PHOTOGRAMMETRIC MEASUREMENT TECHNIQUES FOR QUALITY CONTROL IN SHEET METAL FORMING

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ABSTRACT

Within the Brite/EuRam project “DIGIMAN” a new optical measuring system for the assessment of sheet metal components in terms of shape accuracy and strain distribution has been developed. Based on the photogrammetrically measured geometric parameters of the object the system detects deviations from the desired geometry caused by springback and allows the strain analysis within critical stamping part areas. Such a system was installed at the Institute for Metal Forming and Metal Forming Machine Tools (IFUM) of the University of Hanover. Further systems will be implemented at different car manufactures and producers of sheet metal stamping parts. Typical applications of photogrammetric measurement techniques in sheet metal forming are described in the following paper.

1 INTRODUCTION

Sheet metal forming is one of the most efficient and most economic production processes for mass production of automotive components as well as household articles. Forced by the progressive automation and consistent rationalization, the use of new sheet materials as well as innovations in the press and tool technologies a considerable increase of productivity was obtained in the press shops within the last decades. The intensifying global economical competition as well as the growing consumer demands concerning product quality and costs will accelerate this trend. The demands of car customers are mainly the car design, safety, comfort, engine performance, fuel consumption and especially the aesthetic appearance of the visible parts. Many sheet metal components, as example outer body panels, have an aesthetic function, so that deviations from the desired geometry cannot be accepted. These components require an even curvature of the surface to achieve smooth light reflection and any surface defects are of essential significance and quality control has to focus on them. Assembled outer body panels should have close tolerances. The historical development of the tolerances demanded by the automotive industry is illustrated in Figure 1.

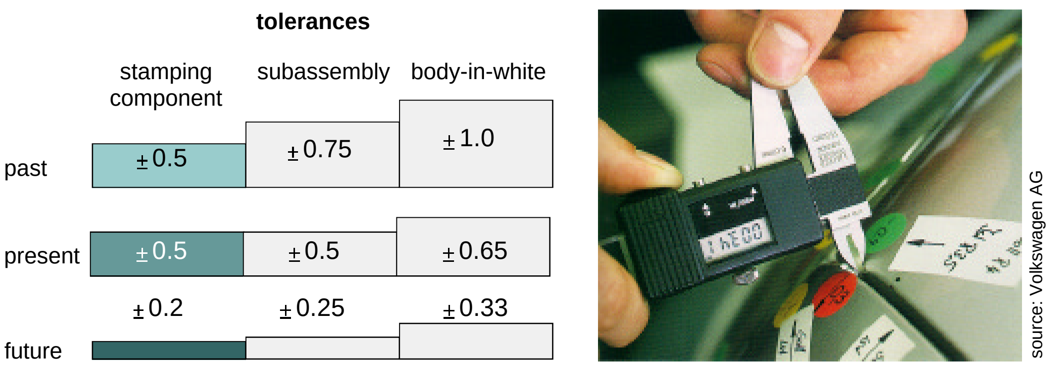

Figure 1: Development of the tolerances in the automotive industry

The growing quality standards especially require optimized processes and efficient methods of quality control. The main objective is a 100%-in-process quality control in press shops.

In the body shops, where the stamping parts are assembled, the punctual geometry measurement (e.g. of welding points) is state-of-the-art. The installation of various laser-sensors is necessary to check the location of one point at a time. However, the number of sensors is limited by the working space of the robots. Furthermore, the consequent reduction of working steps and, thus, the number of assembled parts, implied the enlargement of their size (Figure 2).

Today car side components are mostly pressed in one single stroke. Therefore, the measurement of extensive stamping part areas is indispensable. However the large dimensions of the formed parts are in contradiction to the high resolution required to detect the comparatively small deviations as well as the short time available for the quality control of each part within the scope of the mass production. For the automated joining technique applied in body shop by robots failure-free and accurate stamping parts are an essential prerequisite. The stamping part accuracy has a key position achieving close tolerances in the assemblies

