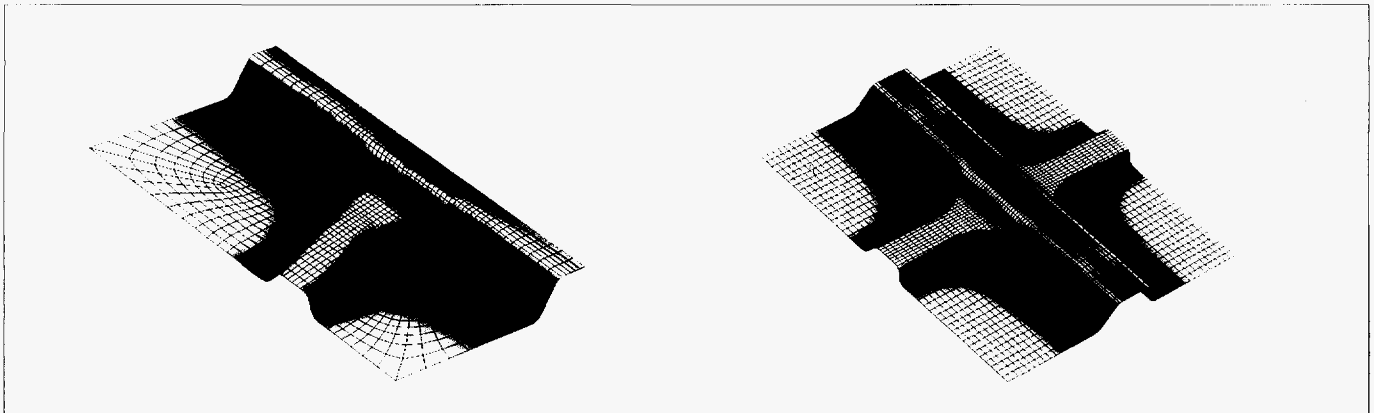
LA-13222

Numerical Simulation of Industrial Superplastic Forming

Final Report



Los Alamos

NATIONAL LABORATORY

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

DISCLAIMER

LA-13222

UC-904
Issued: November 1996

Numerical Simulation of Industrial Superplastic Forming

Final Report

Keith S. Haberman
Joel G. Bennett
Martin S. Piltch

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

Cover: Top: Numerical simulations of superplastic forming.
Bottom: Actual industrial superplastic forming.

NUMERICAL SIMULATION OF INDUSTRIAL SUPERPLASTIC FORMING

by

Keith S. Haberman, Joel G. Bennett, and Martin S. Piltch

ABSTRACT

Superplastic forming (SPF) is a metal forming process that allows a variety of components with very complex geometries to be produced at a fraction of 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 pressure schedules, overall forming time, and the final thickness distribution. This paper discusses the verification and applications of NIKE3D in optimizing the industrial superplastic forming process.

INTRODUCTION

Overview

Los Alamos National Laboratory (LANL) has a cooperative research and development agreement (CRADA) with The Barnes Group whose companies Jet Die and Flameco are making superplastically formed (SPF) parts for the aerospace industry. During the first phase of this CRADA, LANL developed and implemented a pressure control algorithm and a state variable model for Ti-6Al-4V into NIKE3D [1]. The code modifications were initially compared with superplastic forming (SPF) simulations found in the literature. In the second phase of the CRADA, the code was applied to several challenging SPF problems. The final phase of the CRADA addressed concerns associated with using net shape processing.

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),

$$\sigma = k\dot{\varepsilon}^{m} , \tag{1}$$

where σ 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 judgement 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 as a result of 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. Thickness distribution predictions are often based on experience, with the final part development done by trial and error.

CONSTITUTIVE MODEL

Superplasticity is a strain rate and temperature dependent phenomenon that is also influenced by grain size [5],

$$\sigma = k(\dot{\varepsilon}, g, T)\dot{\varepsilon}^{m(\dot{\varepsilon}, g, T)} . \tag{2}$$

Assuming isotropic behavior throughout the material at the superplastic state, the effective stress is given by σ, $\dot{\varepsilon}$ 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 (3) is often employed to describe the constitutive behavior of superplastic alloys on a macroscopic continuum scale, i.e.,

$$\sigma = k(\dot{\varepsilon}, g, T)\dot{\varepsilon}^{m(\dot{\varepsilon}, g, T)}, \tag{3}$$

where the strength coefficient k and the strain rate sensitivity index m are expressed as functions of the effective strain rate $\dot{\varepsilon}$, grain size g, and the temperature T. The NIKE3D Material Model #19, *Strain Rate Sensitive Power Law Plasticity*, given by Equation (4) is very applicable to the superplastic forming process,

$$\sigma = k\dot{\varepsilon}^{m}(\varepsilon_o + \varepsilon^p)^n . \tag{4}$$

The effective plastic strain is given by ε^p, k is the strength coefficient, m is the strain rate sensitivity index, n is the hardening exponent, and ε_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. 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 grain size and temperature. This approach is the one that we have used, and it allows Equation (4) to represent a wide range of superplastic constitutive data (stress versus strain rate).

CONSTITUTIVE DATA

Mosher and Dawson [6] have proposed the following state variable model to accurately represent the material behavior of superplastic Ti-6Al-4V,

$$\sigma = A_{\sigma}\left(\frac{L^{eff}}{L_o}\right)^{p_{\sigma}}\left[\sinh^{-1}\left(\frac{\dot{\varepsilon}}{A_{\dot{\varepsilon}}\left(\frac{L^{eff}}{L_o}\right)^{p_{\dot{\varepsilon}}}}\right)\right]^{\frac{1}{n}}\exp\left(\frac{\overline{Q}}{RT}\right). \tag{5}$$

Here σ is the stress, L^{eff} is the effective grain size, T is the temperature, and $\dot{\varepsilon}$ is the strain rate. The other terms used in Equation (5) are given in Table 1.

