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# ALGORITHM FOR THE GEOMETRIC CONFIGURATION OF THE RECONFIGURABLE MULTIPOINT FORMING DIES

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## ABSTRACT

*Multipoint forming of thin steel plates with special equipments is based on the discrete die-punch reconfigurable tooling concept. The geometric modeling of the die-punch tool requests calculations of the characteristic profiles coordinates of the working surfaces materialized by a number of punches on the height positioned. The paper is concerned with the development of a method for die – punch geometry configuration using Matlab program. On this basis, the theoretical analysis is particularly applied to the simulation of the doubly curved thin steel plate deformation using finite element method. The conclusions obtained from the numerical simulation certify the validity of the developed method.*

**KEYWORDS:** multipoint forming, modelling, FEM, sheet metal

## 1. INTRODUCTION

The reconfigurable multipoint forming (RMPF) is an inexpensively sheet metal manufacturing method used in small batch production. The technology is known also as MPF - Multipoint Forming [6, 7, 9, 10, 15] or DDF - Digitized Die Forming [1-3].

In this manufacturing method a pins matrix approximate the continuous active surfaces of the conventional die. In the pins matrix each pin is vertically aligned according with the part geometry. In this context controlling the height of each pin is one of the main technological problems which assures the geometry of the part and avoids in general the dimpling phenomenon.

On the other hand the control of the pins heights is given by the values of the contact points coordinates between the hemispheric pins ends and the blank surface. The contact points could be established for primary configuration of the multipoint tool and secondly for the reconfiguration of the tool for springback compensation.

Different methods have been proposed for established the contact points coordinates. These methods could be divided in two categories, function of how is defined the part geometry surface.

The first category considers that the equation of the part geometry surface is known. This leads to the use of the classical analytical methods for contact points estimation. Thus, Hardt, Karafillis, Walczky and Papazin [4, 5, 8, 11-14, 17, 18] used such methods in design the multipoint forming die with application in the field of strech-forming, known as reconfigurable tooling for flexible fabrication (RTFF).

The second category, which assures the greatest generality, considers that the part geometry surface is defined by a number of points, this means that the equation of the surface is unknown. These points could be the result of a measuring process using CMM or could be the result of surface discretizations. In this case, the problem of contact points estimation is more complicated. For multipoint forming, Cai [1] proposed a method often use in surface modelling based on NURBS surface, in which the equation of the desired part is parametric defined using NURBS surface with control points. Also, Cai [2] developed another method where using the interpolating formulation of finite element method the pins positions are given by a series of 3 non-linear equations. Paunoiu [15] proposed a method for primary configure of the multipoint forming die based on the surface generation method.

In the paper is presented a method for multipoint forming primary configuration considering that the part surface is defined as a points matrix and the problem solution is obtained using MatLab program. Then using the dynamic explicit finite element method is analysed the deformation of sheet metal. The simulation is made using different curvature radius of a doubly curved surface shape.

## 2. GEOMETRIC CONFIGURATION ALGORITHM

In the final pins position these are in contact with sheet which has taken the part form. The calculus started from the known surface of the part to be obtained.

It is considered a points matrix with $n$ points on direction $x$ and $m$ points on direction $y$. On each point is calculated with MatLab program the normal direction at the surface.

Is obtained the vector:

$$N = N_x \cdot \vec{i} + N_y \cdot \vec{j} + N_z \cdot \vec{k} \tag{1}$$

where: $N_X$, $N_Y$ and $N_Z$ are the component of normal direction on axis $X$, $Y$ and $Z$.

If it is considered the radius $R$ of the pin hemispherical end and the blank thickness $g$, for each node $ij$ , it is calculated the distances ($R + 0.5g$) along the normal direction. In this way is obtained a surface equidistant to the initial surface.

It is necessary to calculate two equidistant corresponding to the upper and lower half die (Fig. 1).

