PREDICTION OF SURFACE STRETCHES AND SHEET METAL THINNING BY SINGLE POINT INCREMENTAL FORMING IN DIGITAL ENVIRONMENT

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ABSTRACT

To remain competitive nowadays the global industry must design and validate new products and production processes already in digital environment. The reason is in market demands, which aspire to price reduction, shortening of delivery times and improving product qualities. Therefore, the development times need to be shortened and unnecessary technological trials have to be omitted.

The paper presents digital validation of innovative technology called single point incremental sheet metal forming of various sheet metal shapes made from steel DC05. Special attention is dedicated to maximal surface stretches and sheet metal thinning prediction. In order to confirm the quality of obtained results from digital environment and their usability in industrial practice the comparison with real experimental results is made and discussed.

Keywords: process simulation, surface stretches, sheet metal thinning, incremental forming

1   INTRODUCTION

Global economy is nowadays witnessed with terms like recession or slow down. This on the other hand means that the only imperative to remain in competition is to develop new product which are cost efficient and friendly too the nature and societies. To get market acceptable solutions companies should introduce innovative products and technologies. From an invention to promotions and sales activities on turbulent markets a lot of important steps must be done. As all this is under constant pressures for time and cost reduction, the process itself should be innovative too.

Before starting a production it is necessary to perform a variety of tests like evaluation the parts shape, functionalities, mechanical properties, materials with their treatments, etc. Experiments under real production conditions are with no doubt time and costs consuming. If the process depends on many process variables it is very difficult, sometimes nearly impossible to respect rules for proper design of experiment followed with statistical evaluations. Only such approach is generating reliable results and justifies financial enrolments.

In the last decades computer supported tools became more and more powerful and capable to solve very complex processes in a reasonable amount of time. They were not used only to help part designers or production engineers to confirm their ideas or to get some better solutions. With more powerful equipment they could use digital environment also to perform digital experiments, to evaluate process robustness or stability.

However, in this investigation, a finite element model of asymmetric single point incremental forming (ASPIF) is proposed in order to predict maximal surface stretches and sheet metal thinning. Numerically obtained results are validating according to real experimental results.

2 ASYMMETRIC INCREMENTAL SHEET METAL FORMING PROCESS

Incremental sheet metal forming process is nowadays well known alternative sheet metal forming method used in particular at small batch and prototype production. The sheet metal could be formed to a complicated unsymmetrical shape without a dedicated die (Figure 1).

In general it is difficult to predict the strain distribution, forces, forming accuracy, etc. after the accumulation of numerous incremental deformation passes [1,2]. One option to calculate above mentioned forming outputs during the whole deformation process in advance is by using finite element analysis (FEA) [3]. Nevertheless, FEA has some difficulties when applied to the incremental sheet metal forming process. The most critical problem is the large number of calculation steps. Since asymmetric incremental forming is a slow process with a time scale of minutes or hours, simulations with standard FEM systems and workstations can be expected to take very long. Compared with the general sheet metal forming processes, the incremental sheet metal forming process has an alternating contact loci, large strain plasticity, high local field gradients, complex tool kinematics, etc., what makes an FEA of the process a challenging task.

