# Finite Element Analysis of AA 6016-T4 Sheet Metal Forming Operations Using a New Polycrystalline Model

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**Abstract.** A major challenge in forming polycrystalline aluminum alloy sheets is their plastic anisotropy, namely the flow stresses and plastic strains depend on the loading direction. This plastic anisotropy is due to the anisotropy of the constituent crystals and the preferred orientations that they assume in the polycrystalline material i.e. crystallographic texture. Recently, in [1] we developed a single-crystal yield criterion that involves the correct number of anisotropy coefficients such as to satisfy the intrinsic symmetries of the constituent crystals and the condition of yielding insensitivity to hydrostatic pressure. This single-crystal criterion is defined for any stress state. It is shown that a polycrystalline model that uses this single-crystal criterion in conjunction with appropriate homogenization procedures leads to an improved prediction of the plastic anisotropy in macroscopic properties under uniaxial tension and shear loadings for polycrystalline aluminum alloy 6016-T4. Moreover, results of FE simulations of cup forming operations demonstrate the predictive capabilities of this polycrystalline model.

## 1. Introduction

The predictive capabilities of elastic/plastic constitutive models based on macroscopic orthotropic yield criteria to describe with accuracy complex forming operations has been demonstrated for a large range of polycrystalline metallic materials (e.g. see [2]). Multi-scale models explicitly account for the plastic behavior at the crystal scale, which is described using a viscoplastic approach based on a power-type law or a rate-independent constitutive model based on the Schmid law, or a regularized form of Schmid law (e.g. see [3]-[5]). While increasingly complex and performant homogenization schemes have been proposed for the micro-macro transition, use of polycrystalline models for solving large-scale boundary value problems is still limited. This is mainly due to the challenges associated with describing the plastic deformation when multiple slip systems are required to accommodate it, and the prohibitive computational cost of performing finite-element (FE) simulations for engineering applications. Recently, Cazacu, Revil, and Chandola [1] developed an analytical yield criterion for FCC single-crystals. For any 3-D stress state, this yield function is $C^2$ differentiable. It fulfils the symmetries requirements associated with the cubic lattice and consequently accounts for the specificities of the plastic flow of the crystal. For 3-D loadings, this criterion involves four anisotropy coefficients, so it can capture the crystal-to-crystal differences in the anisotropy in yield stresses (e.g. differences between the anisotropy in plastic flow of Cu single crystal and Al single crystal, see [1] for more details).

## 2. Polycrystal Model Based on Cazacu et al [1] Single-Crystal Law

In this multi-scale model, the polycrystalline material is represented by a finite set of grains characterized by orientation and volume fraction to reproduce the material texture. Elastic deformations are modeled using Hooke's law for the type of symmetry shown by cubic crystals. The crystal plastic behavior is modeled using the Cazacu et al. single-crystal criterion [1], normality rule, and isotropic hardening described by a Swift-type law. The single-crystal yield criterion is expressed in terms of cubic stress-invariants that were deduced using rigorous theorems of representation of tensor functions (for complete mathematical proofs and further details, see [1]- [2]).

Specifically, relative to the Cartesian coordinate system $Ox_1x_2x_3$ associated with the crystal axes (i.e., the <100> crystal directions), the expression of the effective stress of the crystal, denoted $\bar{\sigma}_{grain}$, is given by:

$$\bar{\sigma}_{grain} = \frac{3}{\left(27 - 4cn_1^2\right)^{1/6}} \left\{ \begin{array}{l} \left[\frac{1}{2}m_1\left(\sigma_{11}'^2 + \sigma_{22}'^2 + \sigma_{33}'^2\right) + m_2\left(\sigma_{12}'^2 + \sigma_{13}'^2 + \sigma_{23}'^2\right)\right]^3 \\ -c\left[n_1\sigma_{11}'\sigma_{22}'\sigma_{33}' - n_3\left(\sigma_{33}'\sigma_{12}'^2 + \sigma_{11}'\sigma_{23}'^2 + \sigma_{22}'\sigma_{13}'^2\right) + 2n_4\sigma_{12}'\sigma_{13}'\sigma_{23}'\right]^2 \end{array} \right\}^{1/6} \tag{1}$$

where $\sigma'$ denotes the Cauchy stress deviator, $m_1, m_2, n_1, n_3, n_4$ are anisotropy coefficients and $c$ is a parameter that describes the relative importance of the second-order and third-order cubic stress-invariants on yielding. The plastic strain-rate of each crystal $\mathbf{d}_{grain}^P$ is uniquely defined for any stress state and can be easily calculated as:

$$\mathbf{d}^P = \lambda \frac{\partial \bar{\sigma}_{grain}}{\partial \boldsymbol{\sigma}} ; \tag{2}$$

where $\lambda$ is the plastic multiplier, and $\bar{\sigma}$ is given by Eq.(1).

