



MATHEMATICAL SIMULATION OF METAL SHEET BENDING WITH ELASTOMERIC PADS

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Abstract: This paper presents a mathematical model and a numerical simulation for metal sheet bending with elastomeric pads made of plasticized polyvinyl chloride. Compression tests were performed in order to determine some characteristics for the materials and the results were used in the simulation program. A correction for the geometry of the elastomeric pad was proposed and the results for the simulation are also presented.

Key words: mathematical model, simulation, elastomer, bending, compression.

1. INTRODUCTION

It was initially believed that elastomers were a part of the rubber group, due to their similar properties. In the 80's, this opinion has changed so that the term of elastomers also included natural or synthetic rubbers and not vice versa. An elastomer is defined as a macromolecular material which at room temperature is capable to return substantially to its original shape and size after the tension removal. A rubber is defined as a macromolecular material which is able to return in one minute to less than 1.5 of its initial length after it had been stretched twice than its initial length and maintained so for one minute.

Therefore, considering these definitions, we can say that all the rubbers are elastomers, but not all the elastomers are rubbers. The group of elastomers does not include the following materials: natural rubber, synthetic rubber and thermoplastic elastomers.

The use of elastomers in the design of the sheet metal forming tools has evolved in the last years, because parts of different shapes and sizes can be achieved using the same active elements. Sheet bending in dies with elastomeric pads is a modern process used often in manufacturing because it offers a wide range of advantages as compared to the classic processes [3]. The precision of the parts is

higher than that obtained by using classic procedures because the elastic material of the pad responds with an opposite force that will create a calibration pressure on the part. The price of the tool is lower because the elastic pad can be used for different parts and the preparation time of the workplace is shorter.

2. CONSTITUTIVE MODEL OF THE ELASTOMERIC MATERIALS

The constitutive model of elastomeric materials is based on the assumption that their mechanical response can be described using the complementary strain potential as a state function. This parameter generally depends on the components of the stress tensor:

$$U = U(\sigma_{ij} | i, j = 1, 2, 3) \quad (1)$$

Once admitted the existence of the scalar potential the strain components can be computed as partial derivatives with respect to the corresponding variables σ_{ij} :

$$\varepsilon_{ij} = \frac{\partial U}{\partial \sigma_{ij}}, \quad i, j = 1, 2, 3 \quad (2)$$

Equation (2) represents the general formulation of a hyper-elastic constitutive

model. In practice, the only problem consists in adopting a convenient expression of the strain potential. In the particular case of the rubber-like materials, this expression should be compatible with two characteristics of their mechanical behaviour:

- a) Isotropy
- b) Isochoric character of the strain field.

Isotropy represents the invariance of the mechanical response with respect to the rotation of the coordinate frame. The isochoric character of the strain field ensures the volume conservation even if large distortions occur (this is the typical behaviour of the elastomeric materials).

In order to fulfil the requirements mentioned above, the strain potential can be expressed as follows:

$$U = U(I_2, I_3) \quad (3)$$

where I_2 and I_3 are the second and the third invariants of the deviatoric stress tensor

$$\sigma'_{ij} = \sigma_{ij} - \frac{1}{3} \delta_{ij} \sum_{k=1}^3 \sigma_{kk} \quad (4)$$

The first invariant is not included in Eq. (3) because it is always zero. The Kronecker symbol has been used in Eq. (4):

$$\delta_{ij} = \begin{cases} 1, & \text{if } i = j, \\ 0, & \text{if } i \neq j. \end{cases} \quad (5)$$

The second and the third invariants of the deviatoric stress tensor are defined in the following manner:

$$I_2 = \begin{vmatrix} \sigma'_{11} & \sigma'_{12} \\ \sigma'_{21} & \sigma'_{22} \end{vmatrix} - \begin{vmatrix} \sigma'_{22} & \sigma'_{23} \\ \sigma'_{32} & \sigma'_{33} \end{vmatrix} - \begin{vmatrix} \sigma'_{33} & \sigma'_{31} \\ \sigma'_{13} & \sigma'_{11} \end{vmatrix} = \sigma'_{11}\sigma'_{22} - \sigma'_{22}\sigma'_{33} - \sigma'_{33}\sigma'_{11} + \sigma'_{12}\sigma'_{21} + \sigma'_{23}\sigma'_{32} + \sigma'_{31}\sigma'_{13} \quad (6)$$

$$I_3 = \begin{vmatrix} \sigma'_{11} & \sigma'_{12} & \sigma'_{13} \\ \sigma'_{21} & \sigma'_{22} & \sigma'_{23} \\ \sigma'_{31} & \sigma'_{32} & \sigma'_{33} \end{vmatrix} \quad (7)$$

