POSSIBILITIES OF USING THE ERICHSEN TEST FOR DETERMINATION OF FORMING LIMIT DIAGRAM AND ITS UTILIZATION FOR HYDROFORMING

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Abstract

Forming limit diagrams (FLD) are used to determine process limitations in sheet metal forming, i.e. as a level of formability assisting in the estimation of stamping characteristics. This paper deals with the experimental determination of a forming limit curve (FLC) using the Erichsen test. In this case, FLC of an austenitic stainless steel X5CrNi18-10 is obtained by performing the Erichsen test with different shapes of specimens. Furthermore, utilization of FLD for evaluation of a hydroforming process is shown in the second part of the paper.

Keywords: Erichsen test, formability, hydroforming, FLD

1. INTRODUCTION

For the production of sandwich panels with a structured surface, a hydroforming technology is successfully used. For this purpose, the austenitic chromium-nickel stainless steel X5CrNi18-10 is used as a blank material. However, in some cases, defects occur during the hydroforming operation - cracking. Therefore, a numerical analysis using the finite element method (FEM) is used to optimize the hydroforming process. Forming limits should be determined for correct evaluation of FEM analysis. If the determination of forming limits using elementary experimental analyzes, e.g. tensile test diagram characteristics, is not considered, then limit curves (zones) of the forming limit diagram (FLD) are a typical analysis, which is aimed at detecting of forming limits of the stamped material. Since the state of strain close to the plane strain is expected at the critical points of the hydroformed part, the objective is to construct the FLD, which is affecting this area. For this purpose, the Erichsen test is used. [1], [2]

2. EVALUATION OF THE FORMING LIMIT DIAGRAM

Analysis of fracture initiation and propagation in sheet metal forming is one of the most basic and widespread analysis. In this case, limit curves of the FLD are a typical analysis, which is aimed at detecting of forming limits of the stamped material. In the forming limit diagram, curves that represent a divide between the safe area and the material failure zone are constructed in a coordinate system representing principal engineering strain (ε_1 and ε_2) or principal true strain (φ_1 and φ_2). An experimental path of the FLC construction is based on an assumption that the material will break in the place with a maximum value of the sheet metal thinning. In this place, necking of the material is realized, i.e. local strain. For this case, a grid strain analysis (grid marking) is used to identify critical places of the stamped part and to evaluate principal strains in these places. A suitable grid is applied on the evaluated part, before its deformation. After the forming operation, the deformed grid is evaluated. In principle, the grid most often consists of circle elements which will become ellipses unless deformation is pure biaxial stretching. Besides basic curves indicating material failure (risk of cracks), areas of other defects, such as wrinkling area, can also be determined in the diagram. In the diagram, after its construction, deformation points are plotted, i.e. values of the major strain on surveyed locations of the stamped part. [3], [4] From the point of view of the circular grid element, there are basically two cases of its geometry changing, see **Figure 1**. Values of the principal true or engineering strain can be determined by the conversion from the obtained dimensions of the deformed elliptical shapes. The classical equation for determining of the circular grid deformation is given by (1).

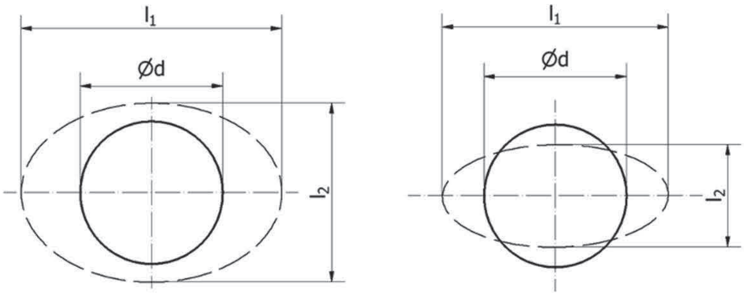


Figure 1 Possible changes in the circle grid element shape

$$\varphi_i = \ln\frac{l_i}{d} = \ln\frac{d+\Delta l_i}{d} = \ln(1+\varepsilon_i) \tag{1}$$

where φ_i [-] is the principal true (logarithmic) strain, l_i [mm] is the dimension of the ellipse axis, d [mm] is the initial diameter of the circle, ε [-] is principal engineering strain.

