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Development of a new procedure for the experimental determination of the Forming Limit Curves

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ABSTRACT

The objective of the paper is to define a new method for the experimental determination of the Forming Limit Curves (FLCs). The procedure is based on the hydraulic bulging of two specimens. The most important advantages of the method are the capability of investigating the whole strain range specific to the sheet metal forming processes, simplicity of the equipment, and reduction of the parasitic effects induced by the friction, as well as the occurrence of the necking in the polar region. The comparison between the FLCs determined using the new procedure and the Nakazima test shows minor differences.

1. Introduction

The formability of metallic materials reflects their capability to undergo plastic deformation until reaching a given shape without defects. The defects that occur during the sheet metal forming processes are necking, fracture, wrinkling or a significant degradation of the surface quality. Any of these defects can be considered as a limiting criterion of the formability. At present, the Forming Limit Curve (FLC) is an instrument widely used for the quantitative description of the sheet metal formability. Various methodologies have been proposed for the experimental determination of the FLCs.

Gensamer [1] was the first researcher who performed a thorough analysis of the strain localization phenomena in the case of sheet metals evolving along different load paths. He published a formability diagram that could be considered as the precursor of the FLCs. Keeler [2] and Goodwin [3] extended the concept proposed by Gensamer by determining a limit curve expressed by pairs of principal strains associated to different load paths located in the tension–tension and tension–compression domains, respectively. Later on, the research was focused on improving the techniques used for grid printing, strain measurement, and definition of the limit strains, as well as on developing the equipment and methodologies suitable for exploring the whole strain range of the FLCs [4]. An exhaustive presentation of this research is given in [5] and new developments in the prediction of the FLCs in [6].

The FLC should cover the entire deformation domain specific to the sheet metal forming processes. In general, the strain combinations span between those induced by uniaxial and equibiaxial surface loads. The subsequent discussion will insist on the experimental methods commonly used for investigating the deformation domain of the FLCs.

The uniaxial tension of flat specimens having circular notches (proposed by Brozzo and de Lucca [7]) allows the exploration of the tension-compression range (left branch of the FLC). By using relatively wide specimens, it is also possible to reach the plane strain point. As a conclusion, the uniaxial tension is suitable only for investigating the positive–negative domain of the FLC.

The positive–positive region (right branch) of the FLC can be reproduced in a hydraulic bulging device equipped with dies having circular or elliptic apertures. Different load paths belonging to the tension–tension domain result by varying the eccentricity of the elliptic aperture [8].

Other procedures used for the experimental determination of the FLCs are those based on the punch stretching principle. Keeler [2] was the first researcher who adopted such a method. He used circular specimens and spherical punches with different radii in order to modify the load path. In general, the punch stretching test developed by Keeler is able to investigate only the right end of the tension–tension FLC branch. Hecker [9] extended Keeler's methodology to the whole tension–tension domain by improving the lubrication of the contact surface between punch and specimen. A notable development of this experimental procedure is due to Nakazima [10]. He used a hemispherical punch having a constant radius in combination with rectangular specimens with different widths. In this way, Nakazima was able to explore both the tension–compression and the tension–tension domains of the FLC. By using circular specimens with lateral notches, Hasek [11] removed the main disadvantage of Nakazima test, namely the wrinkling of the wide specimens.

In order to reduce the frictional effects in the case of the flat punch drawing test, Marciniak [12] developed the so-called double blank method (specimen placed on the top of a carrier blank). He was able to obtain different load paths by modifying the cross section of the punch (circular, elliptic or rectangular). Grosnostajski [13] improved Marciniak's test by changing the geometry of the specimen and carrier blank.

Fig. 1 [11] compares the results provided by different experimental methods developed in the seventh and eighth decades of the previous century. One may notice that none of those procedures are able to reproduce the whole deformation domain of the FLC. Aiming to overcome this drawback, as well as

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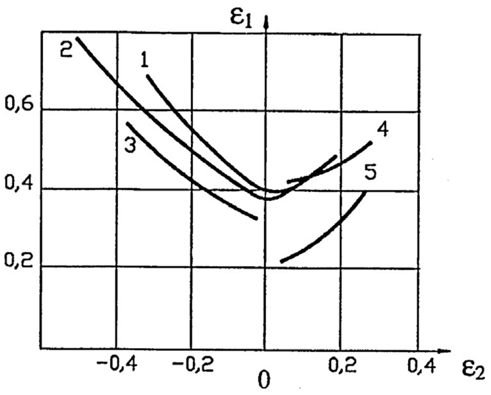

Fig. 1. FLCs determined using different experimental methods: 1—Hasek; 2—Nakazima; 3—uniaxial tension; 4—Keeler; 5—hydraulic bulge test [11].

