Field" must be created, reading the results for stresses, deformation, etc. from the previous simulation.

The result of the corner former with the default sheet metal blank can be seen in Figure 9. The area of the sheet below the black dashed line is excess material, which shall be removed by a subsequent optimization.

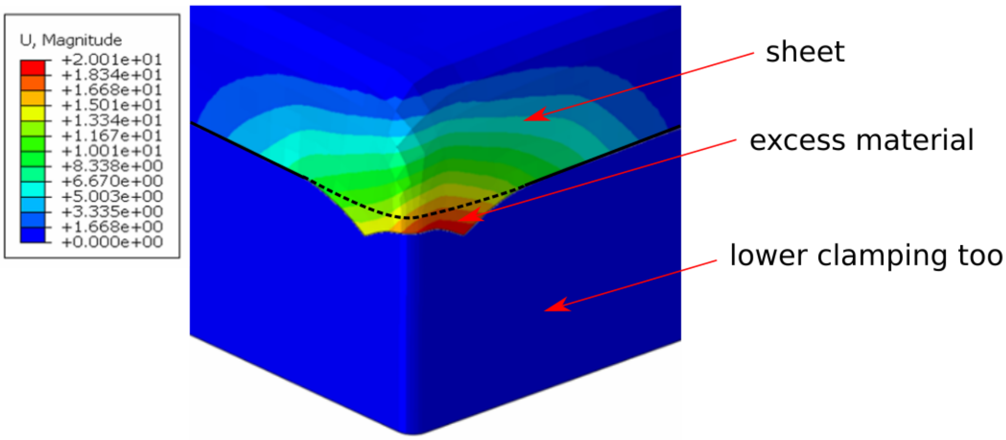


**Figure 9**: Simulation result (with the default sheet metal blank)

## 4 STRATEGY FOR SOLVING THE INVERSE PROBLEM

For solving the inverse problem, the results of the two simulation models are combined. The optimal sheet geometry is determined itertatively as shown in Figure 10. The iteration cycle starts with bending, followed by corner forming. Subsequently, the corner geometry is analysed. If the result is not satisfactory, the blank is adapted by removing excess material. This means, the elements that represent the excess material are removed. With the new sheet blank, the process starts again. The iteration cycle repeats until the corner shape meets the requirements.

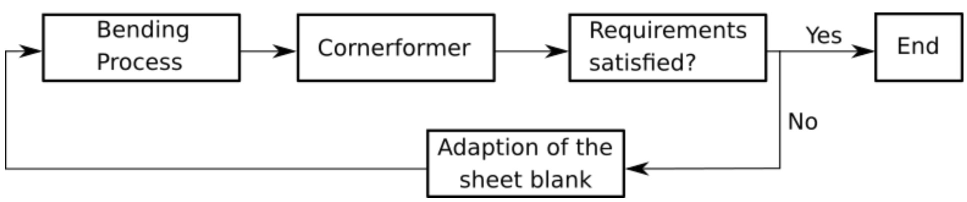


**Figure 10**: Iteration cycle

In the following, the simulation results of the individual iteration cycles are compared. Four iteration cycles were run. Figure 11 shows the contours of the sheet metal blanks, i.e. the results of the iterations are superimposed. The green sheet represents the initial shape. It can be seen that the largest change is between the first and second iteration cycle. Only minor changes were made between the $3^{rd}$ and $4^{th}$ iteration. The blue sheet represents the final state. Note, that with this algorithm the element shapes are becoming non-ideal for higher iteration loops. Remeshing should solve this problem in the future.

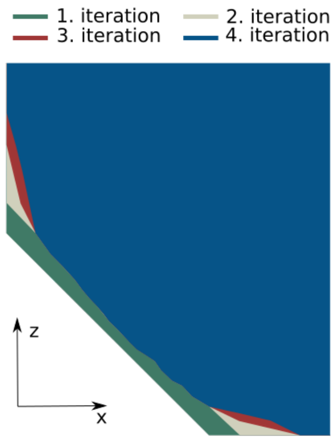


**Figure 11**: Comparsion of the sheet metal blanks

The corner shapes for the individual iteration steps are shown in Figure 12. For better visualization the displacement is shown as a contour plot. It can be seen that with each iteration cycle the corner shape is closer to the desired solution. However, it can also be seen that the mere removal of elements results in an uneven edge shape. As mentioned above, remeshing could improve the contours. The changes between the $3^{rd}$ and $4^{th}$ iteration cycles are minor compared to the previous changes. Therefore, in this analysis the iteration cycle is terminated after the $4^{th}$ iteration.

