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ANALYSIS OF ANISOTROPIC MODEL AND THE EFFECT OF FRICTION COEFFICIENT IN A STRETCH FORMING PROCESS APPLIED TO AA2024 THIN SHEET

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The deep drawing numerical simulation problem represents today an important interest for a sheet forming engineering design. This paper presents the results of Finite Elements Simulation of a stretch forming test based on the anisotropic mechanical behavior describing an AA2024 aluminum alloy. The numerical simulations applied to thin sheets are made using a Hill'48 anisotropic elasto-plastic model. The corresponding material coefficients are measured at 0°, 45° and 90° relative to the rolling direction to take into account the metallic sheet anisotropy. The samples cutting directions relative to the rolling one correspond to the above mentioned angles. Furthermore this study analyzes the effects of the Coulomb friction coefficient on the maximal principal stresses variation and on the obtained punch loads - displacement curves.

Keywords: Stretch forming, finite elements models, aluminum alloy, anisotropic behaviour, friction coefficient.

1. Introduction

Finite Element (FE) analysis has become during recent years a very useful design analysis tool [1]. Today there are several commercial software using FE methods that can be used, such as ANSYS, ABAQUS, LSDYNA, FORGE, COMSOL. This paper deals with the analysis of deep drawing results of an aluminium alloy, especially of a stretch forming process performed using the commercial ABAQUS code.

2. Material properties

For this study, the chosen material is an AA2024 aluminum alloy (Table 1). It is part of the 2000 alloys series with the distinctive feature of having a copper content of approximately 4% and almost unnoticeable small impurities of iron [2].

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Table 1

Composition and properties of aluminum alloys 2024 [3]

Al	Si	Fe	Cu	MN	Cr	Zn	Ti
---	0.5%	0.5%	3.8%-4.9%	0.3%-0.9%	0.1%	0.25%	0.15%

The AA2024 alloy is one of the most popular high-strength aluminum alloys, having a good behavior at high temperatures and a low corrosion resistance. According to its high strength and excellent fatigue resistance, it is used for metallic structures and components, where good and optimal strength to weight ratio is desired [2].

Concerning the mechanical properties it has: a ultimate tensile strength > 420 N/mm^2, a yield strength at 0.2% > 260 N/mm^2, a HD harshness around 120 Kgf/mm^2, a LF 108 cycles of 125 MPa, a Young- modulus E = 71000-74000 MPa and a Poisson coefficient of 0.33. Its main industrial uses are in manufacturing of airframe structural components, aircraft accessories and parts for the transport industry.

3. Theoretical background

Deep drawing process is one of the most popular metal forming methods used in manufacturing hollow pieces by plastic deformation. It can be performed in both hot and cold conditions and involves the use of metallic dies to transform blank sheets of processed material into objects with a desired shape. Specifically, if the depth of the deformed sheet is equal or greater than the punch radius, then the metal forming process can be called deep drawing [3].

If the blank sheet is embedded on its contour, the material is not sliding in the vicinity of the clamping and the plastic process conditions are close to those of a stretching test [1].

The sheet deformation without a preliminary heating of the body is called cold forming, used mainly for relatively small thickness pieces. On the other hand, the sheet deformation is called a hot forming, method used especially for thick or high hardness parts, in order to avoid crack formation or tearing the material. The use of the deep drawing is important for the manufacturing industry especially in the case of high volume production, since unit cost decreases considerably with the increase of the total units produced. It is perhaps easier to obtain cylindrical or axisymmetric objects from a circular metal blank drawn down into a deep product using a single operation, minimizing both production time and total cost. As an example, the manufacturing of aluminum cans is one of the most popular industrial processes [3]. The sheet forming is generally performed on a mechanical or hydraulically press machine using two main active tools: the lower drawing die and the punch [4].

For thin metallic sheets the mechanical anisotropy plays a major influence on the materials elasto-plastic behaviour and on the control of the mechanical properties during service life. Moreover, local crack or fracture can occur, especially when the local plastic strains or the maximal principal stresses exceed certain limits. The absence of a macroscopic fracture is, however, not sufficient to guarantee the success of the forming process and to define the metal formability or its ductility [2].

Experimental and numerical studies are required in order to determine and analyze the influence of the materials rheological behavior and of the tribological conditions on the evolution of all process variables.

