PLASTIC RESOURCE OF LOW-CARBON STEEL DURING IN TECHNOLOGICAL PROCESS OF DEEP DRAWING

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Abstract: *The present study deals with the development of a method involving physical experiment and numerical simulation. The aim is to predict the possibility of maximal use of the plastic resource of a low-carbon steel circular blank subjected to deep drawing. The material hardening curve under uniaxial tension was found experimentally. A series of real physical experiments of deep drawing were carried out. FEM-simulation of the experimentally observed material mechanical behaviour was performed. The variation of the parameters of the stress-strain state in selected areas of the blank volume is shown accounting for the advance of the blank shape transformation.*

The reported results could be used to assess of the residual plastic resource of quality steel products, and to investigate and predict the deformation process development in such material. Thus, stability loss during blank form-change or plastic strain localization could be prevented.

Keywords: DEEP DRAWING EXPERIMENTS, FE-MODELING, PLASTIC DEFORMATIONS

1. Introduction

During changing the form of a solid body (metal blank) under the action of the external load together with the evolution of the existing structural defects new ones are initiated, developed and erased [1]. This yields defect transition covering different levels of initiation, accumulation, interaction, combination and coupling, depending on the plastic strain development. As a result, undesired phenomena such as loss of forming stability, plastic strain localization, fracture may occur. They depend on material structure and deformation regimes, i.e. on material plastic resource. Knowing it is of special importance in the design of any deep drawing technology. Pursuing maximal energy and equipment exploitation, a profitable technology is that allowing the fabrication of a piece only by one work travel of the forming tool. Different experimental methods are used to solve that problem, identifying material plastic resource and studying factors that affect blank stability loss and fracture during deep drawing [2].

Due to the complexity of deep drawing factors, it is a rule that the information gained via the best planned and performed experiment is insufficient to describe in detail the drawing process. Hence, numerical simulation is more and more engaged in the field during the last decade, involving material structural characteristics and forming physical and geometrical parameters.

The aim of the present study is to develop a method comprising a physical experiment and numerical modelling, so that material plastic resource could be maximally made use of. To do this, first uniaxial tension test on low-carbon steel bands is carried out to establish precise values of mechanical characteristics. Afterwards with these values, the deep drawing process is numerically modeled under theoretical limiting forming regimes for low-carbon steels in order to find values of limiting parameters of stress strain state at given geometrical sizes of blank and forming stamp. The real physical experiment of deep drawing is performed parallel to numerical simulation.

2. Experimental basis

The good knowledge of the mechanical characteristics of the material is essentially important in design of pieces obtainable by plastic deformation as well as in design of forming tools. For this reason initially uniaxial tension test experiments are carried out. Specimens are strips of low-carbon steel. The dimensions of the specimens are: a length of 150 mm, width 5 mm and thickness 1.5 mm [3]. The “Stress - Strain” diagrams are presented in Fig. 1. Its yield stress is σ_y = 210 MPa and ultimate strength is σ_u = 440 MPa. Young’s modulus is E = 210 GPa and Poisson’s ratio is ν = 0.32. The mechanical characteristics found are used to design adequate material models and numerically simulate the forming process via the Finite Element Method (FEM).

A series of real physical experiments of deep drawing of low carbon steel were performed in the laboratory. A specially designed deep drawing stamp [4] is fixed to the movable part of a universal testing machine type ZD 10/90 operating in compression. Upon the start of blank deformation an automatic record of the curve “force-travel” also starts in real time, being digitally registered in the computer memory. The stamp parameters are chosen so that to minimize the influence of its design on the material capability to maximal forming. In the specialized handbooks, the maximal ratio of the form-change during deep drawing without blank compromising is varied in the limits $K = D_Z / d = 1.8 \div 2$, where D_Z and d are diameters of blank and piece [1]. The limit blank diameter is calculated as D_Z = 95.4 - 106 mm for punch diameter 50 mm and blank thickness 1.5 mm. Theoretically, K is calculated as 2.7 with precondition about proportion of the maximal tensile stresses in the blank material to its ultimate tensile strength higher than 1.1 [5]. That leads to a limit blank diameter of the order of 143.1 mm. The differences, in the range of 10% in the first case and of 25-30% in the second case, give a ground of one more profoundly numerical investigation on the conditions under which the blank material is breaking.