The multi-scale model using the single-crystal law (1) was implemented in a finite-element (FE) framework. In the FE calculations, the polycrystal behavior is obtained by considering 250 grains per element. It is considered that the total strain-rate of each grain belonging to a given element is equal to the overall strain-rate $\mathbf{D}$. At the time increment *(n)*, the stress in each grain is computed by solving the governing equations, namely:

$$\mathbf{D}_{grain}^{(n)} = \left(\mathbf{R}^{(n)}\right)^T \mathbf{D}^{(n)} \mathbf{R}^{(n)}$$
$$\mathbf{D}_{grain}^{(n)} = \mathbf{D}_{grain}^{e(n)} + \mathbf{D}_{grain}^{p(n)}$$
$$\boldsymbol{\sigma}_{grain}^{(n)} = \boldsymbol{\sigma}_{grain}^{(n-1)} + \left(\mathbf{C}^{el} : \mathbf{D}_{grain}^{e(n)}\right) dt \tag{3}$$
$$\bar{\sigma}_{grain}^{(n)} - Y\left(\bar{\varepsilon}_{grain}^{p\,(n)}\right) \leq 0$$
$$\mathbf{D}_{grain}^{p(n)} = \lambda_{grain} \frac{\partial \bar{\sigma}_{grain}^{(n)}}{\partial \boldsymbol{\sigma}}$$

where $\mathbf{D}_{grain}^{(n)}$, $\mathbf{D}_{grain}^{p(n)}$ and $\mathbf{D}_{grain}^{e(n)}$ are respectively the crystal's total strain-rate, the plastic and elastic strain-rate with $\mathbf{C}^{el}$ being the fourth-order elasticity tensor , $\boldsymbol{\sigma}_{grain}^{(n-1)}$ and $\boldsymbol{\sigma}_{grain}^{(n)}$ are the stress tensors at the beginning and end of the increment, respectively, while $\bar{\varepsilon}_{grain}^{p\,(n)}$ is the equivalent plastic strain in the given grain, $Y\left(\bar{\varepsilon}_{grain}^{p\,(n)}\right)$ is the hardening law, and $\lambda_{grain}$ the plastic multiplier. The stress of the polycrystal at the end of the increment is given by:

$$\boldsymbol{\sigma}^{(n)} = \left(\sum_i w_i \mathbf{R}_i^{(n)} \left(\boldsymbol{\sigma}_{grain}^{(n)}\right)_i \left(\mathbf{R}_i^{(n)}\right)^T\right) / \left(\sum_i w_i\right) \tag{4}$$

where $\left(\boldsymbol{\sigma}_{grain}^{(n)}\right)_i$ is the stress tensor of grain *i*, and $\mathbf{R}_i^{(n)}$ is the transformation matrix for passage from the crystal axes of grain *i* to the loading frame axes, while $w_i$ is the weight of the grain *i*. To describe the macroscopic response of FCC polycrystals, the model given by Eq. (1)-(4) was implemented in

the commercial FE solver Abaqus Standard (implicit solver, see Abaqus (2014)). A polycrystalline aggregate composed of N crystals was associated with each FE integration point. The set of governing equations are solved for each of the constituents crystals using a fully-implicit backward Euler method.

### 3. Application of the new polycrystal model to a textured AA6016-T4

The new polycrystal model presented in section 2 has been applied to the description of the plastic behavior of a polycrystalline AA 6016-T4 alloy. This material has been characterized in the context of the EXACT Esaform 2021 benchmark in uniaxial tension along seven directions in the plane of the sheet as well as in shear along three orientations and measurements of the initial and post-test textures were conducted ( see[6]). The EBSD file provided by the organizers for the initial texture was symmetrized such as to impose orthotropy and 250 crystal orientations representative of the overall texture of the AA6016-T4 alloy were further used as input for all the FE simulations conducted with the polycrystalline model based on Cazacu et al. [1] single crystal yield criterion.