From a mechanical analysis point of view, the deformation state of a homogeneous material element can be described locally by the principal strains computed along the three main directions [2-4]:

$$\varepsilon_1 = \ln\left(\frac{L}{L_0}\right) \qquad \varepsilon_2 = \ln\left(\frac{b}{b_0}\right) \qquad \varepsilon_3 = \ln\left(\frac{h}{h_0}\right). \tag{1}$$

where: L_0 is the initial length, L is the final length, b_0 is the initial width, b is the final width, h_0 is the initial thickness and h is the final thickness.

The conservation of volume for the material element during the plastic deformation imposes in a first approximation:

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 \cong 0\,. \tag{2}$$

The FE numerical models use generally the decomposition of total strains increment into an elastic part and a plastic one using relationship (2) defining the elastic-plastic kinematics.

Starting from the definition of a symmetric Cauchy stress tensor and using specific non-linear anisotropic criterion (Hill’48 or improved ones), based on a FE geometric discretization (using specific mesh), on mechanical equilibrium equation and plasticity theory (general non-linear Prandtl-Reuss equations), the variation of all the mechanical variables can be quantitatively estimated during a specific incremental computation time [4-10].

In the same time it is very important to take into account influence of friction phenomena defining contact interfaces conditions using adequate friction models (Coulomb, Tresca, Tresca-Coulomb) and available coefficients values. From a technological point of view during a sheet forming process the plastic deformations are around 15%-30% and it can be used a Tresca-Coulomb friction law defined by Coulomb fiction coefficient values of maximum 0.1 for lubrication conditions, in the range 0.1-0.3 for a boundary lubrication regime and more than 0.3 for a dry friction contact having generally a maximum of 0.6 [10]. The Coulomb factor can reach values around 0.6 or 0.8 and even close to 1 if the material has an important anisotropy, a surface texture or if the R_a roughness value is greater than 25 μm (condition generally reached for the case of a hot forming process) [11].

4. The finite element modeling of a stretch forming test

The values for the material parameters defining anisotropic behaviour of AA2204 thin sheet were obtained using an adequate initial guess from previous FE simulations of experimental tensile tests performed with the commercial Zebulon code developed in France by Mines Paris Tech. The real experimental data and the obtained numerical results were compared via an interactive-graphics regression method [1, 6]. All numerical simulations of thin sheet tensile tests were performed with an isotropic hardening Voce model [9] defined by:

$$\bar{\sigma} = R_0 + Q\left[1 - \exp(-b\bar{\varepsilon})\right]. \tag{4}$$

Here $\bar{\sigma}$ represents the equivalent stress, $\bar{\varepsilon}$ is the cumulated plastic strain, R_0 is the elastic yield stress, Q is the material consistency and b represents the hardening parameter. Starting from the plasticity theory of metallic sheets and based on the numerical FEM, a Hill'48 anisotropic constitutive model is defined from the formulation of a quadratic equivalent yield stress f([σ]) expressed in terms of the Cauchy tensor [σ] using a reference equivalent stress variation describing the material behaviour along a specific specimen direction ($f([\sigma] = \bar{\sigma})$. The obtained identified material data are shown in Table 2 and Table 3.

Table 2

Identified parameters of an anisotropic unified model using isotropic Voce law describing the reference equivalent stress – plastic strain variation without kinematic hardening

Elasticity		Voce isotropic hardening			Kinematic hardening	
E [MPa]	υ	R_0 [MPa]	Q [MPa]	b	C	D
70000	0.33	230	210	16	0	0

Table 3

Identified Hill's 48 parameters of corresponding anisotropic yield stress criterion

F	G	H	L	M	N
1.35	1.25	1.02	1.95	1.95	1.95

To study the stretch forming capacity of an aluminum alloy, the corresponding performed test uses the following geometric design (Fig. 1).

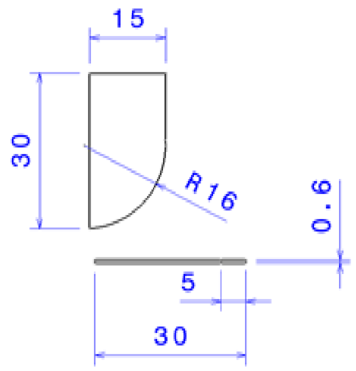


Fig. 1. The axisymmetric geometry used for a stretch forming FE simulation
(all dimensions are in mm)