The FLD construction takes into account multiple states of strain (stress). Therefore, the experimental determination of the FLD should be based on the basic material tests which correspond to the load conditions. Basically, for the experimental determination of the FLC, ISO 12004-1 standard allows the use of any test equipment, which is able to achieve a different strain state during the plastic deformation of the test specimen with using of holding and drawing tools. More precise laboratory determination of the FLC is then prescribed by ISO 12004-2, namely by using of Marciniak test or Nakajima test. Nevertheless, a wide range of testing methods can be used for the FLC evaluating, such as Hasek test, Keeler test, Swift test, Erichsen test, hydraulic bulge test, uniaxial tensile test, etc. Some methods are used for evaluation of the FLC in its entire range for both (positive and negative) φ_2 values. Other methods are applicable only for the small area of the FLC, eventually only for the point of the FLC. [5]

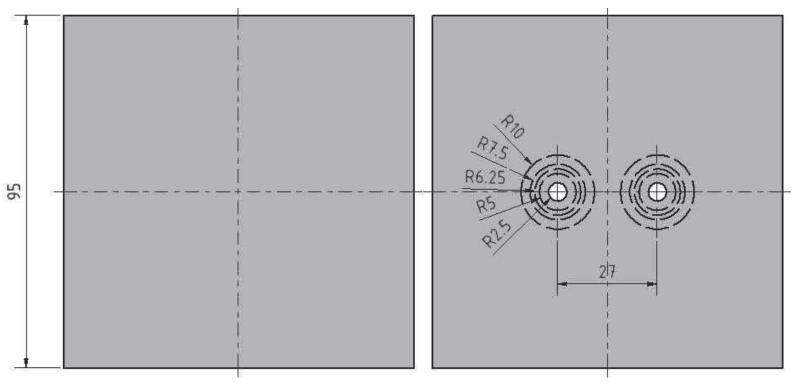
3. MATERIAL AND EXPERIMENTATION

As it was previously stated, austenitic chromium-nickel stainless steel X5CrNi18-10 is the tested material. The main mechanical properties of X5CrNi18-10 sheet metal with thickness of 0.5 mm, determined by performing the uniaxial tensile test, are summarized in **Table 1**.

Table 1 Material properties of X5CrNi18-10 steel

Yield strength	$R_p0.2$	[MPa]	282.8
Tensile modulus	E	[MPa]	$1.99 \cdot 10^5$
Ultimate tensile stretch	R_m	[MPa]	700.1
Poisson ratio	μ	[-]	0.30
Density at 20 °C	ρ	[kg · m^3]	$7.90 \cdot 10^3$

For evaluation of the FLC, the Erichsen deep drawing test was used, a testing equipment Erichsen F4 respectively, with Erichsen Index (IE) evaluation accuracy of 0.001 mm. Material tests were performed on 3 sets of 6 different types of specimens geometry with circular holes, as it is shown in **Figure 2**, for each tested thickness. Overall, two thicknesses of material were tested (0.5 mm and 0.8 mm). After measurement, results from 3 sets of samples were averaged.



Specimen 1 Specimen 2 to 6

Figure 2 Geometry of specimens

For determination of critical strain values, applying of the grid to the tested specimens is necessary. In this case, the grid with circular shape elements of 2 mm diameter was applied to the specimens. The detail of the applied grid is shown in **Figure 3**. For this purpose, an electrochemical etching method was used, see the principle in **Figure 4**. The shape of the grid is determined by a stencil, which is placed on the surface of the specimen (sheet metal). Then, an electric current, which is conducted by an electrode over a felt pad with an electrolyte, affects the stencil (the electrode rolls over the felt pad). By the pressure loading of the electrode, the electrolyte is extruded from the felt pad thru the stencil onto the surface of the sheet metal and the corresponding grid is etched. [6]