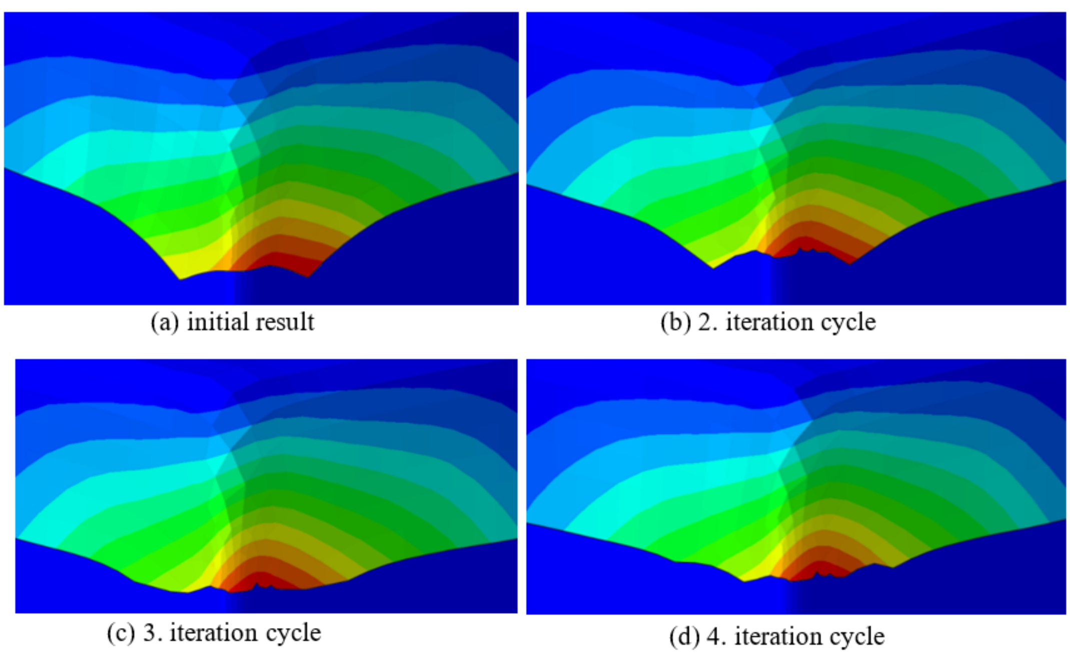


**Figure 12**: comparsion of the resulting corner shapes

Figure 13 shows the side view of the initial result and the $4^{th}$ iteration cycle. The red line represents the desired edge profile. It is clearly visible that the optimization is not yet fully completed, but the edge profile in the $4^{th}$ loop is already close to the desired result. The maximum veritcal deviation from the desired edge height at an element length of 3 mm is 5.06 mm for the initial model and 1.49 mm for the $4^{th}$ iteration cycle.

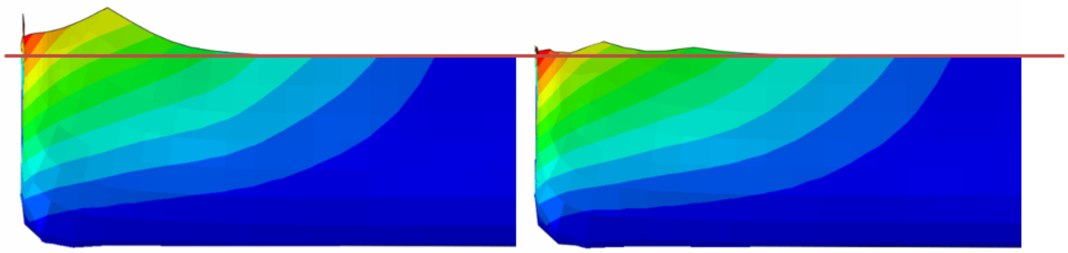

**Figure 13**: Comparsion of the resulting corner shapes

To further improve the results the following steps should be done:

- As it is shown in Figure 13 the optimization by deleting elements leads to an uneven polygonial edge shape. Therefore, the sheet metal blank should be imported into a CAD-programm to smoothen the edges.
- After smoothening, the sheet metal blank is imported into Abaqus and a refined mesh is generated. The iteration cycle can start again.
- Since a significant improvement can already be seen after four iteration cycles, it can be expected that with smoothing and mesh optimiziation a satisfying result can be obtained with a few more iteration cycles.

In addition to the optimization of the sheet metal blank, also the resulting process forces can be evaluated. If the exact geometries of the individual components are known for the specific application, the simulations can be used to analyse the forces, stresses and deformation in the complete machine. If necessary, the process can be adapted to change the maximum loads.

## 5 CONCLUSION

This paper gives an overview of the optimization of a sheet metal forming process performed on two machines. For this sake, a simulation framework has been set up. Main objective was a feasibility study, if it is possible to avoid the final time-consuming step of cutting off excess material.

The presented analysis shows that this optimization is possible. The digital twin presented in [2] can now be extended with this feature. For this study, the component geometries of the corner former have been kept as general as possible, because this part concerns the machine of a third party. Later, in the digital twin these components can be adapted to the specific corner former machine. Thus, the outcome of this work is an efficient simulation framework for the optimization of an industrial combined bending and corner forming process.

A possible further investigation is to extend this study to other material models and determine the influence of the materials. Due to the modularization, the process can be easily adapted to other materials.

## ACKNOWLEDGEMENT

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