For the AA 6016-T4 material of the EXACT benchmark, the values of the anistropy coefficients involved in the criterion given by Eq. (1) are: $m_1 = 0.355$, $m_2 = 0.0973$, $n_1 = 0.341$, $n_3 = 0.103$, $n_4 = 0.0571$ and $c = 0.8$. A two-step approach was taken to parameterize the model, the identification procedure can be found in [6]. In Figure 1 are shown in comparison with data, the results of FE predictions of the anisotropy in uniaxial yield stresses and r-values as well as the biaxial yield surface of the AA 6016-T4 sheet obtained with this set of parameters. Finally, the parameters involved in the isotropic Swift hardening law for the local behavior, .i.e

$$Y\left(\overline{\varepsilon}^{p}\right) = K\left(\varepsilon_0 + \overline{\varepsilon}^{p}\right)^{n}, \tag{5}$$

were determined based on the experimental stress-strain curve in uniaxial tension along $\theta = 0°$ (rolling direction), namely $K = 277$ MPa, $\varepsilon_0 = 0.0089$ and $n = 0.285$. For the simulation of any uniaxial tension test, the specimen is meshed with 570 reduced integration elements (Abaqus C3D8R). At any integration point, the mechanical behavior is calculated using the polycrystalline model (Eq.(1)-(5)) with the 250 crystal orientations representative of the overall texture of the material.
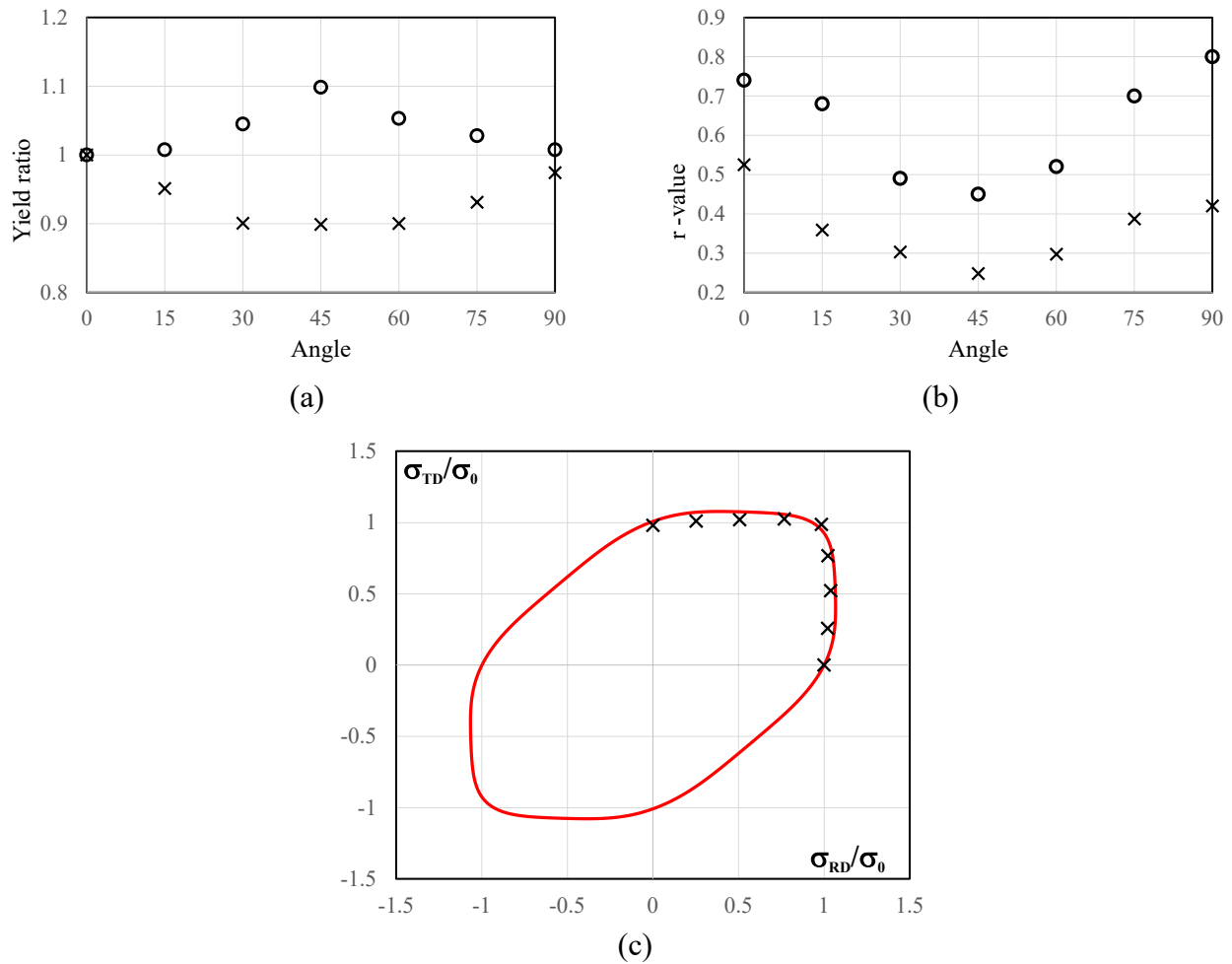
(a)



