Numerical analysis of a backward flow forming operation of AA6061-T6 and comparison with experiments

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Abstract. Incremental forming processes can be used to produce thin products (tubes or sheets)[1]. Very high deformation of the material can be reached taking advantage of the local and cyclic loading of the material. In this study we will focus on backward flow forming of aluminum tubes. In this process, tube thickness is reduced by the combined action of a rotating mandrel that imposes the inner radius and 3 rollers that decrease progressively the tube thickness. An experimental campaign is conducted on a laboratory device to study the influence reduction rate. The corresponding configurations are simulated to understand the mechanical loading path. The material characterization is presented to focus on the influence of the chosen behavior law on flow forming simulation results. Different damage criteria coming from the literature are studied to evaluate their capability to predict fracture and to compare the amount of damage reached for each process configurations. Even if none of them is able to predict accurately damaging configurations, the classical Cockroft and Latham seems to be the only capable to reflect the hierarchisation of configurations.

Introduction
Tube flow forming is an incremental forming process used to produce thin resistant tubes. The incremental loading condition allows the material to reach high deformation without exhibiting fracture. Inner diameter is controlled with a mandrel while thickness is reduced with rotating rollers. Several authors have studied the process from both experimental and numerical point of views [2, 3] comparing mainly global results as geometry or loads but not linking local mechanical variables with fracture prediction.

The objective, in this work, is to develop a numerical model able to understand material loading path, to predict fracture occurrence and to compare it with experimental results.

To save time and material, a lab scale device is used to study the process rather than an industrial device adapted to large tube dimensions. Smaller tubes are machined in the inner material waste coming from industrial preforms preparation as represented in Figure 1. Geometries of the rollers are defined homothetically from the industrial configuration. Dealing with smaller specimens allows also to reduce the associated CPU time.
Figure 1. Dimensions of the initial extruded bar from which the industrial flow forming preforms, lab scale device preforms (hachured) and compression samples are machined.

Numerical model has to be fed with material behavior laws and damage criteria. The computational model is then used to reproduce an experimental campaign in which increasing reduction ratio is applied to exhibit the limitation of the process. Three damage models are then evaluated for the prediction of fracture.

1. Material characterization and experimental flow forming campaign

1.1. Material characterization
The behavior of the material was identified using compression tests. Compression samples were extracted from the initial bar along the extrusion direction, in the same zone were flow forming tubular preforms were also machined. Localization of both tubes and samples are represented in Figure 1. Samples are 12 mm height and 8 mm in diameter.

The samples were tested at different strain rates of 0.001, 0.1 and 10 s⁻¹ and temperatures, 25, 70 and 100 °C to cover the large range of thermo-mechanical conditions encountered in the flow forming process. Load-displacement curves are shown in Figure 2. The identification of the parameters of the behavior law was done in three steps using inverse analysis: strain hardening part first, dependence to the temperature and then dependence to strain rate using an in-house software of inverse analysis [4]. Because of heat generated by plastic deformation at high strain rate, the dependence to temperature must be identified prior to the dependence to strain rate.

Figure 2. Experimental load-displacement curves of compression tests at 0.001 s⁻¹ and 25, 70 and 100 °C (solid lines) and at 10 s⁻¹ at 25 and 70 °C (dotted lines).
A material behavior model depending on both temperature and strain rate should be used in the flow forming simulation to account for heat generated both by plastic deformation and friction with tools. The chosen behavior law follows the Johnson-Cook model but with a Voce hardening part as described in equation (1):

\[
\sigma = \left[ \sigma_0 - (\sigma_S - \sigma_0) \exp (-K\bar{\varepsilon}) \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left(\frac{T - T_R}{T_M - T_R}\right)^m \right]
\]

\(\sigma_0\) is the yield stress (MPa), \(\sigma_S\) is the saturated stress (MPa), \(K\) is a dimensionless parameter describing the hardening effect, \(\bar{\varepsilon}\) is the equivalent plastic strain, \(C\) is a dimensionless parameter describing the material sensitivity to strain rate, \(\dot{\varepsilon}\) is the equivalent strain rate (s\(^{-1}\)) of the test, \(\dot{\varepsilon}_0\) is the strain rate of the reference test (s\(^{-1}\)), \(T\) is the temperature of the test (°C), \(T_R\) is the reference temperature (°C), \(T_M\) is the melting point of the material and \(m\) is a dimensionless parameter describing the material sensitivity to temperature. The values of the identified parameters for AA6061-T6 alloy using compression tests are summed up in Table 1. This law will be denoted as VJC (Voce and Johnson Cook) law in the following.

**Table 1.** Identified values using inverse analysis of the parameters of the Voce-Johnson-Cook (VJC) behaviour law for AA6061-T6 tested in compression.

| Voce hardening part | Temperature Johnson-Cook part | Strain rate Johnson-Cook part |
|---------------------|-------------------------------|------------------------------|
| \(\sigma_0 = 301.16\ \text{MPa}\) | \(m = 0.81\) | \(\dot{\varepsilon}_0 = 0.001\ \text{s}^{-1}\) |
| \(\sigma_S = 362\ \text{MPa}\) | \(T_R = 25\ \text{°C}\) | \(T_M = 632\ \text{°C}\) |
| \(K = 35.57\) | | \(C = 0.005\) |

**Figure 3:** Comparison of experimental and computed curves of force vs displacement

The comparison between the VJC law and the experimental results are compared on Figure 3 for 3 different testing configurations. Correlation is better at the beginning and worse at the end due to excessive large friction after 50% of reduction rate of the specimens.

