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TESTING MATERIALS FOR MODELLING HYDROFORMING

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Abstract: This paper presents experimental procedures, based on different tests, for evaluating the formability limits in the hydroforming process which are capable of generating formability data suitable for an FE modelling of the process. The Nakazima and bulge test allows for determining the yield stress up to considerably higher forming degrees than with a conventional tensile test. Both cases of hydroforming metal sheets and tubes are described. These procedures combined with an optical system deliver exact and relevant data of the quality and degree of the stamping process.

1. INTRODUCTION

Hydroforming is a forming process of hollow sheet parts by fluid pressure. In the beginning of its formation, this process was used only for producing tube-shaped parts. However, as time went on, sheet parts such as autobody parts were included among the products of this method. Hydroforming of sheet metals has four major types including (fig.1) hydrostatic deep drawing, hydrodynamic deep drawing, single-sheet forming at high internal pressure (single-sheet hydroforming) and forming a pair of sheets with a high internal pressure (hydroforming of a pair of sheets).

Knowledge of forming limits is important throughout the entire product design to production cycle. First is the computerized forming process development (virtual die tryout), which requires forming limits for the selected steel type and grade to assess the forming severity (hot spots) for each point on the stamping. Next is the process and tool design stage where specific features of the tooling are established and again computer-validated against forming limits for the specific steel. Troubleshooting tools for die tryout on the press shop floor utilize forming limits to assess the final severity of the part and to track process improvements. Finally, forming limits are used to track part severity throughout the production life of the part as the tooling undergoes both intentional (engineering) modifications and unintentional (wear) changes.

An additional important field of application for FLDs are numerical simulations of transformation processes. The FLC of the material used represents characteristic material identification data for the forming simulations.

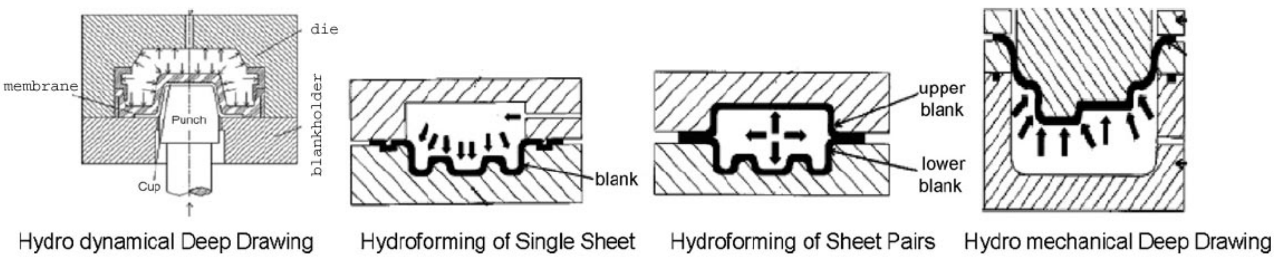

Fig.1. Sheet hydroforming types

Several tests are commonly used to determine the formability of sheet metal at room temperature, such as the uniaxial tension test, the cupping tests, the bulge test and the tests to determine the limiting dome height (LDH) and the forming limit diagrams (FLD).

2. NAKAZIMA TEST

The Nakazima test is a known method to determine the forming limit curve of sheet metal materials.

