INFLUENCE OF INDIVIDUAL FACTORS ON THE RESULTS OF THE CYLINDRICAL CUP DRAWING TEST

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Abstract

The paper concerns the evaluation of the formability of sheet metal by means of the cylindrical cup drawing test, which belongs to the imitation tests of the formability of sheet metal, and the influence of individual factors on the results of drawing. Experimental drawing of cylindrical stampings from a set of blanks from Cu-ETP (also known as conductive copper) sheet with a circular element deformation network was carried out using a special jig in the Department of Mechanical Technology, Faculty of Mechanical Engineering, VSB - Technical University Ostrava. Tensile tests of test bars made of Cu-ETP material were carried out to determine the directional and average values of mechanical properties as well as unconventional formability criteria, i.e. the strain hardening exponent and directional values of the plastic anisotropy coefficient. The experimentally obtained drawing results were verified in the PAM-STAMP 2022 CAE programme. Using simulations and subsequent analysis of the formability of cylindrical stamping using the forming limit diagram of the Cu-ETP material used, the effects of various factors on the results of the cylindrical cup drawing test were evaluated, which include blank material, sheet thickness, magnitude of holding force, lubrication, and radius of curvature of the punch drawing edge.

Keywords: Cylindrical cup, drawing test, formability, sheet metal, forming limit diagram

1. INTRODUCTION

The formability of sheet metal cannot be formulated using a simple index of technological formability, as the sheet metal is exposed to a wide range of stress and strain states during the drawing process, with the interrelationship of the individual variables changing during the real processes. It is appropriate to assess the formability of sheet metal in different deformation states using forming limit diagrams (FLDs) [1-4]. In this way, the formability of deep-drawn sheets, high-strength sheets, as well as sheets whose mechanical properties have been increased in some applications, for example, by unconventional dual rolls equal channel extrusion (DRECE) [5-10], can be assessed. Proper evidence and the identification of materials are important in testing [11]. Forming tools should be surface treated to increase their durability [12]. Residual stresses after forming can be analysed using Barkhausen noise [13].

The technological formability of the sheet can be assessed by simulating tests that imitate a particular technology or model the stress state of one of the two extreme positions, i.e. stretching and deep drawing, or a combination of both [14]. The imitation tests include the cylindrical cup drawing test, which is not standardised. This paper focusses on the effect of various factors on the results.

2. SPECIAL JIG FOR EXPERIMENTAL DRAWING OF CYLINDRICAL STAMPINGS

At the Department of Mechanical Technology, Faculty of Mechanical Engineering, VSB - Technical University of Ostrava, a special jig with a spring-loaded holder (**Figure 1**) is used for experimental drawing of cylindrical stampings (so-called cylindrical cup drawing tests), which is placed on a test blasting machine ZD 40 (VEB Werkstoffprüfmaschinen Leipzig, Germany).

The special jig consists of two parts: a static lower part with an interchangeable die (**Figure 2**) and a vertically movable upper part with an interchangeable drawing punch. The upper part of the jig is attached to the movable crossbar of the ZD 40 blasting machine. By screwing screw 1 into housing 2 with a nut wrench, the screw springs 3 are compressed by the adjustment plate 4. This movement is transmitted by rods 5 to the holder plate 6 and thus to holder 7 itself. The blank is lubricated only on the side of the punch, because a greater friction is advantageous between the punch and the blank, which allows deeper stampings to be achieved.

3. EXPERIMENTAL DRAWING OF CYLINDRICAL STAMPINGS

The circular blanks were made of Cu-ETP copper sheet, which according to Czech State Standard 42 3001 contains 99.9 wt. % copper, 0.06 wt. % oxygen and 0.05 wt. % lead. To determine the maximum size of the blank from which the stamping can be drawn without breakage, the individual diameters of the blank were graduated in 1 mm increments.

Deformation meshes with circular elements arranged in two mutually perpendicular directions passing through the centre of the circular blank, with a regular distance of 8 mm between the centres of each element, were created on Cu-ETP sheet blanks. The diameter of each element was L_0 = (4.783 ± 0.001) mm. A deformation mesh template was created in Autodesk Inventor Professional 2022 and glued to the blank to ensure accurate application of the elements. The deformation mesh was applied with an impression maker with infinitely variable embossing force control (by Radek Cada) (**Figure 3**), adjusted to an impression depth of 0.05 mm, which ensures the least possible influence of the sheet metal by deformation at the impression locations, while maintaining good readability even after large plastic deformation of the material [15].