1.2. Experimental flow forming campaign

Flow forming experiments are conducted in CEMEF on a lab sized flow forming machine [5]. It consists in a backward flow forming device with a rotating mandrel. The tubular preform is clamped on at its end and formed with 3 conical rollers. These rollers are arranged at 120° to each other, they are staggered along the Z axis -the revolution axis of the mandrel- and along the thickness of the preform. Each roller
takes one third of the total depth (Figure 4). The loads can be recorded only on one roller per operation but on all the three directions (radial, tangential and axial).

An important parameter of the flow forming operation is the reduction ratio or thickness reduction ratio $TR(\%)$ which is defined by:

$$TR(\%) = 100 \times \frac{e_0 - e_f}{e_o}$$  \hspace{1cm} (2)

where the reduction ratio is expressed in $\%$, $e_0$ is the initial thickness of the preform (mm) and $e_f$ is the final thickness of the tube (mm).

For the study of the influence of the behaviour law on tool forces in simulation, we have chosen the following flow forming parameters: a mandrel speed of 50 rpm and an axial feed of 0.2 mm/rotation. Lubrication is performed with intensive flow of water-soluble cutting oil.

For the local analysis of the stress state, four flow forming experiments were conducted on 5 mm thick tubes at different reduction ratios using the process parameters listed below:

- **Tube 1**: (TR60 P1): One pass of 60 $\%$ of reduction (expected final thickness is 2 mm)
- **Tube 2**: (TR80 1P1): One pass of 80 $\%$ of reduction (expected final thickness is 1 mm)
- **Tube 3**: 2 passes. The first one (TR80 2P1) of 40 $\%$ ratio (expected final thickness is 3 mm), then a second one on the resulting tube (TR80 2P2) with 66.67$\%$ reduction (expected final thickness is 1 mm)
In this study, the software Forge® was used. It is based on an implicit formulation with a mixed finite element in velocity and pressure [6]. Forge® is dedicated to the numerical simulation of forming processes implying large deformation. Automatic remeshing and parallel computation can be used to handle large plastic strain in the material and high number of nodes necessary to discretise accurately both the part and the local contact areas [7].

To control the volume variation of the tube during the simulation and to reduce the computation time [8], the description of kinematic interaction is modified. The \{mandrel+tube\} system is fixed whereas the rollers are rotating around the system at the actual mandrel rotation speed, $\Omega$. The rotation of rollers around themselves due to friction with the tube is fixed during the simulation. The rotation speed is estimated with:

$$\omega_i R_i = \Omega_{\text{mandrel}} (R_{\text{mandrel}} + e_i)$$  \hspace{1cm} (3)

where $i$ is related either to the roller A, B or C, $\omega_i$ is the roller rotation speed (rpm), $R_i$ is the roller radius (mm), $\Omega_{\text{mandrel}}$ is the mandrel rotation speed (rpm), $R_{\text{mandrel}}$ is the mandrel radius (mm) and $e_i$ is the tube thickness after the roller $i$ (mm). A global view of the 3D flow forming simulation explaining the specific kinematics is available in Figure 6 (a).

![Diagram](image)

**Figure 6**: (a) Global view of a 3D flow forming simulation using Forge®, (b) Meshed tube used in flow forming simulations in Forge®.

In the flow forming process, the contact zone between the rollers and the tube is very small, thus a small mesh size is required to properly describe the contact events. Moreover, the final thickness of the tube, depending on the reduction ratio, varies from 1 to 2 mm in this study. To capture the difference of stress state along the thickness of the tube, the mesh size is chosen to be lower than the half of the theoretical final thickness. However, having a fine mesh size on the whole tube would lead to very long computation time. To prevent that, only half of the tube is finely meshed as shown in Figure 6 (b). Each material point in the flow formed zone of the tube is deformed several times by each roller, at high strain rates and during short contact time, attesting the incremental deformation of the process. Small computation time steps are then required in the simulation, increasing the computation duration of the simulation. The computation time step is arbitrary chosen as half of the time that a roller needs to cover 1° of the tube.

As the tube is lubricated during the experimental flow forming operation, the heat exchange coefficient between the tube and its environment in simulation is set to 2100 W.m$^{-2}$.K$^{-1}$. The heat exchange coefficient between the tube and the tools is set to 2000 W.m$^{-2}$.K$^{-1}$. These values are classically used for cold forming lubricated processes.

As the rollers are rotating around themselves due to friction with the tube, a friction coefficient between the tube and the rollers is put in the simulation. A Coulomb-Tresca friction model is used with the respective following parameters: $\mu = 0.2$ and $m = 0.4$.  

