Prediction of superplastic forming of 7475 aluminium alloy sheets

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Abstract. Superplastic forming is mainly used in the aeronautic and astronautic domains and to fabricate the complex shape parts with the materials hard to process. The numerical simulation is used to predict the superplastic forming process due to the difficulty to predict a forming pressure by a traditional trial and error method. In the article, the superplastic behaviour of a 7475 aluminium alloy has been investigated. Uniaxial tensile tests over a wide range of temperatures and strain rates have been performed. An Arrhenius-type model using strain compensation has been identified. A failure criterion based on the evolution of fracture work is also proposed. This material model has been implemented by user subroutine in numerical simulations (ABAQUS) to predict the ability of the material to form a complex revolution part by superplastic forming. A pressure control algorithm has been developed to minimize the pressure instability and decrease the simulation CPU time. The numerical results, in terms of thickness evolution in the formed component and location of damage-risk zones, have finally been compared to experimental results after the realization of some bulging experiments using the generated pressure cycle.

1. Introduction

Superplastic forming is commonly used to elaborate deep drawn surfaces from thin metallic sheets by bulging processes. It consists in deforming a flange at high temperature by applying a time-dependent pressure [1]. This time-dependent pressure (pressure law) is chosen in order to deform the plate at a constant and low strain rate (usually called the optimal strain rate which is allowed to obtain the best deformation performance) while preventing the formation of defects. The ability to form a given part is generally studied by numerical simulations. They allow generating an optimized pressure law to pilot the strain rate evolution during the process. And the quality of the prediction depends on the material model and the stability of the pressure control.

A good knowledge of the mechanical behavior of the material under superplastic conditions, in terms of mechanical response or damage evolution, is necessary to obtain realistic predictions by numerical simulations.

Superplastic rheological behavior has to be identified by applying representatively thermo-mechanical conditions of superplastic forming, i.e. high temperature, low strain rate and biaxial stress state [2].

Empirical models are generally sufficient to describe the mechanical response of superplastic material. Yang et al. [3] have used a simple Norton-Hoff law to fit experimental strain-stress curves...
obtained by performing uniaxial tensile tests on an aluminium alloy. Zener-Hollomon parameter can also be introduced into this standard model to take the effect of temperature into account [4]. It is generally assumed that the model parameters are not dependent of strain. Otherwise, as proposed by Li et al. [5], to describe the behavior of a 7050 aluminium alloy, the strain compensation can be used. Parameters of the flow rule are thus expressed as polynomial functions of strain. However, these models do not describe the decrease in stress when exceeding a given strain due to damage development in the specimen. However, these models do not describe the decrease in stress when exceeding a given strain due to damage development in the specimen.

Damage in superplastic deformation is of ductile fracture type, it is mainly linked to cavities germination and growth [6]. The knowledge of its evolution during deformation allows predicting the forming limit of the material. Different approaches can be considered to take this phenomenon into account in the material model.

The material fracture can be predicted by coupling the ductile fracture criterion with the constitutive equation of the material. Ragab et al. [7] have indeed shown that the association of flow rules with some laws governing void growth such as Gurson’s, Green’s or Shyma-Oyane’s models leads to good prediction of experimental data. Another approach consists in introducing some state variables in the flow rule. Costa Mattos et al. [8] have for instance modeled the superplastic behavior of anMg alloy by multiplying the flow rule by the term $1 - D$ where $D$ is a damage variable. When $D$ is equal to 0, no damage is present; while $D$ reaches 1, failure occurs.

Furthermore, as proposed by Kim et al. [9], by tracking the evolution of work, the failure is predicted to occur when the fracture work reaches a critical value.

The use of an appropriate pressure control algorithm during Finite Element Modeling (FEM) simulation is also essential to predict the formability of a given part. Pressure control strategies in FEM simulation are generally defined in terms of pressure versus time and are able to generate an optimal pressure cycle which permits to deform a part at the optimal strain rate. Yang has summarized some often used methods [10]. Bonet et al. [11] used an analytical solution to define the pressure cycle for free bulging tests. The results are quite precise but they do not allow simulating industrial problems. Ollivier et al. [12], Rama et al. [13] and Carrino et al. [14] have proposed proportional rules between the equivalent stress and the applied pressure to generate the pressure law by coupling with a logarithmic correction. Bellet [15] and Robert [16] have proposed pressure controls by strain rate or stress ranges, which are more preferred by the industry due to their simplicity and sufficiency.

In the present work, the superplastic behavior of a 7475 aluminium alloy has been investigated by performing uniaxial tensile tests at different temperatures and strain rates. A rheological model using Zener-Hollomon parameter and strain compensation has been identified. Numerical simulations based on this material model have been realized on ABAQUS© to study the ability of the studied material to form complex parts. Failure is predicted by comparing the predicted fracture work to a critical value and a specific pressure control algorithm has been developed. These simulations have finally been checked by comparing numerical results to experimental results obtained by performing some bulging experiments.