TABLE 1

STATE VARIABLE PARAMETERS, TI-6AL-4V

n	$A_{\dot{\varepsilon}}$	$p_{\dot{\varepsilon}}$	$\overline{Q}/R$	A_{σ}	p_{σ}	L_o
1.55	0.251 s^{-1}	-2.73	19,250 K	9.41e-6	-0.643	1 μm

Mosher and Dawson [6] have also proposed the following model to represent the static and deformation enhanced grain growth rates,

$$\dot{L}^{total} = \dot{L}^{static}(T, L) + \dot{L}^{def}(T, L, \dot{\varepsilon}), \tag{6}$$

where

$$\dot{L}^{static} = \frac{L^o}{q} B \exp\left(-\frac{Q_s}{RT}\right)\left(\frac{L}{L^o}\right)^{1-q}, \text{ and} \tag{7}$$

$$\dot{L}^{def} = \dot{L}^{ref}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_d}\right)^p \exp\left(-\frac{Q_d}{RT}\right)\left(1-\frac{L}{L^s}\right). \tag{8}$$

The parameters used in Equations (7) and (8) are given in Tables 2 and 3, respectively.

TABLE 2

STATIC GRAIN GROWTH TI-6AL-4V

B	L^o	q	Q_s/R
$3.67x10^7 s^{-1}$	$1\mu m$	3.78	23,800 K

TABLE 3

DEFORMATION ENHANCED GRAIN GROWTH TI-6AL-4V

$\dot{L}^{ref}$	$\dot{\varepsilon}_d$	p	Q_d/R	L^s
$4.71x10^9 \mu m/s$	$1s^{-1}$	0.7	28,000 K	$22\mu m$

The state variable model allows the constitutive behavior of Ti-6Al-4V to be determined as a function of strain rate, grain size, and temperature. This allows Equation (3) to be completely defined.

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 ensure that the part is quickly formed without exceeding the target or optimal effective strain rate. The strain rate ratio *R* given by Equation (9) is commonly used to describe the maximum effective strain rate with respect to the target or optimal maximum strain rate,

$$R = \frac{\dot{\varepsilon}_{target}}{\dot{\varepsilon}_{maximum}}. \tag{9}$$

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},

$$p_{new} = p_{old} p_{mult} \cdot \tag{10}$$

Here, p_{new} is the new pressure prediction at the start of a new calculational step, p_{old} is the pressure from 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 (11),

$$p_{new} = p_{old} R^n \ . \tag{11}$$

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 (10) 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 (11).

$$p_{new} = p_{old} + \frac{(p_{new} - p_{old})}{w} \ . \tag{12}$$

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 Material Properties into NIKE3D

We have implemented the variable properties into NIKE3D in the following manner. At the beginning of each step, using Equation (5), stress versus strain rate data are 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 Equation (6). Using the stress versus strain rate data, the strain rate sensitivity index m is determined as a 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). These calculations ensure that Equation (4), NIKE3D has a material model that accurately reflects the constitutive behavior of Ti-6Al-4V while accounting for grain growth effects and temperature variations during the forming process simulation.

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 Power Challenge.

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 is composed of Ti-6Al-4V with top and base diameters of 60 mm and 120 mm, respectively, and a height of 55 mm. The initial sheet thickness is 1 mm. The target strain rate is 0.00035 s^{-1}. We have included the effects of grain growth using the state variable model previously discussed, with an initial grain size of 8 μm. 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.

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.

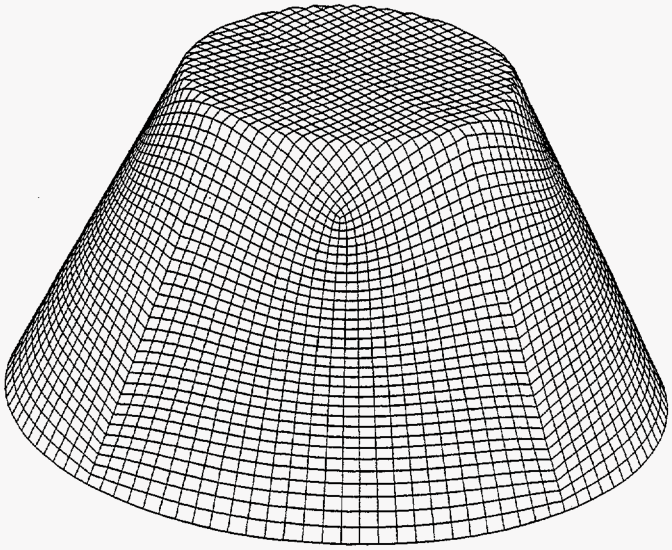


Figure 1. The final deformed shape of the truncated cone.