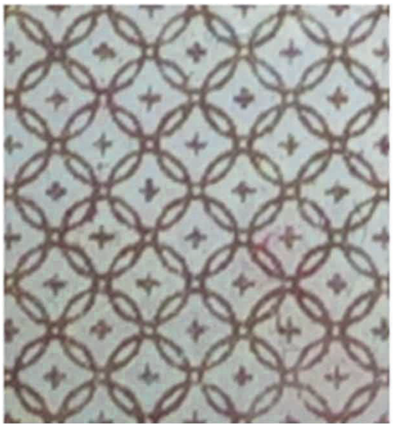


Figure 3 Detail of the grid

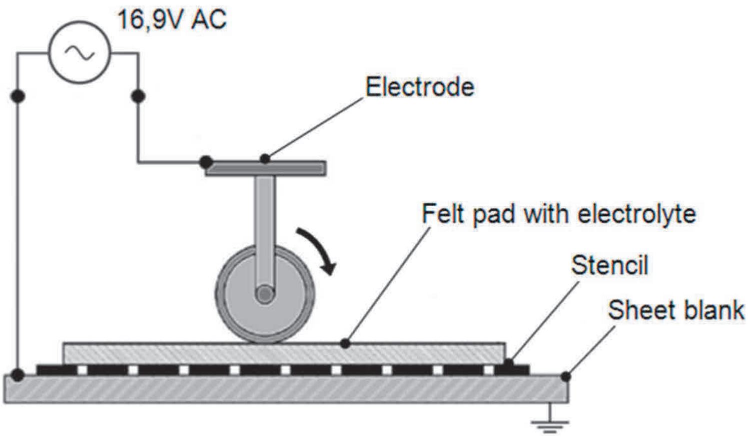


Figure 4 Principle of the electrochemical etching method [6]

After application of the deformation grid, specimens were subjected to the Erichsen test using a testing equipment Erichsen F4. Specimens were clamped to the device so that their centers coincide with the center (axis) of the drawing tool (punch). In this case, the punch is acted to the center of the specimen and its holes are deformed symmetrically. **Figure 5** shows one set of deformed specimens 0.8 mm thick after the test.

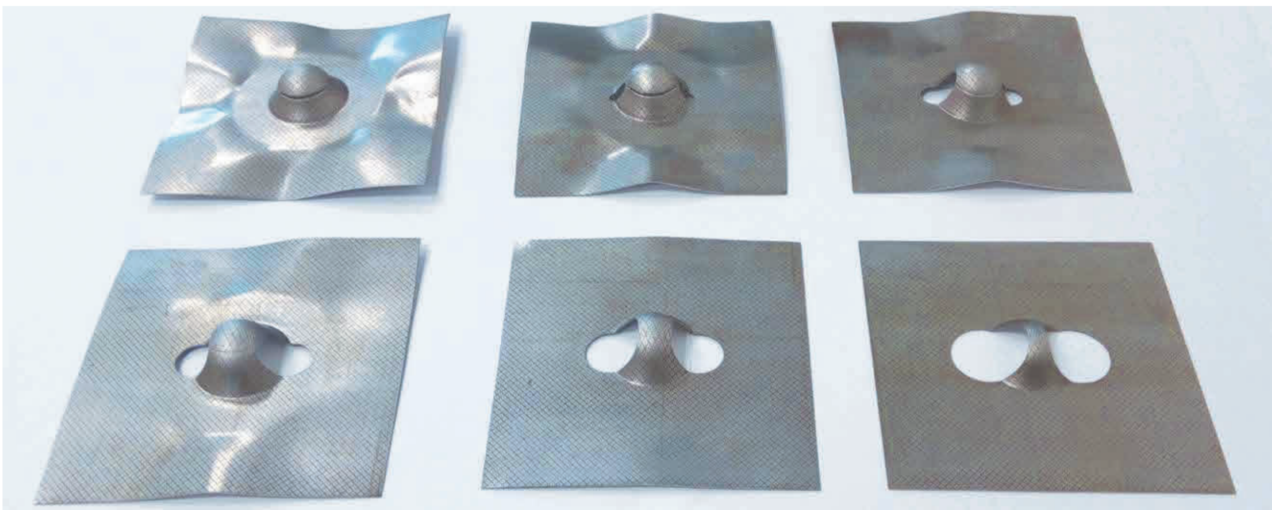
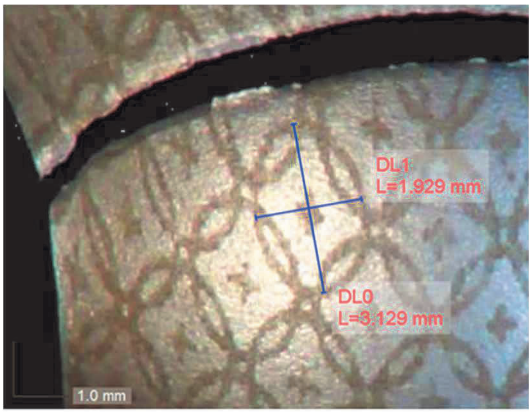