2. Material and experimental methods

2.1. Material

The material used was a rolled 7475 aluminium alloy plate with a thickness of 2mm. The composition is given in Table 1. The initial microstructure was composed of elongated grains in the rolling plane with an average grain size of 12µm calculated by linear intercept method.

|   | Al   | Si    | Fe   | Cu   | Mn   | Mg   | Cr   | Ni   | Zn   | Ti   | Zr   | Pb   |
|---|------|-------|------|------|------|------|------|------|------|------|------|------|
| balance | 0.03 | 0.06  | 1.64 | 87 * | 2.25 | 0.23 | 15 * | 5.79 | 0.02 | 24 * | 16 * |

En %, * en ppm

Table 1. Composition (in wt%) of the 7475 aluminium alloy [1].
2.2. Uniaxial tensile tests

The experimental device used for the tensile tests is shown in Figure 1. The force was measured by a 1kN load cell. The samples' shape was chosen in order to concentrate the deformation in their central part. They were taken from the plate with their tensile direction parallel to the rolling direction. A previous study [17] has shown that the anisotropy for this alloy is negligible. The crosshead displacement was piloted in real-time to ensure a constant strain rate within the central part of the specimens. The temperature was measured by a K-Type thermocouple welded in the central part of the sample. It was monitored in real-time to get as close as possible to the desired thermal cycle and allowed an oscillation of 2°C maximum at the desired temperature. An argon flow in the furnace allows preventing the corrosion of the specimen during the experiment. Tensile tests were conducted until fracture at constant strain rates of $5 \times 10^{-5}$, $2 \times 10^{-4}$ and $5 \times 10^{-4}$ s$^{-1}$. Different test temperatures were studied (477, 497 and 517°C).

![Figure 1. Sketch of the experimental device used for uniaxial tensile tests.](image1)

2.3. Bulging experiments

The experimental device used to perform bulging experiments is presented in Figure 2. This demonstrator has the ability to perform the experiments at a temperature within the range of [300-1100°C] and the accuracy of the displacement sensor is about 0.3%. The forming pressure is applied by using an inert gas (argon) which is introduced in the upper part of the enclosure. It is piloted by either the displacement of the sheet or the forming time. A back pressure can also be used during the forming process to limit the development of the cavitation encountered for some materials. It is thus introduced by an inert gas in the downer part of the enclosure. The die shape used during the experiments allows forming a complex revolution part with a height of 65mm and a maximum radius of 145mm.

![Figure 2. Experimental sketch used for bulging experiments.](image2)
3. Experimental results

3.1. Rheological behavior of the 7475 aluminium alloy under hot tension

Uniaxial tensile experiments at various temperatures and strain rates have been performed. The true stress-strain curves can be found in [17]. Figure 3 shows a 3-D representation of these results for a strain rate of $2 \times 10^{-4}$ s$^{-1}$ and different temperatures (Figure 3a) and for a temperature of 517°C and different strain rates (Figure 3b).

![Figure 3](image)

(a) strain rate of $2 \times 10^{-4}$ s$^{-1}$ and different temperatures  
(b) temperature of 517°C and different strain rates

As shown in Figure 3, stress increases to a plateau where it remains relatively constant, thus showing negligible strain hardening during the deformation. Moreover, stress increases obviously with increasing strain rate and decreasing temperature, which highlights the viscoplastic behavior of the alloy. Damage becomes predominant from a critical strain which depends on strain rate and temperature, which leads to a decrease in stress. Strain rate exhibits a significant effect on the strain to failure. The higher the strain rate is, the earlier the damage occurs. The optimal thermo-mechanical conditions for superplastic forming of 7475 alloy can thus be defined as the conditions for which the highest elongation to failure is obtained, i.e. 517°C and $5 \times 10^{-5}$ s$^{-1}$.

3.2. Rheological behavior of the 7475 aluminium alloy under hot tension

The experimental fracture work is evaluated from the true stress-strain curves by integrating flow stress with respect to the strain until fracture. Its evolution as a function of strain rate at different temperatures is given in Figure 4. It can be noticed that fracture work tends to increase with increasing strain rate at a given temperature. However, it remains stable at 517°C which is the highest testing temperature.

![Figure 4](image)

Figure 4. Fracture work as a function of strain rate at different temperatures.
4. Discussion
A model of the rheological behaviour of the material including strain compensation will be discussed first. Then a failure criterion based on fracture work evolution will be proposed. Finally, these models will be introduced in a numerical simulation to determine the pressure law to apply to form a complex part. The pressure law will then be used to perform bulging experiments with which the numerical simulations results are compared to validate the proposed protocol.