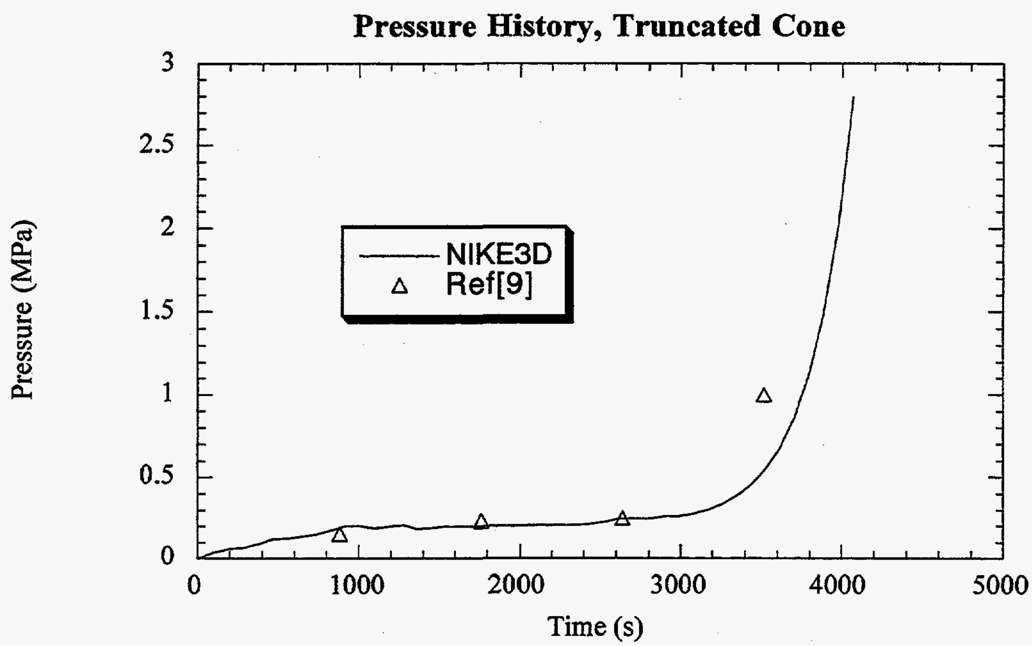


Figure 2. Forming Pressure versus time for the truncated cone of Figure 1, compared with Reference 9 predictions.

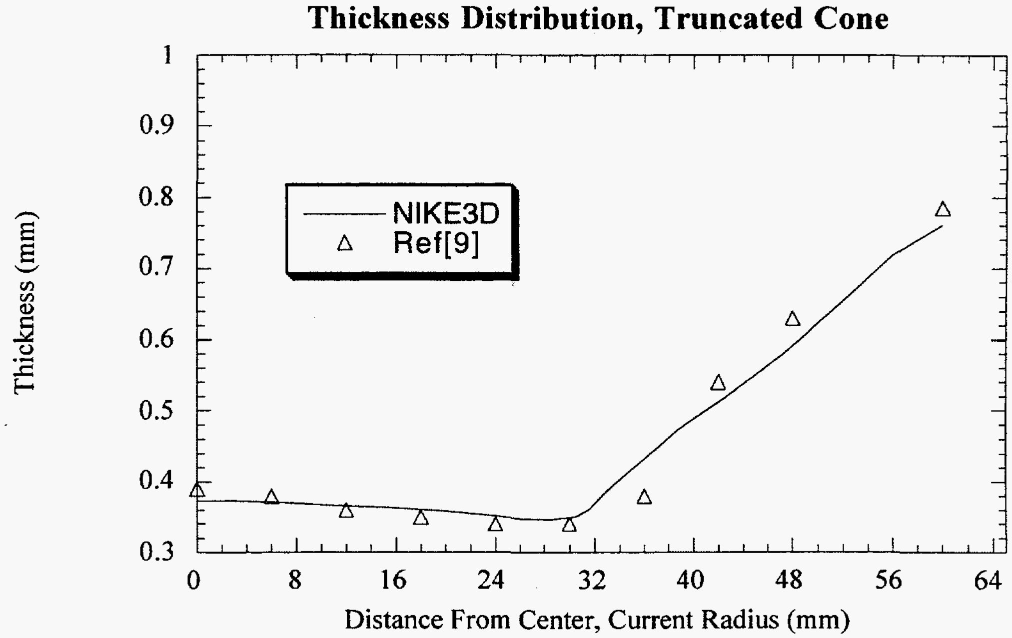


Figure 3. The material thickness distribution compared with Reference 9 predictions.

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 120 mm × 60 mm × 20 mm. The initial sheet thickness is 2 mm. 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 as exhibited in Figure 6, where the box is thicker than measured near the corner, despite being modeled with a sharp transition there.

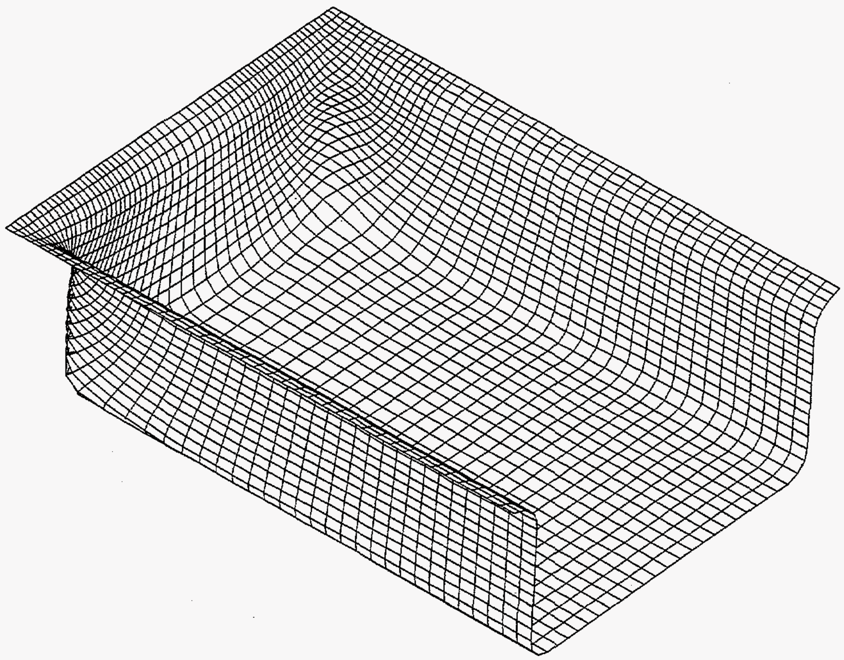


Figure 4. The final deformed half symmetry shape of the rectangular box.

