Modular device for determining forming limit curves – a cost effective approach

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Abstract: The paper presents the realizing and functioning of a modular device for testing the formability of metal sheets. By using the device it is possible to realize experimentally the tests needed for drawing the forming limit curves using the Nakajima and Marciniak methods, but there can be also done researches on deep-drawing. The results gathered from the tests were validated by numerical simulations using the finite element method. The device was designed at the Research Center for Metal Forming of the “Lucian Blaga” University of Sibiu and realised with the support of S.C. Uzina Mecanica Marsa – Sibiu

1. INTRODUCTION

The forming limit diagram (FLD) was developed by Keeler and Backofen, being an efficient way for assessing the formability of metal sheets. FLD is a representation of planar strain space for proportional loading combination of major and minor strains ranging from drawing condition on the left, plane strain loading in the center, and biaxial stretching on the right, as shown in figure 1. FLD represents the limit condition between the safe and unsafe areas with respect to plastic deformation (Banabic et al., 2000).

![Forming limit diagram](image1)

Fig. 1. Forming limit diagram (Hsu et al., 2008)

The most common methods for measuring sheet forming limits are the Nakajima test, which uses a hemispherical punch and a circular grid for the analysis and measurement of strains and the Marciniak test which uses a flat punch and circular grid for the analysis and measurement of strains test and figure 3 is a representation of the Marciniak test.

![Nakajima test](image2)

Fig. 2. Nakajima test (Hsu et al., 2008)

While the Nakajima test is complicated by strain gradients due to friction, normal loading, and bending, the Marciniak test provides in-plane stretching without the influence of friction. In the Marciniak test, a sheet sample is mated with a carrier blank and clamped at the binder. The flat punch stretches the material until failure, which should occur in the unsupported zone, center (pole region) of the sample. Ghosh and Hecker explained the differences between in-plane and out-of-plane stretching and concluded that while the Nakajima test measurements related very well to the stamping of automotive parts, the measured out-of-plane forming limits were larger than those of in-plane stretching. They attributed these higher limits to a different instability condition and a slower strain localization process for out-of-plane stretching. The effects of friction, bending, and tooling
geometry in the Nakajima test influence the migration of fracture location from the balanced biaxial pole position toward the plane strain condition at the upper die entry radius. Strain localization and fracture in the Nakajima test normally occurs near the line separating the punch contact and the unsupported region of the sample (Hsu et al., 2008).

1.1 Deep drawing

Deep drawing is a cold stretch-forming process in which a flat blank of sheet metal is shaped by the action of a punch forcing the metal into a die cavity. The metal is not clamped with draw beads and thus is allowed to slide into the cavity; the bottom of the cup experiences biaxial stretching. Deep drawing differs from other drawing processes in that the depth of the drawn part can be greater than its diameter (fig. 4).

2. DESCRIPTION OF THE EXPERIMENTAL SETUP

2.1 Employed machines and materials

The device designed at the Research Center for Metal Forming was conceived for realising the tests needed for drawing the FLD using the Nakajima and Marciniak methods, but also for tests regarding deep drawing. For this, the device was designed in a modular manner, the active part being exchangeable.

The device allows testing metallic sheet-type blanks with a thickness comprised between 0.5 and 1.2 mm and a maximal tensile strength of 600 MPa.

Figure 5 presents the principle structure of the device.

The active elements - punch, die and blankholder - for the Nakajima and Marciniak tests were designed according to (ISO 12004-2:2008) and for the deep drawing tests, a set of 12 dies were designed for blanks with thicknesses of 0.5, 0.8, 1, 1.2 mm, in which the die radius has been modified. For the Nakajima and Marciniak test, the authors used a blankholder with blocking ribs, while for the deep drawing, a flat ring was used.

The forces needed for the deep drawing and for the blankholding, respectively, are realised with two hydraulic systems: one having a single hydraulic cylinder (figure 6), on which the punch is fastened, and one comprising 4 hydraulic cylinders (figure 7) that will fasten the blank. If it is necessary to block the blank in place, there can be used also blocking screws that fasten the blank between the blankholder and the die.
The hydraulic system for deep drawing develops a force of 200KN, while the blankholding one a force of 100 KN. The linear hydraulic motor has a maximal hub of 250 mm, while the hydraulic motors for blankholding have a maximal hub of 120 mm. The forces required for the deep drawing and for the blankholding, respectively, are indirectly controlled by means of the pressure. The pressure's measurement is done by means of the pressure sensors (S₁ for the deep drawing cylinder and S₂ for the blankholding cylinders), fastened in the hydraulic system at the intake of the linear hydraulic motors. The pressure sensors are connected to a computer by means of the data acquisition device Keithley KPCI 3108 (figure 8). The deep drawing speed can be varied in the range of 1-2 mm/s by modifying the flow inside the hydraulic cylinder using the throttle valve.

Fig. 6. Hydraulic system for the deep drawing cylinder (T - Tank;  F – Filter; P - Pump;  VM – Pressure valve; D₁ – Directional valve 4/3; D₂ – Directional valve 2/2; Dr - Throttle valve; S₁ – Pressure sensor; MHL – Linear hydraulic motor; E₁, E₂, E₃ – Electromagnets; M – Electric motor)

Fig. 7. Hydraulic system for the blankholding (T - Tank;  F – Filter; P - Pump;  VM – Pressure valve; D₁ – Directional valve 4/3; D₂ – Directional valve 2/2; Dr - Throttle valve; S₂ – Pressure sensor; MHL1, MHL2, MHL3, MHL4 – Linear hydraulic motors; E₁, E₂, E₃ – Electromagnets; Electric motor)

The data are acquired, archived, analysed and presented by means of the specialised software package Matlab produced by the company MathWorks. Beneath the archiving of the acquired data, the software realises also a conditioning of the signal (filtering, scaling, data analysis - statistical processing, measurement) and a graphical presentation of the data on a display or on paper, using a printer. The collected data are stored on magnetic memory devices.