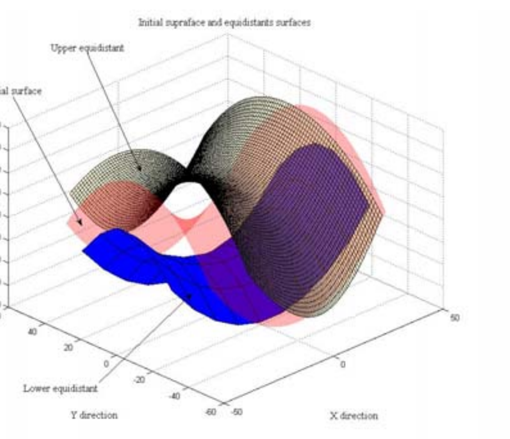


Fig. 1. Initial surface and upper and lower equidistant

The two surfaces have the equations:

$$S_U : \begin{cases} X_{Uij} = x_{ij} + \left( R + \dfrac{g}{2} \right) \cdot N_x; \\ Y_{Uij} = y_{ij} + \left( R + \dfrac{g}{2} \right) \cdot N_y; \\ Z_{Uij} = z_{ij} + \left( R + \dfrac{g}{2} \right) \cdot N_z, \end{cases} \tag{2}$$

for upper equidistant and:

$$S_L : \begin{cases} X_{Lij} = x_{ij} - \left( R + \dfrac{g}{2} \right) \cdot N_x; \\ Y_{Lij} = y_{ij} - \left( R + \dfrac{g}{2} \right) \cdot N_y; \\ Z_{Lij} = z_{ij} - \left( R + \dfrac{g}{2} \right) \cdot N_z, \end{cases} \tag{3}$$

for lower equidistant, $i=1\ldots m$, $j=1\ldots n$, $[x_{ij}, y_{ij}, z_{ij}]$ coordinates of node $ij$.

With MatLab capabilities are generated two new surfaces ($S_{US}$ and $S_{LS}$) overlapped to surfaces $S_U$ and $S_L$, with nodes at even pitch on $x$ and $y$ directions.

If the surfaces pitch corresponds to the pin half side, the nodes of these surfaces will be the position of the hemispheric end of each pin in the upper half die and respectively lower half die.

In order to determine the coordinates of contact points between the pin and the part, in each of the $S_{US}$ and $S_{LS}$ surfaces nodes, it will be calculated the normal at these surfaces,

$$n = n_x \cdot \vec{i} + n_y \cdot \vec{j} + n_z \cdot \vec{k} \tag{4}$$

The contact points coordinates will be give by:

$$P_U : \begin{cases} X_{UC} = X_{US} - R \cdot n_x; \\ Y_{UC} = Y_{US} - R \cdot n_y; \\ Z_{UC} = Z_{US} - R \cdot n_z, \end{cases} \tag{5}$$

and respective:

$$P_L : \begin{cases} X_{LC} = X_{LS} + R \cdot n_x; \\ Y_{LC} = Y_{LS} + R \cdot n_y; \\ Z_{LC} = Z_{LS} + R \cdot n_z. \end{cases} \tag{6}$$

### *2.1. Numerical example*

To proof the method it was applied this algorithm to a surface with equations:

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} - 2 \cdot z = 0 \tag{7}$$

where: $a$=5; $b$=5.

The pin radius is $R = 10\sqrt{2}$ mm and the blank thickness is $g$ = 1mm.

The surfaces have dimensions 100x100 mm$^2$ and the pin grid is formed by 10x10 pins, with distance between ball ends of pin 10 mm.

In Fig. 2 are presented the positions of the contact points as a result of applying the proposed algorithm.

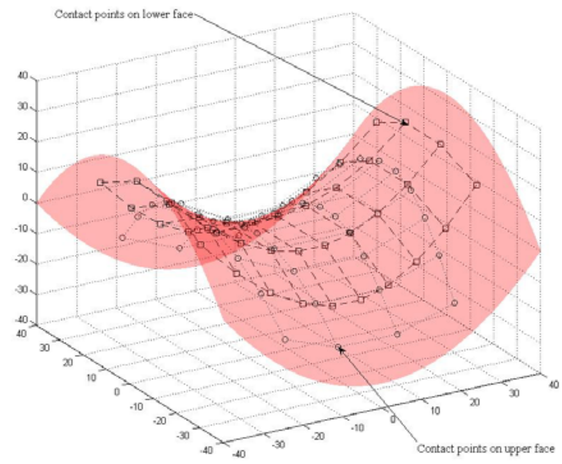


Fig. 2. Contact points on the part upper and lower face

## 3. FEM MODEL AND PROCESS SIMULATION

Based on the above methodology it is possible to design different models for reconfigure multipoint forming dies. The models will be used for simulation the process of multipoint deformation using the dynamic explicit finite element method.

The FEM model is presented in Fig. 3.

