THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAȚI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING, ISSN 1221- 4566,
2010

# The Multi-Physics System in Reconfigurable Multipoint Forming

V. Păunoiu, V. Teodor, N. Baroiu, C. Lalău
"Dunarea de Jos" University of Galati, Department of Manufacturing,
Robotics and Welding Engineering,
viorel.paunoiu@ugal.ro

## ABSTRACT

*One of the methods for increasing the quality of the reconfigurable multipoint formed parts is to use an elastic interpolator between the pins active elements and the blank. The paper presents a numerical model based on the study of the rigid/elastic-plastic medium assembly behavior toward its application to the design of the new controllable multipoint dies with flexible interface. In the first part of the paper, general aspects of material behavior laws are dealt with in reconfigurable multipoint forming system. Then, in the paper proper are presented the simulations results, using finite element approach, regarding the influence of the interpolator thickness and pins penetration toward the parts quality. The parts quality is evaluated in terms of springback and stresses state variation. The results could lead to the development of these new types of equipments which assure the decreasing of the cost testing and production.*

**KEYWORDS:** multipoint forming, rubber forming, numerical simulation

## 1. Introduction

Forming with multipoint reconfigurable dies is a flexible manufacturing stamping technology. It is based on the active elements continuous 3-D surfaces partition with a help of an adequate discrete punches (figure 1), [6]. The desired surface shapes of active elements, which finally will determine the part shape could be obtained by adjusting the heights of these punches. Using a geometrically reconfigurable die, precious production time is saved because several different products can be made without changing tools. Also a lot of expenses are saved because the manufacturing of very expensive rigid dies is reduced.

One of the methods utilized for increasing the reconfigurable multipoint formed parts quality is to interpose an elastic plate (interpolator) between the pins active elements and the blank [6].

The interpolator changes the behavior of all the system of deformation, resulting both advantages and disadvantages o this type of process.

The advantages using the elastic interpolator are: good surface quality of the part as a result of dimpling phenomenon elimination; a uniform pressure distribution upon the blank which assures a uniform material deformation.

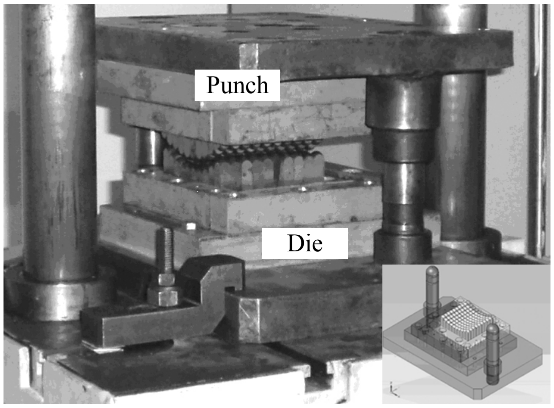


**Fig. 1.** *Technological equipment for reconfigurable multipoint forming*

There are also some disadvantages regarding the properties and thickness of the elastic interpolator used in the system. First disadvantage of using soft materials is that the pins can push through the pad and dimple the sheet metal. Also, this thing happens when the interpolator is two thin. Another one is that when the interpolator is hard, it will not conform to the blank geometry. According to [1], the perfect interpolator would be very soft initially until all the gaps have been filled, then it would become perfectly rigid so it would not fail.

The paper focuses on the study of the interpolator thickness and pins penetration influence toward the part quality in terms of springback and stresses state variations. The study was made using finite element method implemented in Dynaform program.

## 2. Materials Behavior Laws for the Studied System

From the point of view of material behavior, the studied system is composed of rigid, elasto-plastic and hyperelastic elements which correspond to punch and die, to blank and to elastic interpolator.

The rigid material is used for tooling modeling. In finite element method, elements which are rigid are bypassed in the element processing and no storage is allocated for storing history variables; consequently, the rigid material type is very cost efficient. All elements which correspond to the rigid material should be contiguous, but this is not a requirement. If two disjoint groups of elements on opposite sides of a model are modeled as rigid, separate part ID's should be created for each of the contiguous element groups if each group is to move independently. Young's modulus, *E*, and Poisson's ratio, $\upsilon$ are used for determining sliding interface parameters if the rigid body interacts in a contact definition. Realistic values for these constants should be defined since unrealistic values may contribute to numerical problem in contact [8].