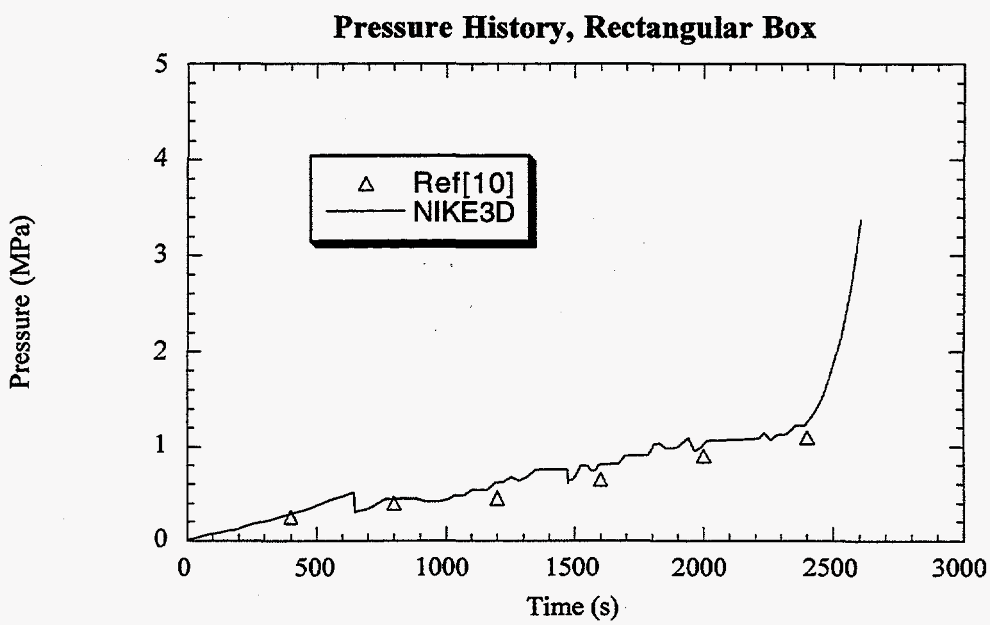


Figure 5. Forming pressure versus time for the rectangular box of Figure 4, compared with Reference 10 predictions.

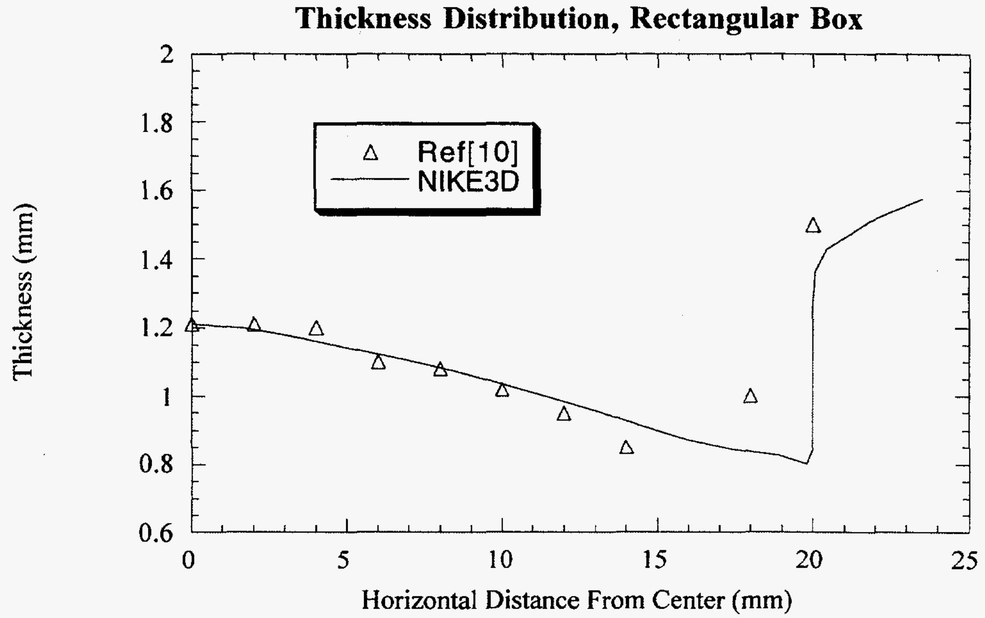


Figure 6. The material thickness distribution compared with Reference 10 measured values.

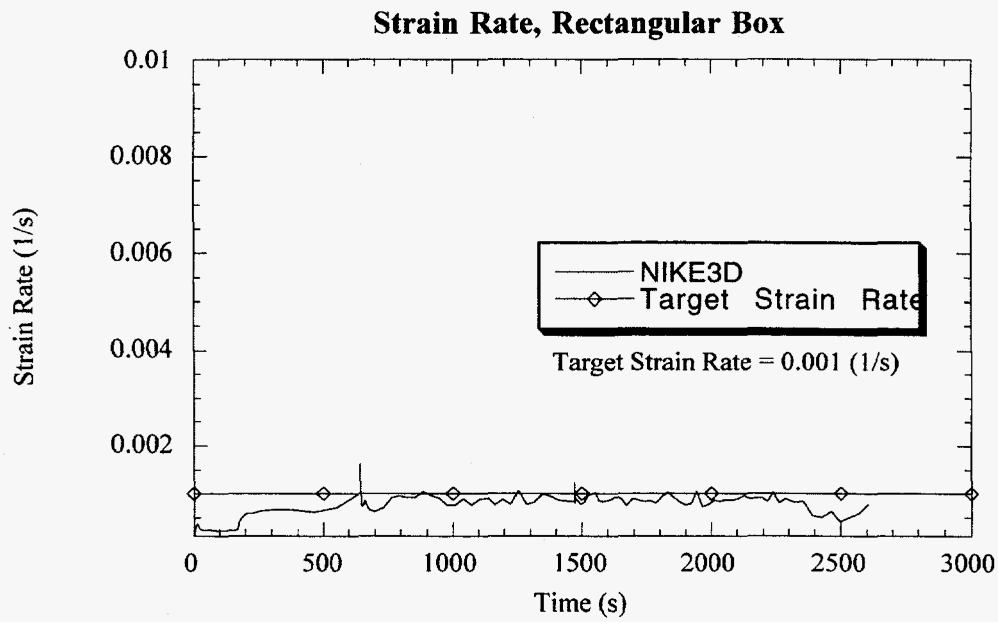


Figure 7. Strain rate history for the rectangular box.

