NUMERICAL SIMULATION OF INDUSTRIAL SUPERPLASTIC FORMING

Keith S. Haberman, Joel G. Bennett, ElRoy L. Miller and Martin S. Piltch, Los Alamos National Laboratory, Los Alamos, New Mexico

Larry K. Leyer and Walter Leodolter, Jet Die, Lansing, Mi
Flame Co, Ogden UT

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Keith S. Haberman, Joel G. Bennett, ElRoy L. Miller and Martin S. Piltch
Los Alamos National Laboratory, Los Alamos New Mexico

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ABSTRACT

Superplastic forming is a metal forming process that allows a variety of components with very complex geometries to be produced at one tenth the cost of conventional machining. The industrial superplastic forming process can be optimized with the application of the finite element method to predict the optimal applied pressure history and the final part thickness distribution. This paper discusses the application the nonlinear implicit, three dimensional finite element code, NIKE3D\[1\] to the problem of numerically simulating and optimizing the superplastic forming of Ti-6Al-4V components.

INTRODUCTION

Overview
Los Alamos National Laboratory (LANL) has entered into a cooperative research and development agreement (CRADA) with The Barnes Group whose companies JET DIE and FLAMCO are making superplastically formed parts for the aerospace industry. LANL participation in these CRADA agreements is funded by the U. S. Department of Energy (USDOE) and require in-kind expenditures from the industrial partner and are a result of the so-called "peace dividend", wherein funds that would normally go into the weapons budgets at the National Laboratories, are redirected to use the experience and expertise at these institutions to address industrial problems of significance that are also related to the defense industry. Because the superplastic forming process is used to produce many aircraft engine components, this CRADA represents an ideal redirection of these funds.

Superplasticity
Superplasticity is the capability of certain polycrystalline materials to undergo extensive tensile plastic deformation. Superplastic deformation is generally characterized by essentially neck and cavitation free large inelastic deformation. Superplastic materials generally exhibit relatively large values of a parameter known as the strain rate sensitivity index $m$, which is shown with relation to stress and strain rate in Equation 1.0.

$$\sigma = k \dot{e}^m$$  (1.0)
Where, $\sigma$ is the flow stress, $\dot{\varepsilon}$ is the strain rate, $k$ is the strength coefficient and $m$ is the strain rate sensitivity index. Ideal Newtonian viscous behavior is found in materials where $m = 1$. An in depth discussion of the superplastic behavior of numerous polycrystalline materials may be found in References [2] and [3].

Superplastic Forming, SPF
Whenever a new aircraft industry part is required, a great deal of experience based engineering currently goes into deciding whether the part can be made to the required specifications and which process should be used to produce the part. Many times the judgment is that the part can most effectively be made by the process of superplastic forming. Superplastic forming is a metal forming process that uses the extreme extendibility of certain alloys to form parts at one tenth the cost of conventional machining[4]. Superplastic behavior provides the possibility of forming shapes that might otherwise be unattainable for a specific alloy. Superplastic forming is carried out under near isothermal conditions within a narrow strain rate range. To retain superplastic properties in the material, and to minimize the overall forming time it is essential to control the strain rate during the forming process. The strain rate is directly controlled by varying the pressure during the forming process. The optimum or target strain rate for a given alloy is often determined by the highest possible attainable value of the strain rate sensitivity index $m$. The highest possible $m$ value must also correspond to a minimum amount of microscopic cavitation. A substantial amount of thinning is likely to occur during the superplastic forming process just due to the large inelastic deformation. Ideally, the final thickness distribution of the formed part should be predicted before the actual forming in order to specify the correct initial sheet thickness. Current thickness distribution predictions are often based on experience, with the final part development done by trial and error. One of the goals of this CRADA is to minimize the trial and error cost associated with the development of a new part that is to be superplastically formed.

CONSTITUTIVE MODEL
Superplasticity is a strain rate and temperature dependent phenomenon which is also influenced by grain size[5].

$$\sigma = f(\dot{\varepsilon}, g, T)$$  \hspace{1cm} (2.0)