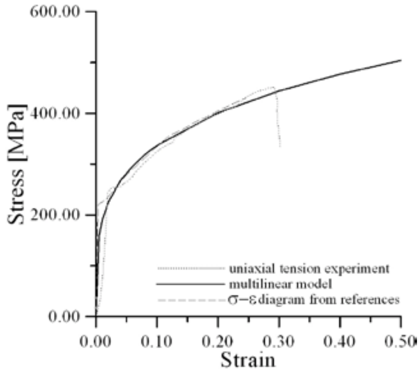


Fig. 1. *The true “Stress - Strain” diagram of the investigated low-carbon steel and the corresponding multilinear model.*

In this study, an experimental and numerical investigation on the deformation behaviour of blanks possessing diameters 105 mm and 116 mm is presented. The blank diameter D_Z = 105 mm is chosen close to the values of the higher admissible limit established and recommended in the practice of sheet metal forming through deep drawing. The blank diameter D_Z = 116mm represents a 10% theoretical increase in the admissible limiting one according to the above precondition concerning the exceeding of material’s tensile strength by the radial tension stresses. Blank thickness is h_0 = 1.5 mm, punch diameter is 50 mm, and die diameter is 54 mm at one-side gap of 2 mm. Radii of rounding-off of die and punch are 10 mm and 12 mm respectively.

Fig. 2 shows diagrams “Drawing Force - Work Punch Travel” found experimentally and via numerical simulation. The experimentally found breaking force for blank diameter 116 mm and punch travel 21.4 mm is 9250 N. The drawing force is 7000 N for blank diameter 105 mm and punch travel 20.3 mm. This travel is near to the breaking for the larger blank, but the difference in the force is about 25%. The maximal drawing force is 8600 N for blank diameter 105 mm and punch travel 30 mm. The numerical simulations produced force values of 8400 N, 7218 N and 8283 N, respectively and the differences are 7.02%, 3.02% and 1.37%. The experimentally found current radius of the broken blank is 54.75 mm, while that found via numerical simulation is .54.226 mm. That indicates a presence of developed plastic flow in the blank flange.

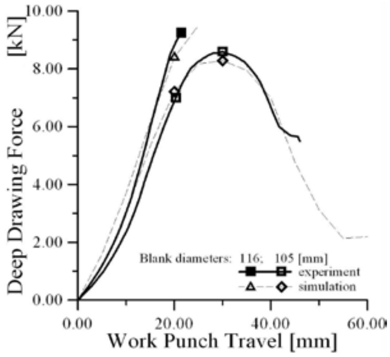
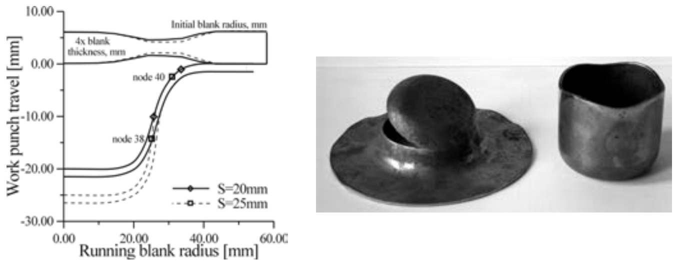


***Fig. 2** Experimental and numerical diagrams “Drawing Force - Work Punch Travel”.*

Fig. 3a shows the numerically obtained changes of the blank thickness (up) and blank form (down) under punch travel of 20 - 25 mm. Blank thinning in the vicinity of the punch rounding-off is also seen. The blank breaks under punch travel of 21 mm - Fig. 3b.

