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The following article appeared in AIP Conference Proceedings 1769, 060015(2016) and may be found at http://dx.doi.org/10.1063/1.4963451

Available from Deakin Research Online:

http://hdl.handle.net/10536/DRO/DU:30090339
Prediction of the Bending Behavior after Pre-strain of an Aluminum Alloy

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Abstract. The present work is focused on the modeling of sheet metal mechanical behavior up to rupture, including anisotropy and hardening. The mechanical behavior of an AA6016 alloy was characterized at room temperature in tension, simple shear and hydraulic bulging. The initial anisotropy was described with the Yld2004-18p yield criterion coupled to a mixed hardening law. Concerning rupture, an uncoupled phenomenological criterion of Mohr-Coulomb type will be used. For the material parameter identification, an inverse methodology was used with the objective of reducing the gap between experimental and numerical data. Finally, validation of the results was performed on bending tests with different amplitudes of tension pre-strain in order to reach or not rupture in the bent area.

INTRODUCTION

The general context of this research work is the forming of sheet metals in bending taking into account pre-deformations. Experimental data came from several previous works characterizing the AA6016 behavior under various strain states, and including bending tests with or without a tensile pre-strain [1-3]. Finite element simulations are an essential part in the design of industrial parts and new projects are now based on virtual forming. Such a virtual approach relies significantly on the quality of the representation of the mechanical model and therefore both on the model and the determination of the material parameters. On one hand, this leads to a direct weight decrease of the part in terms of raw material, which signifies a diminution of the material costs. On the other hand, human costs can be reduced by the diminution of computational times. Indeed, if the constitutive model gets closer to the real behavior of the material, it becomes more reliable.

In order to obtain a model leading to an accurate and reliable description of the material mechanical behavior within a phenomenological approach, a very flexible anisotropic yield function [4] was chosen. A mixed isotropic-kinematic hardening was also considered in order to reproduce the evolution of the yield surface during deformation [5]. Continuing the phenomenological approach, a macroscopic criterion is to be used for the prediction of the rupture [6]. This criterion uses the stress triaxiality and the Lode angle parameter [7] for the calculation of the equivalent plastic strain at rupture.

For a reliable prediction up to rupture of the AA6016 mechanical behavior, a large number of tests must be used to carry out the material parameter identification. Also, the large number of material parameters may induce non-uniqueness of the solution. The final objective is to obtain the smallest gap between numerical and experimental outputs. In regards to the tests used for the identification, the strain data was measured with a digital image correlation device, leading to precise and reproducible outputs and to an accurate strain distribution [1].

The global procedure presented here involves an efficient identification of the coefficients in order to achieve reliable numerical predictions [5]. The final aim is to obtain a precise reproduction of bending tests performed at various magnitudes of pre-strain in tension, with or without reaching rupture in the bent area.
MATERIAL PARAMETER IDENTIFICATION

The material parameters to be identified represent a total number of 22. The anisotropic yield function Yld2004-18p counts a total of 18 parameters. This number reduces down to 14 parameters by assuming that $c^{(i)}_{44} = c^{(i)}_{25} = 1$ (i = 1, 2) as they are related to stresses in the sheet thickness ($\sigma_{yz}, \sigma_{xz}$), which are supposed negligible for plane stress states. The isotropic part of the hardening (modified Voce law) uses 4 parameters as well as its kinematic part, for the two backstress tensors evolution, based on the Armstrong-Frederick law [5]. The initial values for the anisotropy coefficients were set equal to 1, and they were allowed to range from -2.2 up to 2.2. Concerning mixed hardening, the coefficients $\gamma_i$ were kept distinct, by constraining the first one below 8 and the second one above 50, in order to get a rapid and a smooth evolution of the two backstress tensors towards their saturation values.

Nine experiments were used for the parameter identification: uniaxial tensile tests at 0°, 45° and 90° from the rolling direction (RD); simple shear tests at 0°, 45° and 90° from RD; Bauschinger shear tests in RD consisting of loading in one direction at pre-strains of 0.05 and 0.15 and then reloading in the reverse direction; bulge test. The outputs used from the experiments are: (i) Cauchy stress – local strain ($\sigma = f(\varepsilon_{local})$), nominal stress – average strain ($\sigma_{nom} = f(\varepsilon_{avg})$), local strain – average strain ($\varepsilon_{local} = f(\varepsilon_{avg})$), transverse strain – longitudinal strain ($\varepsilon_{yy} = f(\varepsilon_{xx})$) in uniaxial tension (ii) shear stress – strain ($\tau = f(\gamma)$) in simple shear, both monotonic and Bauschinger type (iii) displacement of central point – pressure ($U_z = f(p)$), local strain along RD – local strain along TD ($\varepsilon_{yy} = f(\varepsilon_{xx})$) for the bulge test. For the tensile test, the average strain $\varepsilon_{avg}$ was calculated by taking the displacement $U_z$ of the nodes located at 10 mm from the center of the sample and by using the following equation: $\varepsilon_{avg} = \ln(1 + U_z/10)$; while the local strain $\varepsilon_{local}$ was calculated by taking the average strain component $\varepsilon_{xx}$ over an area of 3x3 mm² area at the center of the sample.