The elasto-plastic material is used for modeling the sheet metal behavior [8]. One model developed by Barlat, Lege, and Brem [9] for modeling material behavior is that the anisotropic yield criterion $\Phi$ for plane stress is defined as:

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

where $\sigma_Y$ is the yield stress and $K_{i=1,2}$ are given by:

$$K_1 = \frac{\sigma_x - h\sigma_y}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2} \quad (2)$$

The anisotropic material constants a, c, h and p are obtained through $R_{00}$, $R_{45}$ and $R_{90}$:

$$a = 2 - 2\sqrt{\frac{R_{00}}{1+R_{00}}\frac{R_{90}}{1+R_{90}}}$$

$$c = 2 - a \quad (3)$$

$$h = \sqrt{\frac{R_{00}}{1+R_{00}}\frac{1+R_{90}}{R_{90}}}$$

The anisotropy parameter p is calculated implicitly. For FCC materials m=8 is recommended and for BCC materials m=6 is used.

The yielding of the material is modeled using a power law:

$$\sigma = K\,\varepsilon^n \quad (4)$$

where: *K* is the material constant; *n* – hardening exponent.

For the elastic interpolator, an incompressible Mooney-Rivlin Rubber model could be used [8]. The Mooney-Rivlin material model is based on a strain energy function, W, as follows:

$$W = A(I_1 - 3) + B(I_2 - 3) + C\left(\frac{1}{I_3^2} - 1\right) + D(I_3 - 1)^2 \quad (5)$$

A and B are user defined constants, whereas C and D are related to A and B as follows:

$$C = \frac{1}{2}A + B$$

$$D = \frac{A(5\upsilon - 2) + B(11\upsilon - 5)}{2(1 - 2\upsilon)} \quad (6)$$

where $\upsilon$ is the Poisson’s ratio, $I_1$, $I_2$, $I_3$ are the invariants of the Chauchy-Green Tensor. More details about the above models are presented in [8]

## 3. FEM Simulation Model

The model was developed using Dynaform finite element program, a nonlinear dynamic software which can simulate different types of sheet metal forming process to predict the stresses, strain, thickness distribution, punch load and effect of various design parameters of tooling on process efficiency and final product.

For the process simulation, in the first step it was constructed tool geometry with fixed configuration without interpolator, considering the obtaining of a single curvature plate with an interior radius of 95 mm, a width of 120 mm (maximum depth is 21.345 mm) and a length of 130 mm. In the second step, in the model between the active elements and the blank were included two interpolators (upper and down rubber). No blankholder was used so the ends of the rubbers are free to expand.

Figure 2 presents the simulation model.

The blank material used in experiments was mild steel, of 1 mm thickness. In simulation, according to equation (4) 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.

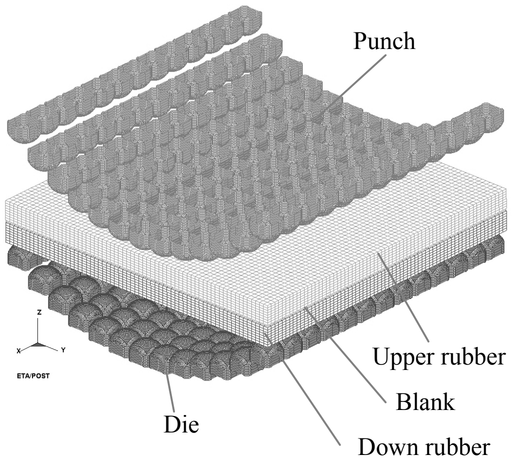


**Fig. 2.** *Tooling for reconfigurable multipoint forming*

The blank is a rectangular plate with the dimensions of 120x130x1 mm and the mesh consists of 900 finite elements.

The FE blank mesh consists of 4-node Belytschko-Tsay shell elements, with five integration points through the thickness of the sheet [4]. The Belytschko-Lin-Tsay shell element is based on a combined co-rotational and velocity-strain formulation. The Coulomb friction law was used with a friction coefficient of 0.125. The punch speed was 100 mm/second.