Figure 1 Special jig for the cylindrical cup drawing test on the ZD 40 test blasting machine

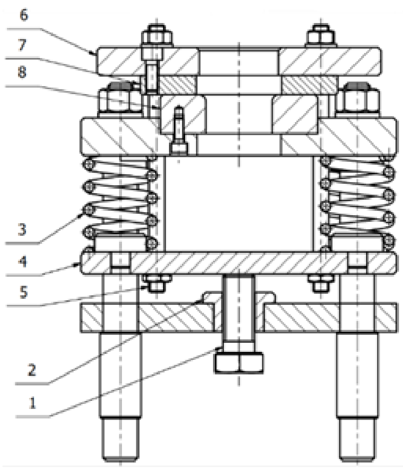

Figure 2 Diagram of the lower part of the special jig with the numerical designation of the individual parts

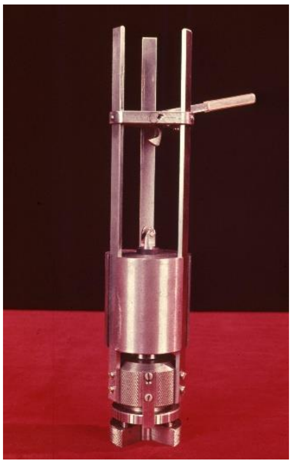

Figure 3 Impression maker with infinitely variable embossing force control

The drawing tool was chosen to be a draw punch with a diameter of 49.5 mm and a radius of roundness of the draw punch edge of 4.2 mm and a die with an inner cylindrical hole of 52 mm diameter and a radius of roundness of the die edge of 7.3 mm. The curvature radii of the punch and die drawing edge were measured on a Wenzel LH65 CNC X3M Premium three-coordinate measuring machine.

The blank was lubricated with grease only on the deformation net side and inserted with the lubricated side on the test tool die. Based on the calculated required holder force F_p for the recommended value of the holder pressure q = 2,45 MPa, the required value of the holder spring compression was determined based on the characteristics of the holder loaded with springs, that is, the dependence of the holder force on the magnitude of the spring compression. The holder was then placed on the blank and, by tightening the nuts of the rods 5 (**Figure 2**), its springs were compressed so that the spring compression reached the calculated value.

On the ZD 40 test machine, cylindrical stampings from each alternative diameter of the circular blank were drawn at a constant speed of 300 mm·min^{-1}. Experimentally, a maximum blank diameter of 102 mm was found, in which no crack in the stamping occurs during the drawing.

The results of the experimental drawing were evaluated using a circular element deformation network. Measurements of the lengths of the main and minor axes of individual ellipses, in which the original circular elements of the deformation network changed after deformation, were made using a special gauge to measure the lengths on curved surfaces (by Radek Cada) [15] with an accuracy of ±0.01 mm.

To obtain input values for the simulation of drawing processes, tensile tests of test bars made of Cu-ETP material were performed at the Department of Mechanical Technology, Faculty of Mechanical Engineering, VSB - Technical University Ostrava. Therefore, the directional and average values of the mechanical properties (R_m = 255 MPa) and the nonconventional formability criteria were determined, i.e., the strain hardening exponent (n_m = 0.281) and the directional values of the plastic anisotropy coefficient (r_0 = 0.54, r_{45} = 0.93 a r_{90} = 0.64). Subsequently, the results of the experimental drawings were verified in the PAM-STAMP CAE programme.

4. EVALUATION OF THE EFFECTS OF INDIVIDUAL FACTORS ON THE RESULTS OF THE CYLINDRICAL CUP DRAWING TEST

The effects of various factors on the results of the cylindrical cup drawing test, which include blank material, sheet thickness, holding force, lubrication, and radius of curvature of the punch and die drawing edge, were evaluated using simulations and subsequent drawability analysis of the cylindrical stamping using FLD of the Cu-ETP material used. All simulation processes were performed under the same conditions as those used in the experimental drawing. The drawing tool was a 49.5 mm diameter punch and a 52 mm diameter inner cylindrical hole die. The diameter of the blank was set at 102 mm with a sheet thickness of 1 mm of Cu-ETP material. The shear friction coefficient was set to μ =0.125.