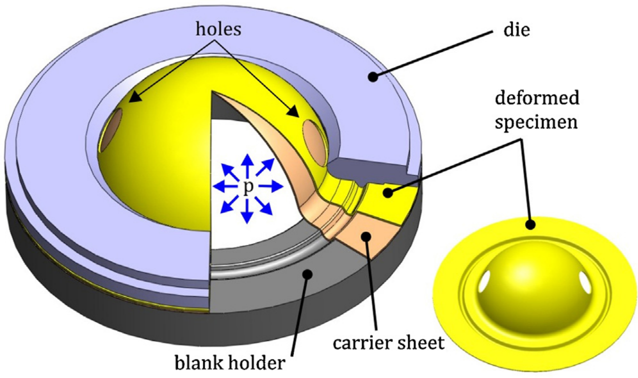

Fig. 3. Schematic view of the new formability test.

the discrepancies of the limit strains provided by different methodologies, a specialized IDDRG workgroup elaborated a standard proposal for the FLC determination recommending the use of the Nakazima or Marciniak tests. The proposal issued by IDDRG was subsequently adopted at international level in the form of the ISO 12004 standard [14]. A description of the experimental procedures analyzed by the IDDRG workgroup and their comparison by means of a "robin test" performed in different laboratories participating in the standardization activity is given in [15]. A presentation of the determination of the FLCs is described in [16] a new method to define the limit strains in [17].

The authors of this paper propose a new procedure for the experimental determination of the FLCs. The methodology is based on the hydraulic bulging of a double specimen. The upper blank has a pair of holes pierced in symmetric positions with respect to the centre, while the lower one acts both as a carrier and a deformable punch. By modifying the dimensions and position of the holes, it is possible to investigate the entire deformation range of the FLC.

2. New experimental procedure for the FLC determination

2.1. Comparison between the new procedure and Nakazima test

Fig. 2 presents a schematic view of the Nakazima test. In the case of this experimental procedure, the sheet specimen is firmly clamped between the die and the blank holder, while the hemispherical punch forces the specimen to deform in the space provided by the circular aperture of the die. The most important disadvantage of the Nakazima test is related to the parasitic effects of the frictional interactions between punch and specimen. Due to these interactions, the strain localization does not occur in the polar region of the specimen. According to the standard ISO 12004 [14], the specimens affected by fracture occurring far from the pole are not relevant and should not be used for the determination of the FLC. Another disadvantage of this method consists in the fact that, besides the specimen clamping, the hydraulics of the experimental device should also assure the ascending–descending motion of the punch. These actions generally increase the complexity of the laboratory equipment needed to perform such a formability test.

Aiming to overcome the disadvantages mentioned above, the authors developed a new experimental procedure based on the hydraulic bulging principle. It is well known the fact that, in its standard version, the hydraulic bulging is only able to reproduce an equibiaxial load state in the polar region of the specimen. The capabilities of this experimental test can be extended if the specimen has a pair of holes pierced in symmetric positions with respect to the pole. Of course, the presence of the holes creates a technical problem, namely the need of sealing the hydraulic chamber of the experimental device. The solution of this problem consists in placing a carrier blank under the pierced specimen. The carrier acts both as a transmitter of the increasing pressure developed by the hydraulic agent and a deformable punch.

Fig. 3 presents the principle of the new formability test. One may notice that the pierced specimen and the carrier blank are firmly clamped between the die and the blank holder. The bulging of the specimen and carrier is caused by the increasing pressure applied on the lower surface of the carrier.

The geometric characteristics of the pierced specimen are the dimensions and the reciprocal distance of the holes. By varying these parameters, it is possible to obtain different load paths during the hydraulic bulge test and, consequently, to investigate the whole deformation range of an FLC. The methodology proposed in this paper allows determining at least five different points on the FLC, in accordance with the specification of the standard ISO 12004-2.