The tooling was modeled as rigid surfaces. The geometry of the tool is characterized in terms of an array of pin positions. The geometrical model of die-punch tool was composed of two working arrays with 100 pins for each array, 10 rows on $x$-direction and 10 rows on $y$-direction. The pins are displayed face to face, both on $x$-direction and $y$-direction. The mesh consists of 488744 numbers of finite elements.

For rubber interpolator was chosen a material type Elvax 460. The properties of the material were: density, $\rho$ – 0.946 g/cm$^3$; hardness Shore ASTM D2240 scale B – 40 and scale A – 80; tensile strength, $Rm$ – 18 MPa; elongation – 750%; flexural modulus – 44 MPa; stiffness, $k$ – 43 MPa; Poisson ratio, $\nu$ – 0.499. Solid elements were used for meshing the rubber interpolator. The interpolator was modeled as Mooney Rivlin Rubber material. The above density, flexural modulus and Poisson ration were used. The thicknesses of the rubbers varied between 2 and 10 mm. The simulations were done also with different strokes for the punch.

## 4. Simulation Results

During these simulations, the penetration of the pins into the interpolator was observed in order to determine its influence. Also the effect of thickness interpolator toward the part quality was determined.

### 4.1. Rubber deformation

Some important observation could be made regarding the rubber deformation.

Figure 3 presents the image of the upper rubber interpolator form after deformation, thickness 10 mm, 23 mm pins stroke.

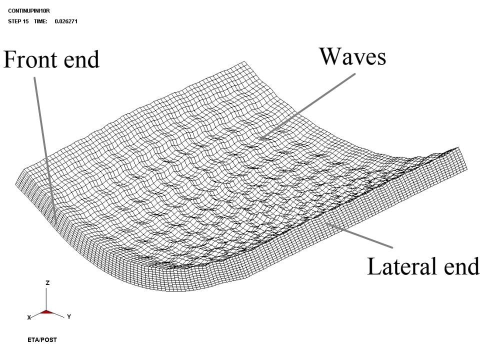


**Fig. 3.** *A rubber interpolator after deformation*

As the part is formed on the die, the interpolator is compressed in the thickness direction by the pins, and thus tends to expand in x direction and bends in y direction. This depends on the rubber thickness and the pins strokes for the same rubber material.

The rubber deformation is characterized by the wave appearance. Their form depends on the gap between the pins, the pins stroke and the rubber thickness.

For smaller interpolator thickness the picks of the waves are rounded (figure 4, a.) and become sharp when the interpolator thickness is greater and the gaps between the pins are filled (figure 4, b.). An interpolator small thickness or a greater pins stroke lead to a non-uniform pressure toward the blank having as a result an uneven supplementary deformation of the blank (figure 5). The maximum pressure is situated in the middle of the rubber.

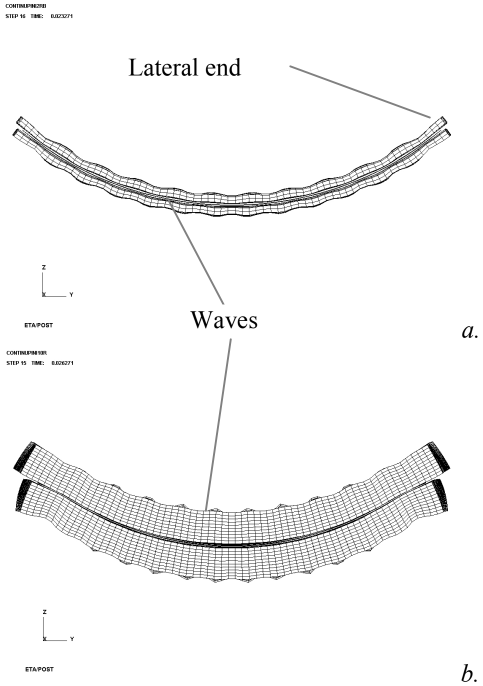


**Fig. 4.** *Front view of the rubber interpolators and blank assembly after deformation: a. 2 mm thickness; b. 10 mm thickness*

The presence of an interpolator with a greater thickness in the system could assure a uniform pressure toward the blank. Figure 6 presents the means stresses variation in the upper and down rubber interpolators for different rubber thickness and the same pins strokes. As it can be see, the increasing of the rubber thickness leads to the reduction of the means stress in the rubber material which will affect the blank deformation.