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.

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.

SUPERPLASTIC FORMING PREDICTIONS

Bracket

Figure 8 shows a Ti-6Al-4V sheet being superplastically formed over a die to produce the bracket shown in Figure 10. In order to minimize production costs associated with trial-and-error process development, the superplastic forming process for this part was first simulated using NIKE3D. The predicted pressure schedule given in Figure 9 was used in the actual forming. The total forming time was predicted to be about 8000 s, which agreed with the actual forming.

Critical regions A through F shown in Figure 8 represent locations where the thickness must not fall below a minimum value in order for the final part to be within specifications. It is essential to determine the final thickness distributions before the actual forming begins in order to minimize production costs.

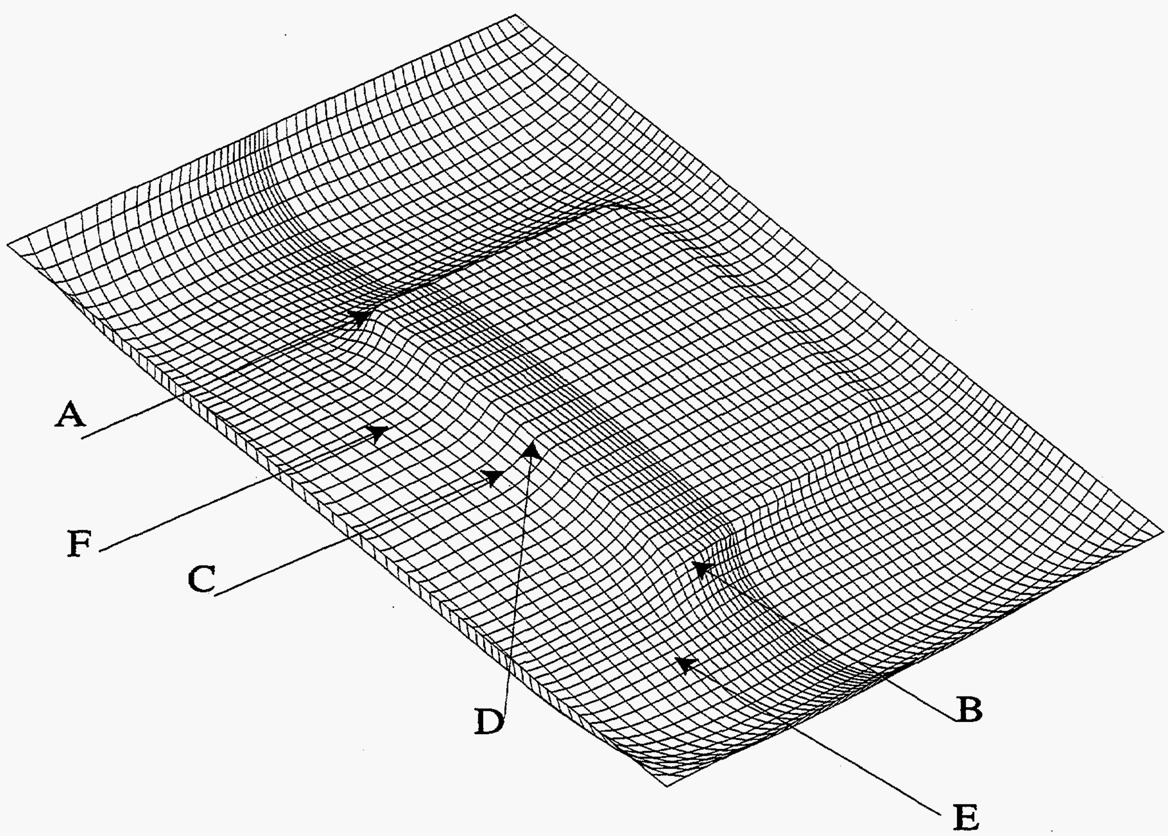


Figure 8. Bracket form.

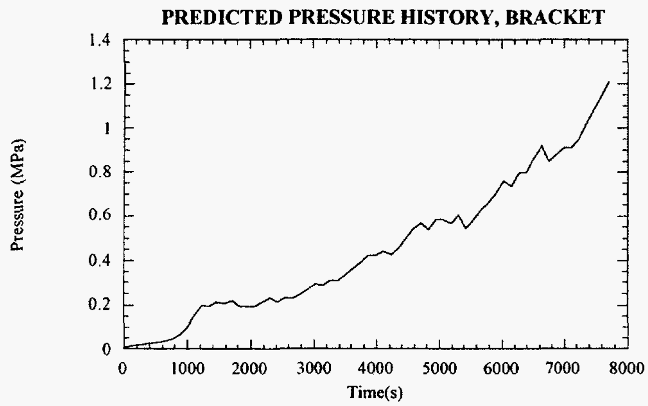


Figure 9. Predicted pressure history.

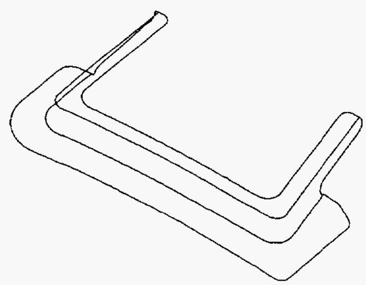


Figure 10. Bracket (final part).

A comparison of the predicted and measured thickness in critical regions A through F are given in Table 4.