Analysis of the drawability of cylindrical stamping from blanks of 102 mm and 103 mm diameter was carried out using the FLD of the sheet metal used. When drawing a cylindrical stamping from a blank of 102 mm diameter (**Figure 4**), the set of points that represent the deformation states on the cylindrical stamping lies below the forming limit curve (FLC) in the FLD and no stamping failure occurred. When drawing a cylindrical stamping from a blank of 103 mm diameter, some of the set of points representing the deformation states on the cylindrical stamping lie in the FLD near the FLC, indicating a high probability of stamping failure. The simulation results are consistent with those obtained experimentally.

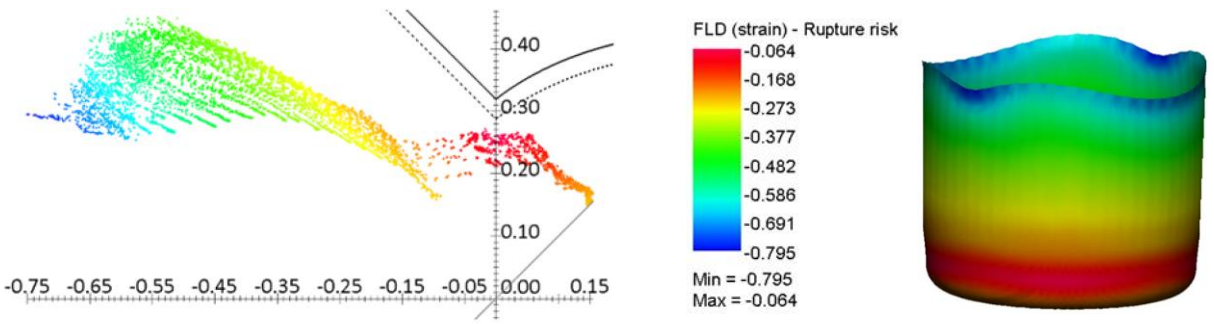

Figure 4 Drawability analysis of a cylindrical stamping from a Cu-ETP material of 102 mm blank diameter, 1 mm thick (n_m = 0.281, r_0 = 0.54, r_{45} = 0,93, r_{90} = 0,64) using FLD

The effect of blank material on the drawing process was investigated by determining the magnitude of the average strain hardening exponent and the magnitude of the average plastic anisotropy coefficient.

The Cu-ETP sheet with an average strain hardening exponent n_m = 0.281 is one of the materials with excellent formability. For comparison purposes, a simulation of the drawing process was carried out on a sheet also with a value of n_m = 0.210. From the comparison of these two variants using FLD, it was clear that in the case of a higher value of the average strain hardening exponent, the FLC in FLD is higher in the direction of the main logarithmic strain axis, i.e. the plasticity stock of the material is higher. In particular, materials with a higher value of the average strain hardening exponent are more suitable for stretching.

The plastic anisotropy coefficients of the Cu-ETP sheet are r_0 = 0.54, r_{45} = 0.93 a r_{90} = 0.64, the value of the average plastic anisotropy coefficient is therefore r_m = 0.76, which corresponds to a material with low formability. For comparison purposes, a simulation of the sheet metal drawing process was also performed with a value of r_m = 1.83, which corresponds to a material with excellent formability. From the comparison of these two variants using FLD, it was evident that the formability of the material decreases with decreasing values of the average plastic anisotropy coefficient.

Analysis of the effect of sheet thickness on the results of the cylindrical cup drawing test was carried out by comparing the results of drawing simulations of a sheet of 1 mm thick (**Figure 4**) and 0.5 mm thick (**Figure 5**). In both DMDs, the set of points representing the strain states on the cylindrical stamping maintains a similar shape, but in the case of the apparatus with a smaller initial thickness (**Figure 5**), the FLC is shifted to lower values of the main logarithmic strains in the FLD, thus placing the set of points representing the strain states on the cylindrical stamping above the FLC, indicating failure of the stamping. A higher initial thickness of the blank has a positive effect on formability as the plasticity stock of the material increases with increasing sheet thickness.

