Implementation of Real Contact Areas into Sheet metal Forming Simulations using Digital Spotting Images

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Abstract. Increasing demands on quality of outer car panels and shortened product development processes fundamentally challenge automotive manufacturers. Development times are significantly influenced by the manufacturing process of dies, which are introduced by the time-consuming manual grinding operations carried out during die try-out. Blue color paste is often used to visualize contact areas between die surfaces and blank to provide a spotting image. The spotting image can be used to evaluate and optimize the pressure distribution. A homogeneous pressure distribution positively influences the forming process in terms of flange draw-in and surface quality. This paper presents an approach for implementing real contact areas into forming simulations based on digital spotting images of active surfaces. Spotting images were produced for different drawing depths and subsequently extracted by image processing. The simulation model presented in this study includes different spotting levels in conjunction with the TriboForm friction model to describe tribological conditions during forming more accurately.

1. Introduction
Car design departments and part development departments create CAD models for all sheet metal parts. The part geometry is the kick-off for the manufacturing process in an early car development stage. The process plan defines the specifications of the different operations such as forming, cutting, and flanging and is crucial for a robust and feasible final part. Figure 1 (a) depicts the drawing operation of a hood part. The addendum extends the hood by a wall, bearing zone and draw beads (Figure 1 (b)).

![Figure 1](image_url)

\textbf{Figure 1.} (a) Drawing geometry; (b) Cross-section A-A of the addendum

Corresponding to the complexity of the part, material flow is controlled in the process by means of bearing areas and draw beads in the binder region. An inhomogeneous pressure distribution in bearing
areas can lead to uneven draw-in of the blank and surface defects due to high pressure areas. It is therefore important to assure a homogeneous pressure distribution in bearing areas to control tribological conditions and material flow during the forming operation. To improve the pressure distribution in bearing areas the contact areas are manually finished after machining and assembling of the casted tools. The first parts are subsequently pressed on try-out presses similar to the production line. Blue color paste is often applied to both sides of the flat sheet or formed part to evaluate real contact areas between the sheet and the tool. After closing the tool, the color transfers from the sheet to the tool surfaces, which is called a spotting image. An ideal spotting image has contact between the upper and lower die at the same time. This method considers the applied forces, the stiffnesses, and the actual surface conditions. Due to straining of the sheet during the forming process, i.e. due to thinning and thickening of the sheet, the initial contact areas can change. Using (ideal) simulation results combined with spotting images help toolmakers to manually improve the contact areas by grinding. Nowadays, the grinded surfaces under applied forces cannot be measured with state of the art systems. However, a novel optical measuring concept is able to capture the real spotting image at a specific drawing state of the forming process [1]. The digital spotting image enables the quantification of the active contact areas which can be used for further optimizing the tools. Tribological conditions during forming process determine the material flow and, therefore, the parts dimensional accuracy and surface quality. Tribological conditions depend on pressure distribution, forming velocity, interface temperature, plastic strain, type/amount of lubrication and the surface topography of both the sheet and the tooling. The improved simulation accuracy by using the TriboForm friction model, accounting for all of these dependencies, has been demonstrated in earlier work of the authors for a body side panel in [2], a door-outer in [3] and a fender in [4]. Combining the TriboForm friction model with an improved description of the pressure distribution in bearing areas will further increase the simulation accuracy, and therefore the prediction capabilities of forming simulations of complex car body parts [5, 6]. Within this paper, a novel method is presented making use of the digital spotting images to accurately describe the bearing areas. This approach closes the process chain with digital feedback from tool try-out to forming simulations to improve forming simulation accuracy. Within the following sections, the part geometry and major objectives are described, followed by the definition of the novel forming simulation approach. The paper concludes with a discussion of the results and outlook for further research.

2. Validation rectangle part
Specifications of the investigated part will be discussed in this section. In addition to the design and material properties of the cup, the digitization process of spotting images in the press is presented as well.