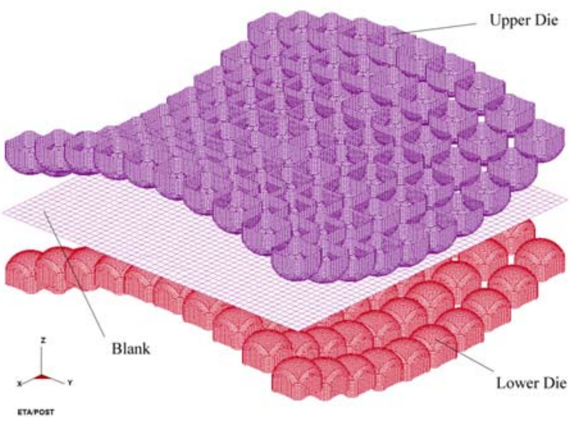


Fig. 3. FEM model of tool for obtaining a doubly curved part

The tooling was modelled as rigid surfaces using the simulation program DYNAFORM-PC. No blankholder was used.

The upper and lower die consists of 100 pins for each, disposed face to face, both on *x*-direction and *y*-direction.

The final geometry is a doubly curved part. According with equation (7) the values of parameters (*a*) and (*b*) for which were designed the tools are 7, 8, 9 and 10. The two parameters are equal in the present analysis. The value 7 means a higher curvature, 10 being the smallest one.

The punch speed was 100 mm/second. A Coulomb friction law was used with a friction coefficient of 0,125.

The blank was a rectangular plate with the dimensions of 100x100 mm. The number of finite elements for blank was 2500.

For simulation it was used 4-node Belytschko-Tsay shell elements, which provide five integration points through the thickness of the sheet metal. The Belytschko-Lin-Tsay shell element are based on a combined co-rotational and velocity-strain formulation. The co-rotational portion of the formulation avoids the complexities of nonlinear mechanics by embedding a coordinate system in the element. The choice of velocity strain, or rate of deformation, in the formulation facilitates the constitutive evaluation, since the conjugate stress is the more familiar Cauchy stress.

The material used in experiments was mild steel, with a thickness of 1 mm. The yielding of the material was modeled using a power law, as:

$$\sigma = K\,\varepsilon^{n} \tag{8}$$

According with the material characteristics, for simulation the *n*-value = 0,22 and *K* = 648 MPa. The *R*-values were set to: $R_{00}$ – 1,87; $R_{45}$ – 1,27; $R_{90}$ – 2,17.

Figure 4 shows the simulated doubly curved part for (*a*) and (*b*) parameters equal with 10. The imagine characterizes a particular defect in multipoint deformation without interpolator which is dimpling.

Dimpling is a result of the discontinuous contacts between the pins and the sheet metal. In the contact zones the loads are strongly localized and this will generate particular maps of stresses and strains in material.

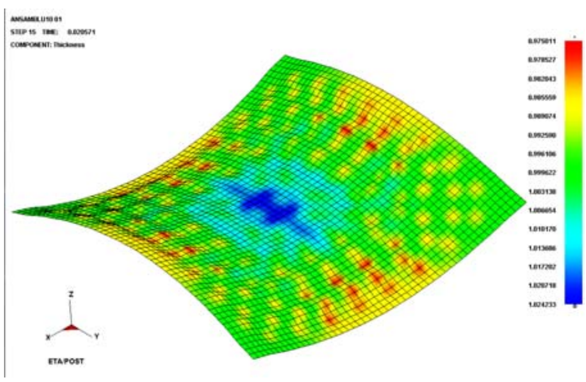


Fig. 4. Thickness variation in multipoint deformation of doubly curved part

In comparison in Fig. 5 is presented the same part obtained using conventional deformation, when the punch and die are bulky. The parameters used in simulation in this case are the same, with the observation that the active elements are continuous surfaces.

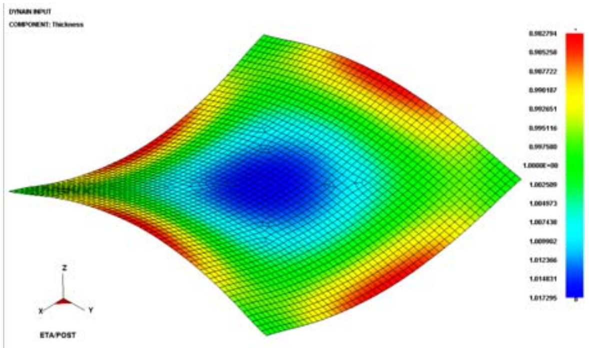

Fig. 5. Thickness variation in conventional deformation of doubly curved part

## 4. RESULTS AND DISCUSSIONS

In the above figures were presented in comparison the qualitative imagines of thickness variation for deformation a doubly curved surface using multipoint deformation and conventional deformation.