3 FEM ANALYSES OF ASPIF PROCESS

The simulations of the asymmetric single point incremental sheet metal forming [4] were performed using the finite element method (FEM) and the commercially available finite-element software Abaqus 6.5. The FEM model of asymmetric incremental sheet metal forming consists of 3D rigid objects (the rod shaped forming tool and the upper and lower blankholder plate) and a deformable blank of the analysed material. The geometry of all objects in FEM model is completely the same as the geometry of the parts performing experimental tests – Figure 1. The material properties of steel DC05 necessary to define the elasto-plastic material behaviour were obtained by the uniaxial tensile test (Table 1). The stress-strain curve was approximated by the Hollomon potential law. In addition, the anisotropic material behaviour described with the Hill quadratic yield criterion was taking into account. The model was considered as rate-independent.
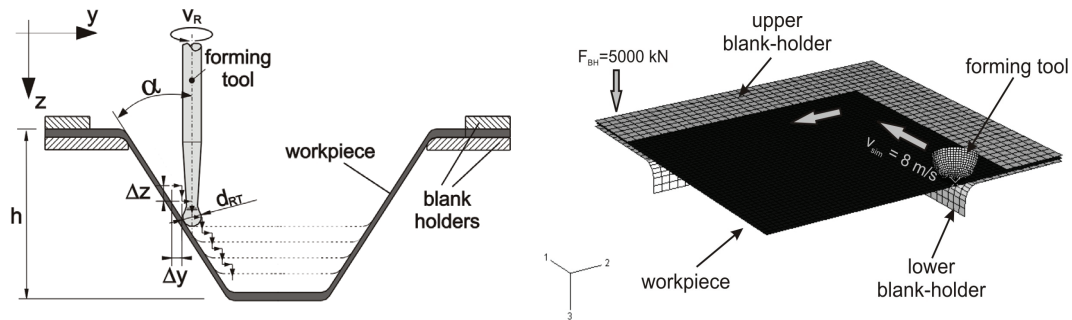
Figure 1: Process parameters of ASPIF [3] (left) and finite element model (1/4) (right).

Table 1: Material properties of steel DC05

C = 531	E = 210	*C..strength coefficient [MPa]*
n = 0.23	ρ = 7850	*n...strain hardening exponent [1]*
r_0 = 1.59	ν = 0.3	*r...material anisotropy according to rolling direction [1]*
r_{45} = 1.06	t_0 = 1	*E..Young's modulus of elasticity [GPa]* *ρ...density [kg/m³]* *ν...Poisson's ratio [1]*
r_{90} = 1.76	R_p = 177	*t_0...initial specimen thickness [mm]* *R_p...yield strength [N/mm²]*

Since the element type itself can greatly influence the results of the simulation, tree-dimensional quadrilateral shell elements with reduced integration (S4R) and five integration points across the sheet thickness were selected. Typically, shell elements assume a plane stress state and have translational and rotational degrees of freedom, usually. The simulation processes of ASPIF were performed in two steps. In the first step the upper blank holder moves down in the *z*-direction and presses the workpiece onto the lower blank holder. In the second simulation step the blank holders remain fixed; whereas the forming tool moves according to predetermined tool path until the finite forming depth is reached. Contact interactions between the surfaces in the FEM model are defined considering the Coulomb friction law. Friction coefficient μ between punch and specimen was assumed to be 0.1, what corresponds to the surface oiling by experimental work [5].

Due to the large number of simulation objects in contact solver convergence problems and material instabilities can occur during the simulation. Therefore, a dynamic explicit method instead of implicit method, which usually fails due to the above mentioned problems, was selected to alleviate this problem. The explicit method based on the principle of virtual work. After neglecting body forces the virtual work can be written as [6]

$$\int_V T_{ij}\delta u_{i,j}dV = \int_S t_i \delta u_i dS \tag{1}$$

, where T_{ij} is the Cauchy stress tensor, $u_{i,j}$ the gradient of the displacements, t_i the traction vector and δ the variational operator.

In addition, the virtual work equation (Equation1) can be modified by an inertia term to

$$\int_V T_{ij}\delta u_{ij}dV = \int_S t_i\delta u_i dS - \int_V \rho\ddot{u}_i\delta u_i dV \tag{2}$$

, where ρ is the density and $\ddot{u}_i$ the acceleration of material particles. From the discretization of this equation yields follows that

$$[M]\ddot{u}^t = \{F^t\} - \{I^t\} \tag{3}$$

, where $[M]$ is the diagonal lumped mass matrix, $\{F\}$ is the applied load vector and $\{I\}$ is the internal force vector at a given time t. Now, an explicit central difference scheme for the time marching is utilized in form of [6]

$$u^{t+\Delta t} = u^t + \Delta t^{t+\Delta t}\dot{u}^{t+\Delta t/2} \tag{4}$$

with

$$\dot{u}^{t+\Delta t/2} = \dot{u}^{t-\Delta t/2} + \frac{\Delta t^{t+\Delta t} + \Delta t^t}{2}\ddot{u}^t \tag{5}$$