According to Abaqus improvements [8], in order to describe the Hill'48 plastic anisotropy, beside the parameters mentioned in Table 3, another six adimensional representative variables have to be defined: three corresponding to the orthogonal axes (R_{11}, R_{22}, R_{33}) and to the shear directions (R_{12}, R_{13}, R_{23}). In order to compute these values, the following formulas are used [5, 7]:

$$F=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right),\ L=\frac{3}{2R_{23}^2};$$
$$G=\frac{1}{2}\left(\frac{1}{R_{33}^2}+\frac{1}{R_{11}^2}-\frac{1}{R_{22}^2}\right),\ M=\frac{3}{2R_{13}^2}; \tag{3}$$
$$H=\frac{1}{2}\left(\frac{1}{R_{11}^2}+\frac{1}{R_{22}^2}-\frac{1}{R_{33}^2}\right),\ N=\frac{3}{2R_{12}^2}.$$

The corresponding R_{ij} values used by Abaqus input material data interface are presented in Table 4.

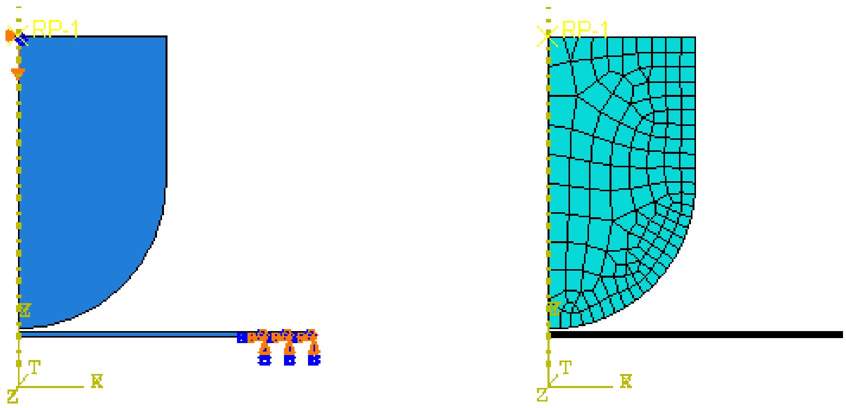
Table 4

The computed R_{ij} values that describe the HILL'48 plastic anisotropy

R_{11}	R_{22}	R_{33}	R_{12}	R_{13}	R_{23}
0.66	0.64	0.62	0.87	0.87	0.87

Starting from the defined reference equivalent stress $\bar{\sigma}$, the stress-strain curve along the sheet rolling direction (0°) can be estimated by $\sigma_{(0°)}=\sigma_{11}=\bar{\sigma}R_{11}$.

The discretization of the FE model defining the stretch forming process was done using quadratic elements and 2D axisymmetric simulations (Fig. 2) were performed using the commercial code Abaqus.



(a) (b)

Fig. 2. Geometry of the FE model defined from commercial Abaqus code interface. (a) Boundary conditions (the metal sheet is considered to be clamped at the edge); (b) Quadratic mesh elements

In accord with the hardening parameters of Table 2 the reference equivalent stress-strain variation used by the Hill'48 plastic anisotropy is presented in Fig. 3.

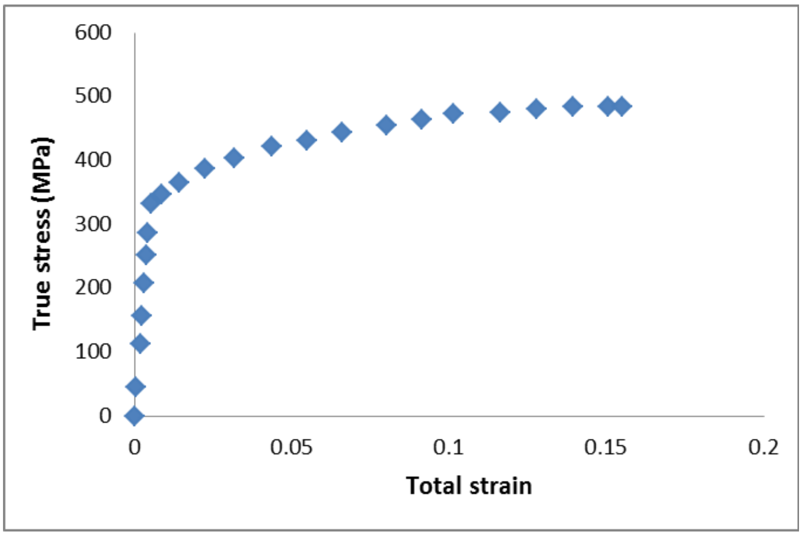


Fig. 3. The reference equivalent stress-strain curve for AA2024 aluminum alloy defined from experimental tensile test

As the contact between the sheet and the punch is defined as an elasto-plastic one, it is important to point out the definition and the consequences of the used local friction laws.

