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FINITE ELEMENT METHOD SIMULATION FOR RECTANGULAR PARTS OBTAINED BY INCREMENTAL SHEET METAL FORMING PROCESS

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Abstract: *The current paper refers to one of the new non-conventional forming procedures for sheets metal, namely incremental forming. Problems occurring during calculation of stress, thinning and the forces in the process of incremental sheet metal forming have been analysed in this paper. The paper presents a study based on the finite element method of incremental sheet metal forming with hemispherical punch. The influence of the main parameters of the forming process is studied. Parameters taken into account were the deep of the obtained part and the punch diameter, the two parameters being varied on two levels.*

Key words: *CAD, CAE, numerical simulation, incremental sheet metal forming, hemispherical punch.*

1. INTRODUCTION

The usage of unconventional metal forming procedures has steadily increased in the automotive, aviation, medical equipment manufacturing and consumer goods manufacturing industries. The producing of parts characteristic for these industries is limited to a reduced variety of shapes and consequently, the conventional forming procedures, which use a complex tools set (die, punch, blankholder) become very expensive [3, 4]. In the past few years, a new sheet metal forming procedure has appeared, at which deformation is done with a punch that comes in partial contact with the blank surface and which is called incremental forming. In order to realize the shape of a part, one of the active elements (usually the punch) has an axial feed movement on vertical direction, continuous or in steps (incremental), while the other element (the die) carries out a plane horizontal movement (Fig. 1).

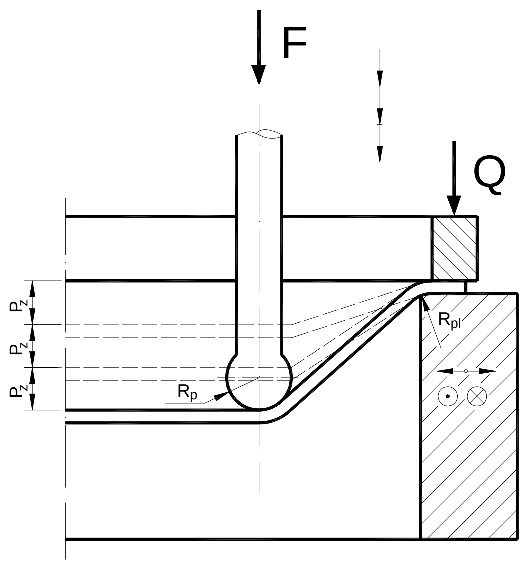

Fig. 1. The principle of incremental sheet forming process.

The procedure has a high flexibility, because with the same punch and with the same die, depending on the movements imposed to the active elements, using the same machine-tool a multitude of hollow shapes can be obtained. Other advantages come also from the possibility to implement the processing on numerical-controlled (NC) machines [3, 4].

During the incremental sheet forming process, a number of characteristic stages in the evolution of the forming process can be depicted. A first stage of the material stretching under the punch action can be illustrated. The second stage consists in the punch movement along the desired trajectory and sure, the third stage the retiring of the punch in vertical direction.

2. THEORETICAL CONSIDERATION ABOVE THE USED FINITE ELEMENT METHOD

In order to establish the influence of the geometric parameters of the forming system on the state of stress and strains at incremental sheet forming process, a numerical investigation method based on finite element method is presented.

For this we use the software Dynaform, general-purpose finite element software for analyzing the large deformation response of the structures. The main solution methodology is based on explicit time integration. Dynaform has eleven different formulations available for the Shell 163 element use in this numerical simulation. The authors select in this case the Belytschko-Lin-Tsay formulation because is fast and use the reduced integration method [2].

The Belytschko-Lin-Tsay shell element was implemented in Dynaform as a computationally efficient alternative to the Hughes-Liu shell element. The Belytschko-Lin-Tsay [7] shell element is based on a combined co-rotational and velocity-strain formulation. The efficiency of the element is obtained from the mathematical simplifications that result from these two kinematical assumptions. The co-rotational portion of the formulation avoids the complexities of nonlinear mechanics by embedding a coordinate system in the element.

Eighteen different contact types have been incorporated in Dynaform. In this numerical simulation we used an automatic surface-to-surface contact algorithm. The main difference between the automatic and general options is that the automatic contact algorithm automatically determines the contact surface orientation for shell elements. In automatic contact, checks are made for contact on both sides of shell elements.