Based on these comments, a conclusion could be made that the numerical FE model satisfactory describes the forming process and could be used during analyzing the stress strain state of the blanks in the next paragraph.



a *b*

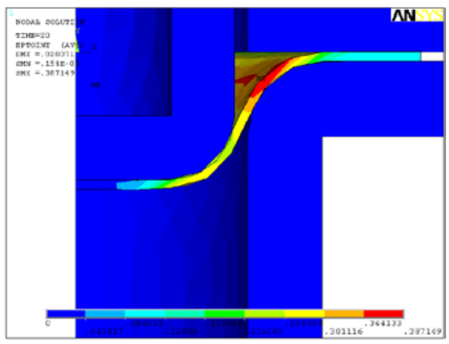
***Fig. 3** Blank shapes: numerically (a) and experimentally obtained (b).*

3. Finite Element Modeling and Analysis

Deformation and fracture of the steel blank was simulated via FEM using ANSYS software package. Because of symmetry, quarters of the volumes of the two blanks are divided in 651 (Visco107) finite elopements with 255 nodes and 777 elements with 300 nodes, respectively for diameters of 105 mm and 116 mm. The process the specific blank holder pressure is 2.47 MPa. The assumed friction coefficients between the blanks and forming tools are 0.16. The forming process is computed in 13 steps for blank diameter 105 mm and punch travel 5 mm per each step. The forming process is computed in 6 steps for blank diameter 116 mm and punch travel 5 mm per each step. With increasing punch travel until 60 mm and until 25 mm, the changes of the two plane blank geometries to cylindrical cup for diameter 105 mm and to fracture for diameter 116 mm are described depending on the distribution of the parameters of the corresponding stress and strain states.

The results are shown in Fig. 4 - Fig. 6. With increasing punch travel forming of cylindrical cup begins under operating of complex stress and strain states. At the beginning of work punch travel the plastic strains are concentrated in the free of contact area between both radii of rounding-off of die and punch. The blank flange is not in plastic state while the free area begins its transformation in cone enveloping the two radii of rounding-off. Along its contour, the flange is loaded by maximal circumferential pressure stresses and zero radial tension stresses. Following the blank radii from the contour to the centre the radial tension stresses increase and the circumferential compression stresses decrease and become tensional. With increasing travel the flange passes in plastic state, its external diameter (the blank contour) begins to decrease. After the beginning of wall forming, the stresses in the material enveloping the punch radius of rounding-off begin to decrease. The maximal stresses and strains are concentrated in the blank material which envelops the die radius of rounding-off. With the next increase of the punch travel, the transformation of the flange in a wall begins. During this forming the blank wall is loaded at uniaxial tension transmitting the drawing force to the die radius of rounding-off, and blank bottom is loaded under minimal biaxial tension.

Fig. 4 shows the distributions of the stress and strain intensities along the blank radius with diameter 116 mm under punch travel 20 mm. This is the moment immediately before the breaking of the blank. In the area appearing under punch before the rounding-off, the strains are minimal of the order of 0 - 0.043 - 0.086 (Fig. 4a). In the flange they are 0.086 - 0.129. The corresponded stresses are 104 -156 - 260 MPa and 260 - 364 MPa (Fig. 4b). In the material enveloping the die radius of rounding-off, strain concentrations are read with maximal intensity 0.34 - 0.38 under stress intensity 416 - 460 MPa. Concentrated strain increase of the order of 0.25 - 0.30 - 0.38 is observed in the blank area appearing on the punch radius of rounding-off under stress intensities 380 – 424 – 468 MPa (Fig. 4b). In Fig. 4 and Fig. 6a,b (with red colour), it is seen that in this blank area, a process of plastic strain localization is initiated, because of the suppressed plastic deformation in the flange which is caused by its larger diameter. These localizations (Fig. 3a) with increasing work travel above 20 mm could lead to fracture, as it is happen in Fig. 2 and Fig. 3. The numerical simulation produced a fracture force amounting to 84 kN under punch travel 20 mm. The experiments performed in the laboratory confirmed the observed fracture effects.