In this paper, the dependence of the strain potential U on the third invariant is considered negligible. As a consequence, U will be defined as:

$$U = U(I_2). \quad (8)$$

For a better agreement with the experimental data, this dependence will be expressed as a polynomial:

$$U = a_0 + a_1 I_2 + a_2 I_2^2 + \dots + a_n I_2^n = \sum_{k=0}^n a_k I_2^k \quad (9)$$

The polynomial order n is chosen according to the volume of experimental data and the desired accuracy of the constitutive model. Generally, the flexibility of the model is increased when higher values of the exponent n are chosen.

The coefficients a_0, \dots, a_n are material constants and result from an identification procedure. In general, the strain potential U must be zero when the second invariant I_2 vanishes. This constraint is fulfilled only if:

$$a_0 = 0 \quad (10)$$

Under such circumstances, Eq. (9) becomes:

$$U = a_1 I_2 + a_2 I_2^2 + \dots + a_n I_2^n = \sum_{k=1}^n a_k I_2^k \quad (11)$$

After replacing the expression of U given by Eq. (11) in Eq. (2), the following of constitutive equations are obtained:

$$\varepsilon_{ij} = \frac{\partial U}{\partial \sigma_{ij}} = \frac{dU}{dI_2} \frac{\partial I_2}{\partial \sigma_{ij}}, \quad i, j = 1, 2, 3, \quad (12)$$

where:

$$\begin{aligned} \frac{dU}{dI_2} &= a_1 + 2a_2 I_2 + \dots + \\ &+ na_n I_2^{n-1} = \sum_{k=1}^n ka_k I_2^{k-1} \end{aligned} \quad (13)$$

and

$$\frac{\partial I_2}{\partial \sigma_{ij}} = \sigma'_{ij}, \quad i, j = 1, 2, 3. \quad (14)$$

By combining Eqs. (12) – (14), the constitutive equations can be put into the explicit form:

$$\varepsilon_{ij} = \sigma'_{ij} \sum_{k=1}^n ka_k I_2^{k-1}, \quad i, j = 1, 2, 3. \quad (15)$$

The main steps of an identification procedures based on the results of axial compression tests will be presented below. The experimental tests are made on cylindrical elastomeric samples. If A_0 is the of cross-section area and h_0 is the height of the undistorted sample, while A and h are the cross-section area and the height of the same sample at a certain moment during the compression test, the condition of volume conservation can be expressed as follows:

$$A_0 h_0 = Ah \quad (16)$$

Considering that the direction of compression represents the axis 1 of the coordinate frame, the strain components can be evaluated using the formulas:

$$\begin{cases} \varepsilon_{11} = \ln \frac{h}{h_0} \\ \varepsilon_{22} = \varepsilon_{33} = -\frac{1}{2} \varepsilon_{11} = -\frac{1}{2} \ln \frac{h}{h_0} = \frac{1}{2} \ln \frac{A_0}{A} \\ \varepsilon_{ij} = 0, \quad i, j = 1, 2, 3, \quad i \neq j \end{cases} \quad (17)$$

The components of the deviatoric stress tensor also have the following expressions:

$$\begin{cases} \sigma'_{11} = \frac{2}{3} \sigma_{11} < 0, \quad \sigma'_{22} = \sigma'_{33} = -\frac{1}{3} \sigma_{11}, \\ \sigma'_{ij} = 0, \quad i, j = 1, 2, 3, \quad i \neq j \end{cases} \quad (18)$$

Under these conditions, the second invariant I_2 becomes (see Eq. (6)):

$$I_2 = \frac{1}{3} \sigma_{11}^2 \quad (19)$$

Because in the particular case of the axial compression test, σ_{11} is the only stress component different from zero, the constitutive model defined by the equation (15) reduces to the following relationship (see also Eq. (19)):

$$\begin{aligned} \varepsilon_{11} &= \sigma'_{11} \sum_{k=1}^n ka_k I_2^{k-1} = \\ &= \frac{2}{3} \sigma_{11} \sum_{k=1}^n ka_k \frac{\sigma_{11}^{2(k-1)}}{3^{k-1}} = \\ &= 2 \sum_{k=1}^n ka_k \frac{\sigma_{11}^{2k-1}}{3^k} \end{aligned} \quad (20)$$