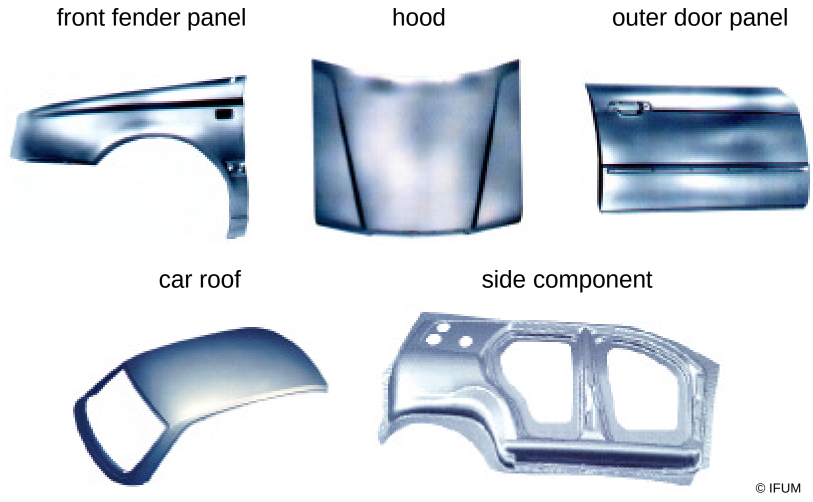

Figure 2: Visible stamping parts of a car (large-sized)

However, sheet metal stamping of components becoming more and more complex is characterized by several structural stamping defects like necking, cracks and wrinkles as well as geometrical deviations due to springback /1-5/ (Figure 3 and 4). Avoiding rejects requires quality control throughout the process chain. Strain analysis is only useful during the try-out of new tools or after production process parameters have been modified (e.g. the lubrication). Springback should be measured during the production process.

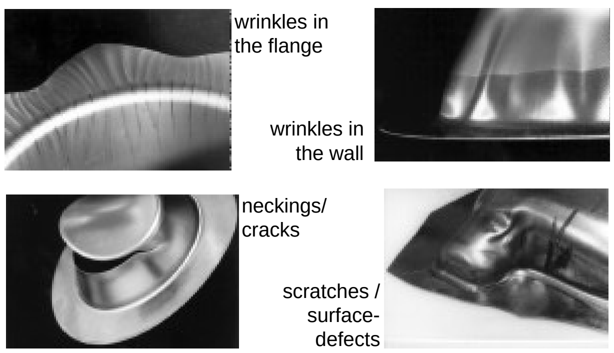

Figure 3: Structural stamping defects

Figure 4: Shape-deviations of formed parts

2 SPINGBACK ANALYSIS

Sheet metal forming processes involve a combination of elastic-plastic bending and stretching deformation of the formed part. These deformations can lead to large amounts of springback upon unloading (e.g. removal of the punch and lifting of the blankholder) due to the redistribution of residual stresses.
The legal demand to reduce the fuel consumption of cars have forced the automotive industry to realize car lightweight concepts using new sheet materials. Nevertheless especially the application of modern high strength steels (HSS) with reduced sheet thickness and aluminum alloys have enlarged the difficulties to obtain close tolerances because of part shape deviations due to springback. The difficulties are still increasing with the automation in production and assembling since springback causes assembly difficulties with adjacent parts.
Springback is influenced by a variety of factors, e.g. mechanical properties of the sheet material, frictional conditions (e.g. sheet and tool topography, lubrication), tool geometry (e.g. die radius, die clearance) as well as process parameters (e.g. blankholder forces) /6-8/. Avoiding springback presupposes homogeneous stress and strain distributions during the forming process. Therefore, springback can be alleviated by the optimization of material flow between the blank holder and the die e.g. by the variation of the tool geometry, the blankholder pressure and lubrication. The prediction of

springback using the finite element method (FEM) is still problematically, because the implemented material and friction laws have to be optimized.
The assessment of the stamping part geometry using tactual coordinate measuring machines is state-of-the-art. This time-consuming method is not capable e.g. to detect part shape fluctuations caused by spreading mechanical properties of the sheet material. Contactless optical measurement techniques have advantages especially concerning the measuring speed as well as the measuring area and therefore have the potential to be applied in-process.
Here projected light can be used to reproduce the stamping part geometry. In this case the reflection behavior of the sheet surface has to be taken into account, especially on uncoated materials. An advantage of the grid projection is that the part could be used in the further production process. However, grid projection is not suitable for the strain analysis.

