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SIMULATION FOR ANALYSIS AND CONTROL OF SUPERPLASTIC FORMING

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Metals and Ceramics Division

FINAL REPORT

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SIMULATION FOR ANALYSIS AND CONTROL OF SUPERPLASTIC FORMING*

T. Zacharia, G. A. Aramayo, S. Šimunović, and G. M. Ludtka,*
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SUMMARY

A joint study was conducted by Oak Ridge National Laboratory (ORNL) and the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy-Lightweight Materials (DOE-LWM) Program. The purpose of the study was to assess and benchmark the current modeling capabilities with respect to accuracy of predictions and simulation time. Two simulation platforms were considered in this study, which included the LS-DYNA3D code installed on ORNL's high-performance computers and the finite element code MARC used at PNL. Both ORNL and PNL performed superplastic forming (SPF) analysis on a standard butter-tray geometry, which was defined by PNL, to better understand the capabilities of the respective models. The specific geometry was selected and formed at PNL, and the experimental results, such as forming time and thickness at specific locations, were provided for comparisons with numerical predictions. Furthermore, comparisons between the ORNL simulation results, using elasto-plastic analysis, and PNL's results, using rigid-plastic flow analysis, were performed.

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INTRODUCTION

Some alloys, produced under special conditions and deformed at a carefully controlled *low strain* rate and high temperature, exhibit extreme ductility, called superplasticity. Superplasticity of metals and alloys is characterized by extreme deformation at high homologous temperatures under the action of small stresses. In uniaxial tension, essentially neck-free elongations in excess of 200% are indicative of superplasticity, although several materials can elongate greater than 1000%. The phenomena of superplasticity can be broadly classified into (1) environmental superplasticity (arising from special environmental conditions) and (2) structural superplasticity (arising from specific microstructural conditions). Although a large number of alloys have been reported as superplastic, only a few are commercially viable. Aluminum alloys are the most widely used superplastic alloys. Only two of these are extensively used in structural applications, e.g., the Supral alloys (Supral 100, 150, and 220) and Al 7475.

Superplasticity allows components typically produced by joining many pieces together into an assembly to be redesigned into a single component, lowering manufacturing cost. Superplastic forming is accomplished by using gas pressure to blow hot sheet into a die cavity or over a preformed shape, in a process very similar to vacuum forming or blow molding of polymer sheet. Superplastic forming is a technology that offers manufacturers advantages in material utilization and cost savings by producing near-net-shaped parts with design features that require rough machining and little or no pre-assembly. Facilities at Oak Ridge include both laboratory and production superplastic forming facilities of conventional and reverse blow-forming processes with an advanced computer-controlled forming gas system for maintaining constant strain rate and precise zone temperature control. Superplastic forming of nuclear weapons components significantly reduces the material requirements and the hazardous materials waste stream, thereby meeting the primary waste minimization goal. To meet this waste minimization goal, computer modeling of the forming equipment and the forming process was used from the inception of the program.

Recently, significant interest is focused on Al 5083 alloy and, to some extent, magnesium alloys for automotive applications. The goal of three times the fuel economy as outlined in the Partnership for a New Generation Vehicle (PNGV) Program will require considerable reduction in the weight of current automobiles. Reducing the weight of the vehicle to improve fuel economy can be accomplished by developing alternative materials and processes. One potential technology is superplastic forming since it is estimated that the number of components, say for example, that will go into the making of a car door, can be significantly reduced by about 90% with a feasible weight reduction of 50%. Superplastic forming can also provide savings as high as 48% above the cost of conventional forming techniques, and the attainment of near-net-shape configurations leading to reduced amounts of scrap. Material behavior, thinning and formed part geometry, and material/tool interactions remain important SPF development needs. An accurate modeling of the deformation process in the superplastic regime can lead to a better exploitation of these advantages. The ability to numerically predict forming behavior is critical to increasing forming rates and decreasing manufacturing cycle times.

With this in mind, the DOE-LWM program initiated a joint, collaborative research effort at Oak Ridge National Laboratory (ORNL) and Pacific Northwest Laboratory (PNL) to assess and benchmark the current modeling capabilities with respect to accuracy of predictions and simulation time. Two simulation platforms were considered in this study, which included the LS-DYNA3D code installed on ORNL's high-performance computers and the finite element code MARC used at PNL. Both ORNL and PNL performed SPF analysis on a standard butter-tray geometry to better understand the capabilities of the respective material models and analysis tools. The specific geometry was selected and formed at PNL and the experimental results were provided for comparisons with numerical predictions at ORNL and PNL. Furthermore, comparisons between the ORNL simulation results, using elasto-plastic analysis, and PNL's results, using rigid-plastic flow analysis, were performed.

