Digital process support in toolmaking by using optical metrology

Peter Essig¹*, Mathias Liewald², Christian Bolay³ and Thomas Schubert³
1 Daimler AG, Mercedes-Benz Sindelfingen, D-71059 Sindelfingen, Germany
2 Institute for Metal Forming Technology, University of Stuttgart, D-70174 Stuttgart, Germany
3 GOM GmbH, D-38122 Braunschweig, Germany
E-mail: peter.e.essig@daimler.com

Abstract. Increasing demands on the quality of outer skin car body panels, shortening product development processes of new car models in the future fundamentally challenge manufacturing companies in international competition. Such challenges emerge, for example, in the field of toolmaking, which plays a decisive role in the value-added chain due to its high time and costs share. Here, the high proportion of manual, experience-based operations in tool tryout often leads to unstable processes requiring many iteration steps until approval. Blue, non-dry colour is applied on sheet metal which creates a spotting image that makes the contact areas between the forming die surface visible. In die tryout, spotting images provide a visual indication of the current phase and also serve as quality criteria of sheet metal components. For this reason, research work reported about in this paper deals with the development of a procedure for generating digital spotting images by using optical 3D coordinate-measuring technology to keep the spotting image permanently available during die tryout phase, for example on smart devices. In fundamental investigations, different influences on the spotting image due to light conditions and STL-mesh size of the scanned geometry are initially examined in order to quantify both the physical and the digital spotting image. The knowledge gained is subsequently validated and further improved by means of test with series press tools. The results demonstrate how digital and physical spotting images are generated and quantified for a reduced time in sheet metal simulation and die tryout phase of large press tools. This is achieved by the systematic provision of process parameters from the series production, such as the force transmission between the forming die surfaces, the local sheet thicknesses and the documentation of process variation in the blank holder by using digital spotting images.

1. Introduction
Increasing demands on component quality and shortened product life cycles extensively challenge manufacturing companies in an international competition. Continuous optimization and further development of production processes therefore are necessary. With regard to the implementation of new optimized processes toolmaking plays a decisive role, especially in the field of sheet metal forming. This is particular evident when considering that manufacturing and tryout of tools for the production of sheet metal parts for the outer skin car body panels of vehicles consumes 44% of time and 32% of costs of tool manufacturing (see Fig.1). After manufacturing physically, press tools are not yet ready to use for series production, but must be successively prepared in the subsequent tryout phase, in order to ensure proper process quality and reliability. Mechanical tryout of tools remain indispensable until
today, since the complex interaction of tool and press results in manufacturing tolerances that cannot be entirely calculated by current simulation models [1].

Figure 1. Analysis of the time and cost shares of engineering and manufacturing using an example of an automotive side panel frame [1].

During tool tryout, optimization loops are performed using trial-and-error-method until the tool finally fulfils production maturity. Here a blank is initially pre-shaped by closing blank holder of the drawing operation. Subsequently the so-called spotting image shown on the left in Fig. 2 is obtained by coating both sides of the blank with blue non-drying paste and by closing the die again to touch blank holder and matrix surface. This method visualizes the force transfer areas of the upper and lower die transferring coloured paste from the blank to the die surface. Based on this spotting image, the toolmaker can specifically adjust retention force of the blank holder by local manual grinding. Since toolmaker decides on his own how much material to remove locally, this person requires an extensive experience concerning the entire tryout process. Due to easy reachability, blank holder is preferred as grinding location. For this reason, the toolmaker have to compare the spotting image of the upper die half of the tool with the coloured blank (see Fig. 2 right). After evaluating the colour transmission and the combination of the different impressions, grinding starts. Challenging especially for large components such as a side panel, because the elements are separated and rotated. Toolmaker defines spotting image as acceptable when the coloured paste from blank transmitted on both sides in a homogenized manner.

Figure 2. Spotting image of a bonnet on the left with local colour transmission from areas with retention; Corresponding active surfaces taken from CAD on the right.