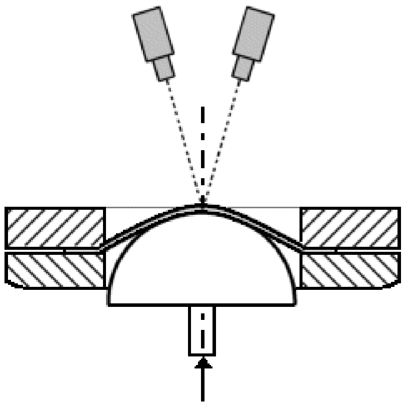

Fig.2. Nakazima test

The Nakazima test is based on the principle of deforming sheet metal blanks of different geometries using a hemispherical punch until fracture occurs (fig. 2). By varying the specimen width, different deep draw and stretch forming conditions occur on the sheet metal surface (from a regular biaxial deformation to a simple tensile load). The characteristic, maximally achievable deformations (prior to breakage) of the different specimen shapes are determined and define the forming limit curve of the corresponding material. So far, a forming limit curve was generally determined by applying a pattern of circles and lines to the sheet metal blanks prior to the forming process. Due to the load on the sheet metal, these circular marks deform to ellipses, the main axes of which represent the strain on the surface in major and minor direction. After the forming process, the "deformed" line patterns were measured manually using measuring magnifying glasses, microscopes and flexible measuring strips. This method is limited by the contour sharpness of the deformed pattern, the time-consuming evaluation, the low local resolution and the subjective and user-dependent recording of measurement values.

In order to meet today's requirements, the characteristics of sheet metal materials must be determined precisely, reproducibly and efficiently. By using the optical measurement system ARAMIS, the preparation of the specimens, the forming process and the determination of the deformation characteristics can easily and reproducibly be carried out such that today exact material characteristics are available at low costs.

3. THE STUDY OF FORMABILITY BY OPTICAL ANALYSIS

By using the optical measurement system ARAMIS, which combines the advantages of photogrammetry with the advantages of the object grating method, the preparation of the specimen and the whole evaluation process for the determination of FLDs can be shortened and the overall costs can be reduced significantly. Photogrammetry is one of the optical methods which leads to the 3D-coordinates of surface points. From this data one gets the displacement vectors, the local strain values, and the contour difference, if the object is deformed. When the object points on the surface of the specimen are arranged like a grating, this is the technique well known in experimental mechanics as grating method. Instead of an expendable line mesh, a stochastic pattern is applied to the surface using a graphite spray that allows a very high local resolution. Due to appropriate calculation methods, the resolution can be increased to sub-pixel range.

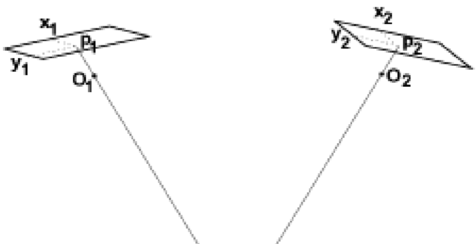

Fig. 3. Diagrammetric arrangement

The photogrammetric arrangement used consists of two cameras and a loading device, where the specimen is placed. The recording devices and the surface must form a triangle. The cameras set up the base. Figure 3 shows the diagrammetric arrangement and the schematic drawing of the optical arrangement.

If the position of the two cameras and two homologous image points p_1 (x_1; y_1) and p_2 (x_2; y_2) are known, the corresponding object point P (X; Y; Z) can be calculated. This procedure is well known as space intersection. Therefore, a geometric model must be defined, which describes the transformation from image points to object points. To describe the transformation from image points to object points, the perspective projection model, that can be described with a collinear assumption, is used. Additional to the parameter of the rotation matrix and the parameter of the projection center, that are known as exterior orientation, the interior orientation parameters of the camera are necessary. They must be calculated through a calibration procedure. For this procedure a special calibration object is needed that has small circular targets with well known diameters attached on the surface. During the calibration process, the calibration object must be recognized with the two cameras from several views.

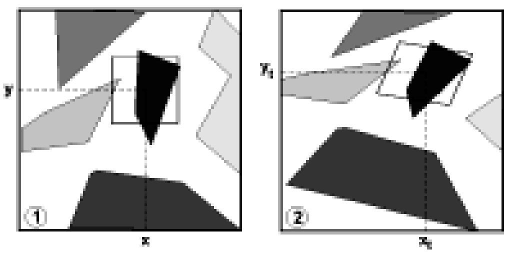

Fig.4. 2D intensity distribution

The goal of the displacement determination is the calculation of the object coordinates for each deformation state for each point P. Here it is important that the point P with the coordinates (X; Y; Z) in the non-deformed state can be found in each deformed state with its new coordinates (X_t; Y_t; Z_t). Only in this case, the displacement and strain can be calculated for this object point. The calculation of homologous image points of two deformation states recognized from two cameras can be achieved by a combination of three 2D displacement calculation processes (fig.4).