Assuming isotropic behavior throughout the material at the superplastic state, the effective stress is given by $\sigma$, $\dot{\varepsilon}$ is the effective strain rate, $g$ is the grain size and $T$ is the temperature. Throughout the literature, the power law form given by Equation 2.1 is often employed to describe the constitutive behavior of superplastic alloys on a macroscopic continuum scale, i.e.,

$$\sigma = k(\dot{\varepsilon}, g)e^{m(\dot{\varepsilon}, g)}$$  \hspace{1cm} (2.1)

where, the strength coefficient $k$ and the strain rate sensitivity index $m$ are expressed as functions of the effective strain rate $\dot{\varepsilon}$ and the grain size $g$. The NIKE3D Material Model # 19, Strain Rate Sensitive Power Law Plasticity, given by Equation 2.2 is very applicable to the superplastic forming process.
The effective plastic strain is given by 
\[ \varepsilon_p = k \varepsilon^m (\varepsilon_o + \varepsilon)^n \]  

(2.2)

The effective plastic strain is given by \( \varepsilon_p \), \( k \) is the strength coefficient, \( m \) is the strain rate sensitivity index, \( n \) is the hardening exponent and \( \varepsilon_o \) is the initial yield strain. In the absence of strain hardening \( n \) can be set to some small value, i.e. 0.0001. In NIKE3D’s Material Model #19, \( k \) and \( m \) can be specified in tabular format as functions of the effective plastic strain and certainly this procedure is one approach. Alternatively, the source code can be modified to specify \( k \) and \( m \) as functions of the effective strain rate and grain size. This approach is the one that we have used and it allows Equation 2.2 to represent a wide range of superplastic constitutive data (stress vs. strain rate).

**CONSTITUTIVE DATA**

Reference [6] has proposed the following state variable model to accurately represent the material behavior of superplastic Ti-6Al-4V.

\[
\sigma = A_o \left( \frac{L_{\text{eff}}}{L_o} \right)^{P_o} \left[ \sinh^{-1} \left( \frac{\dot{\varepsilon}}{A_\dot{\varepsilon} \left( \frac{L_{\text{eff}}}{L_o} \right)^{P_o}} \right) \right]^{-1} \exp \left( \frac{Q}{RT} \right) \]  

(3.0)

Here \( \sigma \) is the stress, \( L_{\text{eff}} \) is the effective grain size, \( T \) is the temperature and \( \dot{\varepsilon} \) is the strain rate. The other terms used in Equation 3.0 are given in Table 1.0.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( A_\dot{\varepsilon} )</th>
<th>( P_o )</th>
<th>( Q/R )</th>
<th>( A_o )</th>
<th>( p_o )</th>
<th>( L_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>0.251 s(^{-1})</td>
<td>-2.73</td>
<td>19,250 K</td>
<td>9.41e-6</td>
<td>-0.643</td>
<td>1 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>

Reference [6] has also proposed the following model to represent the static and deformation enhanced grain growth rates.

\[ \dot{L}_{\text{total}} = \dot{L}_{\text{static}} (T, L) + \dot{L}_{\text{def}} (T, L, \dot{\varepsilon}) \]  

(3.1)

Where,

\[ \dot{L}_{\text{static}} = \frac{L_o}{q} B \exp \left( -\frac{Q_o}{RT} \right) \left( \frac{L}{L_o} \right)^{1-q} \]  

(3.2)

\[ \dot{L}_{\text{def}} = L_{\text{ref}} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_d} \right)^p \exp \left( -\frac{Q_d}{RT} \right) \left( 1 - \frac{L}{L_o} \right) \]  

(3.3)

The parameters used in Equations 3.2 and 3.3 are given in Tables 2.0 and 3.0 respectively.
TABLE 2.0
Static Grain Growth

<table>
<thead>
<tr>
<th>$B$</th>
<th>$L'$</th>
<th>$q$</th>
<th>$Q_s/R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.67x10^7 s$^{-1}$</td>
<td>1 $\mu$m</td>
<td>3.78</td>
<td>23,800 K</td>
</tr>
</tbody>
</table>

TABLE 3.0
Deformation Enhanced Grain Growth

<table>
<thead>
<tr>
<th>$\dot{p}_{ref}$</th>
<th>$\dot{\varepsilon}_d$</th>
<th>$p$</th>
<th>$Q_d/R$</th>
<th>$L'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.71x10^9 $\mu$m/s</td>
<td>1 $s^{-1}$</td>
<td>0.7</td>
<td>28,000 K</td>
<td>22 $\mu$m</td>
</tr>
</tbody>
</table>

PRESSURE PREDICTION/CORRECTION

NIKE3D is a finite element code that simulates the SPF process by calculating a series of equilibrium states in time driven by a load history. The pressure must be controlled during the superplastic forming process simulation to assure the part is quickly formed without exceeding the target or optimal effective strain rate. The strain rate ratio $R$ given by Equation 4.0 is commonly used describe the maximum effective strain rate with respect to the target or optimal maximum strain rate.