The raw data provided by the axial compression test is represented by a table of values $[\Delta h_l, F_l | l = 1, \dots, N]$, where:

$$\Delta h_l = h_0 - h_l \quad (21)$$

is a current variation of the height and F_l represents the associated axial force acting on the specimen. These raw values can be easily transformed into pairs of strain and stress components. More precisely, each pair $[\Delta h_l, F_l]$ is converted into a pair $[\varepsilon_{11,l}, \sigma_{11,l}]$ using the formulas:

$$\varepsilon_{11,l} = \ln \frac{h_l}{h_0} = \ln \frac{h_0 - \Delta h_l}{h_0} = \ln \left(1 - \frac{\Delta h_l}{h_0} \right), \quad (22)$$

$$\begin{aligned} \sigma_{11,l} &= -\frac{F_l}{A_l} = -\frac{F_l}{A_0} \frac{h_l}{h_0} = \\ &= -\frac{F_l}{A_0} \frac{h_0 - \Delta h_l}{h_0} = -\frac{F_l}{A_0} \left(1 - \frac{\Delta h_l}{h_0} \right) \end{aligned} \quad (23)$$

The identification procedure used in this paper is based on the least-square method. The coefficients a_1, \dots, a_n are evaluated by minimizing the error-function:

$$F(a_1, \dots, a_n) = \sum_{l=1}^N \left[2 \sum_{k=1}^n ka_k \frac{\sigma_{11,l}}{3^k} - \varepsilon_{11,l} \right]^2 \quad (24)$$

The minimum constraints:

$$\frac{\partial F}{\partial a_m} = 0, \quad m = 1, \dots, n, \quad (25)$$

generate the following set of linear algebraic equations having the coefficients a_1, \dots, a_n as unknowns:

$$\sum_{k=1}^n \left\{ \frac{k}{3^k} \left[\sum_{l=1}^N \sigma_{11,l}^{2(m+k-1)} \right] \right\} a_k = \frac{1}{2} \sum_{l=1}^N \sigma_{11,l}^{2m-1} \varepsilon_{11,l}, \quad (26)$$

$m = 1, \dots, n.$

Due to its linearity, the solution of this set is straightforward (the authors have used Gauss elimination procedure).

3. IMPLEMENTATION OF THE CONSTITUTIVE MODEL IN THE FINITE-ELEMENT PROGRAMME ABAQUS/STANDARD

In order to prove its applicability and performances, the constitutive model presented above has been implemented as a UMAT routine in the finite-element programme ABAQUS/Standard [1],[2]. In general, the UMAT routine must perform two specific tasks:

- Using the strain components $\varepsilon_{ij} (i, j = 1, 2, 3)$ associated to the current moment of the analysis as input data, the UMAT routine must evaluate the corresponding stress components $\sigma_{ij} (i, j = 1, 2, 3)$;
- For the same moment of analysis, the UMAT routine must also evaluate the components of the so-called tangent elastic modulus,

$$T_{ijkl} = \frac{\partial \sigma_{ij}}{\partial \xi_{kl}}, \quad i, j, k, l = 1, 2, 3. \quad (27)$$

The quantities $T_{ijkl} (i, j, k, l = 1, 2, 3)$ define the relationship between the perturbations of the strain components and the perturbation of the corresponding stresses:

$$D\sigma_{ij} = \sum_{k=1}^3 \sum_{l=1}^3 T_{ijkl} \cdot D\xi_{kl}, \quad i, j = 1, 2, 3. \quad (28)$$

Both the stress components and the tangent elastic modulus associated to the current moment of the analysis are calculated using the constitutive equations presented in the previous section of the paper:

- equations that define the relationship between the deviatoric stress and strain components:

$$\xi'_{ij} = S\sigma'_{ij}, \quad i, j = 1, 2, 3 \quad (29)$$

where:

$$S = \sum_{k=1}^n ka_k I_2^{k-1} = a_1 + \sum_{k=2}^n ka_k I_2^{k-1} \quad (30)$$

$$I_2 = \frac{1}{2} \sum_{p=1}^3 \sum_{q=1}^3 \sigma'_{pq} \sigma'_{pq} \quad (31)$$

- equation that defines the relationship between the hydrostatic components of the strain and stress tensor:

$$\bar{\varepsilon} = \frac{1}{\pi} \bar{\sigma} \quad (32)$$

where $\pi > 0$ is a very large penalty constant.