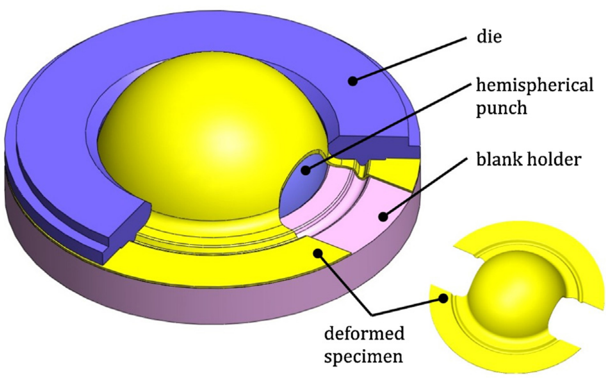

Fig. 2. Schematic view of the Nakazima test.

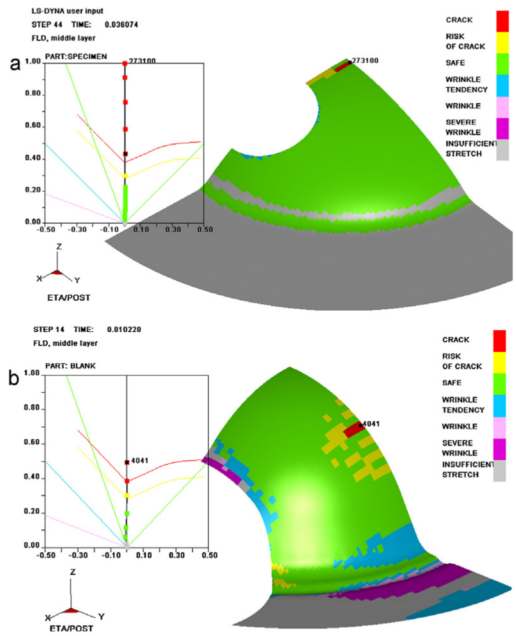

Fig. 4. Localization of the fracture zone for (a) new test and (b) Nakazima test, respectivelly (strain path corresponding to the plane-strain case).

The main advantage of the new experimental procedure consists in the reduction of the frictional effects that may alter the values of the limit strains. This characteristic is a consequence of the small relative sliding of the pierced specimen on the surface of the carrier blank. Because of the reduced amount of frictional interactions, the fracture always occurs in the polar region (see Fig. 4). The simplicity of the laboratory equipment is another advantage that encourages the use of the hydraulic bulging test.

2.2. Numerical simulation of the double specimen bulging process

As mentioned above, the geometric characteristics of the pierced specimen are the dimensions and reciprocal distance of the holes. By modifying these parameters, it is possible to control the strength of the portion located between the holes and, consequently, to determine the evolution along different strain paths of the polar region. If this region is sufficiently narrow, the polar strain path will be located in the tension–compression domain (left branch of the FLC). The evolution in the tension–tension domain is favoured by an increased distance between the holes as well as by the reduction of their dimensions. In general, the presence of the holes will always cause the occurrence of the fracture in the polar area.

The geometric parameters of the specimens allowing the determination of five distinct points located on the FLC have been established by numerical simulation. With this aim in view, a finite element model of the hydraulic bulging test has been prepared using the DYNAFORM programme. The simulation model includes the pierced specimen, the carrier, as well as the die and the blank holder. The dimensions of the die aperture have been defined as follows: diameter 100 mm and fillet radius 6 mm. The pierced specimen and the carrier blank have been modelled as deformable shells. The nominal thickness of 1 mm has been set for the pierced specimen, its base material being an AA6016-T4 aluminium alloy (as defined in the DYNAFORM material library). In the case of the carrier blank, the 0.85 mm nominal thickness has been set, the base material being DC04 plain carbon steel (also defined in the DYNAFORM material library).

Both the limit values and their evolution until the occurrence of the fracture have been analyzed in each test. Fig. 5 provides a synthetic presentation of the numerical results obtained in the case of the AA6016-T4 aluminium alloy. The results provided by the hydraulic bulging experiments performed with the same geometries of the specimens are also plotted on the diagram. One may notice a very good agreement between the numerical simulation and the experimental data, as well as the fact that the characteristic strain paths are closed to linearity in all cases. These aspects confirm the capability of the new methodology to provide accurate values of the strains needed for the experimental determination of the FLCs.