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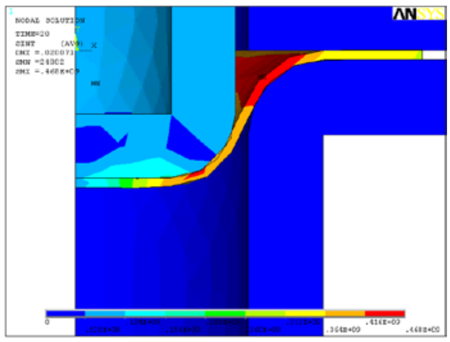
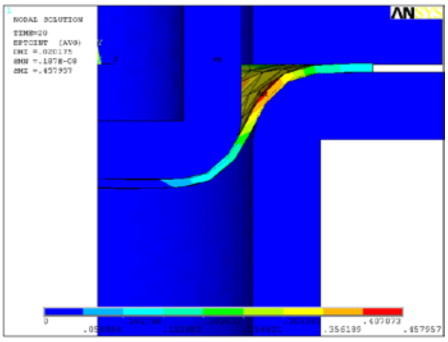


b

***Fig. 4** Strain intensity (a) and stress intensity (b) for deep drawing of a low-carbon steel blank with diameter 116 mm under work punch travel 20 mm.*

It is seen that a qualitative piece with diameter 116 mm can not be manufactured. Yet, the results are different when the blank diameter is reduced under the critical value of 105 mm. Under the same work punch travel of 20 mm, stresses amounting to 220 - 275 - 330 MPa occur and deformation with intensity 0.101 - 0.152 - 0.203 is attained (Fig. 5).



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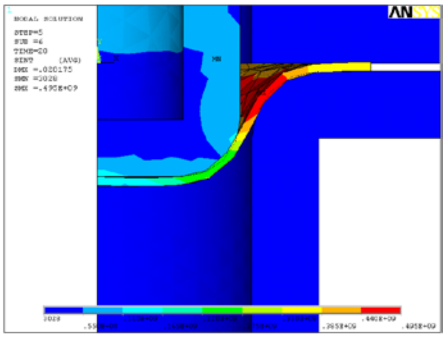
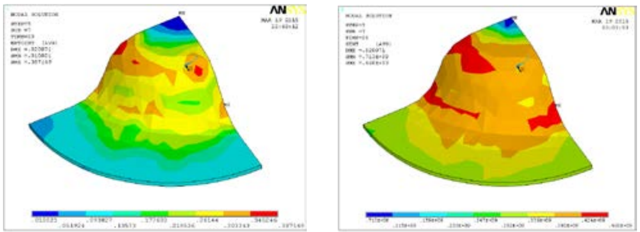


b

Fig. 5 *Strain intensity (a) and stress intensity (b) for deep drawing of a low-carbon steel blank with diameter 105 mm under work punch travel 20 mm.*

The piece height (Fig. 6c,d) obtained by the simulation is 44.48 mm, and the experimentally measured is variable 43 - 46 mm due to the anisotropy (Fig 3b).



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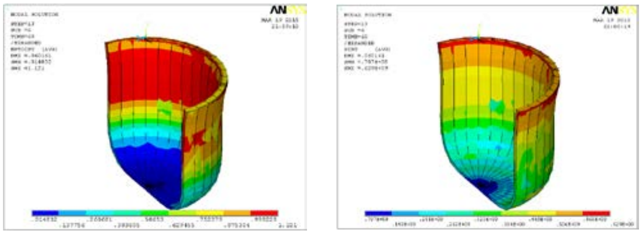
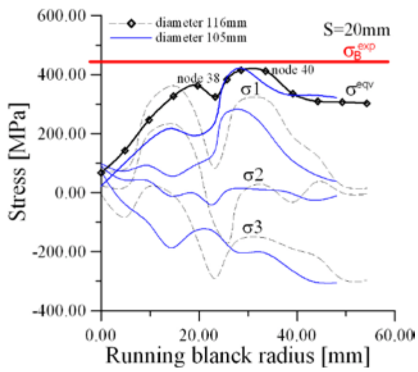


c *d*

Fig. 6 *Strain and stress distributions of the of a blank with diameter 116 mm before fracture at punch travel 20 mm (a, b) and of a blank with diameter 105 mm at punch travel 60 mm (c, d) at the end of the forming process.*