As a prerequisite, tryout process requires knowledge of the current status of dies compared to simulated contact surfaces. Due to the lack of this information, because currently no process documentation takes place, various conflicts can arise affecting the planning and forecasting of terms.
Especially lack of quality of produced parts, giving the right instructions for tool revision is important in order to avoid inefficient and uncoordinated steps leading to increased costs. For this purpose, the status of the die in terms of achieved level of progress in manufacturing should ideally be displayed by a simultaneous comparison of the real die surfaces with the simulated surfaces during tryout. By this approach, grinding iterations can be specifically and justifiably interrupted, since simulated surfaces are already incorporated by the toolmaker based on simulated surface pressure.

Furthermore, the systematic documentation of specific processes and results of tryout on shopfloor today often remains incomplete, as spotting images that would provide more transparency from tool manufacturing to series production are documented. Therefore, no data or information feedback proceeds regarding tryout phase for future projects or components in order to save time and costs. For this reason, the procedure described in this paper involves deriving instructions for action from completed projects in order to reduce the time required for process planning in the long term.

2. Previous Work

In the context of process optimization in toolmaking, two approaches can be classified. On the one hand the conceptual and on the other hand the simulative process optimization. The conceptual approaches cover all processes within the stringent chain of die production. New approaches of digitization and industry 4.0 are increasingly used today for this purpose.

Schick attempts to optimize the tryout process by multiple steps using a pressure-sensitive sensor layer for determining surface pressures between both die surfaces. Measuring the surface pressure serves for detecting deviation from the actual target state in order to automatically grind the contact surfaces in a robotic cell [2]. Bolay uses the blue spotting colour paste to visualize the contact areas between two die surfaces and describes a procedure for evaluating the contact pattern using a grey level analysis [3]. Further patents also deal with the optimization of die production or the launch of series production by quantification of the blue spotting colour paste [4–6].

In addition to patents mentioned, further work within the framework of process optimization in toolmaking provides more detailed concepts by characterizing influencing parameters on tryout process. Stippak's approach identifies essential tryout parameters by means of sensitivity analyses, which must be coordinated and adjusted by the toolmaker during the usual tryout phase of the die. In this way the influence of different parameters on the tryout result is determined before tool revision, thus allowing to carry out only purposeful actions and thus save time [7]. This approach also includes "TryoutAssistant" developed by AutoForm, which is intended to support the toolmaker at the press directly on the basis of Sigma-simulations [AutoForm Engineering GmbH 05.06.2018]. As well in this context, Schuh's work, focuses on digital process support in process optimization. Here, the know-how gained during start of production is systematically recorded and provided for future start-ups according to requirements in order to implement learning and scale effects across different departments [9]. However, these approaches still remain unused in practice and thus present merely a theoretical consideration.

The conceptual optimization approaches used for analysing and documenting tryout processes indeed differ from simulative approaches. For a more detailed prediction of the contact pattern, a detailed modelling of the deformation of press cushion, cushion pins or of the blank holder is necessary. With this respect, Pilhammar investigates in his work, how a spotting image can be predicted by a press cushion simulation. Here, however, problems arise when comparing digital and real spotting images, since no transmission of the colour paste at low pressures from sheet blank to die surfaces perceived. Quantifying the correct scale determination also poses an additional challenge. The results obtained thus show that the structural model developed does not provide a sufficiently accurate prediction of the contact images and should therefore be advanced in further investigations in order to quantify the spotting image [10]. Braedel states in his work that a digital geometry scan cannot be compared with the real spotting image due to the influencing inaccuracies. Based on his investigations, he observes that the appearance of the beads and the distribution of the die cushion force indeed does reveal a major influence on the spotting image [11]. Penther enables by parameterization of the machine and tool
characteristics a complete simulation model which allows a virtual tryout process. For this purpose, cushion pin pressure distribution have to be generated specifically for the press to investigate a more precise simulation model for the cushion [12]. In the context of this approaches in sheet metal simulation, further work pointed out [13–15]. However, this approaches are useful to improve future simulation models in sheet metal forming but need further data acquisition. In this case profound investigations of spotting images enables an efficient way to analyse press influencing parameter.

3. Proposed Approach
For years, the process chain in toolmaking has been subject to a sequence of stringent process steps, so data feedback to specialized departments barely not exist. However, these data from the shopfloor directly support the development process by deriving them as instructions for future process planning. This results in both the shortening the lead time of future projects and are more substantial target-oriented support of current projects.