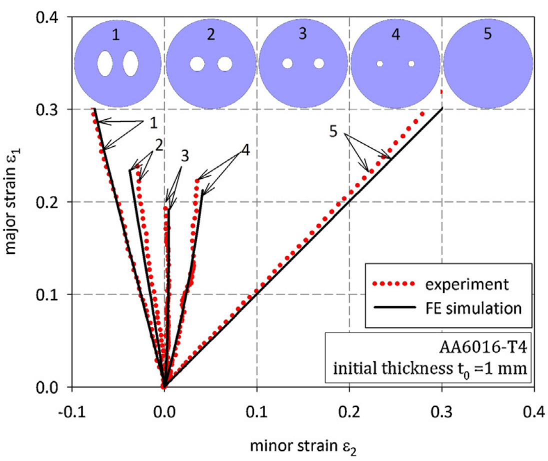

Fig. 5. Strain paths obtained in the hydraulic bulge tests: comparison between the numerical simulation and experimental data.

2.3. Geometry of the specimens

As mentioned in the previous section of the paper, the optimum geometry of the pierced specimens has been established by numerical simulation of the hydraulic bulge tests. The final results of the computations are presented in Table 1 and Fig. 6.

Aiming to obtain a point in the closed vicinity of the uniaxial tension state, the circular holes have been replaced with elliptic ones (see also Fig. 5 – strain path 1). The strain path associated to the equibiaxial load state (strain path 5 in Fig. 5) has been experimentally reproduced by conventional hydraulic bulging (performed in the absence of the carrier blank and using circular specimens without holes). The geometric characteristics of the specimens resulted from the numerical simulation have been tested in a series of experiments aiming to assess the feasibility of the procedure.

Table 1
Characteristic dimensions of the specimens (see also Fig. 6).

Specimen no.	1	2	3	4	5
$a \times d$ (mm)	As in Fig. 6	52×28	60×20	60×12	0×0

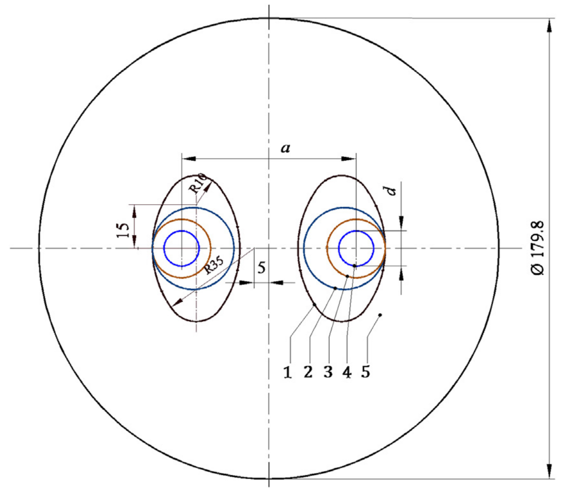

Fig. 6. Geometric parameters of the specimens.

3. Experimental methodology

Fig. 7 shows the experimental device used to determine the FLCs by hydraulic bulging. The equipment consists in a universal sheet metal testing machine ERICHSEN model 142-20 and an

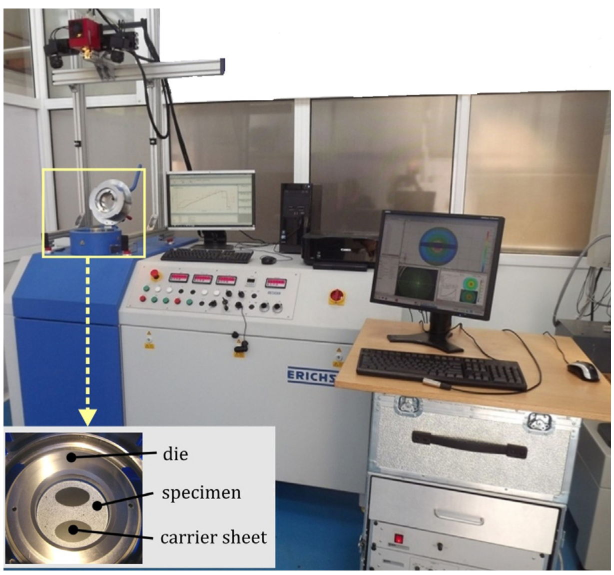

Fig. 7. Equipment used for the experimental determination of the FLCs.

Table 2
Mechanical parameters of the AA6016-T4 aluminium alloy sheet having the nominal thickness of 1 mm.

Angle from RD	$R_{p.02}$ (MPa)	R_m (MPa)	r	σ_b (MPa)	r_b
0°	139.26	264.26	0.64	140.76	1.05
45°	137.23	261.22	0.53		
90°	136.30	260.10	0.64		

ARAMIS optical strain measurement system. The evaluation of the limit strains conforms to the specifications of the international standard ISO 12004-2.