Figure 5 Geometry of specimens after the Erichsen test

After the Erichsen test, deformed grids around cracks were analyzed on all specimens. Measurements were carried out microscopically using computer aided image analysis. The SSM-3E stereo microscope with a USB camera, was used for evaluation of the grid ellipses dimensions. Evaluation of observed specimens was performed using PC and Dino Capture 2 software, respectively. Determination of ellipses dimensions by the microscopic measurement is shown in **Figure 6**.



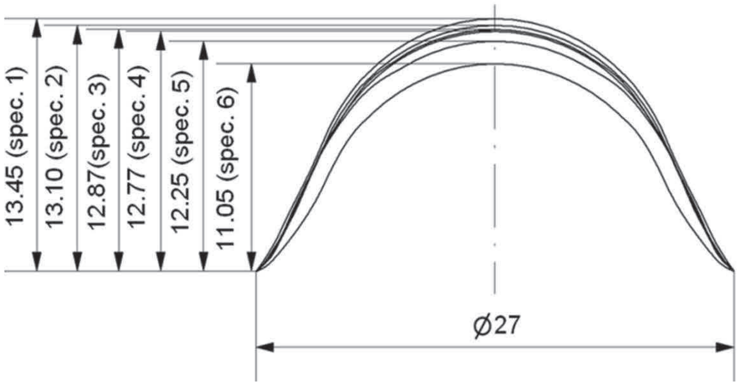


Figure 6 Evaluated grid

Figure 7 Shapes of deformed specimens

Before the FLD construction, results affecting by the curving of the specimens geometry was investigated. **Figure 7** shows deformed specimens shapes for one set of deformed specimens 0.8 mm thick after the Erichsen test. After this shape correction of results, the FLD for two thicknesses of X5CrNi18-10 steel (0.5 mm and 0.8 mm) was constructed, see **Figure 8**. Each point of the diagram represents averaged values of 3 measurements on the specimen (evaluation of the grid ellipses dimensions).