4.1. Modeling of the rheological behavior
During superplastic deformation of 7475 aluminium alloy, the steady state flow stress can be related to the strain rate and the temperature in the form of an Arrhenius kinetic rate equation [18]:

$$\dot{\varepsilon} = A \left[ \sinh (\alpha \dot{\varepsilon}) \right]^n \exp \left( -\frac{Q}{RT} \right)$$

with $\dot{\varepsilon}$ is the strain rate, $A$ and $\alpha$ are constants, $\dot{\varepsilon}$ is the steady flow stress, $n$ is the stress exponent, $Q$ is the activation energy, $R$ is the gas constant and $T$ is the absolute testing temperature.

The effect of strain rate and temperature on the hot deformation behavior of a material can be described by the Zener-Hollomon parameter [19]:

$$Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right)$$

Then, the flow stress can be rewritten as a function of $Z$ parameter:

$$\dot{\varepsilon} = \frac{1}{\alpha} \ln \left( \left( \frac{Z}{A} \right)^{1/n} + \left( \frac{Z}{A} \right)^{2/n} + 1 \right)^{1/2}$$

After calculating the material constants ($\alpha$, $n$, $Q$ and $A$) in above equation, it can be shown that these constants are strain-dependent. Values of material constants calculated at four different strains (0.05, 0.15, 0.25 and 0.35) are given in Table 2. They increase when the strain increases. Strain compensation has thus to be taken into account to accurately predict the flow stress. It has been assumed that the material constants are polynomial functions of the strain [5, 20]. The best fitting correlation is obtained with a second order polynomial. The material constants expressions are summarized in Table 3. The identified parameters can be checked by comparing experimental and predicted data, as shown in Figure 5. It can be seen that the predicted data can efficiently represent the flow behavior of the alloy under the entire studied experimental conditions.

| Parameter | Strain Level |
|-----------|--------------|
| $\alpha$  | 0.05 0.15 0.25 0.35 Average |
| $n$       | 1.608 1.799 2.041 2.411 1.964 |
| $Q$       | 232.2 247.5 263.9 302.0 261.4 |
| $\ln A$   | 27.19 29.51 31.97 37.71 31.60 |
Figure 5. Comparison between experimental (gray) and predicted flow stress data by the constitutive model.

Table 3. Polynomial expressions of material constants for an Arrhenius-type equation.

| Parameter | Expression |
|-----------|------------|
| $\alpha$  | $0.5369\varepsilon^2 - 0.1402\varepsilon + 0.1378$ |
| $n$       | $4.077\varepsilon^2 + 0.937\varepsilon + 1.559$ |
| $Q$       | $338.4\varepsilon^2 + 61.49\varepsilon + 228.9$ |
| $\ln A$   | $50.60\varepsilon^2 + 9.483\varepsilon + 26.67$ |

4.2. Formulation of a failure criterion

The approach proposed by Kim et al. [9] for hot forming of a magnesium alloy is adopted in this study. A damage variable $\Psi$ for ductile fracture is used and compared with the fracture damage value $\Psi_f$ which is obtained at the effective fracture strain $\varepsilon_f$:

$$F = \frac{\Psi}{\Psi_f} = \int_0^\varepsilon \left[ \frac{f(\sigma_y)}{\Psi_f S(\varepsilon, T)} \right] d\varepsilon$$

(4)

where $F$ is the normalized damage value, $f(\sigma_y)$ is a stress function, $\varepsilon$ is the effective strain, and $S(\varepsilon, T)$ is a damage strength parameter which depends on the effective strain rate $\dot{\varepsilon}$ and the temperature $T$. Material fracture occurs when $F$ reaches 1. The expression of $f(\sigma_y)$ is a function of the damage criterion chosen (Freudhental [21] or Cockroft-Latham [22]). In the case of Freudhental criterion, the stress function is the effective stress $\bar{\sigma}$, which gives the normalized damage value as:

$$F = \frac{\Psi}{\Psi_f} = \int_0^\varepsilon \left[ \frac{\bar{\sigma}}{\Psi_f S(\varepsilon, T)} \right] d\varepsilon$$

(5)

The temperature and strain rate dependence of $S$ can be represented by using the Zener-Hollomon parameter $Z$. The denominator in equation (5) is thus replaced with a function $H(Z)$:
\[ F = \frac{\Psi}{\Psi_f} = \int_0^z \left[ \frac{\bar{\sigma}}{H(Z)} \right] d\bar{\varepsilon} \]  

(6)

Since \( F_{\tau,\tau_j} = 1 \), equation (6) gives:

\[ F = \frac{\Psi}{\Psi_f} = \int_0^z \left[ \frac{\bar{\sigma}}{H(Z)} \right] d\bar{\varepsilon} \]  

(7)

where \( W_f \) is the fracture work. The expression of \( H(Z) \) can thus be found by using the tensile data. Kim et al. [9] have shown that \( H(Z) \) can be expressed as a polynomial function of \( \ln Z \). The fracture work obtained for the 7475 alloy as a function of \( \ln Z \) is shown in Figure 6.