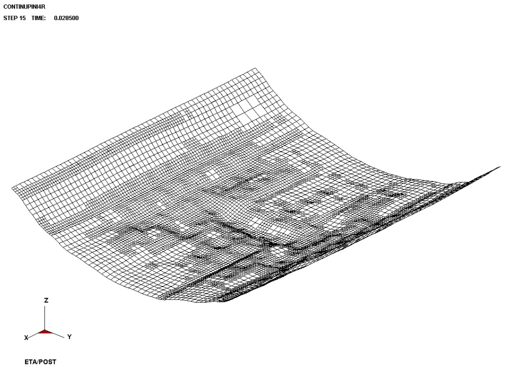


**Fig. 5.** *Uneven blank deformation, rubber interpolator 4 mm thickness, 25 mm pins stroke*

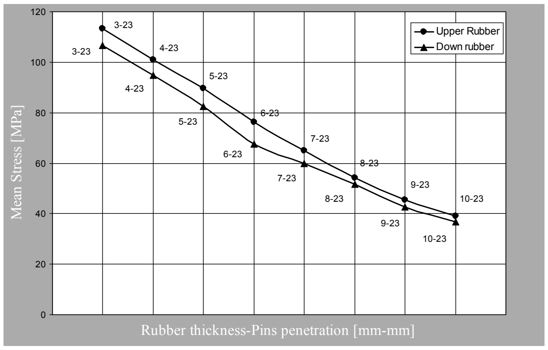


**Fig. 6.** *Mean stresses variation in the rubber interpolator*

In the considered fixed configuration of the pins, for the established geometry, for a greater rubber thickness, appears a phenomenon of supplementary bending of the lateral ends of the rubber in y direction which will affect the part geometry.

### 4.2. Blank deformation

The geometry considered is affected by the rubber presence in terms of profile radius and depth.

First, the blank deformation was evaluated in terms of springback. The springback was defined in relation of the three parameters presented in figure 7.

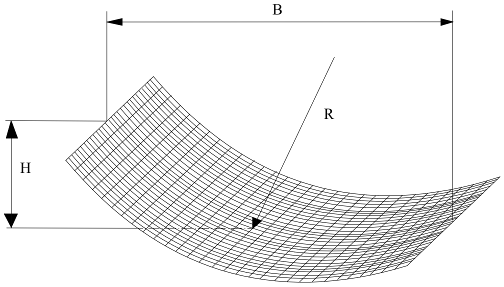


**Fig. 7.** *Parameters for springback definition*

The springback was calculated on the relation:

$$\Delta S=\frac{V_i-V_f}{V_i} \tag{7}$$

where: ΔS is the value of the springback, S is one of the three parameters; $V_i$ – initial value of the one of the three parameters; $V_f$ – final value of the one of the three parameters.

The obtained values of the springback for different process parameter are presented in table 1.

The part springback value when the part is unloaded from the die is affected by the rubber thickness and depth of penetration (table 1).

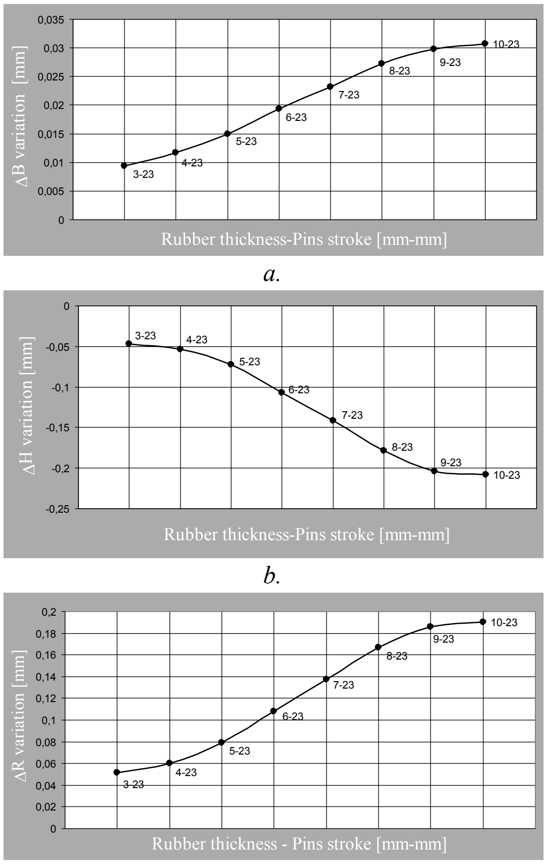
**Table 1.** *Values of springback parameters*