TABLE 4

PREDICTED AND MEASURED THICKNESS DISTRIBUTION

Critical Region	Predicted Thickness (in.)	Measured Thickness (in.)
A	0.0476	0.0480
B	0.0474	0.0480
C	0.0537	0.0597
D	0.0597	0.060
E	0.0574	0.065
F	0.0594	0.064

Predicted and measured thickness given in Table 4 are in close agreement. The predicted results differ from the measured on average by a few thousandths of an inch, with the predicted results being conservative or "thinner" in this case. The differences result primarily from not knowing the exact values of the static and kinetic coefficients of friction, which dictates whether material will stick to the die or thin from sliding and deforming along the die surface.

The information presented in Table 4 demonstrates that this analysis procedure can be used in other cases where experienced-based engineering does not provide clear answers on what the pressure schedule, overall forming time, and final thickness distribution are going to be for a given superplastic forming process.

Waffle Structure

Consider the problem of determining how changes in the geometry of a die will affect the final thickness distribution, pressure schedule, and actual forming time. For this example we will consider the superplastic forming of two waffle structures shown in Figures 11 and 12. These two geometries are similar but have noticeable differences.

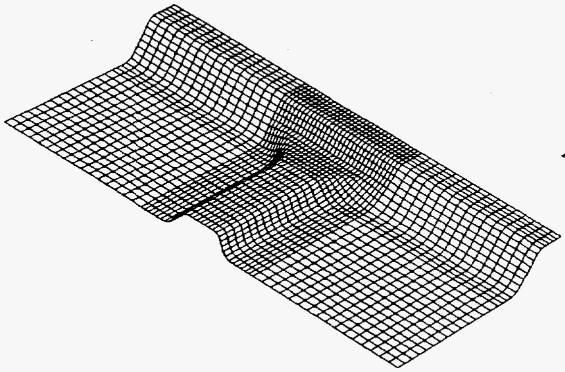


Figure 11. Waffle structure A.

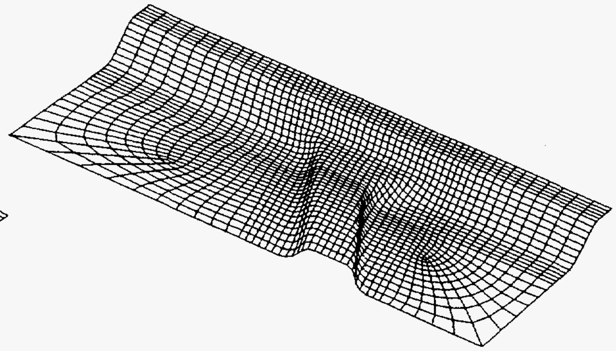


Figure 12. Waffle structure B.

The pressure schedules for the Waffle Structure A and Waffle Structure B are given in Figure 13. It is seen that Waffle Structure B is 500 seconds behind Waffle Structure A in ramping up the maximum allowable forming pressure of 1.37 MPa. Waffle Structure A is completely formed in 3310 seconds, while Waffle Structure B is completely formed in 2900 seconds. The thickness distributions for Waffle Structure A and B are given in Figures 14 and 15, respectively.

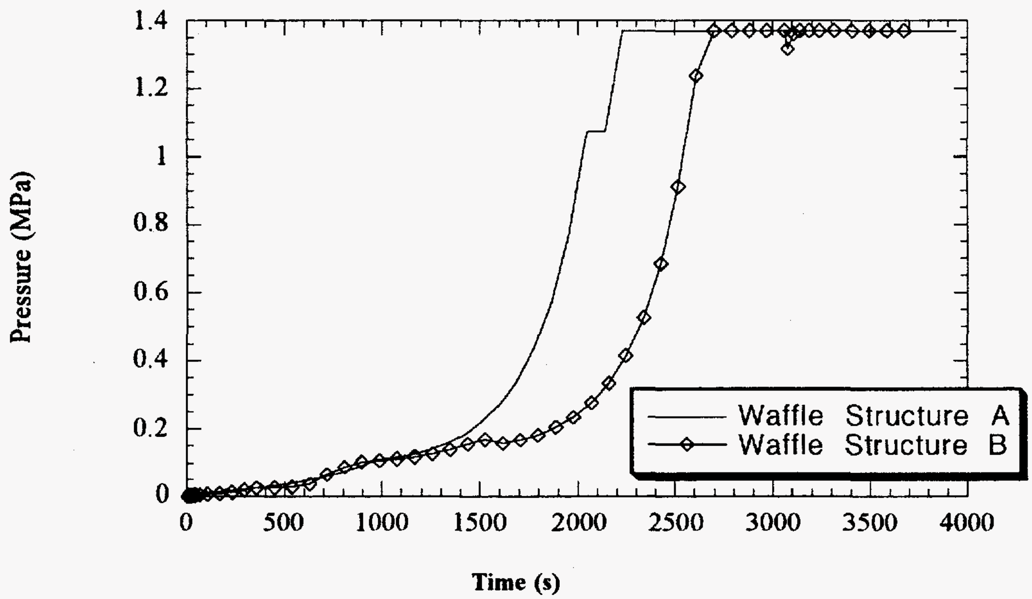


Figure 13. Predicted pressure schedule.