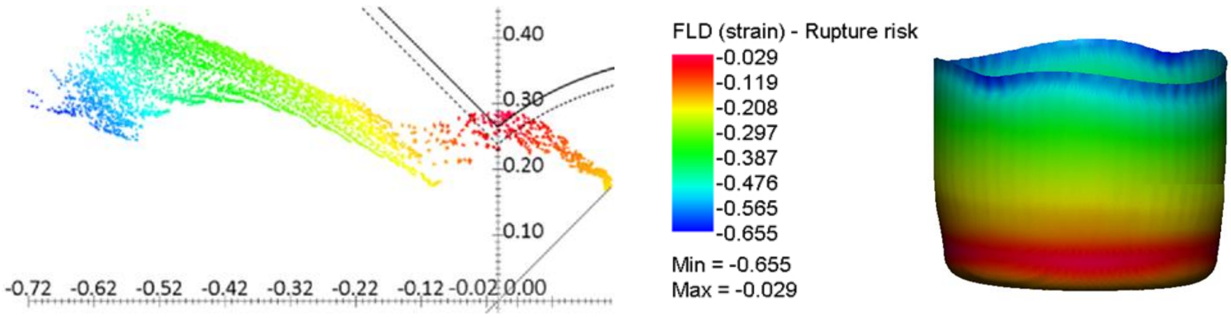

Figure 5 Drawability analysis of a cylindrical stamping from a Cu-ETP material of 102 mm blank diameter, 0.5 mm thick (n_m = 0.281, r_0 = 0.54, r_{45} = 0,93, r_{90} = 0,64) using FLD

For the given combination of punch and die, the required holding force F_p = 9,600 N was calculated. To analyse the effect of the size of the holding force on the drawing, in the simulation an insufficient holding force F_p = 1,000 N and then an excessively large holding force F_p = 20,000 N were deliberately chosen. In the event of insufficient holding force, waves on the stamping flange were generated and drawn into the drawing gap, causing the sheet to jam and, due to the continued movement of the punch, to tear off the bottom of the stamping, which was reflected in the FLD by the appearance of a set of points above the FLC. At a holding force of F_p = 20,000 N, when the blank was held with a force too large, the strength of the material above the radius of curvature at the bottom of the stamping was exceeded and a crack appeared in the FLD with a plurality of points above the FLC.

To analyse the effect of the shear friction coefficient on the drawing of the cylindrical stampings, the limiting values of the shear friction coefficient μ = 0.10 (**Figure 6**) and μ = 0.15 (**Figure 7**) were compared. The diagrams show that with a lower value of the shear friction coefficient, the set of points representing the deformation states on the cylindrical stamping shifts towards lower values of the main logarithmic strains, thus reducing the risk of failure.

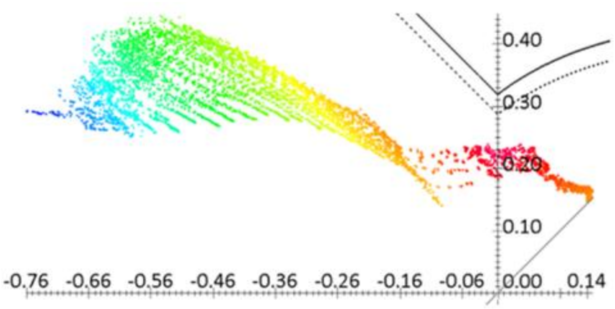

Figure 6 Drawability analysis of a cylindrical stamping from Cu-ETP material for shear friction coefficient μ = 0.10 using FLD

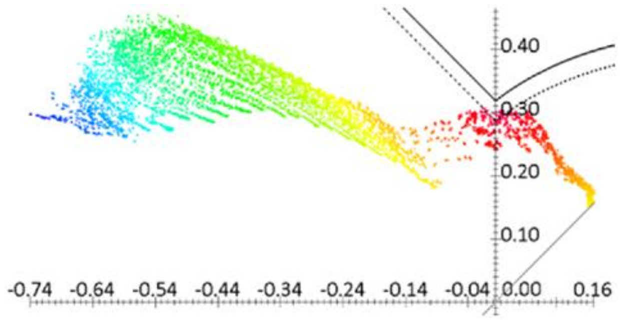

Figure 7 Drawability analysis of a cylindrical stamping from Cu-ETP material for shear friction coefficient μ = 0.15 using FLD