(b)



(c)

Fig. 1. Predictions of the anisotropy of the AA 6016-T4 alloy using the polycrystalline model based on the single-crystal law [1]: (a) Uniaxial tensile flow stresses; (b) Lankford coefficients ( r-values); (c) Predicted yield surface section in the biaxial plane $\left(\sigma_{RD}, \sigma_{TD}\right)$ (no shear). Data represented by cross symbols. All stresses are normalized by the yield stress along the rolling direction, $\sigma_0$; RD and TD denote the rolling and transverse direction, respectively.

Comparisons between the experimental stress-strain curves and the FE simulations of the response of under uniaxial tension along the rolling direction (RD) and transverse direction (TD) and shear loadings along RD and 45 to RD are presented in Figure 2 and Fig. 3, respectively.
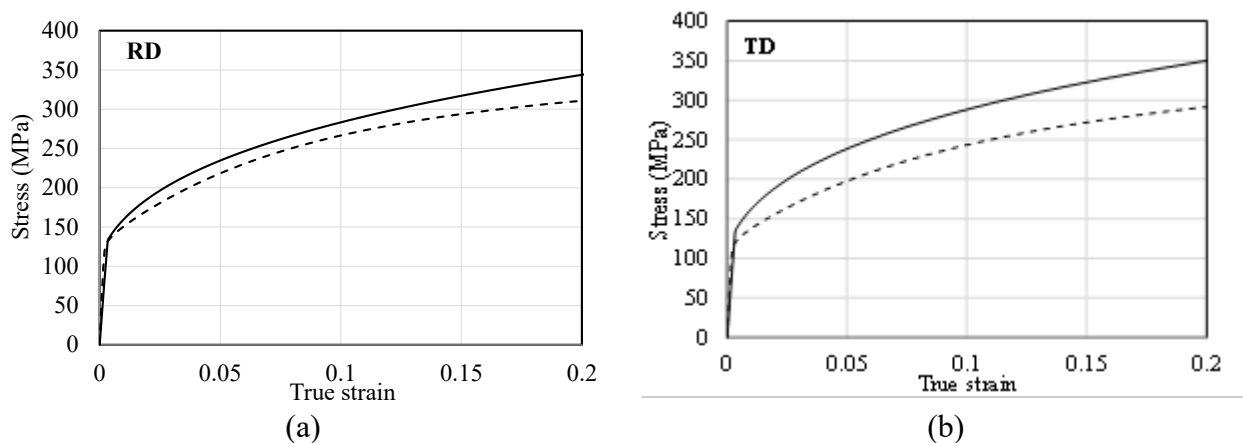


(a)



(b)