In difference from the larger diameter, here in the central blank area which is below the punch, the strains are minimal, little bit over the theoretical plastic strain limit of 0.02, in the range of 0 - 0.05 (Fig. 5a). In the blank flange the strains are in the range of 0.152 - 0.2 - 0.254, almost two times more intensive than the observed in the previous case, i.e. a developed plastic flow appears in the flange. The corresponded stresses in the bottom and the flange are 110 - 165 MPa, far below the yield stresses and significantly over them in the range of 330 - 385 MPa (Fig. 5b). The concentrated strains in the blank material which appears on the die rounding-off are also more intensive in the ranges of 0.356 - 0.4 - 0.457 under stresses of 385 - 440 - 495 MPa. Strain intensity in the blank material covering the punch rounding-off is almost two times lower 0.1 - 0.15 - 0.2, and the stresses are also lower 220 – 275 MPa. Based on these numerical data, the conclusion is imposed that the blank with diameter 105 mm is more favourably loaded. The material continuity is saved under stability of the changes in the blank form according to this assigned by the forming tool.

Under maximal drawing force of 83 kN punch travel of 30 mm, the stress intensity at the punch rounding-off is 257 - 322 MPa, while strain intensity is 0.095 - 0.190 - 0.285. The blank does not break, while the final product is shown in the right of Fig. 3b. The increasing strains from minimal elastic in the bottom to maximal plastic along the height of the wall are seen. The formed cup is produced by the transformation of the flange of blank with diameter 105 mm into the cup wall under stresses in the ranges of 445 - 506 - 568 MPa. That is caused by the punch work travel larger than 25 mm when both the radii of rounding-off of die and punch are enveloped by the blank material.



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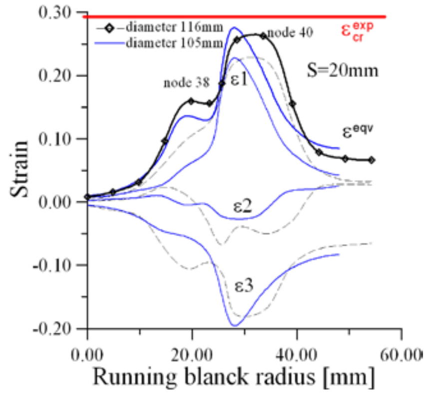
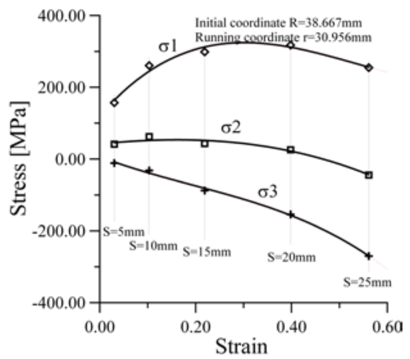


b

Fig. 7 *Principal stress and strain distribution along the blank current radius.*

The distributions of the principal stresses and strains along the blank radius are shown in Fig. 7. The effect of the strain concentration in the free of contact area is clearly seen. With diameter 116 mm for current blank radius between 10 and 20 mm, the maximal principal radial stresses σ1 approach the uniaxial tensile strength σ_B of the blank material (Fig. 1). After this area they decrease and break the material (Fig. 2 and Fig. 3), with sharp increase of the stains in elements 38 and 40 (Fig. 7b), and increasing punch travel from 20 mm to 25 mm (Fig. 8). With blank diameter 105 mm the stresses operating in the same area have lower values, fracture is not obtained. Here, the principal negative circumferential compression stresses σ3 have absolutely maximal values, while with the larger diameter 116 mm, here, the compression circumferential stresses increase sharply from 0 to absolute (compression) maximum. At the expense of that, the tension along the thickness increases with increasing radial tension which leads to thinning and next breaking (Fig. 9). With diameter 105 mm the stresses along the thickness are close to zero. The conclusion follows that increase of the blank diameter leads to suppression of the plastic flow development in the flange which causes an exchange in the roles of the thickness stresses and circumferential stresses. This phenomenon produce thinning and breaking with the larger diameter, and with the smaller diameter envelopment of the punch roundness radius by the blank material subjected to circumferential compression stresses, keeping the thickness and establishment of favourable conditions for transmitting the drawing force by the wall to the flange. In our opinion, the differences between the uniaxial tensile strength σ_B^{exp} and fracture strain ε_{cr}^{exp} and the corresponding equivalent stresses σ^{eqv} and strains ε^{eqv} numerically identified on the experimental basis represent remained plastic resource which is consumed with increasing punch travel to 25 mm.