The determination of the current stress state consists in the solution of the nonlinear set given by Eq. (29) considering $\sigma'_{ij}, i, j = 1, 2, 3$ as unknown quantities. Any appropriate numerical procedure can be used for this purpose (e.g., Newton's method). The authors have used the HYBRD1 routine from the mathematical library MINPACK-1. These routine implements a solution strategy based on Newton's method.

As soon as the components of the deviatoric stress are determined, Eq. (32) provides the

hydrostatic part $\bar{\sigma}$. Finally, the current stresses are calculated using the additive decomposition:

$$\sigma_{ij} = \sigma'_{ij} + \delta_{ij}\bar{\sigma}, \quad i, j = 1, 2, 3 \quad (33)$$

The evaluation of the tangent elastic modulus starts from the additive decomposition of the strain tensor:

$$\varepsilon_{ij} = \varepsilon'_{ij} + \delta_{ij}\bar{\varepsilon}, \quad i, j = 1, 2, 3 \quad (34)$$

By perturbing this decomposition, one obtains the relationship:

$$D\varepsilon_{ij} = D\varepsilon'_{ij} + \delta_{ij}D\bar{\varepsilon}, \quad i, j = 1, 2, 3 \quad (35)$$

The strain perturbations in the right-hand side of the above formula result from the constitutive equations (29) – (32). More precisely, the perturbation of equations (29), (30) and (31) leads to the formula:

$$D\varepsilon_{ij} = SD\sigma'_{ij} + \sigma'_{ij}DS, \quad (36)$$

where,

$$DS = S'DI_2, \quad (37)$$

$$S' = \sum_{k=2}^n k(k-1)a_k I_2^{k-2}, \quad (38)$$

$$DI_2 = \sum_{p=1}^3 \sum_{q=1}^3 \sigma'_{pq} D\sigma'_{pq}, \quad (39)$$

$$D\sigma'_{ij} = D\sigma_{ij} - \delta_{ij}D\bar{\sigma}, \quad (40)$$

$$D\bar{\sigma} = \frac{1}{3} \sum_{r=1}^3 \sum_{s=1}^3 \delta_{rs} D\sigma_{rs}. \quad (41)$$

In the same way, the perturbation of the hydrostatic stress is obtained from the constitutive equation (32):

$$D\bar{\varepsilon} = \frac{1}{\pi} D\bar{\sigma} \quad (42)$$

After combining Eqs. (35) – (42), the following relationship is obtained:

$$\{D\varepsilon\} = \left\{ \begin{array}{l} \frac{1}{\pi}[A] + S[B] + \\ + S'\{\sigma'\}\{\sigma'\}^T [C] \end{array} \right\} \{D\sigma\}, \quad (43)$$

The following matrix notations have been used in Eq. (43)

$$\{D\varepsilon\} = [D\varepsilon_{11}, D\varepsilon_{22}, D\varepsilon_{33}, 2D\varepsilon_{12}, 2D\varepsilon_{23}, 2D\varepsilon_{31}]^T, \quad (44)$$

$$\{D\sigma\} = [D\sigma_{11}, D\sigma_{22}, D\sigma_{33}, D\sigma_{12}, D\sigma_{23}, D\sigma_{31}]^T, \quad (45)$$

$$\{\sigma'\} = [\sigma'_{11}, \sigma'_{22}, \sigma'_{33}, \sigma'_{12}, \sigma'_{23}, \sigma'_{31}]^T, \quad (46)$$

$$[A] = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (47)$$

$$[B] = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{3} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2}{3} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{2}{3} \end{bmatrix}, \quad (48)$$

$$[C] = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{3} \end{bmatrix}. \quad (49)$$

Eq. (28) is equivalent with the matrix relationship:

$$\{D\sigma\} = [T]\{D\varepsilon\}. \quad (50)$$

By comparing Eqs. (43) and (50), one may easily notice that:

$$[T] = \left(\frac{1}{\pi} [A] + S[B] + S'\{\sigma'\}\{\sigma'\}^T [C] \right)^{-1} \quad (51)$$

Eq. (51) defines the tangent elastic modulus of the elastomeric material in accordance with the constitutive equations (29) – (32). The calculation of this matrix represents the second task that should be performed by the UMAT routine.