3 VISIOPLASTIC ANALYSIS

For the design of new forming tools the knowledge of critical strain conditions in the stamping part is necessary to avoid failures, e.g. cracks due to excessive sheet thinning. During the design of the forming tools numerical simulation, especially finite element analysis (FEM) is used for the prediction of formability. During the try-out process and in case of modifications of process parameters of the forming process (e.g. change of the sheet material) the experimental strain analysis using the method of visioplasticity has to be applied. This method permits a statement about the influence of the used sheet material, tool design, the blank shape and the tribological conditions on the final part quality.
Strain analysis in sheet metal forming is usually accomplished by marking a grid of known dimension on the flat sheet blank and measuring the deformed grid on the part after the stamping process. For the evaluation of the strain-rates and strain-distribution circles or square texture patterns have to be fixed to the surface to identify corresponding points at different deformation stages. Following two different methods are described /9/, which have specific advantages and disadvantages concerning an automated computer-based evaluation.

3.1 Circle grid analysis

In a homogenous forming process circles marked on the undeformed sheet will distort to ellipses of major and minor axes, as illustrated in Figure 5. Assuming proportional deformation the principal directions are coincident with these axes. Assuming incompressibility the principal strains φ_1, φ_2, φ_3 can be calculated with the principal elongations l_1, l_2 and the circle diameter d_0:

$$\varphi_1 = \ln\left(\frac{l_1}{d_0}\right) \quad (1) \qquad \varphi_2 = \ln\left(\frac{l_2}{d_0}\right) \quad (2) \qquad \varphi_3 = -(\varphi_1 + \varphi_2) \quad (3)$$

In sheet metal forming usually the forming limit diagram (FLD) is plotted as shown in Figure 6. The FLD provides information about how much a particular metal can be stretched before necking or fracture occurs. The necking strains are obtained under a variety of biaxial forming conditions so that most of the practical stamping conditions are duplicated. Therefore, the FLD provides an indication of the material behavior under actual forming conditions. There are several forming conditions of particular interest: stretch forming, plane strain, uniaxial tension and deep drawing. The forming limit curve (FLC), also shown below, represents the material specific strain limit, which a part can bear without fractures. It is plotted on the forming limit diagram to show how close a particular part is to the forming limit under the specific strain state. The circle grid analysis is advantageous for finding strains at single measurement points in sheet metal components by measuring the length and direction of the principal axes of the ellipse. However, it is less convenient for a computer-based determination of strain distributions in whole regions.

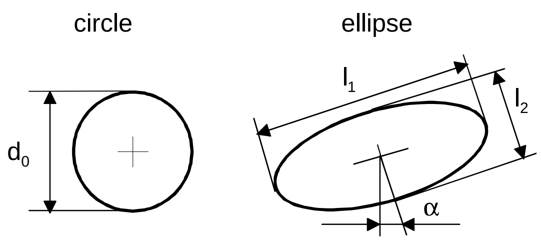

Figure 5: Deformation of a circle in a homogenous field

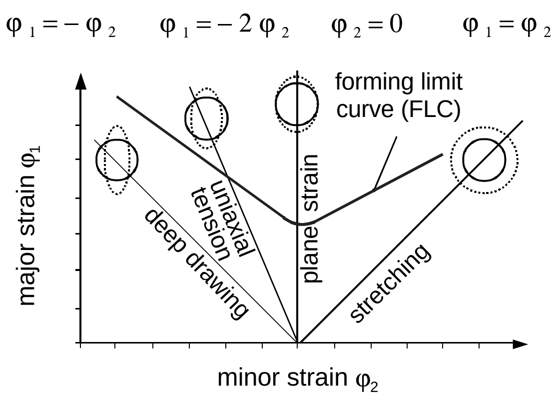

Figure 6: Forming limit diagram (FLD)