BACKGROUND

A phenomenological basis for superplastic flow was provided by Backofen et al.[1] in terms of the now well-known relationship:

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

which relates the flow stress to the strain rate under isothermal and constant grain size conditions. The strain rate sensitivity index, "m" and "K" (strength coefficient), are material constants dependent on environmental conditions like temperature and grain size.

The variation of $\ln(\sigma)$ with $\ln(\dot{e})$ is found to be sigmoidal as shown in Fig. 1. The strain rate sensitivity index "m" is defined as the partial derivative of the log of true stress with respect to the log of true strain rate, or simply, the slope of the curve shown in Fig. 1. At high "m" values, the necks present are diffuse, and the extreme elongation is the result of the very high resistance to neck growth. Therefore, regions I and III where "m" is low are not associated with optimum superplasticity. In region IIb, "m" decreases with increasing strain rate. This region is regarded as the range in which superplasticity is gradually lost due to competition from less rate-sensitive processes. In region IIa, optimum superplastic deformation is obtained. Under these conditions the flow stress is very small, and the material exhibits negligible work hardening. The strain sensitivity index "m" is found to increase with decreasing grain size.

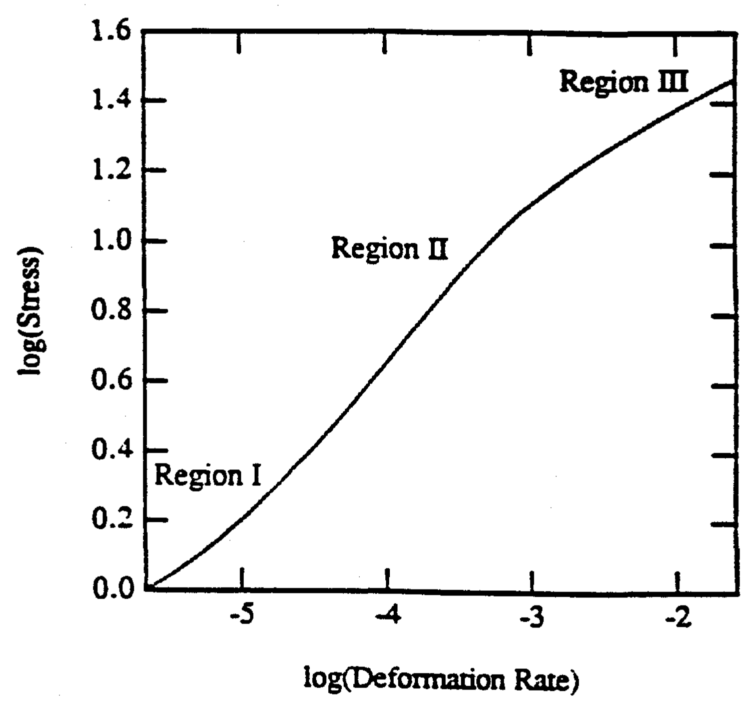

Figure 1. Three regions of typical superplastic behavior.

The stress at a given strain rate and temperature decreases with grain size. The dependence of stress on grain size can be described by the relation:

$$\sigma|_{\dot{\varepsilon},T} \propto L^{a}, \tag{2}$$

where "L" is the grain size and "a" is a constant in the range of 0.5 to 3.0. Under optimum superplastic condition, the relation:

$$\epsilon|_{\sigma,T} \propto \frac{1}{L^{b}} \tag{3}$$

with "b" having values from 1 to 5 is applicable.

The temperature dependence of both stress and strain rate in the optimum superplastic region appears to be exponential as given by:

$$\sigma_{t}|_{\dot{\varepsilon},T} \propto \exp(Q_{\dot{\varepsilon}}/kT) \tag{4}$$

and

$$\dot{\varepsilon}_{t}|_{\sigma,T} \propto \exp(Q_{\sigma}/kT), \tag{5}$$

where "Q" is an apparent activation energy (coefficient) (since "m" is dependent on temperature), where "K" is the Boltzmann constant, and "T" is the absolute temperature.

CONSTITUTIVE RELATIONS

ORNL STRAIN-RATE-SENSITIVE POWER-LAW PLASTICITY MODEL

The material model used in the ORNL analysis describes the yield stress by the following relationship:

$$\sigma_{y} = K\epsilon^{n}\,\dot{\varepsilon}^{m}, \tag{6}$$

where "m" (strain rate sensitivity coefficient) for this Al 5083 alloy has the value of 0.467, and "K" and "n" are functions of plastic strain and have values specified in the following table.