In this respect the method presented here aims to produce digital spotting images and to further process or to feedback acquired tryout data (see Fig. 3). In the tryout phase, the spotting images as a main element for the visualization of force transfer of the press are digitized by existing and applied optical metrology. Digitalization of the spotting image reflects the entire force transmission of a forming operation, since active surface pairs involved in the forming process directly influence colour transmission.

Figure 3. Potential data feedback in the die manufacturing process chain.

3.1. Production Of Digital Spotting Image
Current measuring process of large die geometries integrates the digital spotting image by assigning colour information to STL-mesh surface by merging individual measurements. Conventional geometry scanning starts with a photogrammetry measurement providing the scanner orientation in space for spatially extended measurement objects. Photogrammetry is based on central perspective imaging when photographing a measuring object from different perspectives. This method relates to the 2.5-dimensional measurement methods, in which three-dimensional coordinates are obtained from a triangulation process. A complete scan of geometry, requires several images from different perspectives. Thereby redundant acquisition of measuring marks reduces measurement uncertainty [16].

Optical measuring method used for geometry scanning refers to strip projection. Hereby geometry is measured by means of projected light and dark stripes scattering onto the component. The finer the projected stripes, the higher the dimensional resolution. The binary pattern subjects to ambiguity, similar to incremental path measurement. However this problem can be solved by multiple exposures with different patterns. Finally geometry is calculated by a point cloud up to 100,000 measuring points [17].

Fig. 4 shows how a three-dimensional, digital spotting image is produced from the two individual measurements. Subsequently, the alignment images are projected onto the STL-mesh by means of the measuring marks via their beam paths. Quality of the generated colour meshes significantly depends on the number of projected images, the recording mode of the used SLR-camera and the marks used. The size of the STL-mesh elements also influencing the result.
3.2 Influence Of Environmental Conditions On Colour STL-Mesh

Modern use of digital spotting images in the die tryout phase first requires a more detailed investigation in order to evaluate the usability of the generated results in the process chain. Fields of application are the tryout process support and data feedback. In tryout process a detailed visualization and an efficient generation is needed. In the context of data feedback into the sheet metal forming simulation and process planning, the digital image must provide sufficient accuracies and STL-mesh quality. For this reason identification of suitable recording modes that fits for the environmental condition in the workshop during generation is useful. In addition, the intense reflections of the die and sheet surfaces must be taken into account.

For the investigations carried out flat material samples were used. The materials investigated involved on the one hand cast iron (ENJS-2070), from which the later series tools are manufactured, and on the other hand the two main sheet materials steel (CR5) and aluminium (AL6-OUT). The samples were applied with blue colour paste in defined areas (see section 1). The framing of the areas are applied with a laser marking machine of which the later quantification takes place (see Fig. 6 left). Validation of the recording modes, different materials and post-processing of the STL-meshes conducted on complex die geometries.

3.3 Recording Mode of SLR-Camera

Table 1 lists the different recording modes of the SLR-camera. “Standard TRITOP” describes the used mode for a photogrammetry measurement in GOM which simply tries to record the alignment marks as an aid for large geometry scans. The other modes differ in the longer flash and exposure time which generates brighter images. Variation in white balance leads to an adaption of the light colour for enabling to indoor workshop conditions. However, the spatial orientation points such as coded marks or scale bars must still be recognized by the software despite the adjustments of the recording modes.

| Settings               | ISO | Exposure | Flash          | White Balance |
|------------------------|-----|----------|----------------|---------------|
| Standard TRITOP        | 200 | 125      | 1/8            | “Flash”       |
| Adapted plane          | 200 | 125      | 1/8 with Diffuser | “Shadow”     |
| Adapted complex 1      | Low | 1.6      | 1/4            | “Sun”         |
| Adapted complex 2      | Low | 1.6      | 1/4            | “Neon Tube”   |

Fig. 5 depicts the differences between the measurement images of the recording modes. The two recording modes described as "Adapted complex" lead to a free of reflection image of the real die. In
contrast, the colour impressions of the two colour modes "Standard TRITOP" and "Adapted Plane" are less suitable for the producing of digital spotting images, since the colours on the surface lose intensity and are problematic to evaluate due to reflections.