3.2 Nodal strain analysis

The determination of the principal elongations and principal strains φ_1 and φ_2 from nodal points is clearly tedious if performed manually. A fast computer-based strain analysis using square grids or any array of nodal points requires more complex algorithms compared with circle grid analysis. Although, the identification of square grids - and this is the essential advantage – can easier be automated using photogrammetry and image processing techniques, which reduces processing speed significantly. In previous papers /10-15/ different methodologies for measuring large strain fields, based on these techniques are described.
Plasticity analysis should be done incrementally since pure proportional deformation may not always be assumed. Because the strain is locally inhomogeneous extensive calculations are required. Several methodologies are supposed with different approaches /16-19/.
One possible evaluation method is the "modified tangent method" /20/, which is based on the "coefficient method" /21/ applied for strain determination of distorted square grids. The main advantages are that the forming history is taken into consideration, which is important in case of changing principle strain directions and local forming inhomogeneities /22/.
Based on the calculation of angles and distances in an arbitrary three-dimensional space as represented in Figure 7 the principal strains φ_1 and φ_2 are determined.

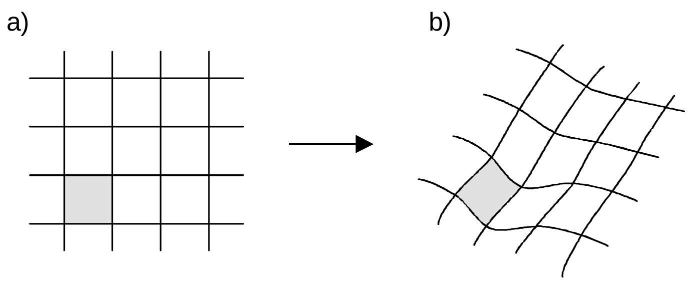

Figure 7: Square grid on the undeformed blank (a), deformed grid measured in the u,v-plane (b)

4 SETUP OF A NEW PHOTOGRAMMETRIC MEASURING SYSTEM PROTOTYPE

Digital image processing combined with photogrammetric algorithms is a powerful tool for a quick and accurate measurement of surface geometry and strain-states. The new system allows the measuring of strains as well as the determination of 3D-surfaces of the formed sheet metals. While for strain measurements a grid is printed to the sheet metal directly, the optical surface measurement requires any kind of texture on the surface which can be either a projected pattern or a fixed pattern. This surface marking is necessary for the identification of discrete points whose 3D co-ordinates can be derived by photogrammetric methods /23-25/. The accuracy of the 3D coordinates depends on the size of the object and the resolution of the digital image capturing device.
A prototype of the newly developed measuring system was installed at IFUM in Hanover (Figure 8).