4. NUMERICAL SIMULATION OF A SHEET METAL BENDING PROCESS WITH ELASTOMERIC PAD

The capabilities of the constitutive model presented above have been tested by numerical simulation of a sheet metal bending process with elastomeric pad. The calibration of the material model (defined in the UMAT routine) is made using the experimental data provided by a standard compression test, which allows the determination of the dependence between the height variation of the specimen and the compression force. The material coefficients resulted from the identification procedure presented in the previous section have been passed as input data to the finite element ABAQUS.

The material of the deformable pad is polyvinyl chloride (PVC). Its elastic characteristics were obtained by introducing the plasticizer dimethyl phthalate, which is the methyl ester of phthalic acid.

The specimens used in the compression test have been prepared according to the prescriptions of the standard SR ISO 815-A1:1995, in the shape of circular disks with $29,0 \pm 0,5$ mm diameter and $13,0 \pm 0,2$ mm thickness. These samples were subjected to compression on the universal testing machine INSTRON 1196. The axial force (F) vs. height variation (Δh) diagram recorded by the testing

machine (Figure 1) has been converted into a diagram relating the sectional stress and the axial logarithmic strain. In the next stage, the experimental data resulted from the conversion have been used for calibrating the constitutive model of the elastomeric material.

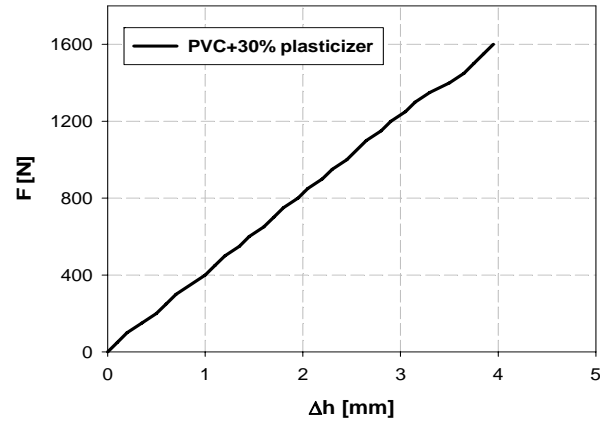


Fig.1. Compression curve for PVC with 30% plasticizer

The metallic sheet used in the numerical simulation is aluminium AA 1050-O. The mechanical behaviour of this material has been described using the elastoplastic constitutive model defined in ABAQUS/Standard. The following material parameters characterizing the elastic / plastic behaviour of the AA 1050-O sheet metal have been adopted [5]:

- Young's modulus: 69 GPa
- Poisson's ratio: 0.33
- Conventional yield stress: 30 MPa
- Ultimate strength: 50 MPa
- Total elongation: 40 %.

The dimensions of the blank subjected to bending are as follows: thickness 1 mm, length 70 mm and width 55 mm. For the U bending simulation, a punch with 10 mm radius was used. The dimensions of the deformable pad are the following ones: length 150 mm, height 110 mm and width 55 mm. After repeated simulations, it was established that the elastomeric pad should have the geometry presented in Figure 2. This geometry is able to achieve a full bending of the metallic blank around the punch profile.

The finite-element simulation provided numerical values of the stresses and strains in the bent regions of the blank, as well as in the pad. The values were obtained for different stages of the bending process. Figure 3 presents

the distribution of the von Mises equivalent stress associated to the final stage of the forming process.

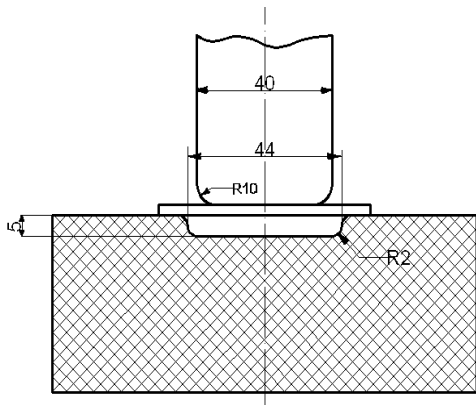


Fig. 2. Proposed geometry of the elastomeric pad

Table 1 presents the minimum and maximum values of the von Mises equivalent stress (σ) in the elastomeric pad and in the bent part. These stresses have maximum values when the punch stroke also has the maximum value.