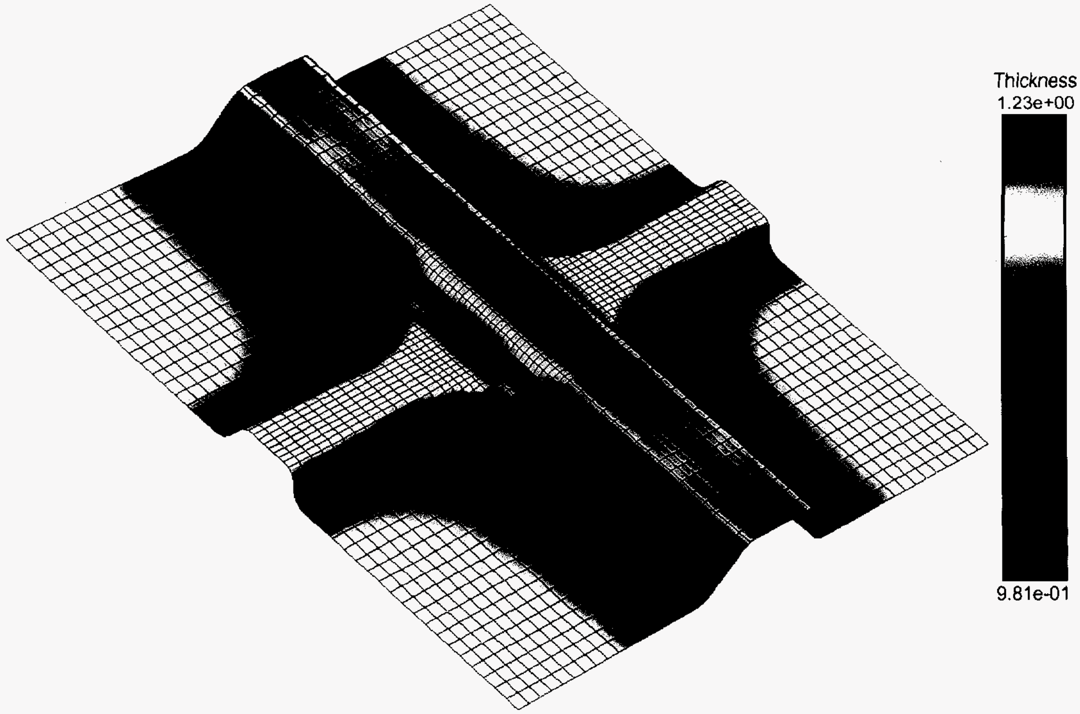


Figure 14. Final thickness distrubution, waffle structure A.

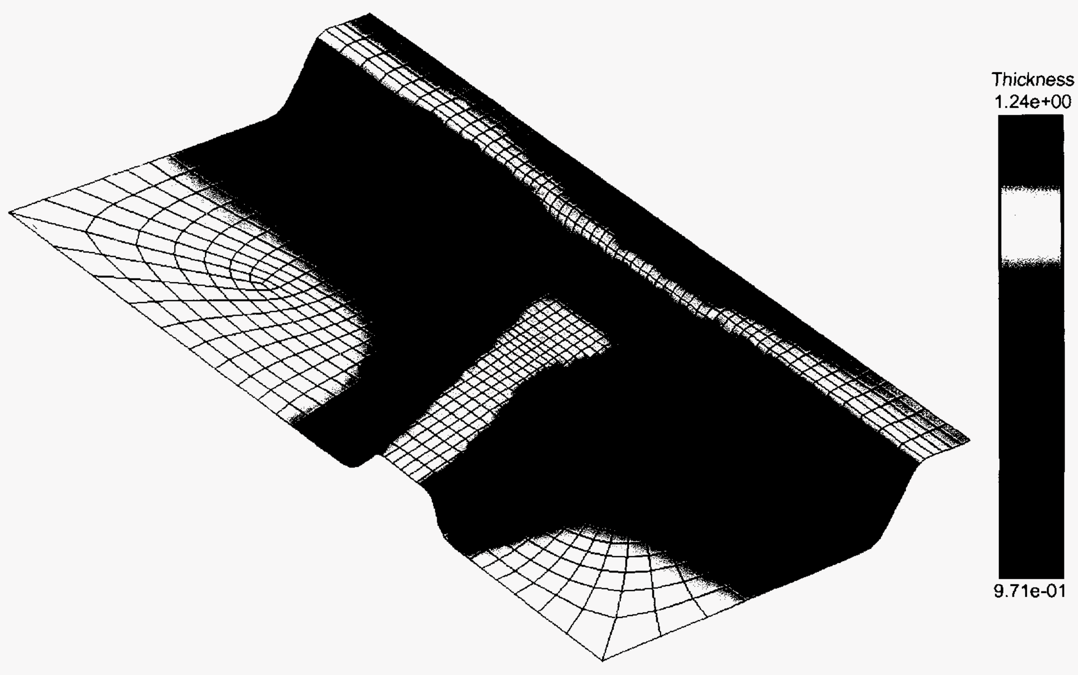


Figure 15. Final thickness distribution, waffle structure B.

NET SHAPE SUPERPLASTIC FORMING

The superplastic forming process produces parts with nonuniform thickness distributions. This can be easily seen in Figures 14 and 15. Prescibing the correct nonuniform initial sheet thickness will result in a uniform final thickness distribution. Determining the initial sheet thickness for a complex three-dimensional forming problem where the material properties are functions of the strain rate, grain size, temperature, and friction between the deforming sheet and the die surface is an iterative process.

Thickness Modification Scheme (Brute Force Method)

Consider the classical SPF problem of forming a hemisphere. Starting the forming with an initial sheet thickness of 3 mm will result in a nonuniform thickness distribution shown in Figure 16. Assume some ideal uniform final thickness distrubution t_{ideal}. Let the thickness difference t_{diff} be the difference between the ideal thickness and the final thickness t_{final}. The new thickness distribution for the next run is,

$$t^{i+1} = t^{i} + t_{diff} \,. \tag{13}$$

After several runs, the modified thickness distribution will be thicker in regions that thin during the forming process. In this case, the hemisphere geometry required 8 runs to achieve an initial thickness distribution given in Figure 17 that would yield the near net shape form given in Figure 18.