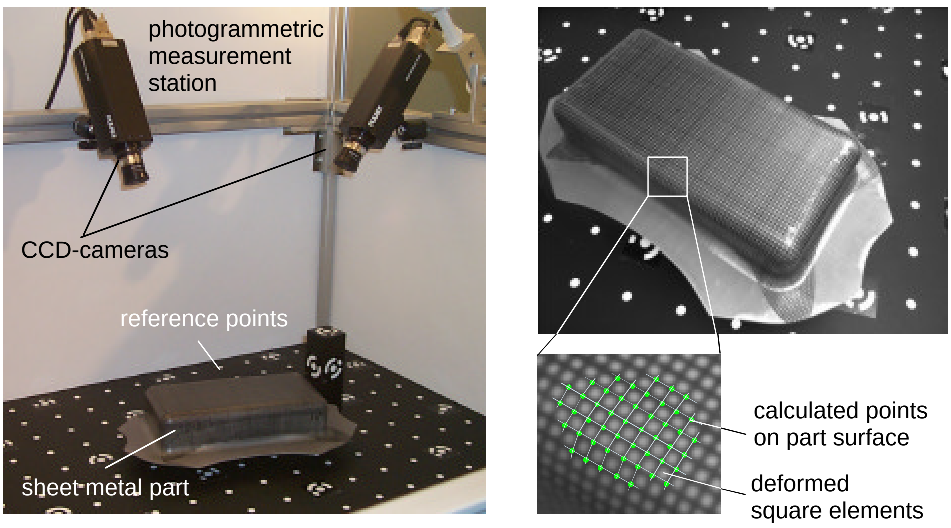

Figure 8: Photogrammetric measurement system

The size of the measuring cell and the number of cameras is flexible and depends on the size and the complexity of the stamping. The current cell consists of 4 Pulnix TM 1300 cameras with 1300 x 1030 sensor elements and different illumination components. The cameras are controlled by a Mikrotron framegrabber and allow a synchronous image acquisition. 32 cameras can be added to the system. For the measuring of surfaces a projection unit has been integrated. The whole system is controlled by a NT-Workstation for the image processing, data evaluation and visualization of results.
The software includes modules for the calibration and orientation of the cameras. In a first step all necessary parameters for interior and exterior orientation are determined, using a calibration field with coded targets, which is integrated in the measuring cell /26/. For the calibration process a resection with additional determination of camera parameters is used. After calibration a fully automatic measuring of the printed or projected grids can be done.
The similar algorithms for the strain and surface measurement are object based. Starting from one point the algorithm predicts new points at the surface and does a measurement in at least two images. With the results of this measurement object points are predicted, projected to the images, measured and directly re-projected to the object. This measuring strategy allow to consider the local shape of the object and to predict the local shape for the further measurements. One advantage of the system is the use of more than two cameras. Critical or disturbed object details can be measured from different positions. This possibility make the system more robust against reflections.
The current measuring time of approx. 400points/second is sufficient for the foreseen application. The accuracy of the system depends on the object size and the number of images, which are used for the determination of the grid points and is between 1:20000 and 1:50000 of the object size.

5 APPLICATION EXAMPLES OF THE DEVELOPED SYSTEM

In the following the main features of the new photogrammetric measurement system are demonstrated with two examples representing typical applications in sheet metal forming. In the first example the acquisition of the surface geometry of an aluminum car seat component with grid projection is described. The second example exhibits the strain analysis of a rectangular model stamping part utilizing visioplasticity. The verification of the measured data is performed with results of a finite element (FEM) simulation.

5.1 Surface geometry measurement of a seat component

The measurement of the stamping part surface geometry is important to achieve information about shape deviations caused by dents, sink marks and especially springback of the sheet material. In this case the springback behavior of a car seat component made of the aluminum alloy AA5182 with a sheet thickness s_0 = 1.0 mm and a surface area of 500 x 500 mm was examined. Since analyzing springback only requires the surface geometry instead of a fixed grid projected light was applied.
Therefore, a square grid was vertically projected onto the flat part's surface (Figure 9a). The applied customary slide projector was additionally equipped with a light source control to adjust contrast between the shaded grid lines and the illuminated part's surface. A special sized slide (30 mm x 30 mm) was used to achieve the largest possible projection area. The distance of the vertically projected grids was approx. 2.5 mm.

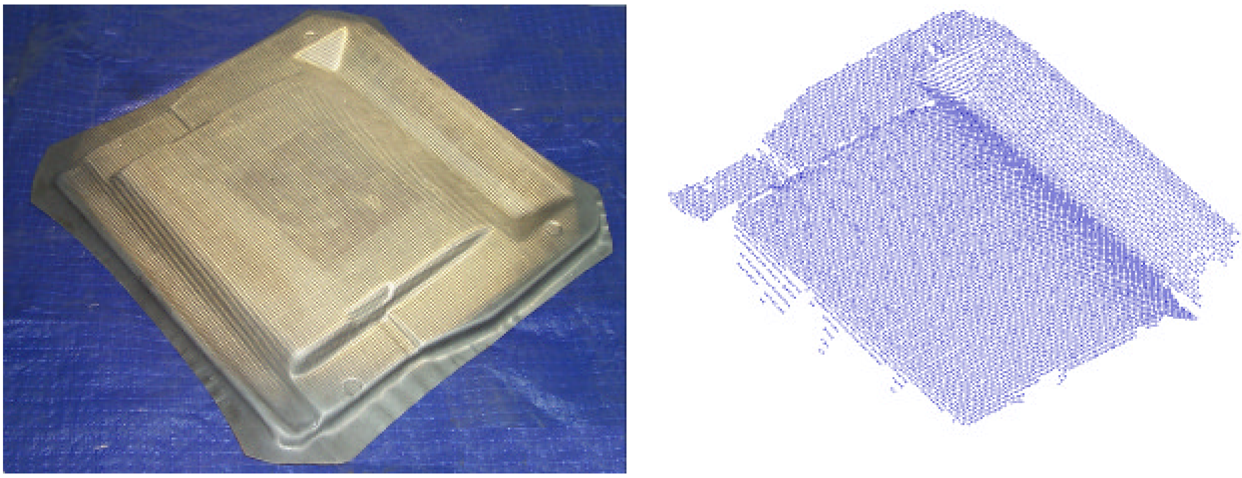

Figure 9: Square grid projection on a seat component (a) and measured 3D-point cloud (b)