For isotropic materials the von Mises yield criterion is written in a Cartesian system coordinates (Oxyz) starting from all the stress components defining the Cauchy tensor [10]:

$$f(\sigma)=0.5\left[\left(\sigma_{xx}-\sigma_{yy}\right)^2+\left(\sigma_{yy}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{xx}\right)^2+6\left(\tau_{xy}{}^2+\tau_{yz}{}^2+\tau_{xz}{}^2\right)\right]=\bar{\sigma}^2. \quad (5)$$

This equation shows immediately that a particular friction shear τ applied to a plastic contact area between solid bodies is limited:

$$\tau \le \bar{\sigma}/\sqrt{3}. \quad (6)$$

For a stretch forming process only the friction between the punch and blank is taken into account, generally defined by a classical Coulomb law. The corresponding shear stress τ_c is computed from the contact pressure p_c [10-12]:

$$\tau_c = \mu p_c. \quad (7)$$

In the case of small elasto-plastic deformations, assuming a smooth contact surface: $p_c \approx k\bar{\sigma}$ and $k \approx (1 \div 1.2)$ and starting from the von Mises plastic criterion

(5), a maximum theoretical value of the Coulomb coefficient can be defined by $\mu_{\max} = 1/\sqrt{3}$.

Considering the equation (7) the corresponding friction law becomes rather a Tresca-Coulomb one:

$$\tau_c = \min\left(\mu p_c, \bar{\sigma}/\sqrt{3}\right) . \tag{8}$$

According to a classical Hill'48 anisotropic behavior the yield plastic criterion, generalizing the von Mises expression, is written in the form:

$$\begin{aligned} f(\sigma) = F\left(\sigma_{xx}-\sigma_{yy}\right)^2 + G\left(\sigma_{yy}-\sigma_{zz}\right)^2 + H\left(\sigma_{zz}-\sigma_{xx}\right)^2 + \\ + 2L\tau_{xy}{}^2 + 2M\tau_{yz}{}^2 + 2N\tau_{xz}{}^2 = \bar{\sigma}^2. \end{aligned} \tag{9}$$

If an isotropic friction is taken into account for body interfaces, the maximum value of the local Coulomb coefficient becomes $\mu_{\max} = 1/\sqrt{2\min(L,M,N)}$. Some rolling conditions leads to a more pronounced anisotropy of the sheet and L, M or N shear Hill parameters can reach values around 0.5-1. Together with the influence of the surface roughness, if the contact pressure values becomes small compared to the equivalent stress value ($p_c < \bar{\sigma}$), the Coulomb coefficient can have a maximum value close to the unit.

5. Numerical results

The numerical simulations were realized under a maximum punch displacement of 8 mm. The considered sheet orientations were respectively chosen at 0°, 45° and 90° with respect to the initial rolling direction (0°). All the numerical tests performed using different values for the friction coefficient from 0.01 to 1.2 proved that this parameter does not influence the final deformed shape.

Starting from the contour plot from Fig. 4 and from the graph of Fig. 5 it can be noted that the Max Principal Stress increases with the friction coefficient. For a low friction coefficient equal to 0.01 the obtained Max Principal Stress is 381.4 MPa. Increasing it from 0.5 to 1.2 the Max Stress increases also, up to an almost stationary value of 387.3 MPa.

It can be observed in Fig. 5 that, concerning the first zone, the friction coefficient has a visible influence on the Max Principal Stress (from 381.4 MPa to 387 MPa). In the second zone, with μ between 0.577 and 1.2, the influence of the friction coefficient on the stresses remains almost constant. It is thus highlighted the existence of a maximum value for the Coulomb coefficient, around 0.577. These results are also proved by the material behaviour (Von-Mises or Hill criterion) and by the theory of elasto-plastic contact applied to tool-workpiece interfaces, where inelastic deformations occur during a forming process.