The specimens used in the hydraulic bulging tests have been cut using a laser system from AA6016-T4 aluminium alloy sheets having the nominal thickness of 1 mm. The dimensional characteristics of the specimens are shown in Table 1 and Fig. 6. As previously mentioned, the carrier blanks have been cut from DC04 plain carbon steel sheets having the nominal thickness of 0.85 mm. The most relevant mechanical parameters of the AA6016-T4 aluminium alloy sheet are listed in Table 2. These values have been established by uniaxial tensile tests performed on specimens cut at angles of 0°, 45° and 90° measured from the rolling direction, as well as by biaxial tensile tests performed along the rolling and transverse directions (last two columns of Table 2 which list the biaxial yield stress and the biaxial coefficient of plastic anisotropy).

4. Results

Five sets of hydraulic bulging tests have been performed using the methodology presented above. The geometric characteristics of the specimens used in the experiments have been established according to the data given in Fig. 6 and Table 1. For all specimens the fracture is located in the polar region. This fact is benefic for the accuracy of the strain measurement with optical systems. The localization of the fracture at the pole also proves that the friction between the specimen and the carrier blank is negligible.

Fig. 8 compares the FLCs obtained using the methodology proposed by the authors and the Nakazima test (according to the specifications of the international standard ISO 12004-2). In both cases, the limit strains have been measured using the ARAMIS system. Each measuring point represents the mean value of three specimens. The limit strains have been determined according to the standard ISO 12004-2 methodology implemented in the ARAMIS system. One may notice from Fig. 8 that the limit strains obtained in the plane-strain case (corresponding to the strain path 3 in Fig. 5) are almost the same for both methodologies. In the uniaxial and biaxial regions, the FLC obtained when using the new methodology is slightly translated to lower values of the principal strain ε_1. This fact is in agreement with the theoretical considerations presented in the literature (see, for example, Fig. 9.7 in Ref. [18]). Because the fracture takes place at the pole in the case of the hydraulic bulge test, the corresponding limit strains are smaller than in the case of the hemispherical punch stretching. When the rigid punch is used (Nakazima test), the frictional interactions reduce the strain level in the polar region and distribute the strain over a larger area. This leads to a better formability of the sheet metals subjected to the hemispherical punch stretching.

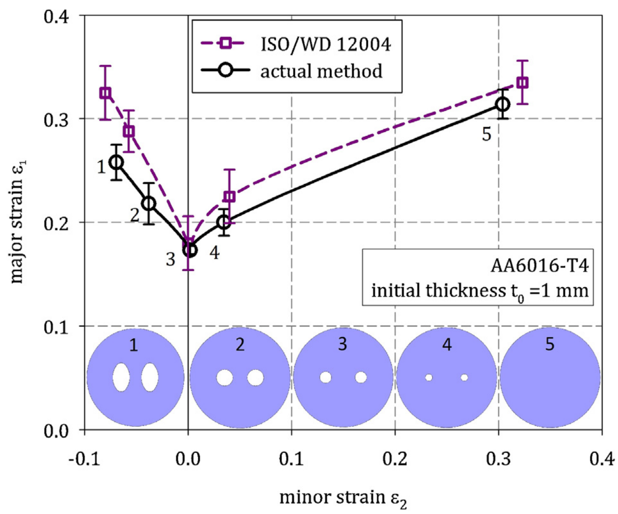

Fig. 8. Forming Limit Diagram of the AA6016-T4 sheet metal.

5. Summary and conclusions

This paper describes a new procedure for the experimental determination of the FLCs. The methodology is based on the hydraulic bulging of a double specimen. The upper blank has a pair of holes pierced in symmetric positions with respect to the centre, while the lower blank acts both as a carrier and a deformable punch. By modifying the dimensions and reciprocal position of the holes, it is possible to investigate the entire deformation range of the FLC. The most important advantages of the method proposed by the authors are the following ones: capability of investigating the whole strain range specific to the sheet metal forming processes; simplicity of the equipment; simplicity of the specimen configuration; reduction of the parasitic effects induced by the frictional interactions between the specimen and the other elements of the experimental device; occurrence of the necking and fracture in the polar region of the specimen. One should also mention two disadvantages of the bulging test: limitation of the specimen thickness due to the maximum pressure achievable by the hydraulic equipment and dependence of the fracture conditions on the accuracy of the specimen positioning in the formability testing device.

Acknowledgements

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