2.1. Rectangle cup
A suitable tool geometry was designed to validate the new simulation approach. Different bead geometries have been defined within this tool geometry, based on the material thickening in corner areas and the tribological change due to variation of the pressure distribution. Figure 2 shows the tool geometry and final part with specific bead geometries. On the long side of the rectangle, a lock bead with a bead radius of 2.5 mm and a height of 5 mm is designed. Compared to the lock bead, the round bead has a bead radius of 6.5 mm and a height of 5 mm. Both bead geometries are specified with the same groove radius on the binder of 8 mm. The active contact surfaces were increased by 0.1 mm, compared to the corner areas, to allow material thickening. Furthermore, clearance behind the bead area of 0.1 mm is defined to prevent tool contact. The lock beads introduce a targeted thinning of the material, which in turn leads to thickening of the sheet in the corner areas. Ensuring the transformability of investigation results, the designed tool geometry reproduces series like die design.
2.2. Material properties

Equal to the previous research work by the authors in [1-3], the presented work is focusing on AL6-OUT aluminum blanks [7] with a thickness of one millimeter from the material supplier Constellium. The binder and the upper die are manufactured from cast iron to represent series tools for outer body parts. The used cast iron material is EN-JS2070. After manufacturing, the tools were manually grinded and finished by the toolmaker equal to the finishing treatment of tools in the try-out process. Due to the grinding process the tools have a specific surface roughnesses. Surface measurements with µsurf were carried out on the tools and used as input for the TriboForm friction model [8]. Figure 3 shows a top view of the measured surface textures of the blank holder and upper die. In this case, $S_a$ is the extension of $R_a$. Compared to $R_a$ (line), the $S_a$ value is the difference in height of each point for the arithmetical mean of a surface.

![Figure 3](image)

**Figure 3.** (a) surface properties of the binder with $S_a$ 0.4; (b) upper die with $S_a$ 0.6

2.3. Operating parameters

Three operating conditions were chosen for further investigation based on simulations performed in AutoForm. Table 1 shows the investigated operating conditions with characteristic forming parameters. The process window is limited (in terms of binder force and drawing depth) due to the material properties of aluminum and the die design.

The tests were performed on an AIDA NST-S2-6300 servo press. Core features of the press are:

- Press type: single-action servo-mechanical press with draw cushion
- Nominal force: 6300 kN
- Slide drive: eccentric
- Stroking rate: 1 – 30 l/min
In order to validate simulation results, the parts were marked with a measurement grid. This grid was applied using electrolytic acid etching. Evaluating the formed parts by using the measurement system *ARGUS* from *GOM GmbH* allows the calculation of major/minor strains and thinning. To ensure the repeatability of the tests at least three parts for each operating condition were prepared with a grid.

**Table 1.** Investigated operating conditions with specific forming parameters

| Test | Drawing depth [mm] | Binder force [kN] | Lubrication [g/m²] | Stroke rate [1/min] |
|------|--------------------|-------------------|--------------------|--------------------|
| RD1  | 27                 | 90                | 1.2                | 7                  |
| RD2  | 23                 | 110               | 1.2                | 7                  |
| RD3  | 20                 | 150               | 1.2                | 7                  |

**2.4. Digitalization setup**

The main focus of this investigation is the digitization of the spotting image inside the press and the implementation into forming simulations. The digitization is performed with the *TRITOP* measuring system from *GOM GmbH*. Figure 4 shows the digitization setup.

![Figure 4](image)

**Figure 4.** (a) different coded measurement elements next to the tool; (b) standardized SLR-camera position with tripod for digital spotting images; (c) digitalization of spotting image with *TRITOP*

At first, a reference measurement was generated. This was achieved by placing coded marks, non-coded marks and scaled objects in the press, see Figure 4 (a). The reference images were generated around the measurement object to achieve the smallest possible measurement error. Reproducibility was achieved due to the use of a tripod, shown in Figure 4 (b). Images for the spotting image acquisition were reduced to a small number as shown in Figure 4 (c).