Here it is important that one image is defined as the reference state. After determining all 2D displacement fields, the homologous image points can be easily calculated. All image points x_{pi}, y_{pi} describe the same object point. With this information, the object coordinates for each state can be calculated by space intersection.

After the determination of the displacement field, the strain distribution can be numerically calculated. One way to calculate the surface strain is through the transformation of the 3D displacement distribution into a 2D displacement distribution. After doing this, the strain can be calculated in the 2D spaces. This algorithm can be described with the following steps: for each of the object points P_u and P_v a tangential plane is calculated. For this purpose, the object points in the neighborhood are used (fig. 5a). This rectangular area is referred to as the object facet.

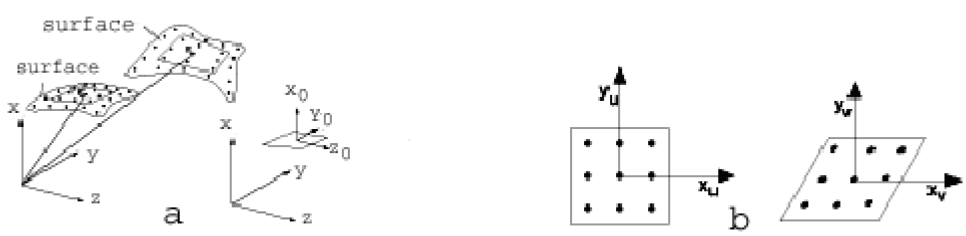

Fig. 5. a - Determination of the tangential planes b - Projection onto tangential plane

The object points in these object facets are projected onto the tangential plane. This must be done in the direction of the normal vector of the tangential plane. Therefore, the

problem can be defined as 2-dimensional (fig. 5b). The calculation of the deformation gradient can be completed as described in the literature.
In conclusion, the optical measurement system ARAMIS allows a high local resolution and highly precise strain analyses in sheet metal forming. The measurement procedure is based on the determination of the displacements of the sheet surface structure during the forming process. Through the possibility of the determination of a stochastic structure on the one hand the local resolution is very high, but also the preparation time for the surface structuring is shortened in comparison to conventional etching methods. Using the optical strain measurement ARAMIS a procedure is described to determine the forming limit diagrams of sheet materials.

4. HYDRAULIC BULGE TEST FOR TUBES

As tubular hydroforming becomes a competitive process for the mass production of automotive parts, a tube's material properties must be consistent. To predict variations in material properties, many tube producers use the uniaxial tensile test. Because the specimens for the tensile test are collected before a tube is bent and welded, they are not always accurate. To predict variations in tube property accurately, it should be tested under a biaxial state of stress.
Variations in tube material properties may result in a high scrap rate, reduced productivity, and the need for a large inventory. Variations are unavoidable if the tubes are manufactured from strips either supplied by different companies or from coils from one supplier but from different heats or batches.
The forming limit diagram (FLD) of tubular materials ought to be established, because it directly influences the formability of the hydraulic forming processes.