For material model we used an anisotropic elasto-plastic model definition: 3 Parameter Barlat. Anisotropic plasticity model developed by Barlat and Lian is use for modelling material behaviour in forming processes. Both exponential and linear hardening rules are available. The anisotropic yield criterion for plane stress is defined as [1]:

$$2\sigma_Y^m = a\left|K_1 + K_2\right|^m + a\left|K_1 - K_2\right|^m + c\left|2K_2\right|^m, \qquad (1)$$

where σ_Y is the yield stress, a and c are anisotropic material constants, m is Barlat exponent, and K_1 and K_2 are defined by:

$$K_1 = \frac{\sigma_{xx} - h\sigma_{yy}}{2}, \qquad (2)$$

$$K_2 = \sqrt{K_1^2 + p^2\sigma_{xy}^2}, \qquad (3)$$

where h and p are additional anisotropic material constants. For the exponential hardening option, the material yield strength is given by [2, 6]:

$$\sigma_Y = k\left(\varepsilon_0 + \varepsilon^p\right)^n, \qquad (4)$$

where k is the strength coefficient, ε_0 is the initial strain at yield, ε^p is the plastic strain, and n is the hardening coefficient.

3. THE FINITE ELEMENT MODEL

The finite element network associated with the part's geometry is built so that it allows an unfolding of the analysis in good conditions, without necessitating a re-discretisation because of its exaggerated distortions. The part, discretised as a shell, deformable body, is composed of 2441 Thin-Shell-163-type elements. Because of the way in which the elements are connected, the network contains 2490 nodes. The blank and the die, at the final stage, are presented in Fig. 2.

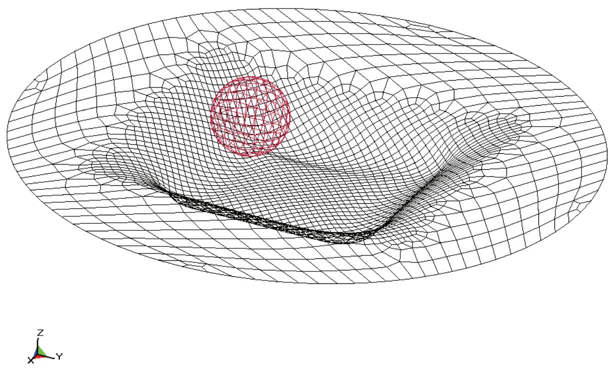

Fig. 2. The die and the blank at final stage.

A shear factor of 5/6, and a total of 5 integration points through the thickness were used in order to catch the variation of the stresses and strains through the thickness. The hourglass control based on Belytschko and Tsay viscous formulation was selected in order to avoid problems with single point Gaussian integration. A coefficient of 0.1 was selected for in-plane, bending and warping hourglass.

The material associated with the part's elements corresponds to a deep-drawing sheet DC03, the mechanical characteristics being retrieved as an ASCII file after the obtaining of the real characteristic curve on an Instron tensile testing machine.

The Dynaform material model 36 (Barlat's 3-parameter plasticity) was chosen because it can accommodate in-plane an isotropic yield behaviour. This model combines isotropic elastic behaviour with anisotropic plastic potential developed by Barlat and Lian [1]. This model also includes an isotropic linear strain-hardening rule, which is satisfactory since there are not significant plastic-strain reversals in the model. The considered elasticity modulus is $E = 0.7\text{e} + 5$ MPa, the transversal contraction coefficient is $\nu = 0.27$, the initial thickness $g = 1$ mm while the flow stress is $\sigma_Y = 195$ MPa, effective elastic strain $\varepsilon_0 = 0.003$, the strength coefficient $K = 465$ MPa and hardening coefficient $n = 0.21$. The anisotropic characteristic's width to thickness strain ratio values $R_{00} = 1.04$; $R_{45} = 0.86$; $R_{90} = 0.72$. The Y coordinate is the rolling direction.

The forming system consisting from hemispherical punch, die and blankholder are considered.

A thin sheet circular blank, placed on an active die with rectangular working zone is considered. The punch is placed unsymmetrical and, in the first stage, has a perpendicularly movement on the sheet level. In the second stage the punch follow a rectangular trajectory around the active die borders.

There are not imposed boundary conditions, on the nodes placed on the circumference because the blank-holder eliminate this necessity. In order to define the contact the option "automatic surface-surface" was chosen.

Two different values of the hemispherical punch diameter and two different deeps of the parts are taken into consideration. The most important geometric parameters of the forming process are presented in Table 1.

Four separate different analyses were performed, corresponding to the dimensional combinations from Table 1, in order to depict the changes at the level of material stress, strains and the forces due of this parameters [5].