For the different operating conditions only the relevant spotting images were taken during the tests. Alignment with the reference measurement was established by introducing measurement marks with magnets inside the press. By implementing the reference measurement only once, the process time was significantly reduced. The spotting images were recorded for the binder and the upper die. Additional to the operating conditions from Tab. 2.1, different drawing states were investigated. The different drawing states are defined from “0” to “1”. Drawing state “0” is equivalent to binder closure, where only the beads are formed and the active surfaces come into contact. Drawing state “0.5” describes half of the drawing depth for the particular operating point. Finally, drawing state “1” indicates the spotting image of the formed part.
For evaluating the captured spotting images, the color information of each image is mapped onto the 3D CAD surfaces of the binder and the upper die. In this way a colored mesh is generated, that allows a further extraction of the contact surfaces by following the approach described in [9, 10]. In the final step of data processing, boundary curves are generated for the forming simulation. The adaption of the forming simulation by accounting for active contact areas changing over the drawing depth is described in the following section.

3. Simulation model considering real contact areas

In the following section, two simulation models are presented and compared. The first model describes the reference simulation, following the conventional simulation approach of process planning. The second model describes the extended simulation model with real digitized contact areas from the spotting images per operation condition.

3.1. Reference model

For the reference simulation, AutoForm Forming R8 in conjunction with the TriboForm FEM Plug-In for AutoForm was used. To describe the draw beads the 3D bead model was adopted. Bearing zones in the corner areas and behind the bead areas realize the behavior of thickening effects. Due to the no-bearing zones, an applied force results in a homogeneous surface pressure in the retaining contact areas. Figure 5 shows the implemented no-bearing zones. To account for accurate friction conditions, the measured surface roughnesses of the binder and the upper die (see Figure 3), sheet (1.1 µm) and lubrication amount (1 g/m²) was used as input for the TriboForm friction model.

![Figure 5. Specification of active contact areas due to no-bearing zones on the binder geometry](image)

3.2. Spotting image simulation model

As for the reference simulation, the 3D bead model with the TriboForm friction model was used. Active contact areas are extracted from the digitized spotting images from which boundary curves were generated as input for AutoForm. Table 2 shows the contact areas for operation condition RD3 at 150 kN binder force, from which can be observed that the active contact area changes according to the drawing state.

It can be observed that the contact areas are shifting and changing between drawing states 0.5 to 1. Thinning of the blank material in the area of the lock beads reduces the contact area. Contrarily, the sheet metal thickens in the corner areas and additional contact areas are introduced.
Table 2. Change of spotting images for binder and upper die, loaded with 150 kN. Linear increase of surface area content for the binder; upper die constant surface area content

| Drawing state | 0       | 0.5     | 1       |
|---------------|---------|---------|---------|
| **Binder**    | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| **Surface area [mm²]** | 5177.2 | 6545.5 | 8230.5 |
| **Upper die** | ![Image](image4) | ![Image](image5) | ![Image](image6) |
| **Surface area [mm²]** | 11560.2 | 12350.5 | 11589.9 |

Comparing the change in contact areas for the different operation conditions, a conversion to different surface pressures is possible. Figure 6 (left) shows the decrease in surface pressure over the drawing depth. The pressure distribution changes per time step and, therefore, for every drawing depth. Analyzing the contacting surface area for the different spotting images, it becomes clear that the surface pressure decreases due to the increase of surface area. Especially the graph for the binder (Figure 6 (left)) shows a linear decrease of the pressure distribution. Compared to the binder, the graph for the upper die shows only a slight change of surface pressure during forming. These average values show the variation of the pressure distribution during the forming process. Therefore, considering the change in contact areas in forming simulations will improve the prediction of the real forming processes. Focusing on the results from the line graphs, only the spotting images from the binder were implemented in the new forming simulation model.