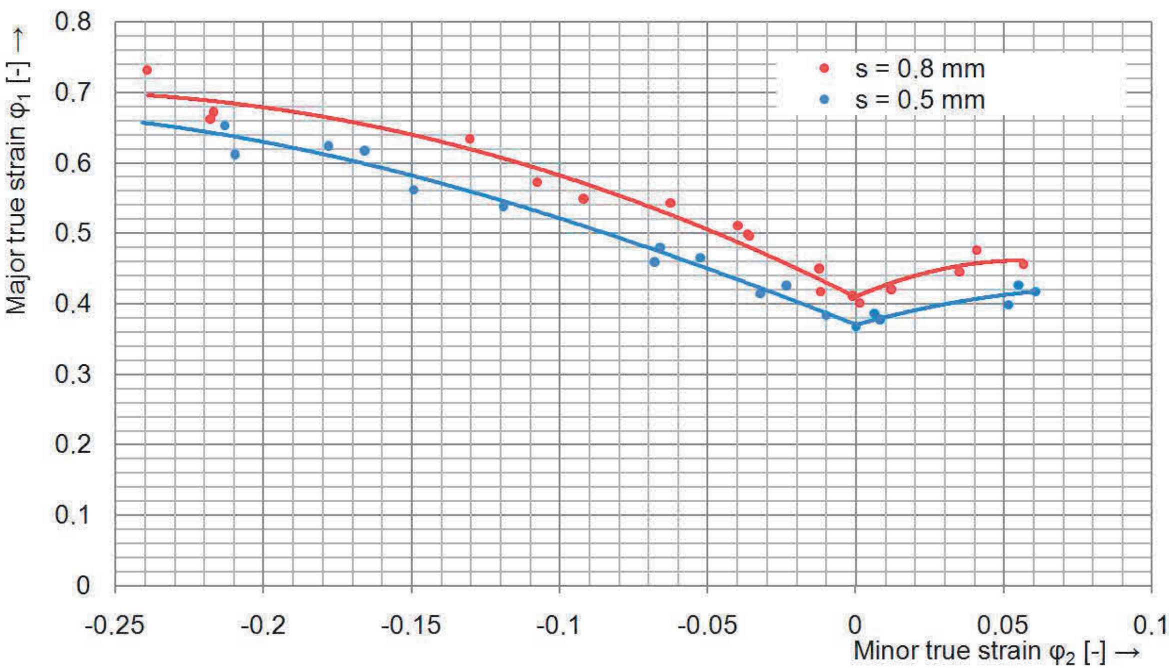


Figure 8 Forming limit diagram for X5CrNi18-10 steel

4. UTILIZATION OF THE FLD FOR THE NUMERICAL ANALYSIS OF HYDROFORMING

Constructed FLD curves were used for sheet metal formability analysis during the hydroforming of the sandwich panel structured surface, which is a set of pyramidal cavities. Manufacturability of the structured surface using the pillow hydroforming was tested on specimens with the formed area dimensions of 150 × 150 mm. Each specimen consists of two sheets, which are welded by a laser beam welding around the formed area. For this purpose, a hydroforming device was used, see **Figure 9** and **Figure 10**.

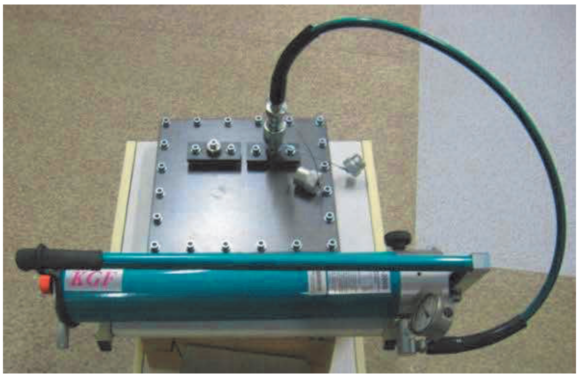


Figure 9 Hydroforming device with hydraulic pump

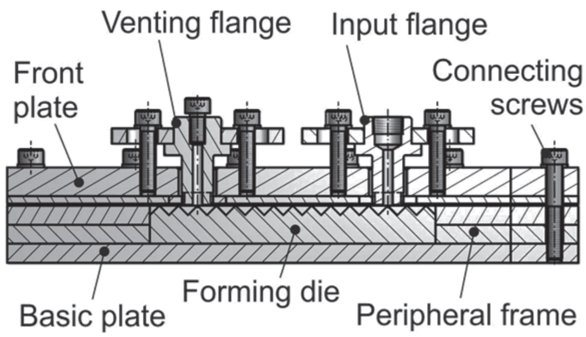


Figure 10 Cross section of hydroforming device [7]

An example of the hydroformed specimen with the structured surface, which is formed by a pyramidal structure with an apex angle of 60° is shown in **Figure 11**. An initial thickness of the specimen was 0.8 mm. As a result of insufficient rounded of the die edges (1mm radius), defects were occurred on the top of pyramids during the hydroforming process for forming pressure of 650 MPa, see **Figure 12**.

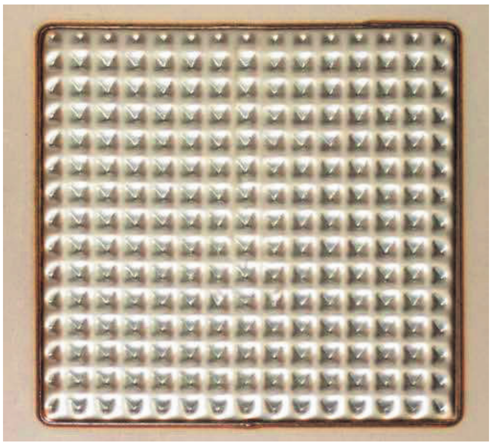


Figure 11 Hydroformed specimen

Figure 12 Detail of the defect - crack

Therefore, the hydroforming process was analyzed by the finite element method using ANSYS LS-DYNA software. For simplicity of a calculation, a symmetry of the part was used and therefore it was calculated only with half geometry. **Figures 13** and **14** show the results of the forming limit analysis for the hydroformed part.