Figure 6 presents the quantitative variation of the thickness considering the two processes, for the case when (*a*) and (*b*) parameters from equation (7) are equal with 10. The measurements were done in x direction according to Figs. 5 and 6. Only a half of part was measured. It can be observe that in the case of conventional deformation the curve of thickness variation is smooth. In the case of multipoint deformation, even the values of thickness variation are not so important, the curve is not smooth as a result of the localized contact between the pins and the material. In both cases in the sheet edges regions appears material thinning and in the middle of the sheet the material is thicker. Even these variations are small, its influenced the stresses and strain state in material.

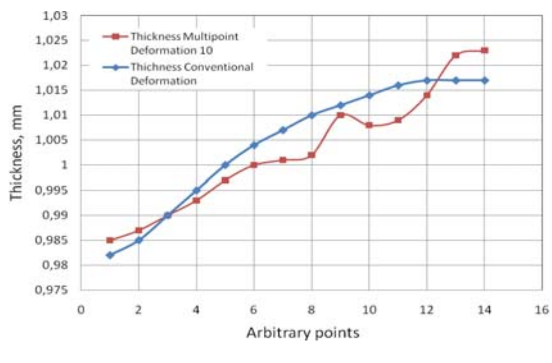


Fig. 6. Thickness variation in conventional and multipoint deformation of doubly curved part

Figure 7 presents a comparison of the thickness variation considering the different values for (*a*) and (*b*) parameters from equation (7). The measurements were done in (x) direction according to Figs. 5 and 6. The curves are not smooth because of localized deformation, regions with a greater thickness alternate with regions with smaller thickness. With decreasing the values of the two parameters, this means the curvatures radii becomes greater, the thickness variation is more pronounced.

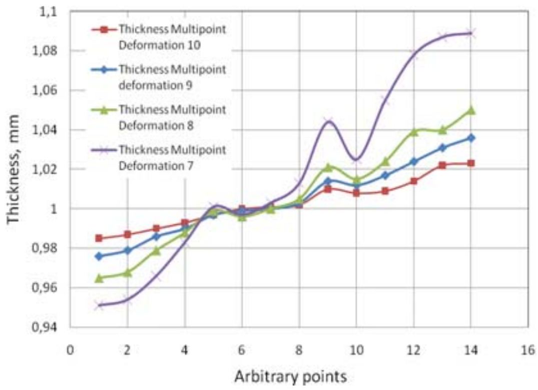


Fig. 7. Thickness variation in multipoint deformation of doubly curved part

The variation of mean stress in conventional and multipoint deformation is presented in Fig. 8, for the case when (*a*) and (*b*) parameters from equation (7) are equal with 10. The effect of localized deformation is clearly present following the two curves from the figure. In the case of conventional deformation in material, the mean stress has both negative and positive values, the curve is smooth and the values of stresses increasing from the sheet edge to the middle of the part. The variation is comprised between -71.22 to 202.98 MPa. The measurements were done also in (x) direction according to Figs. 5 and 6. In the case of multipoint deformation the mean stress has only positive values and in the measurement direction these values are variable. The minimum value is 35.06 MPa and the maximum is 170.90 MPa.

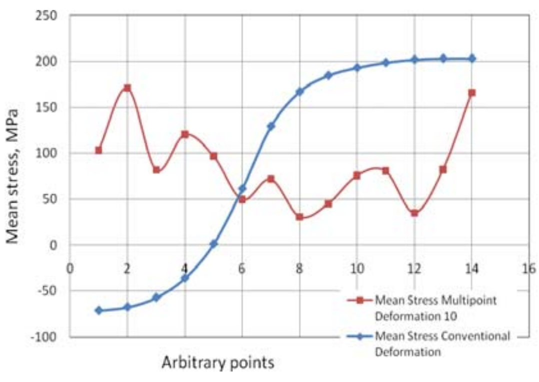


Fig. 8. Mean stress variation in conventional and multipoint deformation of doubly curved part

Figure 9 presents the variation of the mean stress in multipoint deformation considering two different values for *(a)* and *(b)* parameters from equation (7), 10 respectively 7. In this case, with increasing the curvature radii, the positive values of mean stress are increasing but in the material appear also negative values of this stress. For instance, the stress decrease ranges from about 241 to - 45 MPa.