| Rubber thickness-Pins stroke | Values of springback parameters | | |
|---|---|---|---|
| | ΔB | ΔR | ΔH |
| 2-21 | 0,0291 | -0,2231 | 0,1969 |
| 2-23 | 0,0150 | -0,1021 | 0,0990 |
| 3-22 | 0,0225 | -0,1550 | 0,1499 |
| 3-23 | 0,0094 | -0,0466 | 0,0517 |
| 4-23 | 0,0117 | -0,0532 | 0,0601 |
| 5-22 | 0,0290 | -0,2093 | 0,1886 |
| 5-23 | 0,0150 | -0,0725 | 0,0789 |
| 5-24 | 0,0141 | -0,0139 | 0,0352 |
| 6-21 | 0,0337 | -0,2653 | 0,2260 |
| 6-23 | 0,0193 | -0,1066 | 0,1079 |
| 6-25 | 0,0224 | -0,0047 | 0,0423 |
| 7-20 | 0,0334 | -0,2610 | 0,2221 |
| 7-23 | 0,0232 | -0,1411 | 0,1375 |
| 8-19 | 0,0353 | -0,2824 | 0,2370 |
| 8-23 | 0,0272 | -0,1782 | 0,1669 |
| 8-27 | 0,0155 | -0,0398 | 0,0563 |
| 9-18 | 0,0359 | -0,2741 | 0,2345 |
| 9-23 | 0,0298 | -0,2036 | 0,1856 |
| 9-28 | 0,0162 | -0,0591 | 0,0720 |
| 10-17 | 0,0401 | -0,3221 | 0,2641 |
| 10-20 | 0,0365 | -0,2863 | 0,2409 |
| 10-23 | 0,0307 | -0,2080 | 0,1905 |
| 10-29 | 0,0197 | -0,0898 | 0,0986 |
| 10-30 | 0,0197 | -0,0901 | 0,0991 |

For the same depth of penetration, and different rubber thickness, the values of springback are presented in figure 8. When the rubber thickness is increasing the values of the springback as related to the width and to the radius are also increasing and the springback values depending on the profile radius are decreasing. This is due to the fact that using a fixed rigid configuration of the tool, different rubber thickness and the same stroke, the obtained radius of the parts are different, increasing with increasing thickness of the rubber.

The increasing of the rubber thickness leads to the decreasing of the Von Mises stresses (figure 9), and to an increasing of the elastic stresses in the metallic part, respectively to an increasing of the amount of springback.

The decreasing of the Von Mises stresses are in accordance with the mean stresses variation in the rubber (see figure 6).



*a.*

*b.*

*c.*

**Fig. 8.** *Springback variation for the same pins stroke: a. width variation; b. height variation; c. radius variations*

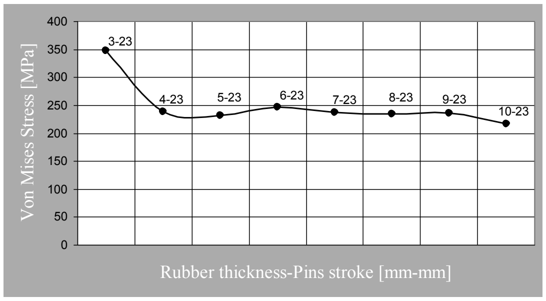


**Fig. 9.** *Von Mises stresses variation for the same pins stroke and different rubber thickness*

The depth of penetration in the rubber transfers load to the sheet, thus affecting the amount of the springback. This thing is presented in figure 10.

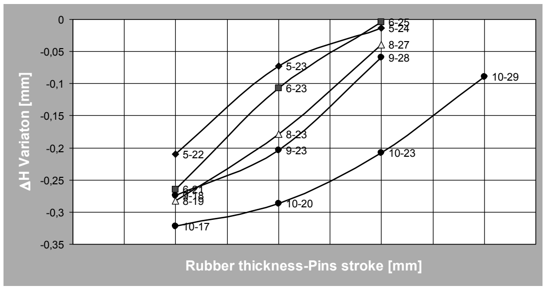


**Fig. 10.** *Springback variation in terms of height variation, for the different pins strokes and rubber thicknesses*

With increasing the pins stroke and the rubber thickness the amount of springback will also increase.