$$R = \frac{\dot{\varepsilon}_{target}}{\dot{\varepsilon}_{maximum}}$$

When $R$ is less than 1.0 the pressure must be decreased and if $R$ is greater than 1.0 the pressure must be increased. During the numerical simulation, the pressure can be adjusted using a pressure multiplier $p_{mult}$.

$$p_{new} = p_{old} \cdot p_{mult}$$ (4.1)

Here, $p_{new}$ is the new pressure prediction at the start of a new calculational step, $p_{old}$ is the pressure form the previous step. The pressure multiplier is determined as a function of the strain rate ratio $R$. At the start of the numerical simulation the pressure is chosen to be very small, i.e., 0.0001. During the first several steps the pressure can be aggressively increased until $R$ approaches 1.0 using Equation 4.2.

$$p_{new} = p_{old} R^n$$ (4.2)

The parameter $n$ can be chosen to be equal to the strain rate sensitivity index $m$ or some other value depending on the desired aggressiveness of the pressure control. After the first several steps when $R$ is about equal to 1.0, $n$ should be decreased to avoid large increases in the pressure multiplier. If the pressure predicted by Equation 4.1 is too high and the strain rate ratio $R$ is less than 1.0 for one or more iterations occurring during a step, the pressure can be cut back using Equation 4.2.

$$p_{new} = p_{old} + \frac{(p_{new} - p_{old})}{w}$$ (4.2)
The cut back parameter $w$ is chosen to be greater than 1.0, i.e., 1.2. The pressure multiplier scheme provides a simplistic way of controlling the pressure without generating a substantial amount of computational overhead during the solution. References [7] and [8] discuss other algorithms used to control the pressure during the numerical simulation of the superplastic forming process.

**NIKE3D**

NIKE3D is a three dimensional, fully implicit, nonlinear finite element code for analyzing the static and dynamic response of inelastic solids, shells and beams. It is best applied to static or low rate dynamic problems in structural mechanics. NIKE3D has been chosen for the analysis of superplastic forming because of its robust contact algorithms and rate sensitive plasticity material model. The Hughes/Liu shell element is also available which includes thickness changes resulting from large membrane strains.

**Implementing Variable Properties into NIKE3D**

We have implemented the variable properties into NIKE3D in the following manner. At the beginning of each step, using Equation 3.0, stress vs. strain rate data is generated for a specified grain size and temperature. The incremental grain growth is determined using the time step size and the total grain growth rate, which is computed using Equations 3.2 and 3.3. Note that the deformation enhanced grain growth rate is determined using Equation 3.3 where $\dot{\varepsilon}$ is the maximum effective strain rate from the last completed step. Using the stress vs. strain rate data, the strain rate sensitivity index $m$ is determined as function of the strain rate by evaluating the slope of the curve at the local effective strain rate. The strength coefficient is determined as a function of effective strain rate using the local values of effective strain rate, stress, $m$ and solving for $k$ using Equation 1.0. These calculations ensure that Equation 2.2, NIKE3D's Material Model # 19 accurately reflects the constitutive behavior of Ti-6Al-4V while accounting for grain growth effects. Although the method we use here is approximate, it appears to give good results.

**COMPARISONS WITH SPF SIMULATIONS IN THE LITERATURE**

Several superplastic forming simulations appear in the literature and we have used them to qualitatively (and quantitatively where enough information is given) compare our algorithms to their results[9,10]. The following superplastic forming problems were taken from the literature and were reanalyzed using NIKE3D. The calculations were carried out using a SiliconGraphics Indigo 2 Extreme work station with an 200MHz R4400 processor.

**Truncated Cone**

This problem is presented in the literature by Reference [9] where it is modeled using a non-newtonian viscous constitutive law and membrane elements. Coulomb sticking friction was assumed but no friction coefficients were given. Reference [9] included the effects of grain growth using a different model than the one presented in this paper.

The truncated cone composed of Ti-6Al-4V with top and base diameters of 60 mm and 120 mm respectively and a height of 55mm. The initial sheet thickness is 1mm. The target strain rate is $0.00035 \text{s}^{-1}$. We have included the effects of grain growth using the
state variable model previously discussed, with an initial grain size of 8 \( \mu m \). In our model the effects of friction were included in this analysis with static and kinetic friction coefficients of 0.7 and 0.6 respectively. Only one quarter of the problem is actually modeled with symmetry boundary conditions imposed on the interior edges. The deforming sheet was modeled with 1093 elements. The final deformed shape of the truncated cone is shown in Figure 1.