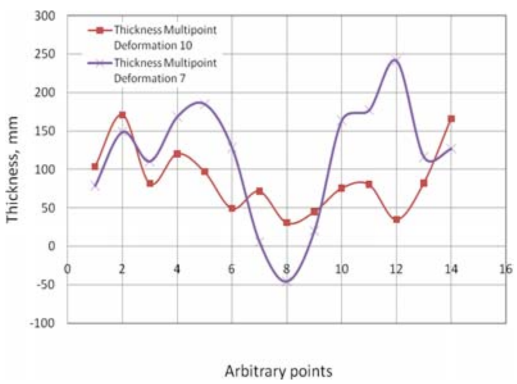


Fig. 9. Mean stress variation in multipoint deformation of doubly curved part

The Von Mises stresses are given by:

$$\sqrt{2}\sigma_C = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (9)$$

where: $\sigma_1$, $\sigma_2$, $\sigma_3$ are the normal, principal stresses and are a measure of the level of the flow stress in material.

Figure 10 shows the Von Mises stresses variation in conventional and multipoint deformation for the case when *(a)* and *(b)* parameters from equation (7) are equal also with 10. Again in multipoint deformation these stresses take different values in different contact points having an alternate variation.

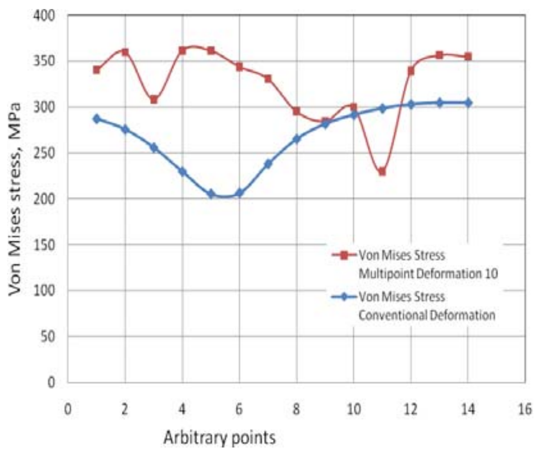


Fig. 10. Von Mises stress variation in conventional and multipoint deformation of doubly curved part

Figure 11 presents the variation of axial force during multipoint forming of doubly curved part for the considered cases. The curves of forming force versus time (which depends on punch travel) are similar to each other. The differences in magnitude are given by the contact state. At the beginning of forming process the values of forces are small because only a few of pins are in contact with the material. With increasing the punch travel, more and more pins get into contact with the sheet and the force increases very much. At the end of punch travel the force reaches its maximum because almost all the punches are in contact with the material. The word *almost* is very important, because in the case of small radii of doubly curved part, at the end of the process, most of the pins are in contact with the sheet. When the radii are increasing the numbers of the pins in contact with the sheet are decreasing, in the present analysis, especially the pins from the border of the punch are losing their contact with the material.

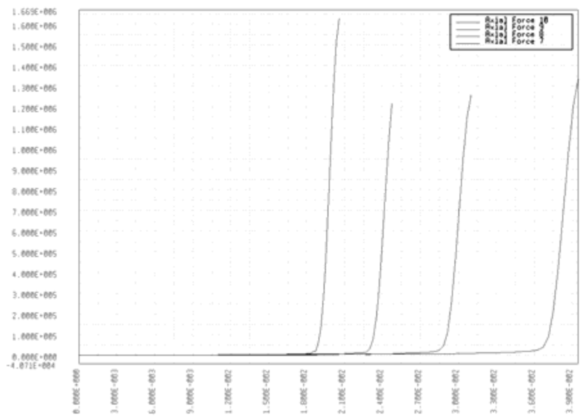

Fig. 11. Axial force variation in multipoint deformation of doubly curved part:
Axis x – Time; Axis y – Force value in [N]

## 5. CONCLUSIONS

This paper presents an algorithm for establish the contact points between the sheet metal and the active elements in multipoint forming. Based on this some models for simulation the process of deformation using the finite element method was developed. The numerical experiments show the effect of localized deformation. The localized deformation reduced the surface quality of the part due to the presence of dimpling. In material the stresses alternate, in the zones of contact points the values of stresses are bigger and outside of these zones their values are smaller. Also the concentrated stresses cause wrinkles in the non-contact areas. To avoid these variations the solution will be the use of an interpolator between the sheet metal and the active elements of the die.