## 5. Conclusions

In the present study, it was considered a fixed rigid configuration of the tool, the same friction coefficient between the system components, different rubber thickness, different pins penetrations, free rubber expansion, and the same rubber material for the elastic interpolators.

The presence of the interpolator changes the behavior of the sheet metal blank which affects the part quality.

It is obviously, when the interpolator thickness is small and when the pins stroke is big appears geometrical form errors in the part sections. When the rubber interpolator thickness is big, the process of deformation could be affected because of the uncontrolled flow of the elastic medium. This is more accentuated when the pins stroke is big.

On the other hand, the geometry of the part will affect the rubber deformation with a negative influence toward the metallic part quality. At a big thickness of the elastic interpolator, one could obtain different part curvature, depending on the pins stroke.

The obtained results could lead to the development of these new types of equipments which assure the decreasing of the cost testing and production.

### Acknowledgements

The authors gratefully acknowledge the financial support of the Romanian Ministry of Education and Research through grant PN_II_ID_1761/2008

## References

**1. Eigen G.,** *Smoothing method for discrete die forming*, PhD Thesis, MIT University, Massachusetts, 1992.
**2. Socrate S., Boyce M.,** *A finite Element based die design algorithm for sheet-metal forming on reconfigurable tools*, JEMT, vol. 123/489, 2001, pp. 489-495.
**3. Paunoiu V., Oancea N., Nicoara D.,** *Simulation of Plate's Deformation Using Discrete Surfaces, Materials Processing and Design: Simulation and Application*, Proc. Numiform'2004, Ohio State University, American Institute of Physics, Melville, pp. 1007-1010.
**4. Belytschko T., Liu W.K., Moran B.,** *Finite Elements for Nonlinear Continua and Structures*, Wiley, New York, 1996.
**5. Cai Z.Y., Li M.Z.,** *Multi-point forming of three-dimensional sheet metal and the control of the forming process*, Int. J. Pressure Vessels Piping, vol. 79/4, 2002, pp. 289–296.
**6. Paunoiu V., Cekan P., Banu, M., Epureanu, A., Nicoara D.,** *Simulation of the Combined Reconfigurable Multipoint Forming and Rubber Forming*, Proc. 12th International Conference on Metal Forming, STEEL RESEARCH INTERNATIONAL: 549-554 Sp. Iss. 2 2008.
**7. Paunoiu V., Teodor V., Epureanu, A.,** *Springback Compensation in Reconfigurable Multipoint Forming*, Proceedings of the 8th WSEAS International Conference on System Science and Simulation in Engineering (ICOSSSE '09): 180-185 2009
**8. ***** *LS-DYNA User's Manual – Nonlinear Dynamic Analysis of Structures*, Livermore Software Technology Corporation, 1999.
**9. Barlat, F., Lege, D.J, Brem, J.C.,** *A six-component yield function for anisotropic materials*, Int. J. Plasticity, 7, pp. 693-712.

### Sistemul multi-fizic de deformare multipunct reconfigurabil

Rezumat

Una dintre metodele utilizate pentru creşterea calității pieselor obținute prin deformare multipunct reconfigurabilă este aceea a folosirii unui interpolator elastic între pini şi semifabricat. Lucrarea prezintă un model numeric bazat pe studiul comportării ansamblului de medii rigid/elasto-plastic/elastic în vederea aplicării lui la proiectarea unor noi matrițe reconfigurabile cu interfață flexibilă. In prima parte a lucrării se prezintă aspecte generale privind legile de comportare ale materialelor utilizate în sistemul de reconfigurabilitate considerat. Apoi se prezintă rezultatele simulărilor numerice, în element finit, privind influența grosimii interpolatorului şi a cursei pinilor asupra calității pieselor deformate. Calitatea pieselor este evaluată în funcție de variația revenirii elastice şi a stării de tensiuni. Rezultatele obținute pot conduce la dezvoltarea acestor noi tipuri de echipamente care asigură, scăderea costurilor de testare şi de fabricare.