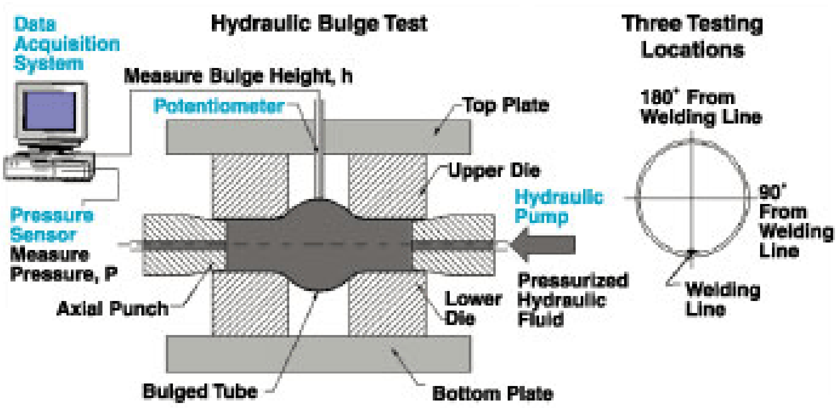

Fig.3. Hydraulic bulge test [4]

It is known that within one tube, its properties can vary along its circumferential direction because of roll forming and welding operations. Material properties can vary from one tube to another even if they are manufactured from the same coil because of variations in the material properties of the sheet along its width.
Formability is an important characteristic in tube hydroforming. Various parameters are available to measure formability, such as bulge height at the bursting pressure and the percentage of wall thinning. The hydraulic bulge test simulates the state of biaxial stress a tube undergoes during hydroforming
During each bulge test, a tube's internal pressure and bulge diameter are continuously measured and pressurized until the tube bursts (fig.3). This data is used to calculate the tube's wall thinning percentage. These results are plotted on a bar graph to compare the formability of different tube sets.
By determining material properties of different sets of tubes manufactured from the same coil, we can study the effect of the hot-rolling operation on sheet material properties across its width. Studying the formability around a tube's circumference leads to conclusions about the effects of bending and welding operations around its circumference.

During tube hydroforming, several forming parameters, including the loading path, material properties, die design, and friction at the tube–die interface, significantly influence the results.
The hydraulic bulge test allows measurements of the hardening behavior up to strains of about twice those achieved in uniaxial tension.

5. PNEUMATIC BULGE (BIAXIAL) STRETCHING

It is known that Nakazima test results (hence the generated FLCs) are dependent on many experimental conditions; primarily, die and punch geometries, blank holder force, lubrication, deformation rate (punch speed), sheet thickness, and the criterion for determining the end of the test [5]. The last point is a major issue in any mechanical testing method, which motivated a recent effort by Geiger and Merklein [2] to develop a new method for detecting the onset of necking by the existence of load instability.

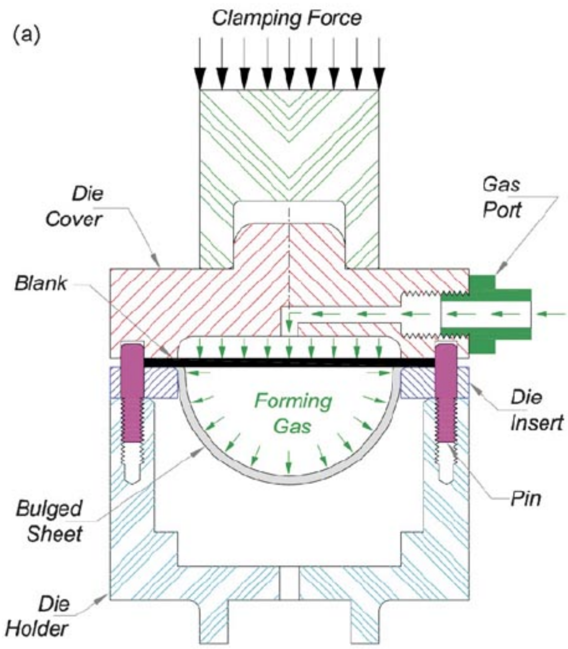

Fig.4. Pneumatic bulge test [1]

Pneumatic stretching (bulging) represents an attractive alternative to mechanical punching, promising a more representative and accurate determination of forming limits in sheet metals.
A schematic of the pneumatic bulging (stretching) setup used in this investigation is shown in fig. 4. A blank is secured between a die mask and a die cover, by a compressive clamping force. The blank is formed by pressurized argon gas; the pressure of which is prompted and controlled via an electronic pressure controller. Four elliptical die inserts (masks) are used to produce ellipsoidal bulged domes with different biaxial strain ratios (fig.5). The selected aspect ratios (k) are 1.0 (circular), 0.8, 0.6 and 0.4. These geometrical aspect ratios represent the ratio between the minor and major axes of the elliptical die inserts, and do not necessarily equal the biaxial strain ratio at the apex of the bulged ellipsoidal dome.