Table 1

Geometric parameters of the forming process

Case	C1	C2	C3	C4
Blank sheet diameter – D [mm]	120			
Initial sheet thickness – g [mm]	1			
Active die radius – R_{pl} [mm]	6			
Clearance between punch and active die – j [mm]	7			
Punch diameter – d [mm]	12	12	20	20
Deep of the part – h [mm]	6	10	6	10

4. THE RESULTS OF NUMERICAL SIMULATION

The numerical results of the simulation were centred on the determination of the equivalent Von Misses stress, the effective strain, the percentage of sheet thickness reduction, the forming limit diagram, and the press tonnage.

A process of plastic deformation of this kind is difficult to control, due to some characteristic aspects such as: a relatively small contact surface of the tools with the blank; the strengths appearing in the material must be superior to those which bring it in the plastic state, but they must be less than the critical ones; the state of biaxial stretching is the least favourable to the plastic deformation processes. Because of this fact, the results of the numeric analyses in the non-linear field are oriented towards the description in a qualitative and quantitative way of the strain process results.

A series of quantitative aspects of the four studied situations are presented in Table 2.

In Fig. 3 the state of Von Misses stresses for the case C4 is presented. This state is presented at the final stage of the punch trajectory. A maximum value of 344.5 MPa was obtained.

The effective strain (case C4) has a non-uniform distribution, as it can be noticed in Fig. 4. The maximal values are however, during all the process that not suffers severe thinning or cracks, above a level of 0.41.

The simulated stress and strain state indicates the possibility of attaining the plastic state of stresses on the whole surface of the piece (after Von Misses plasticity criteria). However, it can be observed a significant localization of the stress in punch trajectory. This fact leads to the local apparition of higher corresponding specific thickness reduction for case C4 (Fig. 5).

An approximate maximum thickness reduction percent of 25.3% may be observed in the zone corresponding of punch trajectory, but also noticeable is the fact that the initial thickness is kept unchanged for more than 75% of the blank surface.

The flow limit diagram is presented in Fig. 6.

Figs. 7 and 8 presents graphically, based on the simulation, the variation of the two force types during the forming process, for the case C4. We selected the vertical force F_z and one of the horizontal forces F_y.

The other horizontal forces F_x has a similar variation with F_y and is not presented in this paper. The maximum

Table 2

Quantitative aspects of the four studied cases

Quantitative results	The case symbol			
	C1	C2	C3	C4
Maximum principal stress σ_1 [GPa]	319.7	357.4	319.3	334.4
Maximum equivalent stress σ_{VM} [GPa]	334.1	386.6	326.2	344.5
Maximum principal strain ε_1 [mm/mm]	0.25	0.46	0.20	0.33
Maximum equivalent strain ε_{VM} [mm/mm]	0.32	0.59	0.25	0.41
Minimum thickness g_{min} [mm]	0.81	0.63	0.86	0.74
Maximum thickness reduction s_{max} [%]	18.64	36.20	13.81	25.26
Maximum forces on vertical direction F_z [kN]	5.46	8.73	5.68	10.98
Maximum forces on horizontal direction F_x [kN]	1.30	3.47	1.32	3.30
Maximum forces on horizontal direction F_y [kN]	1.34	3.56	1.36	3.41
Total energy [J]	61.99	158.8	65.33	165.28
Hourglass energy [J]	0.993	1.487	0.906	1.412
Energy consumpted by friction [J]	11.35	22.44	12.16	25.23

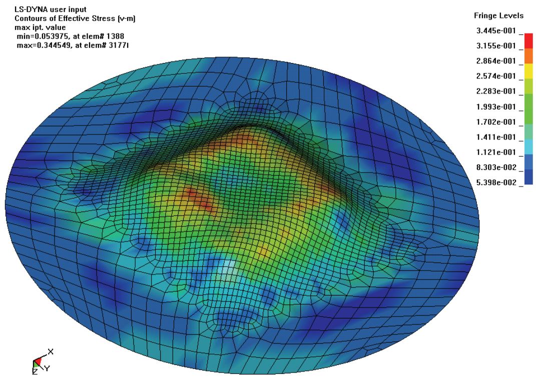

Fig. 3. The distribution of equivalent Von Misses stress.

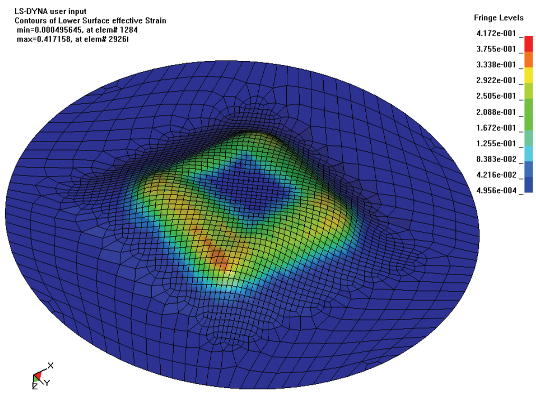

Fig. 4. The distribution of effective strain.