The identification of the parameters was performed with an inverse approach, which consisted of reducing iteratively the gap between predicted and experimental results, calculated by an objective function. The finite element (FE) simulation software calculated iteratively the output files with a specific set of parameters and the optimization algorithm updated the material parameters, following the procedure shown in Fig. 1. This inverse methodology was developed in Fortran and Python with the softwares Abaqus and SdL/SiDoLo. Abaqus was used to perform the numerical simulations with the addition of a user-defined material subroutine (UMAT) [8]. The end criterion was defined by a minimal variation of the objective function of $10^{-7}$ between two iterations. The derivatives of the objective function were calculated initially with a perturbation of $5 \times 10^{-3}$. The number of iterations for the identification has an upper limit of 500. Some parameters of the material were fixed to a constant value: Young’s modulus E, Poisson’s ratio $\nu$ and the exponent a in Yld2004-18p function. Their value is respectively 71.2 GPa, 0.33 and 8. E and $\nu$ were calculated by taking the average value from the experiments [1] and the parameter $a$ was set to 8, which is the standard value for face-centered cubic materials.

![Diagram of the parameters identification process](image-url)

**FIGURE 1.** Illustration of the parameters identification process.
The objective function \( S_{\text{obj}} \) was calculated as a sum of squared residuals. Outputs can be stresses, strains or displacements depending on the experiment and were output at the same ‘time’ in experiments and in numerical simulations. The selected \( S_{\text{obj}} \) was written as [5]:

\[
S_{\text{obj}}(x) = \sum_{\alpha \in \alpha} S^{\text{UT-S}}_{\text{obj}}(x) + \sum_{\alpha} S^{\text{UT-E}}_{\text{obj}}(x) + \sum_{\alpha,\beta} S^{\text{Shear-S}}_{\text{obj}}(x) + S^{\text{BT-U}}_{\text{obj}}(x)
\]

In Eq. 1, superscripts are defined as follow: UT-S: stress in uniaxial tension, UT-E: strain in uniaxial tension, Shear-S: stress in simple shear, BT-U: displacement in bulge test.

The sums were performed on the different orientations \( \alpha \) to RD and at different pre-strains \( \beta \) for Bauschinger shear tests. Sub-objective functions \( S^{\beta}_{\text{obj}} \) were calculated by adding the squared differences at all points between experimental and numerical results with a weighting factor for each type of tests (cf. superscripts if Eq. 1). In order to minimize the objective function, the Levenberg-Marquardt gradient-based algorithm was used. Figure 2 presents the results after identification at 0° from RD. The objective function decreased by 67.3% after the optimization process. The contribution of the two Baushinger tests was up to 70.6 % of its final value, over a total of 19 outputs.

**FIGURE 2.** Experimental and numerical comparisons at 0°/RD with final parameters: (a) tension, (b) strain localization up to rupture in tension, (c) simple shear with Bauschinger shear at 0.05 and 0.15 pre-strain, (d) hydraulic bulging.

**BENDING PREDICTION**

The purpose of the developed model is to have a good representation of the bending test with a tensile pre-strain. The identified parameters were used to perform both the pre-strain and the bending simulations. The bending process consisted of a blank laid upon two fixed rollers, with a moving blade, cf. Fig. 3 (a). The rollers were of 30 mm diameter, 70 mm long and were separated by a smallest gap of 2 mm. The blade had a radius of 0.38 mm and its two sides were inclined by 6° from its symmetry plane.
FIGURE 3. (a) Device designed for the bending of sheet specimen over a very small radius; (b) Load versus displacement of the blade for 0.45 pre-strain and comparison with the predictions obtained with either an isotropic or mixed hardening model. In the central part, the damage indicator was calculated without pre-strain (red) and with a 0.45 tensile pre-strain.

The pre-strain was performed at 0° from RD, along the X axis. The bending was then done at the specimen center, in case of a homogeneous tensile pre-strain or at the center of the localized strain area, in case of necking. The numerical simulation of the bending test was performed using implicit time integration with Abaqus standard. One fourth of the blank was considered, divided by two along its width and its length. For the mesh, 3D 8-node linear elements with reduced integration (C3D8R) were used. Friction between the blank and the rollers increased the load needed to bend the sheet, and a value of 0.15 was kept, leading to a correct description of the load [1]. The tools were represented by rigid analytical surfaces. The mesh used for the tensile pre-strain sample was made of about 120,000 elements with 12 elements in the thickness at the central area and down to 6 elements further away. Having an important number of elements allowed for a good description of the stress transition in the thickness during the bending process.

Figure 3 (b) shows the load – displacement curves in bending for a 0.45 tensile pre-strain. The experimental curve was stopped when the load started to fall off, corresponding to the occurrence of cracks on the exterior edge of the blank [3]. The same displacement was taken in the finite element simulation. The experimental and numerical curves show some discrepancies but tend to the same shape. Out of comparison’s sake, a prediction was obtained with an isotropic hardening model, which parameters were identified from the same database. Concerning the damage indicator, it was calculated with the strain to fracture and the equivalent plastic strain. Its four parameters (three for the strain to fracture and one for the damage indicator) were identified using uniaxial tensile tests in the three presented directions from RD and bulge test up to rupture in order to reach the closest value to 1 for each test. In Fig. 3 (b) it has a positive initial value because of the tensile pre-strain and it comes really close to 1 for the 0.45 tensile pre-strain, which indicates the onset of fracture [6].

CONCLUSION

In this work, the mechanical behavior of the aluminum alloy AA6016 was investigated up to rupture; experiments were carried out in previous works and only the modeling and material parameters identification were addressed here. The anisotropic yield criterion Yld2004-18p was coupled with a mixed isotropic-kinematic hardening. Therefore, a total of 22 parameters were identified by an inverse methodology from an experimental database including a total of 19 outputs. The number of available tests led to a precise characterization of the material with a good agreement between numerical and experimental data.

As for the validation, bending tests without and with pre-strain at various amplitudes were considered. These experiments were performed in order to obtain deformations up to rupture with different strain paths. For all the bending tests, load-displacement curves were compared. Overall, numerical and experimental curves exhibited small discrepancies.
REFERENCES