Fig.2. Comparison between experimental stress-strain curves (dashed line) in uniaxial tension and FE simulations obtained with the polycrystalline model for AA 6016-T4: (a) RD direction; (b) TD direction.
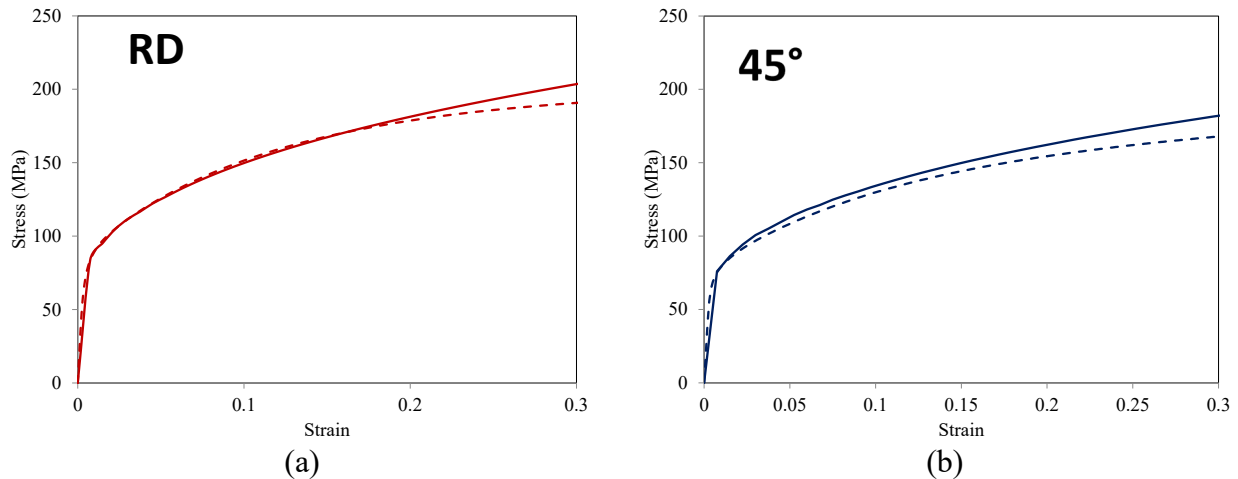
Fig.3. Comparison between the experimental stress-strain curves (dashed line) in shear and FE simulations obtained with the polycrystalline model for AA 6016-T4 (a) RD direction; (b) at 45° to the RD direction.

### 3.1. Application to forming a cylindrical cup

The polycrystalline model based on the Cazacu et al [1] single crystal criterion (see Eq.(1)) was applied to model forming of a cylindrical cup and respectively a square cup from the AA6016-T4 alloy sheet. Experimental data are available only for the cylindrical cup. In all the FE simulations presented hereafter, a polycrystalline aggregate composed of 250 orientations representative of the overall texture of the material is associated with each FE integration point.