The images were taken from different directions using four CCD-cameras. The 3D-surface shape data (approx. 30.000 measured points) were gathered by the photogrammetric evaluation of the images (Figure 9b). The comparison of the

measured 3D-point cloud with the CAD model of the stamping part supplies a statement about geometrical deviations of which relevant springback parameters (e.g. the bottom curvature) can be derived.
The vertical projection of square grids using one projector is sufficient for the surface acquisition of flat-shaped parts. For more complex stamping part geometries additional projectors and cameras are necessary. With respect of error-free image processing overlapping of the projections have to be prevented. Therefore, further investigations have to be made to synchronize the CCD-cameras and projector units. An alternative method may be the contemporaneous overlapping of colored grids, which presupposes the use of different optical filters and modifications of the image acquisition software algorithms.

5.2 Strain analysis of a rectangular model part

This second example demonstrates the strain analysis of a rectangular model stamping part utilizing the method of visioplasticity.
For the calculations of the strain-state it is necessary to process the 3D-coordinates of points, which are fixed on the parts surface. The software algorithms for the surface measurement (either projected or fixed grid) are similar. An additional software module for the visioplastic analysis using algorithms similar to those published in /21,22/ was developed at IFUM and implemented in the proposed system.
To apply fixed grids on the sheets different marking techniques (e.g. electrochemical etching, laser marking and printing) have been investigated at IFUM. As a result of the tests silkscreen printing yields the best results concerning applicability for different sheet materials. Surface reflection behavior due to different sheet coatings and illumination, wear resistance, which are of particular importance to achieve accurate grids and a sufficient contrast for the image processing, were taken into consideration as well.
For the investigations experimental deep drawing tests as well as FEM simulations were performed. Following the procedure of the investigations is explained with one example:
A zinc coated blank sheet out of the soft steel grade DC05 (sheet thickness s_0 = 1.0 mm) was marked with a 2.5 mm square grid using silk-screen printing technique. For the deep drawing a rectangular model tool (220 mm x 110 mm) was used. For the strain analysis especially the transition area between the punch radius and the side walls in the corner areas are of special interest, since the highest strain rates and - in case of failure – the occurrence of optimum cracks /27/ can be observed here.
A comparison between the major strains φ_1 calculated with measured data and by FEM-simulation is shown in Figure 10. For the simulation of the deep drawing process the FEM software "PAM STAMP" was used.