Equation 3 must be modified by an artificial damping term in order to compensate for possible density manipulations in the structure to [7],

$$[M]\ddot{u}^t + [C]\dot{u}^t = \{F^t\} - \{I^t\} \tag{6}$$

The central difference algorithm is conditionally stable, which means that the time step Δt is subjected to a limitation that can be approximated by

$$\Delta t \le \frac{L_S}{C_S} \tag{7}$$

, where L_S is the characteristic element size and C_S the speed of sound in the workpiece material being simulated. The stable time step is usually very small. As a consequence of the small time steps, the explicit method is numerically very stable. However, the explicit method becomes only advantageous if it is sped up by mass scaling or reduction of the process time. Clearly, these numerical tricks demand careful interpretation of explicit calculation results, as the solution can be considerably affected by inertia forces. Consequently, the admissible range for mass and time scaling has been evaluated for several processes (e.g. deep drawing, hydroforming, indentation, etc), yielding the conforming result that a punch velocity of up to v=30m/s can be used without significant impact on local stresses and reaction forces [8]. On the other hand, Prior [9]

recommends that using explicit formulation punch velocity should not exceed v=10m/s, if the properties of the material to be formed are not dependent on the forming speed. According to both recommendations total duration of the process corresponds to the forming time for a smooth tool travelling at a feed rate of 8 m/s in our case. Applying the load in the smoothest possible manner requires that the acceleration changes only a small amount from one increment to the next. If the acceleration is smooth, it follows that the changes in velocity and displacement are also smooth. It is worth pointing out that sudden, jerky movements cause stress waves, which can induce noisy or inaccurate solutions. Moreover, a mass scaling scheme inducing an average time step of 1.5E-7s was used. This value was chosen in accordance with prior investigations and available literature sources in which the results of the FEA had been successfully compared to experimental data.

4   EXPERIMENTAL PROCEDURES, RESULTS AND DISCUSSION

The experimental work of this investigation was carried out on a CNC-controlled milling machine – SECMU. The basic technological parameters needed to perform the experimental test are presented in Fig. 1 (i.e. α [°] - wall angle, v_R [rpm] – tool rotation speed, h [mm] – forming depth, d_{RT} [mm] - tool diameter, Δz [mm] - vertical step size, Δy [mm] - horizontal step size and f_{RT} [mm/min] - feed rate). They were determined on the basis of preliminary researches [4]. It should be noted that the motion of the forming tool depends on test conditions and the shape of the particular workpiece. The tool path includes the movement in 3D space, as well as synchronized rotation along the z-axis. In order to confirm the quality of obtained results from digital environment and their usability in industrial practice the comparison with real experimental results will be made and discussed. Special attention is dedicated to the principle true strains (φ), and sheet metal thinning (ε), which is calculated from principal true strains. Both values are important in sheet metal practice in order to define critical forming areas on the product. Generally, there are many various methods to perform deformation measurement of the workpiece, as for instance Digital Image Correlation Technique (DICT) is a data analysis method which uses a proprietary mathematical correlation method to analyze digital image data taken while samples are subjected to mechanical stresses, laser scanning and others.

In these experimental procedures the deformations of the workpiece are measured using graphometric analysis based on size and direction investigation of the major strains of the particular sheet metal area by changing the coordinate measure grid, which is printed on the specimens before the forming process. In case of circular grid, circles are distorted into ellipses after deformation, and strains are measured in major and minor directions of the ellipses. The circular grid method is used to evaluate local deformation at a prescribed position but is inappropriate for measuring global distribution of deformations. In this case it is more convenient to use square grid pattern, which requires special equipment.

In a view of deformations measuring and analysing in addition, it is also very important to know whether the ASPIF process can be considered as a process of proportional deformation. First insight on the proportionality of a deformation can be given by measuring and plotting the strain paths of particular circles during the process. Boogaard [10] found out that serrated strain paths can be detected during strain measurement, showing that the loading is non proportional. For this reason it is more appropriate to speak about principal surface stretches (proposed by J.M. Allwood) instead of principal true strains whenever the deformation is analysed on the workpiece

surface. Therefore, this terminology will be used for deformations measured experimentally and for analysis of the results in addition.