Let us first discuss the FE simulations of a circular cup. A total of 10900 reduced integration elements (Abaqus C3D8R) have been used to mesh a quarter of the blank, resulting in the consideration of 2 725 000 grains in the FE simulation. Fig. 4 shows the simulation results obtained with our polycrystalline model; the blank of thickness 1 mm and radius of 57.5 mm being drawn by a punch of radius 30 mm into a die of opening radius of 31.2 mm and maintained with a blank-holder force of 40 kN. Note that our new polycrystalline model predicts an earing profile which is in very good agreement with the experimental one. Specifically, it predicts a four-ears profile with ears located at RD and TD and a minimum cup height at 45° from RD, as observed experimentally. The predicted average height is: $h_{avg} = 33.92$ mm against $h_{avg} = 34.10$ mm experimentally (0.6% difference), a cup profile amplitude of 2.61 mm against 2.29 mm experimentally (10% difference). Furthermore, our polycrystalline predicts a maximum cup height of of 35.39 mm against 35.27 mm experimentally (0.3% difference) and a minimum height of 32.78 mm against 32.99 mm experimentally (0.6% difference). Fig. 4(b) shows a comparison between the predicted forming force in function of the punch stroke with the experimental data, while Fig. 4(c) shows the predicted full drawn cup isocontours of plastic strain.
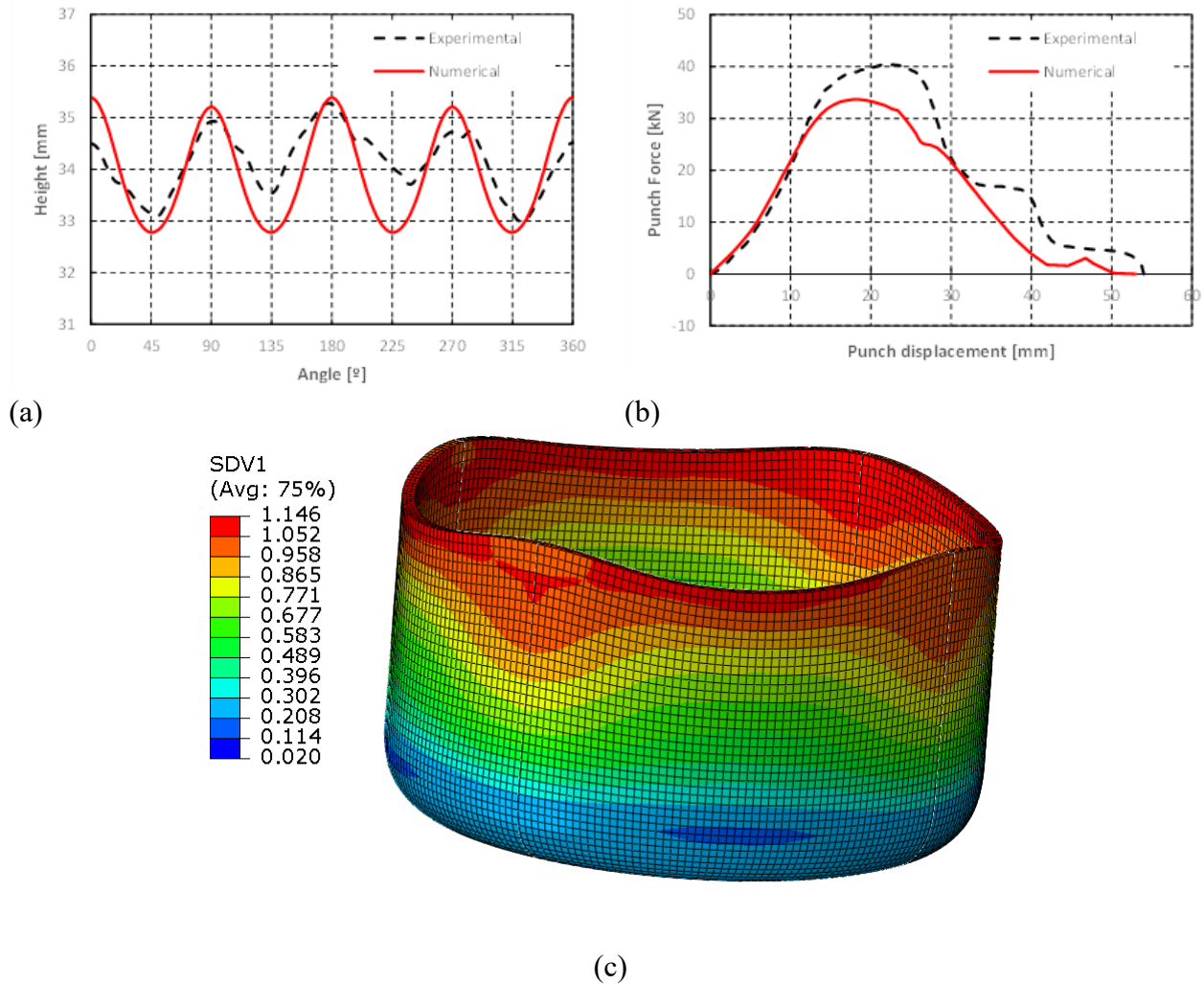
(a)

(b)



(c)

Fig. 4. FE results obtained with the polycrystalline model based on the Cazacu et al [1] single crystal criterion (solid line) and data on AA6016-T4 (dashed line): (a) earing profile (b) forming force vs. punch stroke (solid line) and data (dashed line). (c) Isocontours of the equivalent plastic strain.