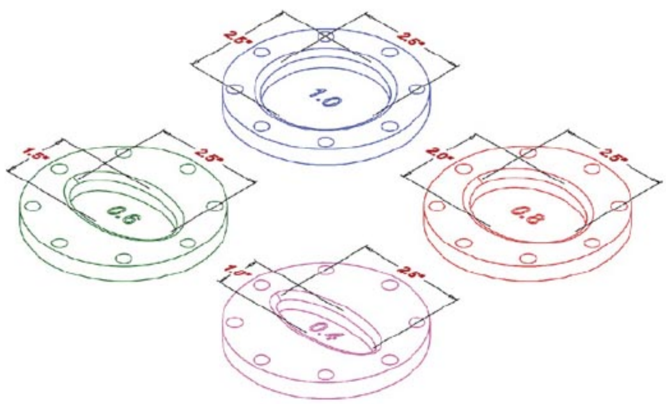

Fig.5. Elliptical die inserts with different aspect ratios

For each die insert, a die cover was prepared with a matching elliptical recess, in order to ensure perfect clamping and eliminate any possibility for slippage or sheet drawing during forming. Holes in the die inserts and covers fit two pins in the die holder to guarantee their alignment. The bulging setup was designed to have a broad range of applicability, mirrored by the selected temperature and pressure limits.

6. CONCLUSIONS

To determine the biaxial yield stress by means of the Nakazima and bulge test, a sheet metal board is clamped between the blank holder and the stamper and is loaded with pressure. By continuously increasing the pressure, the specimen is further loaded biaxially and deformed until failure. The equation to determine the yield stress is based on the membrane theory and therefore is used preferably for a low sheet metal thickness.

Due to the biaxial state of stress, the material failure by local necking and following crack occurs considerably later with the bulge test than with the tensile test (uniaxial state of stress). The bulge test allows for determining the yield stress up to considerably higher forming degrees than with a conventional tensile test.

Thus, the ARAMIS system combined with a conventional sheet metal test machine is an excellent method to improve the determination of the yield stress for simulation calculations and other applications.

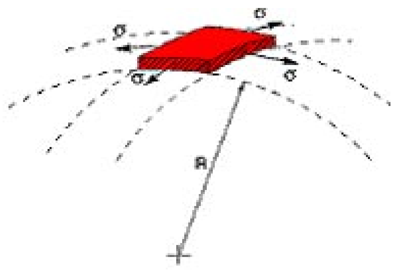

Fig.6. Representation for the local biaxial yield stress

Due to the synchronous recording with two cameras, stereo image pairs result (left and right image). By comparing the deformed pattern with the original pattern, the respective current deformation state can be determined. Such images are recorded for the entire image sequence from the beginning of the deformation up to the breaking and are then evaluated. ARAMIS can thus record and evaluate the complex deformation process of the specimen until it breaks.

In the bulge test, the effective material load (yield stress) is determined by the current shape of the specimen, the equivalent total strain at the top of the dome and the current pressure. The flow curve is calculated from the oil pressure, the local shape (curvature) and the current thickness of the sheet metal at the top of the dome of the specimen (fig. 6).

ARAMIS allows high-resolution, easy and precise recording and evaluation of deformation tests. The measuring data is graphically displayed and converted to current material characteristics. In addition, local effects are captured and represented thus allowing for a complete understanding of the local material behavior during the forming process.

The determined local characteristic values now allow for precisely calculating in advance the material behavior during the forming process such that optimum tool shapes can be generated with the simulation.

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