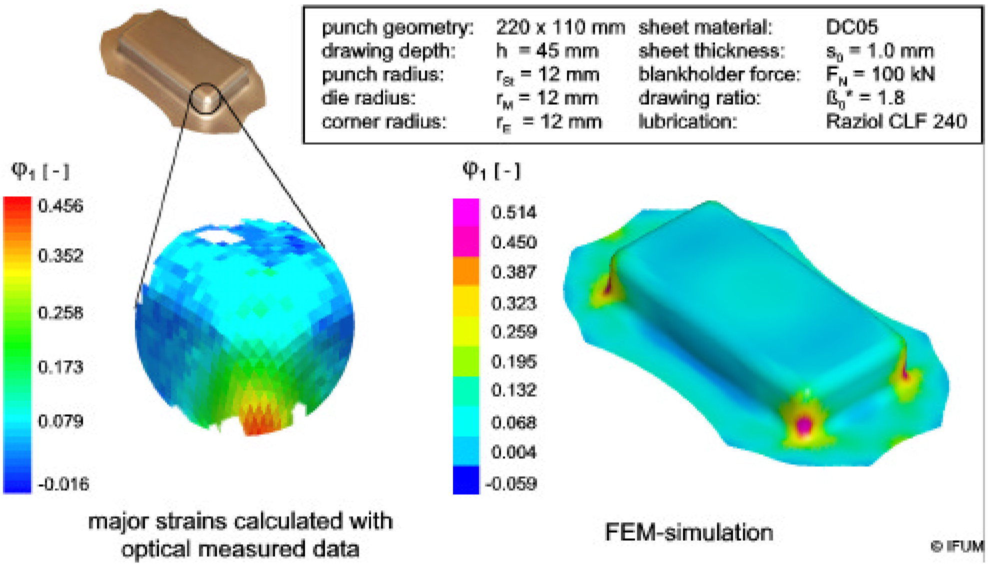

Figure 10: Verification of a FEM-simulation by automated strain analysis

As shown in Figure 11 and 12 the principal strains φ_1 and φ_2 were plotted in forming limit diagrams (FLD). As expected all strains are located below the forming limit curve (FLC), which was determined in former investigations. Therefore, in the investigated corner area no critical strain state is determined. A comparison of both forming limit diagrams shows a comparatively high coherence ($\Delta\varphi < 4$ %). Major strain φ_1, minor strain φ_2, principal strain direction, effective strain φ_V (von Mises), sheet thickness s and thinning Δs can either be visualized with a 3D-viewer or exported into ASCII files.

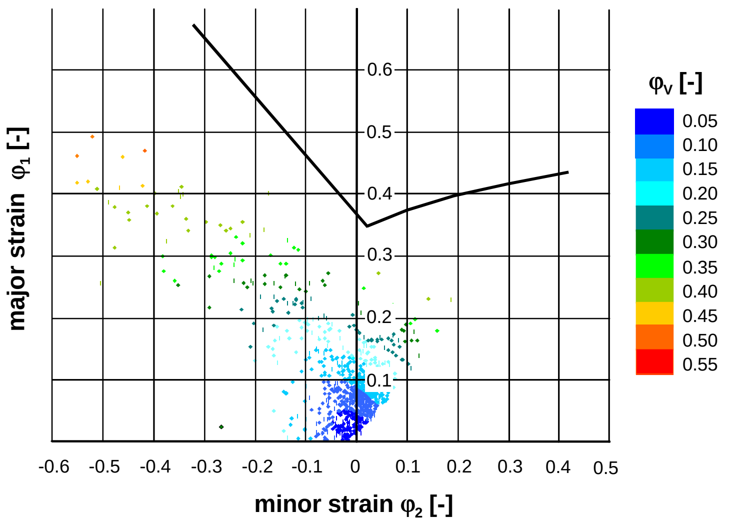

Figure 11: FLD (calculated from measured data) and FLC

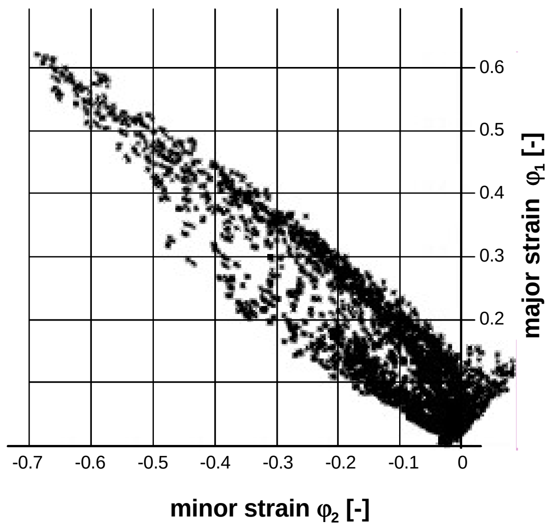

Figure 12: FLD (FEM-simulation)

6 CONCLUSION

The quality of a car body is substantially determined by the stamping parts. This results in increased requirements on the accuracy of the stamping parts produced in press shops. However, these requirements can only be fulfilled by an optimal layout of the forming process and a 100% quality control in the press shops both during the tool try-out and during the production by means of optical measuring techniques.
Therefore, a new photogrammetric measuring system for the assessment of sheet metal parts in terms of shape accuracy and strain distribution has been developed within the Brite/EuRam project “DIGIMAN”. Based on the optically measured geometric parameters of the stamping part the system is able to detect deviations from the desired geometry with springback analysis and critical strain distributions utilizing visioplasticity. A first prototype was installed at the Institute for Metal Forming and Metal Forming Machine Tools (IFUM) of the University of Hanover. In the future it is planned to implement further industrial photogrammetric systems for the measurement of large-size outer-body panels with adequate accuracy in press shops at different car manufactures and producers of sheet metal parts.

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