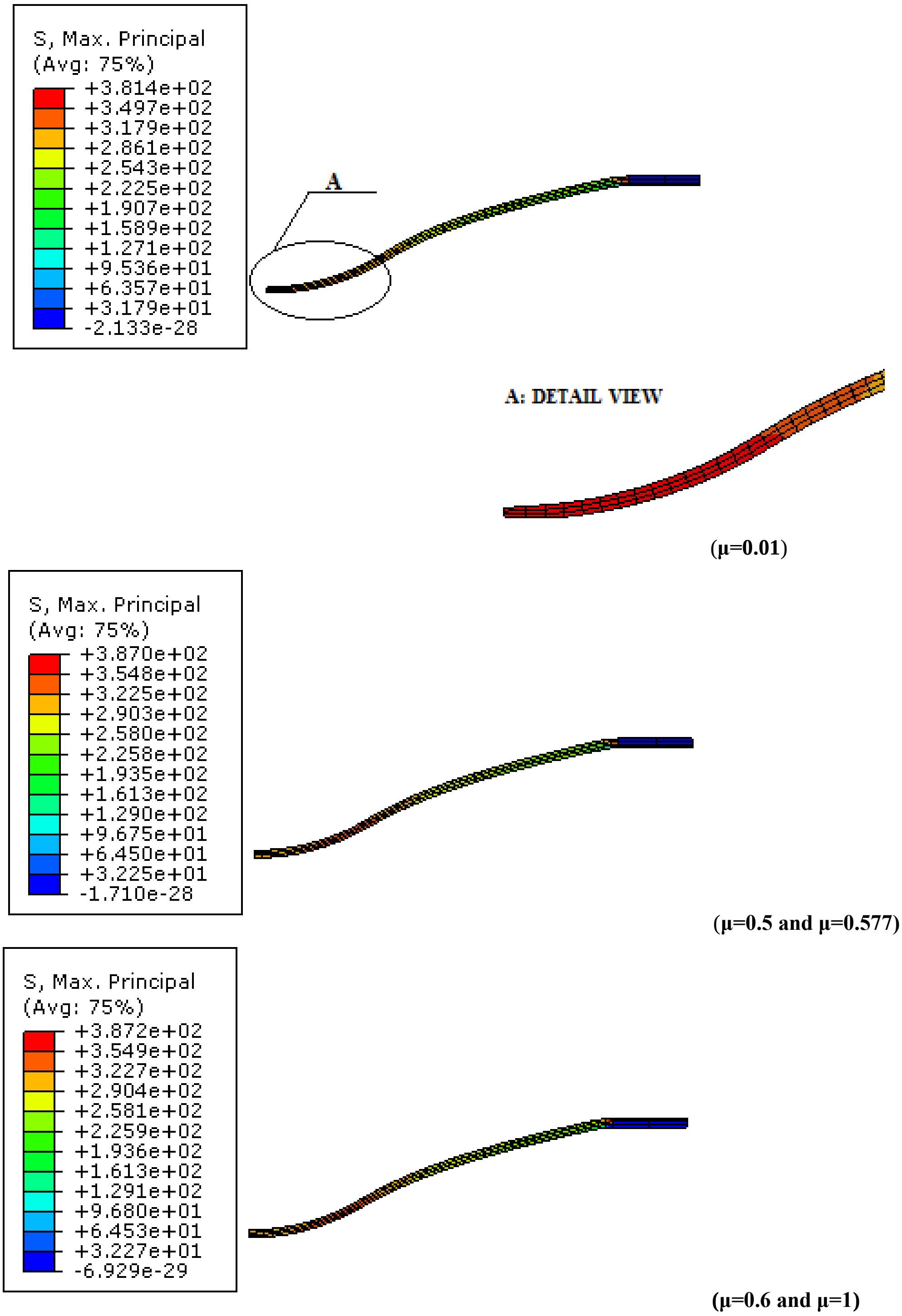


Fig. 4. Contour plot of the Max Principal Stress at the end of the loading stage (depth of 8 mm) for different values of the local Coulomb friction coefficient μ.