![Figure 1, The Final Deformed Shape of the Truncated Cone](image)

**Pressure History, Truncated Cone**

![Pressure History, Truncated Cone](image)

Figure 2, Forming Pressure vs. Time for the Truncated Cone of Figure 6.1.0, Compared with Reference [9] Predictions
Figure 3, The Material Thickness Distribution Compared with Reference [9] Predictions

The pressure history is shown in Figure 2. The thickness distribution is shown in Figure 3. The pressure history and thickness distribution are in good agreement with Reference [9].

The Rectangular Box

This problem is presented in the literature by Reference [10] where it is modeled using several different finite element codes and element types. Sticking friction was assumed but no friction coefficients were given.

The box is composed of Al-Li 8090 and has dimensions of 120mm x 60mm x 20mm. The initial sheet thickness is 2mm. The target strain rate is 0.001 s⁻¹. The strength coefficient \( k \) and the strain rate sensitivity index \( m \) are assumed constant with values of 169.64 MPa and 0.478 respectively. In our model the effects of coulomb friction were included with static and kinetic friction coefficients of 0.5 and 0.4 respectively. Only one quarter of the problem is actually modeled with symmetry boundary conditions imposed on the interior edges. The final deformed shape of the rectangular box is shown in Figure 4. The pressure history is shown in Figure 5. The pressure history in Figure 5 is in good agreement with that presented by Reference [10] for the MARC-3D analysis using cubic continuum elements. The thickness distribution is shown in Figure 6. Figure 7 shows the strain rate history compared with the target strain rate. As can be seen in this figure, our pressure control algorithm is very effective in maintaining the maximum effective strain rate at or near the superplastic forming target strain rate. We believe that the most uniform thickness distribution will be achieved with this approach and there is some evidence to support this claim exhibited in Figure 6, where the box is thicker than measured near the corner, despite being modeled with a sharp transition there.
In the model used by Reference [10] there is a 6° draft angle on the side walls of the die. However, in our model there is no draft angle. Reference [10] illustrated that five different models of this problem would give five different pressurization rates, but that the thickness distributions from all models were within acceptable agreement with measured values.

![Pressure History, Rectangular Box](image)

**Figure 4, The Final Deformed Half Symmetry Shape of the Rectangular Box**

**Figure 5, Forming Pressure vs. Time for the Rectangular Box of Figure 4, Compared with Reference [10] Predictions.**
Thickness Distribution, Rectangular Box

![Thickness Distribution Graph]

Figure 6, The Material Thickness Distribution Compared with Reference [10] Measured Values

Strain Rate, Rectangular Box

![Strain Rate Graph]

Figure 7, Strain Rate History for the Rectangular Box

Although the thrust of the work we have done in this program is for Titanium, we have used this problem for comparison because Reference [10] presents some amount of experimental data. Ultimately The Barnes Group will supply a considerable amount of experimental superplastic forming data as this program enters the next phase.
CURRENT DAY SPF CHALLENGES
The Barnes Group is currently involved in superplastically forming parts that are far more complicated than the examples illustrated in the previous section. An almost daily challenge is to determine if a complex part can be formed using SPF within specification given by the designer. Although we will not present any specific part, we will illustrate these challenges with the following example.

The Double Curvature Problem
Consider the problem of forming a Titanium sheet around an edge which has a shape similar to the three dimensional curvature shown in figure 8. As the sheet forms around the curved edge, various regions will be in tension and compression, affecting the thickness distribution in the formed part. Figure 9 shows the compressive and tensile normal stress distribution in the deforming sheet. In the tensile regions the sheet will thin substantially, depending on the curvature of the die. In the compressive regions the sheet may thicken but if the sheet thickness in the compressive regions is too thin initially, wrinkling may occur. Figure 10 shows the thickness distribution for the deforming sheet.

![Figure 8, The Double Curved Problem Die Mesh](image)

The challenge is to be able to size the initial thickness such that the thinnest section is within design specification, while preventing wrinkling in compression. Currently experience is used to estimate whether a part can be formed without wrinkling and its starting sheet thickness. We have illustrated here that we can calculate the final thickness but no wrinkling criteria has yet been implemented. As more confidence is gained in predicting the final thickness distribution, these methods can be used to supplement the experience base currently used in superplastic forming. In conclusion, we believe that NIKE3D is highly applicable to the simulation and optimization of the industrial superplastic forming process.
REFERENCES


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