Table 1. Material properties for aluminum 5083

Strain Range	n	K
0.00 - 0.02	0.6781	546,100
0.02 - 0.04	0.4195	198,600
0.04 - 0.09	0.1917	95,410
0.09 - 0.70	0.000	60,130
0.70 - 1.70	-0.2515	54,970

INTERNAL STATE VARIABLE MODEL:

The material model in Eq. (6) does not account for the evolution of the microstructure of the material as the deformation proceeds. It is known, for example, that the strain rate sensitivity index, "m", is not constant during the deformation and that its change as the internal microstructure evolves must be accounted for.

An internal state variables (ISV) constitutive model has been developed by ORNL to take into consideration the evolution of the internal microstructure of the superplastic material. Generally, numerous mechanisms and their respective evaluations govern the deformation during processing. It is not possible to separately account for each such mechanism as this will lead to a cumbersome model, and all mechanisms that exist may not be known. The ISV class of constitutive models is attractive for deformation processing applications in that the integrated effect of all operating mechanisms may be assumed to be represented by a small number of macroscopic internal variables.

$$\bar{\epsilon}^{p}=f\,(\tilde{\sigma},\theta,s). \qquad (7)$$

The evolution of the internal state variable, "s", is given as:

$$\dot{S}=g\,(\tilde{\sigma},s,\theta) \qquad (8)$$

Where $\bar{\epsilon}^{p}$ is the plastic strain, θ is the temperature, and σ is the effective Cauchy deviatoric stress.

Thus, as deformation proceeds, Eq. 8 may be integrated to obtain the current value of "s". This model, however, was not validated against experimental results under the current program because of limited material data. A series of stress-strain tests, at a wide range of strain rates for a range of elevated temperatures at which the material exhibits superplastic behavior, are now required to obtain realistic values for the material constants. Additional validation tests need to be performed for this model.

COOPERATIVE GRAIN BOUNDARY SLIDING (CGBS) MODEL

ORNL is currently investigating the Cooperative Grain/Interphase Boundary Sliding model and its relevance to optimal structural superplasticity. Sliding and diffusive flow are interdependent processes, and the slower of the two mechanisms would dictate the overall rate of deformation. In the Ashby-Verall[2] model, diffusion controls the rate of flow, but the CGBS model considers the grain/interphase boundary sliding as rate controlling. In this model, the atomic ensemble around the excess free volume (of the order of 0.01 Ω, where Ω is the atomic volume in the lattice) is a basic unit of flow. The constitutive model is given by the equation:

$$\dot{\epsilon} = [(C_1/\sigma_m) \{(\sigma_i-\sigma_o) (\sigma_m+\alpha(\sigma_i-\sigma_o-2\sigma_m))+(\sigma_m)^2\alpha\exp(-1/\alpha)\}]. \tag{9}$$

Where C_1, m, and ∝ are material properties and σ relates to the state of stress of the material.

The isostructural strain rate-stress relationship (constitutive model) was calculated very accurately using five experimentally determined constants, which are given below in Table 2 for Al-12Si alloy. Work was also performed for Al-33Cu and Al-33Cu-0.4Zr alloys. As would be expected, these constants were found to be sensitive to the grain size.

Table 2. Material parameters for Al-12Si

T (K)	σ_i (MPa)	σ_m (MPa)	σ_o (MPa)	C_1(1/Pas)
831	0.1	0.27	0.53	0.000140
811	0.3	0.32	0.40	0.000120
791	0.2	0.43	0.68	0.000090
763	0.2	0.77	1.20	0.000066

Currently, detailed tensile tests are being conducted at 10 degree temperature intervals for Al 5083 alloy to experimentally evaluate the constants first as a function of temperature and then as a function of initial grain size. These data will be used to simulate a complex-shaped component such as the re-entrant-shaped model to evaluate the accuracy of the new constitutive model.

HAMILTON-GOSH MODEL

The constitutive relation used at PNL relates the strain rate as a function of the current flow stress, "σ", and the total grain size "d". Three sources of data for aluminum alloy 5083 were utilized to develop and implement the model. First, a series of tensile tests was conducted by researchers at Washington State University (WSU) and PNL for the 5083 alloy that was produced by the Kaiser Aluminum Company and later rolled into sheet at PNL. In addition, the results reported by Iwasaki et al.[3] and Imamura and Ridley[4] were used to help characterize the static and deformation-enhanced grain growth of other sources of 5083 alloy. Least-squares curve fitting was used to reduce these data to the following constitutive form:

$$\dot{\varepsilon}_{tot} = \frac{A_I(\sigma - \sigma_o)^{1/M}}{d^{Pt}} + A_{II}\sigma^n \qquad (10)$$

where "σ" is the current flow stress, "σ_o" is the initial flow stress, "d^{Pt}" is the total grain size, and "A"'s are constants established for near-zero strain. "M" is the maximum strain rate sensitivity exponent, "n" is the power low creep exponent, and "σ_o" is the threshold flow stress. This equation was suggested by Hamilton et al.[5]

A relationship for the current grain size was also developed for input to Eq. 10. The rate of total grain growth was taken as the sum of the static and deformation-enhanced rates.