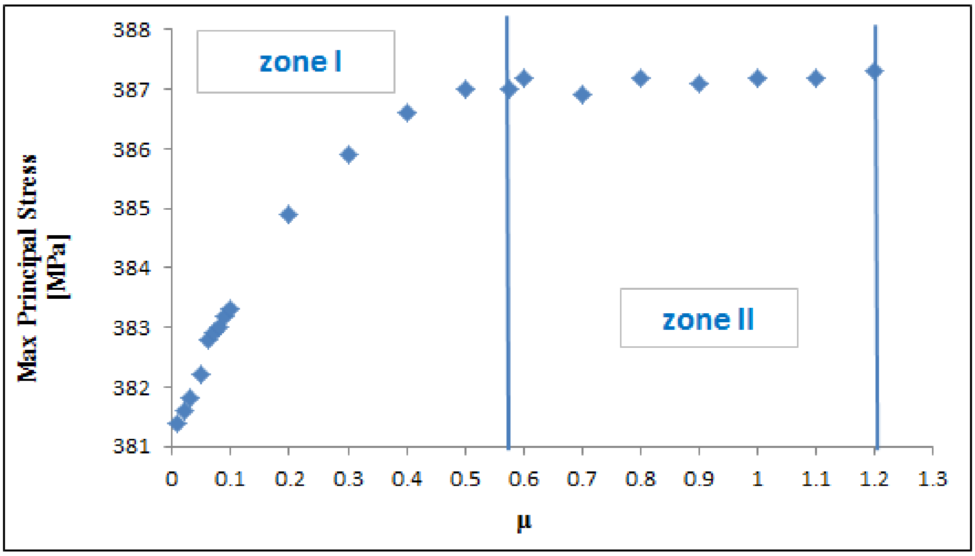


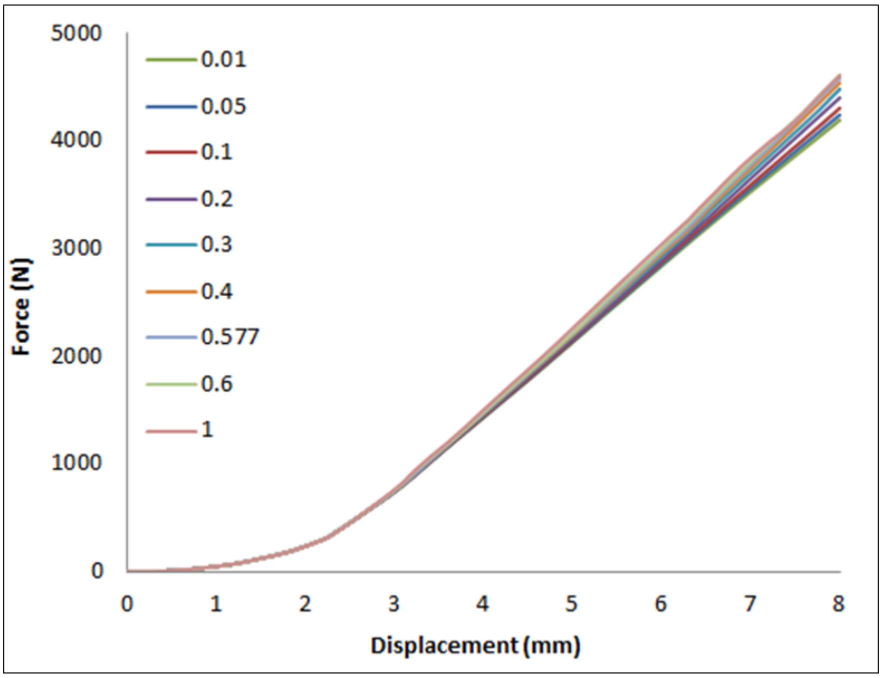
Fig. 5. The variation of Max Principal Stress for different values of local Coulomb friction coefficient μ.

Furthermore, concerning the studied material (behavior defined in Table 2 and Table 3), the critical local Coulomb coefficient value μ_{crit} defining a maximum limit vary between $\mu_{max} = 1/\sqrt{2\min(L,M,N)} \approx 0.506$ (L = M = N = 1.95) and $\mu_{max} = 1/\sqrt{3} \approx 0.577$ (L = M = N = 1.5). However greater values for the friction coefficient can be reached if L, M or N have small values ($\mu_{max} \approx 0.707$ for L = M = N = 1. and $\mu_{max} \approx 1.$ for L = M = N = 0.5) or if a small contact pressure occurs on the tool-workpiece interface in the case of a more pronounced surface texture or surface roughness [10-11].