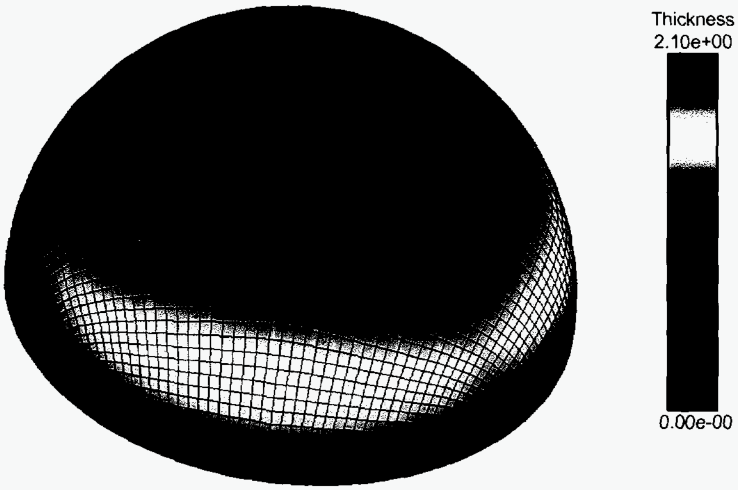


Figure 16. Hemisphere with nonuniform final thickness distribution.

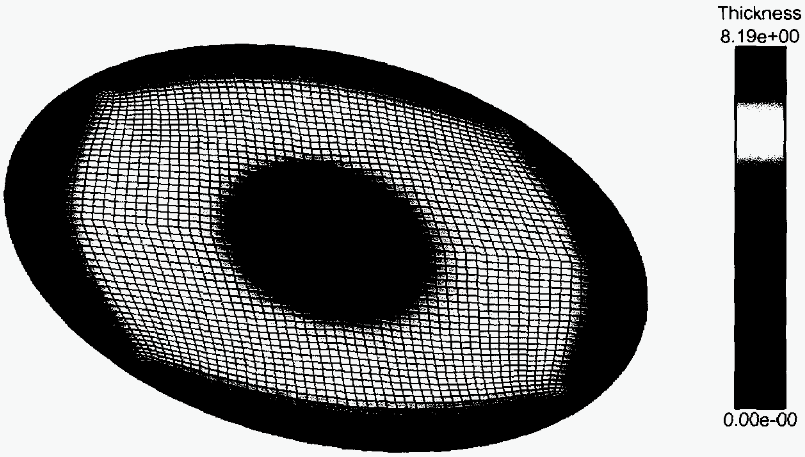


Figure 17. initial sheet thickness.

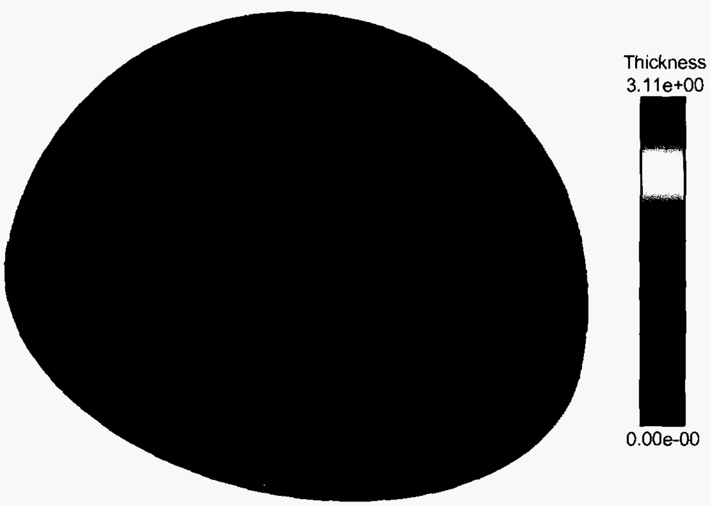


Figure 18. Near net shape final form.

REFERENCES

1. Maker, B. N., Ferencz, R. M., and Halquist, J. O. *NIKE3D(A Nonlinear, Implicit, Three Dimensional Finite Element Code for Solid and Structural Mechanics) User's Manual*, University of California, Lawrence Livermore National Laboratory report UCRL-MA-105268, January, 1991.

2. Pilling, J., and Ridley, *N., Superplasticity in Crystalline Solids,* (The Institute of Metals, Pittsburgh, 1989).

3. Sherby, O.D., and Wadsworth, J., "Superplasticity – Recent Advances and FutureDirections," *Progress in Material Science*, Volume 33, pp. 169–221, 1989.

4. Leodolter, W., The Barnes Group, Flame Co., private communication, 1994.

5. Ghosh, A. K., and Hamilton, C. H., "Mechanical Behavior and Hardening Characteristics of a Superplastic Ti-6Al-4V Alloy," *Metallurgical Transactions A*, Volume 10A, pp. 699–706, 1979.

6. Mosher, D. A., and Dawson, P. R., "A State Variable Material Model for Superplastic Titanium-6Al-4V," *Titanium '92 Science and Technology*, Volume II pp. 1907–1914, 1992.

7. Bonet, J., Wargadipura, H. S., and Wood, R. D., "A Pressure Cycle Control Algorithm for Superplastic Forming," *Communications in Applied Numerical Methods*, Volume 5, pp. 121–128, 1989.

8. Rama, S. C., and Chandra, N. "Development of a Pressure Prediction Method for Superplastic Forming Processes," *International Journal of Nonlinear Mechanics*, Volume 26, No. 5 pp. 711–725, 1991.

9. Bonet, J., Wood, R. D., and Zienkiewicz, O. C. "Finite Element Modeling of the Superplastic Forming of Thin Sheet," *Superplasticity and Superplastic Forming*, The Minerals, Metals & Materials Society, 1988.

10. Lee, S., and Lee, J. "Comparison of Superplastic Formability Predictions Using 2-DPlane Strain and 3-D Modeling," *Materials and Manufacturing Process*, Volume 9, No. 1, pp. 45–58, 1994.