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## REFERENCES

**[1] Cai Z.Y., Li, M.Z.,** *Digitized die forming system for sheet metal and springback minimizing technique*, Int J Adv Manuf Technology (2006) 28: 1089–1096, pag. 1089-1096

**[2] Cai, Z.Y., Li, M.Z**., *Optimum path forming technique for sheet metal and its realization in multi-point forming*, J Mater Process Technology, 110:136–141, 2001

**[3] Cai Z.Y., Li, M.Z.,** *Digitized die forming system for sheet metal and springback minimizing technique*, Int J Adv Manuf Technology (2006) 28: 1089–1096, pag. 1089-1096

**[4] Hardt, D.E., Rzepniewski, A., Pi, A.,** *Cycle-to-Cycle Feedback Control and its Application to Sheet Metal Forming*, Proceedings of the JSME/ASME International Conference on Materials and Processing, Oct. 2002.

**[5] Hardt, D.E., Siu, T.-S.,** *Cycle to Cycle Manufacturing Process Control*, First Annual SMA Symposium, Singapore, Jan. 2002.

**[6] Gavan, E., Paunoiu, V., Dimache, A.,** *Comparative Study for Single-Curved Plates Forming with Continuous and Reconfigurable Die-Punch Assembly*, Analele Universității Dunărea de Jos din Galați, fasc. V, 2004, pag. 81-85, ISSN 1221-4566

**[7] Gavan, E., Paunoiu, V., Dimache, A.,** *Cylindrical Thick Plate Forming with Reconfigurable Die-Punch Tool*, TMCR, Chişinău, 20035, pag. 400-404, ISBN 9975-9975-3-2

**[8] Karafillis, A. P., and Boyce, M. C.,** *Tooling Design in Sheet Metal Forming using Springback Calculations*, Int. J. Mech. Sci., 34, pp. 113–131,1992

**[9] Li, M.Z., Cai, Z.Y., Sui, Z., Yan, Q.G.,** *Multi-point forming technology for sheet metal*, J Mater Process Technology 129(1–3):333–338, 2002

**[10] Li, M.Z., Liu, Y.H., et al.,** *Multi-point forming: a flexible manufacturing method for a 3-D surface sheet*, J. Mater. Process. Technolology 87 (1999) 277–280.

**[11] Nakajima, N.,** *A Newly Developed Technique to Fabricate Complicated Dies and Electrodes with Wires*, Bulletin of Japanese Society of Manufacturing Engineers (JSME), Vol. 12, No. 54, 1969, pp. 1546-1554

**[12] Owodunni, O.O., Diaz-Rozo, J., and Hinduja, S.,** *Development and Evaluation of a Low-Cost Computer Controlled Reconfigurable Rapid Tool, Computer-Aided Design and Applications*, 1, 1-4, 2004, 101-108.

**[13] Papazian, J.,** *Tools of Change*. Mechanical Engineering, Feb. 2002, pp. 31-40

**[14] Papazian, J. M., Anagnostou, E.L., Christ, R. J., Hoitsma Jr.D., Ogilvie, P., and Schwarz, R.C.,** *Tooling For Rapid Sheet Metal Parts Production*, 6th Joint FAA/DoD/NASA Conf. on Aging Aircraft, San Francisco, CA, USA, September 16-19, 2002

**[15] Paunoiu, V., Oancea, N., Nicoara, D.,** *Simulation of Plate's Deformation Using Discrete Surfaces, Materials Processing and Design: Simulation and Application*, NUMIFORM, 2004, OHIO State University, American Institute of Physics 0-7354-0188-8, pag. 1007-1010

**[16] Valjavec, M. and Hardt, D.E.,** *Closed-loop Shape Control of the Stretch Forming Process over a Reconfigurable Tool: Precision Airframe Skin Fabrication,* Proceedings of the ASME Symposium on Advances in Metal Forming, Nashville, Nov. 1999.

**[17] Walczyk, D.F., Hardt, D.E.,** *Design and analysis of reconfigurable discrete dies for sheet metal forming*, J Manuf Syst 17:436–454, 1998