![Figure 6](image7)

**Figure 6.** Line graphs of surface pressure for binder and upper die from zero drawing state 0 to 1 for different binder forces

Based on the obtained results, a new simulation model was developed. The new simulation model, including real contact areas, was implemented by generating a simulation model including three drawing operations. For the different operations, the drawing depth was divided into sub-steps as shown in Table 3. In the respective drawing states, boundary curves of the real digitized contact area were imported and defined as bearing zones.
| Drawing state | 0    | 0.5  | 1    |
|--------------|------|------|------|
| RD1          | 0 – 6.75 mm | 6.75 – 20.25 mm | 20.25 – 27 mm |
| RD2          | 0 – 5.75 mm | 5.75 – 17.25 mm | 17.25 – 23 mm |
| RD3          | 0 -5 mm   | 5 – 15 mm    | 15 – 20 mm    |

4. Results

In the following section, the results of the different operation conditions are presented and discussed. Evaluating the obtained results, the draw-in and major strain where chosen as validation measures. Figure 7 shows the measurement locations. Measurement location 1 and 2 describes the location where the draw-in was measured. The major strain is analyzed in three different sections, represented by 90, 35, and 0. In the following figures, the draw-in is shown in the upper left corner and the major strain is plotted in the remaining quadrants. The results are presented from RD1 (lowest binder force) to RD3 (highest binder force).

![Figure 7](image)

**Figure 7.** Specific part evaluation scheme for main validation parameters draw in and major strain

In Figure 8, the results corresponding to operation condition RD1 is shown. For RD1 a binder force of 90 kN was used. Analyzing the draw-in data, it becomes clear that the prediction accuracy is increased in the area of the round bead. For the major strain, all three sections give an increased prediction accuracy in the bottom of the part. Towards the round bead, both models gives an underprediction compared to the real measured major strains.
Figure 8. Result plot for test RD1 with binder force 90 kN and 27 mm drawing depth

For operating point RD2 (see Figure 9) with a binder force of 110 kN a nearly similar result as RD1 is shown. The major strain in section 90 and 35 is accurately predicted. The prediction of strains in 0° is limited after the wall area towards the bead area. Discrepancies might be introduced by a faulty interpretation of thinning in the spotting image, which might lead to local differences in pressure distribution.
For RD2, the major strain is most accurate predicted for the 35° case. This indicates that the shift in contact areas due to thickening is effecting the simulation results.

Results of the last operation condition (RD3), with the highest binder force of 150 kN, is shown in Figure 10 The draw-in for the lock-bead (section 1) shows a good correspondence. Also the major strain in the lock-bead section for the bottom and wall area shows a good correspondence. Due to the smaller drawing depth the major strain in the round bead section is better predicted by the reference model. The ratio of the two parameters binder force and drawing depth influences each other and requires further investigation in series dies to clarify the effect for the round bead section.
Overall, results show that the material flow and the thinning effect can be improved by accounting for active contact areas. This was established by an improved digitalization process to capture more precisely the color of the spotting image. To include spotting images into forming simulations extended effort is required. Therefore the segmentation and image processing was improved with specific python-libraries, enabling an enhanced extraction of real contact areas. In addition, the effort can be reduced significantly by choosing a limited set of spotting images. Transferring the findings of the rectangle cup to series dies/parts prove the benefits of the new simulation approach.

5. Conclusion and outlook
In this paper it is shown that the spotting image changes over the drawing depth. Thinning/thickening of the sheet during the forming process changes the spotting image and therefore the pressure distribution. The decrease of the pressure distribution due to thickening effects in the corner areas is an important parameter in forming simulations and should be properly accounted for. It is shown in this paper that an increased prediction of the pressure distribution increases the predicting capabilities of the forming simulation. Besides the effect of the material thinning, the spotting image represents press and tool characteristics indirectly. For the die try-out process, this investigation showed that the drawing state to evaluate the die performance best is for the final part spotting image. This state includes the effect of thinning on pressure distribution during the forming simulation.
Further studies will focus on validating the presented simulation approach on series dies and parts. In addition, other press and tool parameters like cushion pins or tool stiffness will potentially increase the simulation accuracy. Characterizing specific friction conditions for lock beads and round beads can possibly improve the prediction of major strains and draw-in in these areas.
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