The virtual instrument created in the Matlab software is presented in figure 9. The signals are received, by means of the conditioning modules, by the acquisition device on the two channels, on the first channel from the pressure transducer integrated in the hydraulic circuit for actuating the hydraulic cylinder that drives the punch and the second channel from the pressure transducer from the blankholding hydraulic circuit that drives the blankholding ring. The two electrical signal are transformed from electrical voltage into pressure by means of a multiplying block. The multiplication factor was determined individually for each transducer, using a gauging process.

The deformations were measured using an optical analyser Aramis 2M. Aramis is a non-contact optical 3D deformation measuring system. Aramis analyses, calculates and documents material deformations. The graphical representation of the measuring results provides an optimum understanding of the behavior of the object to be measured.
The optical analyser allows the indirect checking of the forming speed, because the Aramis system is able to determine in real time the deep drawing depth and time.

Fig. 9. Virtual instrument for data acquisition and processing

The practical realising of the device was possible with the help of S.C. Uzina Mecanica Marsa – Sibiu (figure 10).

Fig. 10. Experimental device

2.2. Results

The installation for drawing forming limit curves was tested with a sheet of magnesium alloy AZ31B with a thickness of 1 mm (Girjob et al., 2006). For this test, the authors used the Nakajima method, the punch being hemispherical. The forming limit curve obtained for the analysed alloy AZ31B is presented in figure 11.

The experimentally obtained results were compared to those obtained theoretically, by numerical simulation using the finite element method for the circular sample. In order to compare the results, there were analysed the distributions of the maximal and minimal strains and the variation of the sample's thickness. For the experimental part, the strain distribution maps were realised using the software associated with the optical strain measurement system - Aramis, which was used for measuring the sample. The results were compared for a punch displacement of 28.175 mm.

For the maximal strains $\varepsilon_1$ (fig. 12, fig. 13), there can be noticed a similar distribution in the two types of analyses, the theoretical one and the experimental one. The maximal main strains are reached in the pole area, their values being of 0.1369 in the case of the numerical simulation and of 0.1372 in the experimental case. These values decrease with the increase in the distance from the forming pole. The material's anisotropy is reflected in larger strains of the nodes placed on the material's rolling direction and in smaller strains on the transversal direction.

Fig. 11. Forming limit curve for the sheet of magnesium alloy AZ31B

Fig. 12. Distribution of the maximal strains, determined experimentally

Fig. 13. Distribution of the maximal strains, determined through numerical simulation
The distributions of the $\varepsilon_2$ strains (fig. 14, fig. 15) are also similar in the two cases, the theoretical analysis and the experimental analysis. Their maximal values are reached in the pole area, they being of 0.1172 in the case of the numerical simulation and of 0.1174 in the experimental case. These values decrease with the increase in the distance from the forming pole. For these strains, it can be noticed that the values of the strains, corresponding to each colour gradient, are distributed along an ellipse whose axes are oriented along the rolling direction and along the transversal direction, respectively. The material's anisotropy is reflected in larger strains of the nodes placed on the material's transversal direction and in smaller strains on the rolling direction.

Fig. 14. Distribution of the minimal strains, determined experimentally

Fig. 15. Distribution of the minimal strains, determined through numerical simulation

With regard to the change in the material's thickness (fig. 16, fig. 17), it can be noticed that the thickness is minimal in the forming pole area, its value being of 0.8116 mm (the maximal reduction being of 18.84% compared to the initial sample thickness of 1 mm). The reduction of the material's thickness decreases with the increase in the distance from the forming pole. When comparing the results obtained by numerical simulation with those obtained experimentally, there can be noticed a similar distribution of the material's thickness reduction (for the experimental results, the Aramis system calculates the material's thickness reduction and not its thickness, therefore the colour range is reversed in the two cases). The maximal value of the thickness reduction is of 18.84% in the case of the numerical simulation and of 18.7% in the experimental case, respectively.

Fig. 16. Distribution of the sample's thickness reduction, determined experimentally

Fig. 17. Distribution of the sample's thickness reduction, determined through numerical simulation

Fig. 18. Comparison of the forming force

Figure 18 presents the evolution of the forming force in the case of the numerical simulation and in the case of the experimental testing, respectively. Here, the values of the forces determined by numerical simulation were multiplied.
by a factor of 4, given the fact that the numerical simulation was done only for a quarter of the part. When analysing the evolution of the forming forces, there can be noticed a similarity of the two curves, the maximal values being 56.4 kN in the case of the numerical simulation and of 58.1 kN, respectively, in the experimental case.

3. CONCLUSIONS

The device presented in this paper allows the experimental, practical determination of the forming limit curves for various types of metal sheets with thicknesses comprised between 0.5 and 1.2 mm and a maximal tensile strength of 600 MPa, using the Nakajima and Marciniak methods, respectively. Also, it allows the realising of deep drawing tests. The obtained results can be used for validating the theoretical results obtained through numerical simulation with the finite element method.

A significant cost reduction in the experimental determination of forming limit curves is achieved due to the modular nature of the device, it allowing the usage of both methods, Nakajima and Marciniak, by exchanging the active elements. Due to the fact that the device has its own actuation system, it can function independently and does not require to be mounted on a press or on a tensile testing machine.

REFERENCES