However, circle grid measuring on particular formed workpiece was made by an optical measurement system (CCD camera) with accurate x-y coordinate table as presented in Figure 2. The results are further used to calculate major principle surface stretches φ_l, which are major in the plane of the sheet metal, and the minor principal surface stretches φ_d, which are minor in the plane of the sheet metal.

Among numerous measured surface stretches values only maximal major principal surface stretch φ_{lm} on each of four measurement areas, presented in Figure 2, are taking into account in order to asses numerical model.
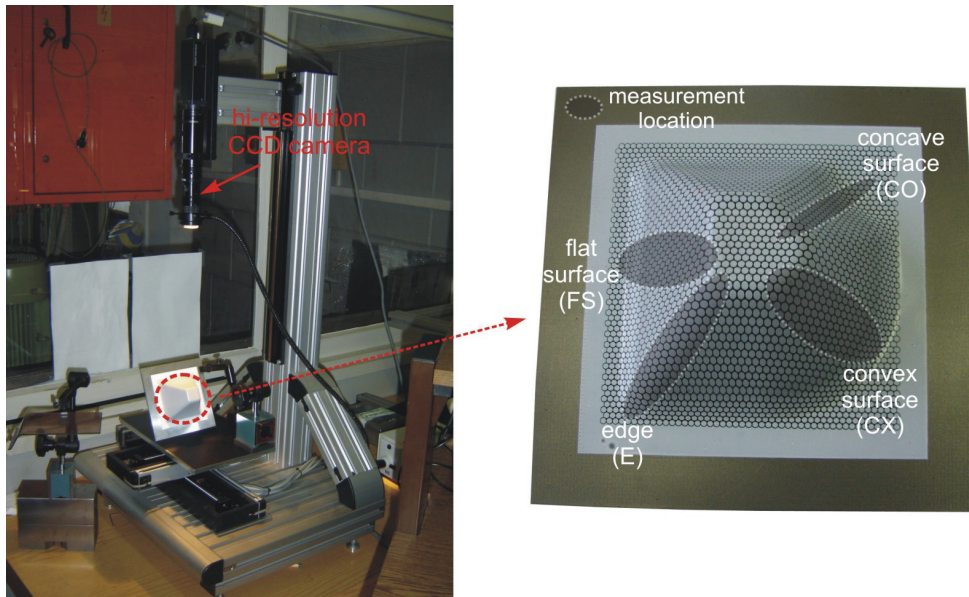

Figure 2: Contactless x-y measurement system (x-y table with CCD camera) and measurement locations of principle surface stretches.

In order to avoid any undesired issues arising from friction between the forming tool and the workpiece, a special lubricant was used.

5   QUALITY ASSESSMENT OF THE NUMERICAL MODEL

The quality of the numerical model was estimated on the basis of comparison between predicted and measured output data on four selected measurement locations of the test data set, which was selected randomly in the range of design of experiments made by Petek [4]. Test data set is presented in Table 2.

Table 2: Selected test data set.

Test	α [°]	d_{RT} [mm]	Δz [mm]	f_{RT} [mm/min]	v_R [r.p.m.]
1	60	10	0.5	1800	55
2	65	10	0.7	1500	75
3	60	12	0.9	2300	60
4	55	14	0.7	3100	45

In this investigation mean absolute percentage deviation (MAPD) is considered to compare the relative performance of the developed model, which is expressed as:

$$MAPD = \frac{1}{m} \sum_{i=1}^{m} \left| (\hat{y}_i - y_i) / y_i \right| \cdot 100 \qquad (8)$$

, whereas m is the number of test data, y_i is the known target value from the independent test data set, and $\hat{y}_i$ is the corresponding prediction.