To analyse the effect of the radius of curvature of the die drawing edge on the drawing of the cylindrical stampings, the radius of curvature of the die drawing edge r_t = 4 mm (**Figure 8**) and r_t = 15 mm (**Figure 9**) were compared. The diagrams show that as the radius of roundness of the die edge increases, the set of points representing the deformation states on the cylindrical stamping shifts towards lower values of the main logarithmic strains, thus reducing the risk of failure. If too small a radius of curvature of the die edge is used (**Figure 5**), some of the points representing the deformation states on the cylindrical stamping lie above the FLC, indicating the failure of the stamping. Since the radius of the drawing edge increases, the area under the holder decreases at the same time; a greater holding force must be applied.

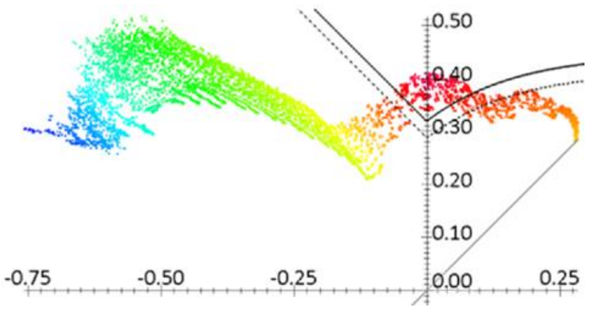

Figure 8 Drawability analysis of a cylindrical stamping from Cu-ETP material with radius of curvature of the die drawing edge r_t = 4 mm

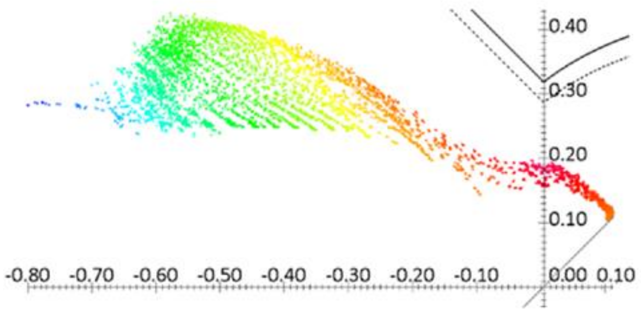

Figure 9 Drawability analysis of a cylindrical stamping from Cu-ETP material with radius of curvature of the die drawing edge r_t = 15 mm

To investigate the effect of the radius of curvature of the punch drawing edge on the drawing of cylindrical stampings, the radius of curvature of the punch drawing edge r_p = 1 mm and r_p = 8 mm were compared with the otherwise unchanged dimensions of the drawing tool. The diagrams showed that as the radius of curvature of the punch drawing edge increases, the set of points representing the deformation states on the cylindrical stamping shifts towards lower values of the main logarithmic deformation, i.e. the risk of failure decreases.

5. CONCLUSIONS

The effects of individual factors on the results of the cylindrical cup drawing test were evaluated using sheets mechanical properties tests, simulations, and a subsequent analysis of the drawability of the cylindrical stamping using the forming limit diagram of the Cu-ETP material used. In the case of a higher value of the average strain hardening exponent, the FLC in the FLD is higher in the direction of the axis of the main logarithmic strains, i.e. the plasticity stock of the material is higher. In particular, materials with a higher value of the average strain hardening exponent are more suitable for shutdown. As the value of the average plastic anisotropy coefficient decreases, the formability of the material decreases. A higher initial thickness of the blank has a positive effect on formability, as the plasticity stock of the material increases with increasing sheet thickness. Adjusting the holding force according to the calculation prevents the formation of waves or excess of the tensile strength of the material. With a larger radius of curvature of the drawing edge of the punch and the die, the set of points representing the deformation states on the cylindrical stamping moves towards lower values of the main logarithmic deformations; i.e. the risk of breakage is reduced, but at the same time the risk of the so-called secondary waviness that occurs on the free part of the sheet between the punch and the die increases.

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