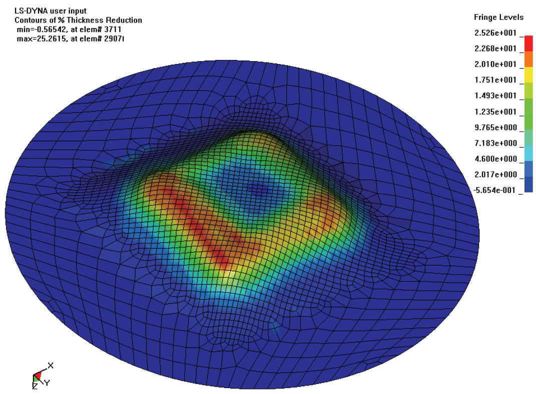

Fig. 5. The percentage of sheet thickness reduction.

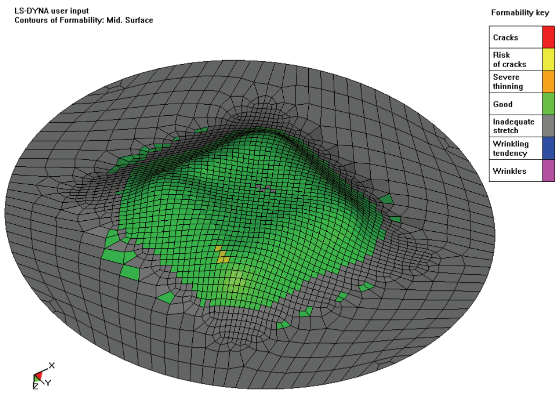

Fig. 6. The flow limit diagram.

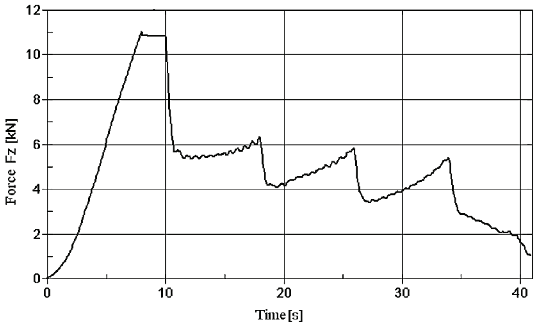

Fig. 7. The variation of the F_z force during the process.

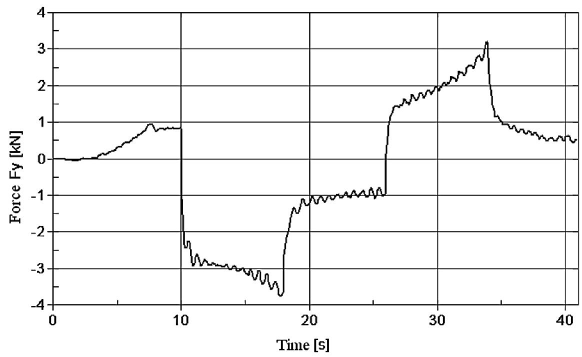

Fig. 8. The variation of the F_y force during the process.

values for the presented forces are 10.98 kN for F_z and 3.41 kN for F_y.

4. CONCLUSIONS

The analysis referring to the simulation of the incremental forming of sheets metal allows the emphasising of following conclusions:

- Analyzing the values of the stresses in the four cases one can notice that for the both stresses (principal and equivalent) the highest weight belongs to the deep of the part as these increase with its increase. The punch diameter also influences the distribution and maximum values of the principal and equivalent stresses. The maximum values of the stresses decrease with the increase of the punch diameter. This is due to the fact that, at smallest diameters of the punch the forming zone is localised on a small surface nearest the contact surface between the blank and the punch.
- Both strains and the thickness reduction have the same variation relative to the deep of the part of the punch and also the punch diameter. The effective strain and the thickness reduction increase with increase of the deep of the part value and decrease with the punch diameter. From the above mentioned items one can notice that the most unpropitious case is the C2 (the smallest punch diameter and the highest value of the deep of the part) where both the effective strain and the thickness reduction attain the maximum values. That case is near the limit of the forming capacity of the material.
- Both the force on *z* direction and the force on *y* direction have significant variations function of the parameters taken into account in the current analysis, meaning that the analysis has indeed taken into account the influence factors with the highest weight.
- The deep of the part also influences both the force on vertical direction F_z and the force on horizontal direction F_y, as these increase with its increase.
- The punch diameter influences the F_z force linearly, the force increasing with the punch diameter increase.

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