Table 1

Von Mises equivalent stress (σ)		
Bent part		
Equivalent stress	Maximum	Minimum
σ [N/mm ²]	$+5,5 \cdot 10^1$	$+2,3 \cdot 10^{-5}$
Elastomeric pad		
Equivalent stress	Maximum	Minimum
σ [N/mm ²]	$+6,8 \cdot 10^0$	$+2,97 \cdot 10^{-5}$

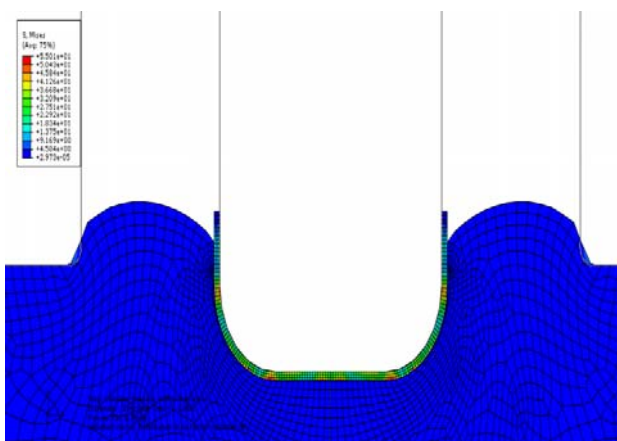


Fig. 3. Distribution of the equivalent stress

The diagram from Figure 4 shows the variation of the bending force as resulted from the finite element simulation, in the case of a

deformable pad with the following composition: PVC 70% and 30% plasticizer, and a punch having the fillet radius $R = 10$ mm. One may notice the accelerated evolution of the force in the second stage of the forming process, when the metallic sheet is fully embossed in the pocket of the elastomeric pad.

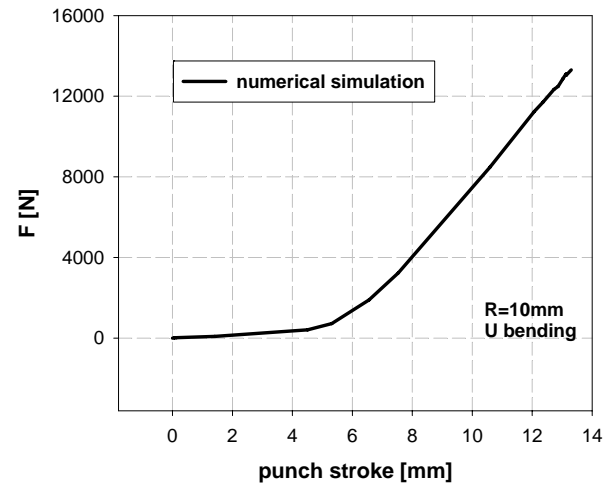


Fig. 4. Variation of the bending force during the bending process (punch radius $R=10$ mm)

5. CONCLUSIONS

Using the finite-element programme ABAQUS, the simulation of the bending with an elastomeric pad is possible. The characteristics of the sheet material must be determined, as well as those of the elastomeric material used for the pad. By introducing this data in the program, the numerical analysis of the bending process can be performed.

Unlike other theoretical approaches found in published papers worldwide, the constitutive model developed by the authors has the advantage of simplicity and also the advantage of the possibility of identifying the material parameters using only the experimental results provided by standard compression tests.

The proposal of a plasticizer polyvinyl chloride as a material for the deformable pad is a challenge in this area, if taking into account that PVC is a thermoplastic material which is friendlier with the environment than rubber. It can be also observed after the simulation, that this material seems to have the same advantages for sheet metal bending as compared to the classical technology.

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SIMULAREA MATEMATICA A INDOIRII TABLELOR METALICE CU PLACI ACTIVE DIN ELASTOMERI

Rezumat: In lucrare se prezintă un model matematic și simularea numerică a indoirii tablelor metalice utilizând plăci active elastice realizate din policlorură de vinilul plastifiată. Teste de compresiune au fost realizate pentru determinarea unor caracteristici de material iar rezultatele au fost utilizate în programul de simulare. In final s-a propus o geometrie a plăcii din elastomer iar rezultatele simulării sunt de asemenea prezentate.

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