Fig. 8 shows the distribution of the principal stress and strain obtained for the larger blank in nodes 40 and 38 belonging to the upper blank surface and possessing initial radii 38.66 mm and 29.0 mm and current radii 30.95 mm and 25.68 mm. These are the stress and strain history in the broken blank area.



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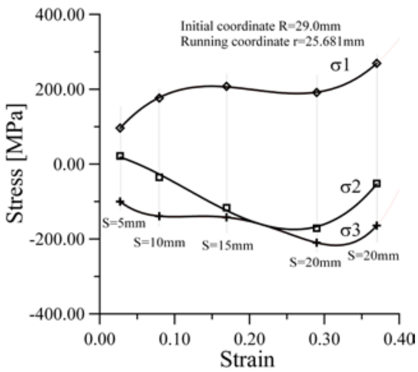

b

Fig. 8 *Development of the principal stresses in the fracture area.*

The first node is chosen in the middle of the flange and the second is chosen in the middle of the area initially appearing over the die rounding-off. It is seen that in the two nodes (as well as, in the area between them, and also, in a ring blank area possessing initial radii around and over them) with increasing punch travel form 0 to 5 mm there are no developed plastic strains. That also shows concentrations of the strains in the areas with smaller initial radii between both radii of rounding-off. The plastic flow in the ring defined by the two radii is initiated after punch travel 10 mm. At the first node with the increasing travel from 15 to 20 mm the principal strains are increased from 0.2 to 0.4, and at the second node they are smaller from 0.17 to 0.30, but there the increase is almost in two times. At the first node, the stress state is constant tension/ increasing circumferential compression/minimal thickness tension. At the second node, similar stress state in radial and circumferential directions is seen, but under lower tension values close to these of uniaxial yield stresses. Here, the difference is that the compression load along the thickness is almost commensurable to this in the circumferential direction. This is the area with initial radius 29 mm, in which with increasing punch travel to 25 mm follows a sharp increase of the maximal principal tension radial stress (Fig. 8b) sharp increase of strain intensity (Fig. 7b) and strain localization and breaking is obtained finally (Fig. 3b, Fig. 6a,b).

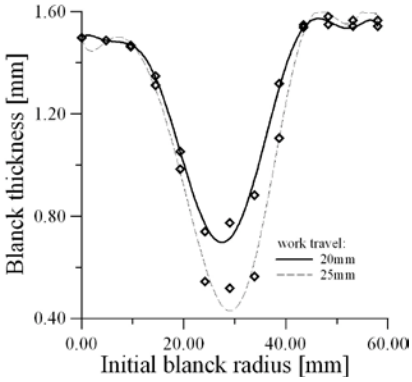

Fig. 9. *Blank thickness before and during breaking with travel 20 - 25 mm.*

4. Conclusion

Considering deep drawing, the stressed state varies in different blank areas (Fig. 4 - Fig. 6). This yields different degree of material strain-hardening and as a result-different carrying capacity (Fig. 7). Here, the initial blank diameter has an essentially important significance, because its size combined with its mechanical material's characteristics (Fig. 1) determines the flange resistance against the change of its form into a piece wall trough plastic deformation. Hence, good knowledge on the material characteristics and the variation of the stressed and strained states is needed to predict material mechanical behaviour and make maximal use of its plastic resource. From point of view fracture mechanics, the processes developed in fractured blank area (Fig. 8 and Fig. 9) could be investigated more particularly by the concentration of both the methods experimental observation and numerical modeling in such an area as the identified here, its stress strain state, possible structural changes and prevailing mechanisms of plastic deformation.

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