![Diagram](image)
To evaluate the capability to predict fracture of the tubes, damage criteria are computed. Several criteria can be found in the literature for analysis of flow forming [8, 9]. In the following we will focus on the Latham & Cockroft damage depending on the first principal stress, the Oyane based on triaxiality evolution and a variation of the Lou & Huh criterion [10] expressed with respect to local shearing conditions as described in equation (4).

\[
D_{CLN} = \int_0^{\bar{\varepsilon}} \langle \sigma_1 \rangle d\bar{\varepsilon}
\]

\[
D_{Oy} = \int_0^{\bar{\varepsilon}} \langle 1 + \frac{\eta}{A} \rangle d\bar{\varepsilon}
\]

\[
D_{Shearing} = \int_0^{\bar{\varepsilon}} \langle \frac{\sigma_1 - \sigma_3}{\bar{\sigma}} \rangle d\bar{\varepsilon}
\]

where \(\sigma_1\) and \(\sigma_3\) with first and last principal stress components and \(\bar{\sigma}\) the equivalent von Mises stress. \(\eta\) the stress triaxiality \(A\) a parameter depending on the material here taken to 3. \(\langle \cdot \rangle\) a function defined as:

\[
\langle x \rangle = x \quad \text{if} \quad x > 0
\]

\[
\langle x \rangle = 0 \quad \text{if} \quad x \leq 0
\]

\(\bar{\varepsilon}\) the plastic deformation.

The local mechanical path undergone by the material in flow forming is complex, multiaxial and cyclic. It is then difficult to point out what are the most damaging stress states.

2. Experimental campaign results vs simulation modeling

2.1. Forming forces

Flow forming simulations is compared to experimental results for the 60% of programmed thickness reduction, in the same processing conditions. The forces on the first roller are measured and compared to the simulated ones on Figure 7.

![Figure 7](image_url)

*Figure 7.* Radial (a), tangential (b) and axial (c) loads on roller A (kN) as a function of process time (s) experimentally and simulated by Forge®.
The force is first increasing when flow forming the conical part and reaching a plateau both in simulation and experimentally when the tubular part is flow formed at a constant reduction ratio. Radial force is the highest and is well predicted by the numerical model. Axial force is also well predicted while radial component is underestimated by the simulation. It can be noticed that the value of this component is quite low and is experimental accuracy poor depending on the force sensor capacity.

2.2. Effect of the reduction ratio
We will focus on the radial component of the force that is the highest value and the most representative and limiting of the process (on industrial plant it is the only one recorded). The plateau values of radial forces are reported for different reduction ratio in Figure 8. The force is increasing with the reduction ratio.

![Figure 8](image)

**Figure 8.** Evolution of forming load with the reduction ratio(a) and fracture observed for 80% TR

The increase of the reduction ratio leads to fracture for 80% reduction in one step. However, for the third tube the same global reduction ratio is programmed in 2 flow forming steps as above. This tube did not show any fracture. Different computed damage criteria are then analyzed on 4 configurations to see which ones can predict the increase of the reduction ratio should lead to an increase of damage and a reduction ratio of 80% leads to more damage when achieved in one pass rather than in two.

2.3. Analysis of local mechanical variables
The plastic strain evolution is analysed with computational sensors on Figure 9.. Those sensors are recording of mechanical and thermal variables associated to given material points of the tube all along the simulation. One is located close to the outer surface, solicited by the roller, the second, close to the inner surface, nearby the mandrel.

The plastic strain is globally higher on the outer surface, values for 80% (TR801P1) are higher than 60% (TR601P1) and 40% (TR80 2P1) but values for 80% in 2 passes (TR802P2) is higher than the one for one pass (TR801P1). For 40%, the outer surface is highly deformed, this reduction ratio is not representative of “flow forming” conditions and then difficult to compare with values obtained with higher TR. However, the expected order is respected on the inner face of the tube.
3. Results analysis

Evolution of plastic strain is used as a fracture criterion for monotonic strain path undergone during standard identification test. In flow forming the level of cumulated plastic strain withstood by the material is very high and coming from complex, cyclic and non monotonic loading path, it cannot then be used directly as a fracture criterion. It was thus interesting to notice that plastic strain is increasing with reduction ratio but for an equivalent final reduction rate of 80 % higher plastic strain evolution is different if one or two passes are used. The distribution of plastic strain within the tube thickness is then an interesting observation to study further in the future.

Damage criteria are giving different prediction. Oyane or the shear-based criterion are predicting decreasing damage with increasing reduction ratio. Only the Latham and Cockcroft based on the first principal stress and thus the tensile configuration allows to reach the expected hierarchy of the configurations. The difference between the 2 routes of 80 % is however small.
As a conclusion tube flow forming is complex to analyze because the material is incrementally and cyclically deformed reaching values of plastic strain almost impossible to reproduce with standard characterization testing. Classical damage criteria are not giving a clear answer, enhanced formulation must be considered. Mechanical analysis can provide information for the prediction of flow formability, but some metallurgical aspects are neglected in the approach and could help to understand more accurately the capability of the material to be deformed without fracture.

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