**Figure 6.** Fracture work as a function of \( \ln(Z) \) determined from the stress-strain curves.

To calculate \( Z \), an average value of \( Q \) is used i.e. \( Q = 261.4 \text{kJ/mol} \). \( H(Z) \) can be expressed as follows:

\[ H(Z) = 0.1 \left[ \ln(Z) \right]^2 - 5.6 \ln(Z) + 81.4 \]  

(8)

4.3. Application to the forming of a complex part

The pressure control algorithm proposed by Bellet [15] is implemented by default in ABAQUS©/Standard. This algorithm generates pressure law by taking a referenced strain rate value into account. This method gives globally good results and is commonly used in industrial applications. However, it needs to decrease the time increment to compensate the instabilities in the generated pressure law. Moreover, this method is limited by the use of implicit solver and the creep law. In this study, this algorithm has been modified based on the form proposed by Robert [16] in order to improve the pressure law stability and to reduce the CPU time. The modifications have been implemented in ABAQUS©/Standard by FORTRAN subroutine, which allows to use a wide range of material behavior by programming a UMAT subroutine and to control more efficiently the pressure evolution. The major correction proposed by Yang [23] besides the form proposed by Robert [16] consists in introducing a viscous factor \( \mu \) to pilot the pressure evolution and a strain corrector curve of \( \dot{\varepsilon}_{\text{ref}} \) to adjust the maximal strain \( \varepsilon_{\text{max}} \):

\[ \frac{P_{\text{max}}}{P_n} = \left[ -5(r_{\text{max}} - 1)^3 - 0.5(r_{\text{max}} - 1) + 1 \right] \exp(-\mu r_{\text{max}}) \]  

(9)
$P_{n+1}$ and $P_n$ are the pressures at the increments $n+1$ and $n$, respectively; $r_{\text{max}} = \dot{\varepsilon}_{\text{max}} / \dot{\varepsilon}_{\text{ref}}$ is the strain rate ratio between the computed maximum value $\dot{\varepsilon}_{\text{max}}$ and the referenced optimum value $\dot{\varepsilon}_{\text{ref}}$. Figure 7a compares a pressure law corrected with a $\mu$ value of 0.4 and a non-corrected one. It can be noticed that this correction acts like a viscous pressure which generates a much more continuous pressure evolution. The Figure 7b shows the corrector curve of $\dot{\varepsilon}_{\text{ref}} = f(\dot{\varepsilon}_{\text{max}})$.

(a) comparison between non-corrected and corrected pressure law

(b) strain rate corrector for the optimal strain rate

Figure 7. Major corrections proposed.

This algorithm has been used to predict the ability to form a complex revolution part. The ABAQUS© simulation is built using a quarter of the revolution part with symmetry conditions on the straight edges. The sheet is meshed with thin shell elements. The die is modeled by a discrete rigid surface. The implicit solver is chosen and the contact model uses classical “hard contact” options and Coulomb friction with a coefficient of 0.2. The material behavior and failure criterion detailed above are implemented by user subroutines. The reference strain rate is chosen within the range $[5 \times 10^{-5} - 5 \times 10^{-4} \text{s}^{-1}]$. Figure 8 presents the model and the thickness evolution at 6000s.

(a) numerical model

(b) simulation results

Figure 8. Numerical simulation of the superplastic forming of a complex revolution part.

The generated pressure law allows forming the component with the new algorithm. The optimal strain rate is corrected by the law presented in Figure 7. The generated law is used to perform bulging experiments. The thickness evolution in the formed component is measured. Figure 9 shows the location of the thickness measurements on the component and a comparison between numerical and experimental results. It can be noted that numerical results are in good agreement with experimental results. Moreover, as shown in Figure 10, the damage criterion is maximal in the zone near points 5 and 6 (on Figure 9) which have already been identified as a critical zone in previous study [24].
5. Conclusions

A material model allowing the description of the superplastic behavior of a 7475 aluminium alloy has been identified by performing isothermal hot tension tests within the following temperature and strain rate ranges: [477 - 517°C] and [5.10^{-5} - 5.10^{-4} \text{s}^{-1}]. After the optimization of the pressure control algorithm and the development of user subroutine, numerical simulations of the superplastic forming of a complex revolution part have been realized by ABAQUS. The conclusions are as follows:

1. An Arrhenius-type constitutive equation including strain compensation allows predicting the mechanical response of a 7475 aluminium alloy under the thermo-mechanical conditions studied.
2. A failure criteria based on the evolution of fracture work is sufficient to predict the damage-risk zones during the superplastic forming process.
3. The use of a viscous factor in the pressure control algorithm allows improving the stability of the pressure law.

6. References

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