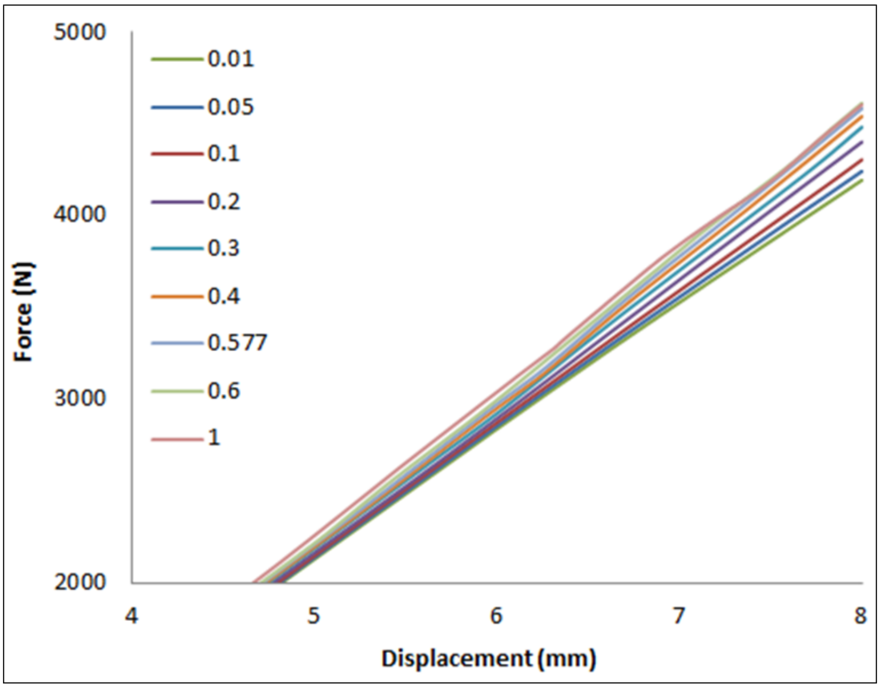
Concerning the punch load variation, as it can be seen in Fig. 6, the obtained curves confirm that the corresponding friction sensitivity increases with the plastic deformation. This becomes significant after 4 mm (50% of total displacement) and more visible beyond 6 mm (75% of total displacement).

For $\mu \geq \mu_{crit} \approx 0.5$ the corresponding sensitivity load is practically insignificant and these results confirm again the observed Maximum Principal Stress stationary value in Fig. 5 (zone II).

Starting from all these numerical results it can be concluded that the contact theory corresponding to small elasto-plastic deformations can be also applied for metallic materials with a plastic anisotropic Hill behaviour.



(a)



(b)

Fig. 6 Numerical load-displacement curves for different values of Coulomb friction (a) displacement range between 0 mm and 8 mm; (b) zoom after 4 mm displacement.

6. Conclusions

In this paper the influence of the anisotropic behavior characterizing an AA2024 aluminum alloy thin sheet was studied. A Hill'48 plastic criterion was used together with the local Coulomb friction coefficient in order to assess the sensitivity of the FEM results of a stretch forming test to these variables. For the contact between the metal sheet and the die, the hypothesis of smooth local surfaces with a small roughness was assumed. A blank specimen with a thickness of 0.6 mm has been chosen. Incremental time computations were realized under a maximum punch displacement of 8 mm.

The numerical tests were performed for a friction coefficient in the range 0.01-1.2, according to the technological values characterizing dry contact between aluminium and other metal alloys, in order to study the impact on the Max Principal Stress and on the punch load. It can be observed, from the load-displacement curves and from the contour plot of the Max Principal Stress corresponding to the end of the loading stage, an increase of the latter with the former.

Concerning the Max Principal Stress variation, a stationary value is reached near a critical friction coefficient value. Therefore, the existence of the first zone, defined by an upper bound of the friction coefficient around 0.57, confirms the suitability of the used Tresca-Coulomb friction model. For the second zone, where the friction coefficient exceeds the above mentioned critical value, the Max Principal Stress has an almost constant value, phenomenon consistent with an increase of the local shear plastic deformation at the die-sheet contact area. As a general conclusion the contact theory taking into account small elasto-plastic deformations and small roughness, which assumes that the contact pressure can be estimated by the corresponding equivalent yield stress, is also confirmed for anisotropic materials defined by a Hill'48 criterion.

In a future research work the formalism and the influence of an anisotropic friction behaviour will be analyzed, taking into account a variation of Coulomb friction coefficient along the three principal directions of the metallic sheet: longitudinal or the rolling direction (0°), median (45°) and transversal one (90°).

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