### 3.2. Application to forming of a square cup

Our polycrystalline model (Eq(1)-(5)) is further applied to the prediction of the shape of the blank during the forming of a square cup. The geometry of the process is similar to the one used for the NUMISHEET 1996 benchmark [7]. A blank with initial dimensions 170x170x1 mm$^3$ was drawn into a square cup by a square punch of side dimension 70 mm into a die opening of dimension 74x74 mm$^2$. A blank-holder force of 40 kN was applied. A total of 9747 reduced integration elements (Abaqus C3D8R) have been used to mesh a quarter of the blank, resulting in the consideration of 2.4 millions grains in the F.E. simulation. In Fig. 5(a)-(b) are presented the isocontours of the displacement norm according to our polycrystalline model for a punch stroke of 20 mm and 40 mm, respectively.
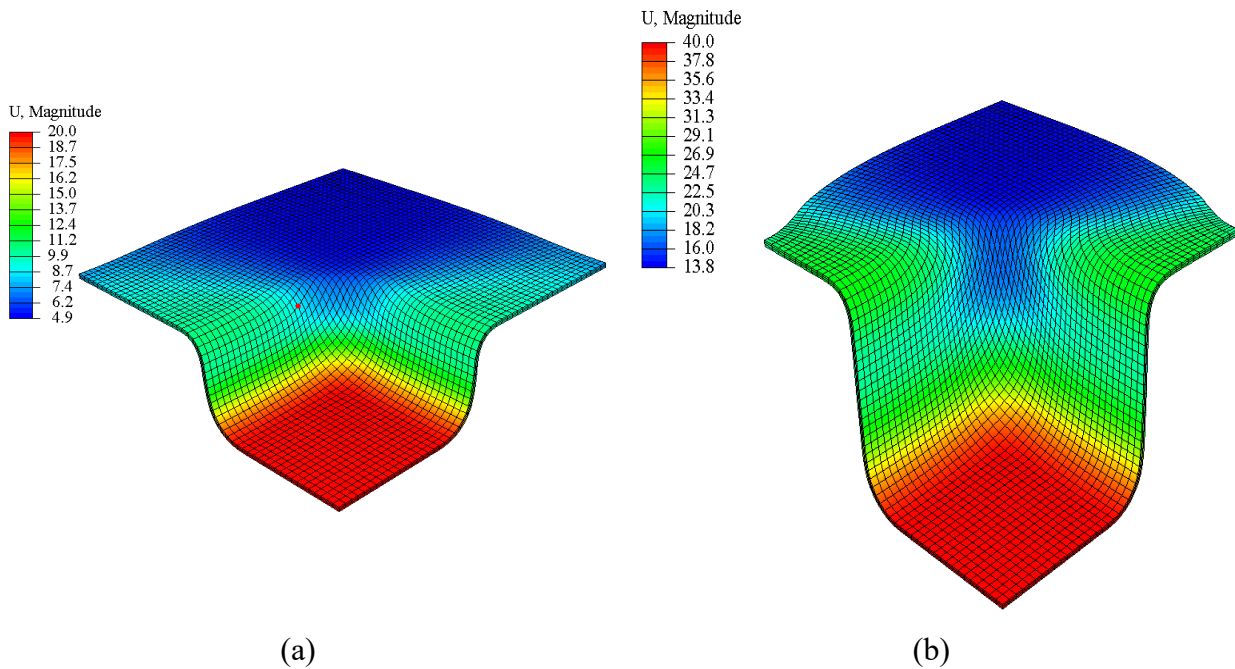
(a)                                           (b)

Fig. 5: Isocontours of the displacement during deep-drawing of a square cup: (a) punch stroke of 20 mm and (b) punch stroke of 40 mm.

## 4. Summary and Conclusions

In this paper, we have illustrated the capabilities of a new polycrystalline model to predict the response of AA 6016-T4 under mechanical tests and forming operations. Key in the formulation of this polycrystalline model is the use for the description of the plastic behavior at the crystal scale of the recent single-crystal yield criterion [1]. This cubic single-crystal yield criterion is defined for any stress state and involves the correct number of anisotropy coefficients required to satisfy the intrinsic symmetries of the cubic lattice and the condition of yielding insensitivity to hydrostatic pressure. The micro-macro transition was done making the isostrain Taylor assumption. It was shown that this polycrystalline model predicts the plastic anisotropy in macroscopic properties under uniaxial loading and shear with accuracy. Moreover, F.E. simulations of cup forming processes demonstrate the capabilities of this polycrystalline model to describe quantitatively the shape of the drawn parts. Specifically, the numerical predictions of the earing profile of the cylindrical cup according to the new polycrystalline model are in very good agreement with experimental data, namely it predicts fours ears with the minimum height located at 45° to the rolling direction, as in the experiments. Furthermore, the average cup height and height amplitude are accurately predicted. Although no data were available for comparison, the predictions for the case of a square cup made from the same sheet appear to be reasonable.

## References

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