**Figure 5.** Differences of the defined camera modes; reduction in reflections but more noisy for modes “Adapted complex 1&2”. Sharp images got by modes “Standard TRITOP” & “Adapted Plane”.

### 3.4. Quantification Of The Colour STL-Mesh

For the use of digital spotting images beyond an application in the documentation of achieved levels of progress in tryout phase, these must be quantified with regard to their accuracy. For this purpose, target elements such as defined geometries on the investigated samples were used to enable a comparison with the generated colour STL-meshes. Purpose of this investigation was to achieve an accuracy of 0.1 mm concerning target element. Ensuring the results obtained in further work steps, e.g. the numeric simulation of forming processes, lead to a reliable application.

Fig. 6 shows the comparison between target (laser grooved mark) and actual values (colour mesh). Actual colour route defining a curve and vertically measured on target line. The right side shows the influence of the STL-mesh size on the qualitative result of the colour STL-mesh. Each vertex is assigned to a colour value, so for better results local STL-mesh refinement becomes essential.

**Table 1**

| Validation | Meshrefining | Digital Spotting Image |
|------------|--------------|------------------------|
| Actual     | Iteration 1  | Iteration 2            |
| Target     | Iteration 2  |                        |

**Figure 6.** Validation of the colour STL-mesh (left); Effects of a STL-mesh refinement on the visual result (right).
A further increase in STL-mesh refinement increases the amount of data but also the demands on the graphical system, which become visible by the black graphic errors. Refining STL-mesh twice, the deviation of the colour information is reduced to a minimum. However, refinements more than two iterations leads to visualization problems and a large datasets.

Table 2 lists further results examined for the investigated recording modes for the flat material samples. The investigations depicts that colour STL-meshes produced principally qualify for further processing in the interfaces to the tryout process because deviation fit within acceptable range.

Table 2. Measurement deviations of the different materials for the individual recording modes.

| Material        | Cast Iron (ENJS-2070) | Aluminium (AL6-OUT) | Steel (CR5) |
|-----------------|-----------------------|---------------------|-------------|
| Refinement It. 1| 0.09                  | 0.165               | 0.12        |
| Refinement It. 2| 0.01                  | 0.025               | 0.112       |
| Standard TRITOP | 0.21                  | 0.12                | 0.453       |
| Adapted plane   | 0.23                  | 0.17                | 0.314       |
| Adapted complex 1| 0.113                | 0.21                | 0.133       |
| Adapted complex 2| 0.124                | 0.22                | 0.124       |

Results of aluminium blank compared to the other materials deviate more in the “Adapted complex”-modes, tendency for stronger reflections at complex geometries reason this. However, the deviation at cast iron ranges in the aim of 0.1 mm, so further data processing for sheet metal simulation gets workable.

Manual grinding of the toolmaker in z-direction is extremely precise but in flat extension not that local. So, generated digital spotting images are already sufficient for an application in terms of grinding support and documentation.

To improve further results it will be useful to modify the SLR-camera for example by adding polarization foils to minimize reflections of the cast iron surface. However, a change in the measurement process could lead to an increase in efficiency of time in digitization of the spotting image. For this reason, avoiding time-consuming geometry scan through ATOS-scanner by mapping the photogrammetry measurement onto CAD-data is useful. For a detailed evaluation of the achieved level of tryout progress it becomes necessary to export the digitized spotting images to forming simulation for example AutoForm. Data evaluation must include knowledge about the basic mechanism proceeding during the generation of a spotting images in the workshop level. Also an image processing of the generated spotting images is helpful to reconditioning the data.

4. Conclusion
The investigations in this paper show a general approach for digitizing spotting images from the tryout phase on shopfloor with optical metrology. Suitable recording modes for the generation of high quality colour STL-meshes determined for minimized deviation, so further applications increasing cost and time efficiency in toolmaking can be implement.

Comparison between the real contact areas and the simulated areas from process planning a feedback and estimation becomes possible. However, if simulated surfaces are grinded into blank holder but the part quality is not accurate, grinding process interrupts and process planning must develop an improved simulation. In addition, learning effects across projects increases and time shares in process planning reduced through integrated documentation of digital spotting images.
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