Obviously, a model is considered to have good predictive ability if the MAPD is close to zero. From the results presented in Figure 3 it could be observed that mean absolute percentage deviation of the numerical model are very close to the optimal value (MAPD=0) in case of maximal major principal surface stretch and maximal sheet metal thinning prediction on all of four measuring locations.
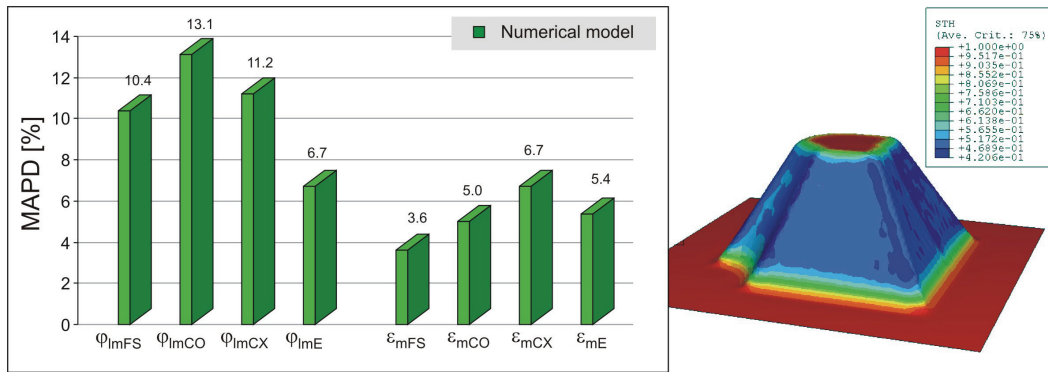

Figure 3: Quality assessment of the numerical model (left) and sheet metal thickness prediction after ASPIF (right).

In both cases the numerically obtained results can deviate due to the explicit dynamic method used, where mass forces may influence on the forming results in spite of low forming speeds. Moreover, care must be taken with the choice of mesh size and element formulations, as this affects the stiffness of the mesh. The selection of the mesh element type plays very important role. In our investigations 3D shell elements with reduced integration (S4R) and five integration points across the thickness were selected in order to achieve shorter calculation time. For these elements

it is significant that they have only one integration point according to top element surface. Generally, with increasing mesh density and the application of the element type without reduced integration S4 the FEM results would be better. This means that better FEM results of output values can only be obtained at greatly increased calculation times, unless the adaptive re-meshing would be applied.

However, if the model whose mean absolute percentage deviations are minor than 15% is appropriate for practical application in order to get insight into real forming condition and forming results afterwards.

6   CONCLUSIONS

In this research digital validation of asymmetric single point incremental sheet metal forming technology of various sheet metal shapes made from steel DC05 is presented. Regarding to obtain results it can be concluded that the quality assessment of the numerical model can be considered as a reliable.

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PROCENA VELIČINE RAZVLAČENJA I STANJENJA LIMA PRI INKREMENTALNOM DEFORMISANJU U DIGITALNOM OKRUŽENJU

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REZIME

Da bi se zadržala konkurentnost na globalnom niovou, proces projektovanja i testiranja novih proizvoda i proizvodnih procesa danas se mora izvoditi u digitalnom okruženju. To je posledica pre svega stožijih zahteva tržišta, usmerenih ka smanjenju cene koštanja, skraćenju vremena isporuke i poboljšanja kvaliteta proizvoda. Drugim rečima, vreme razvoja proizvoda mora biti skraćeno i nepotrebne probe izostavljene.

U ovom radu prikazana je inovativna tehnologija inkrementalnog (singl pint) deformisanja lima. Postupak inkrementalnog deformisanja delova različitih oblika od čelika DC05 analiziran je putem numeričkih simulacija baziranih na MKE. Posebna pažnja bila je posvećena proceni veličine maksimalno mogućeg razvlačenja i stanjenja lima. Da bi se potvrdila tačnost rezultata dobijenih numeričkim putem i mogućnost primene u industrijskim uslovima ovi reyultati su upoređenji sa eksperimentalnim.

Ključne reči*: Simulacija procesa, razvlačenje, stanjivanje lima, inkrementalno oblikovanje*