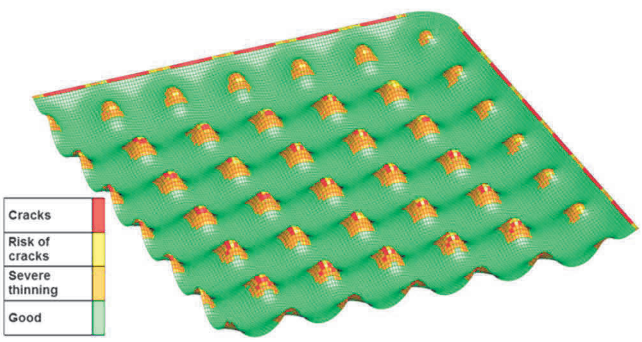


Figure 13 Formability analysis

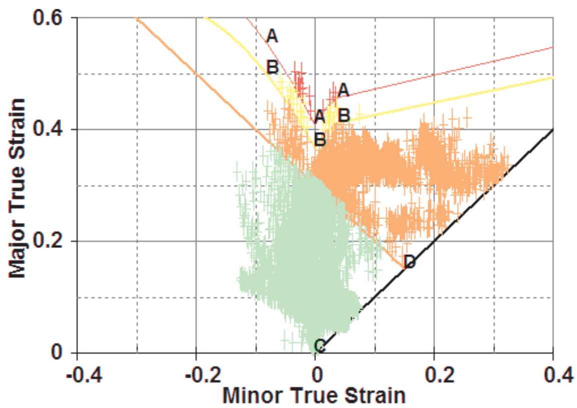


Figure 14 Forming limit diagram

As it is apparent from the FEM analysis, when the die is rounded with a radius of 1 mm then the FLC is exceeded, i.e. defects are created. With the formability analysis using FLD, safety radius of the hydroforming die was found as 2 mm. With this rounding value, the part can be formed without problems, as it is shown in **Figure 15** and **Figure 16**, i.e. FLD for the above-mentioned hydroforming die adjustment.

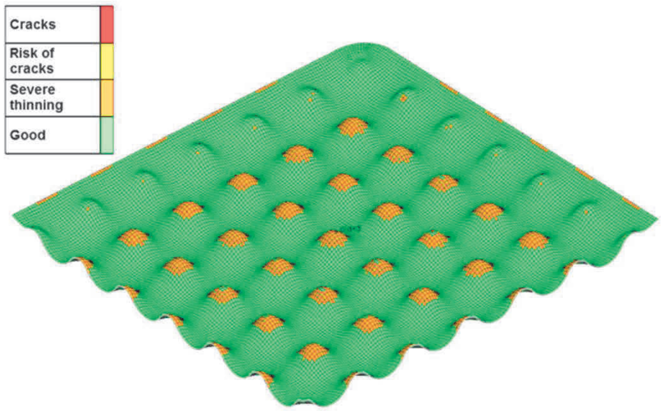


Figure 15 Formability analysis

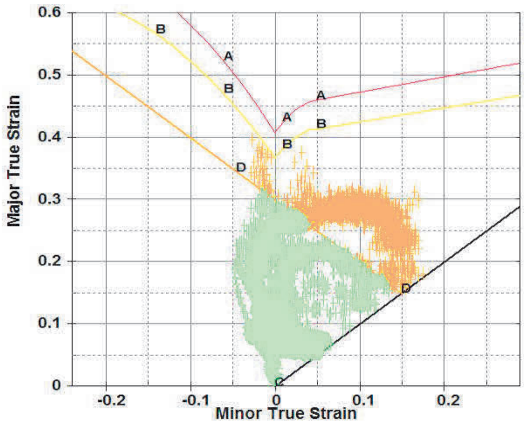


Figure 16 Forming limit diagram

5. CONCLUSION

In this paper, the experimental determination of the FLD for X5CrNi18-10 steel was constructed. For this purpose, the Erichsen test was performed with different shapes of specimens. Experiments have demonstrated the ability to construct the FLC for a fairly wide range of minor strain by this way. The usability of the constructed FLC was verified in the formability analysis of the hydroformed part with the structured surface using FEM analysis, in which the FLC was also used for optimization of the hydroforming die shape.

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