MODEL DESCRIPTION

A long, rectangular "butter tray," Fig. 2, was chosen for the comparisons of forming tests and model results. The long tray provides a plane strain section in the center of the long side, plus areas of biaxial straining as the sheet forms into the corners. The forming tests performed at PNL show that the corners of fully formed trays typically exceed 150% of engineering strain. The die used to form the trays has a rectangular cavity that is 2 in. (5.08 cm) wide, 8 in. (20.3 cm) long, and 1 in. (2.54 cm) deep. A die entry radius of 0.125 in. (0.32 cm) makes the transition from the flat rim to the rectangular cavity. The blank thickness is 0.078 in. The forming conditions for the analysis are given in Table 3. The objective of this joint research project was to perform independent analyses of this geometry and compare results to better evaluate the accuracy and efficiency trade-offs.

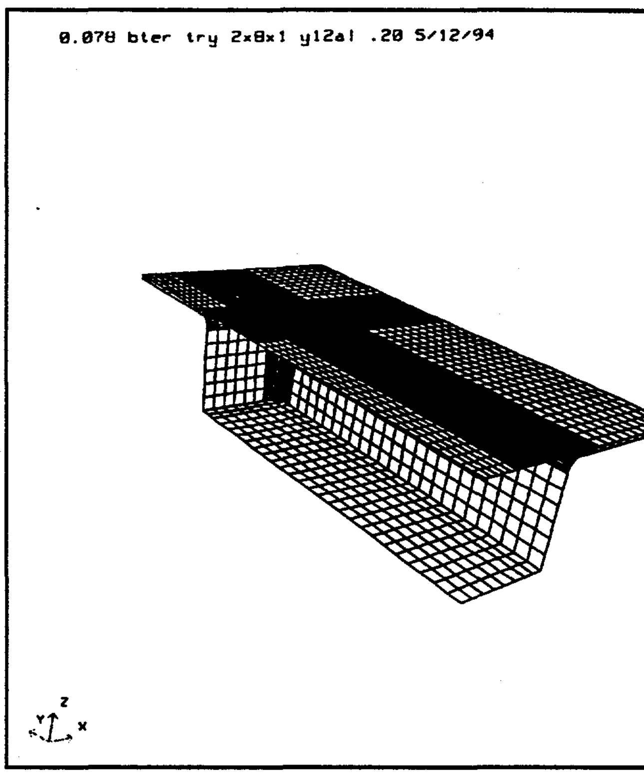

Figure 2. Butter tray geometry chosen for test comparisons.

Table 3. Forming conditions

Temperature:	525° C
Strain rate for forming:	0.001 in./in./s
Blank dimensions:	8 x 2 x 1 in.
Coefficient of Coulomb friction:	Two cases, 0.2 and 0.5

RESULTS

Analysis was performed on a standard butter tray geometry (i.e., long, rectangular box section) to better understand the capabilities of rigid plastic flow and full elastic-plastic models. This geometry was selected for the purpose of the collaborative project. PNL used the rigid plastic model developed by Hamilton and Gosh,[4] for which the constitutive relation is given in Eq. (10), whereas ORNL used the constitutive relation described in Eq. (6). The ISV model and the CGBS model were not used for the comparison because appropriate materials property data were not available. Currently, work is under way to develop the materials properties database for Al 5083 for use with these models.

PNL performed a series of interrupted tray-forming experiments for comparison with numerical simulations. These experiments were performed using the pressure history shown in Fig. 3. The fine-meshed, quarter-sheet models shown in Fig. 4 were used to compare the bulge height versus time and thinning predictions of the model with the forming experiments. A coefficient of friction of 0.2 was used. The finite element analysis was performed using a model with and without the stress correction applied to the constitutive model. The stress correction factor adjusts calculated values based on material constants evaluated using short tensile specimens to actual values associated with longer tensile specimens that are shown to be more accurate constants. Figure 5 presents a comparison of the bulge height versus time for the models (stress corrected and uncorrected) and experiments[6]. The results indicate that by including the stress correction, there is an increase in the time required for the bulge to touch the bottom of the die cavity from 5 to 6 min. Thus, it is estimated that the inaccurate test procedures,

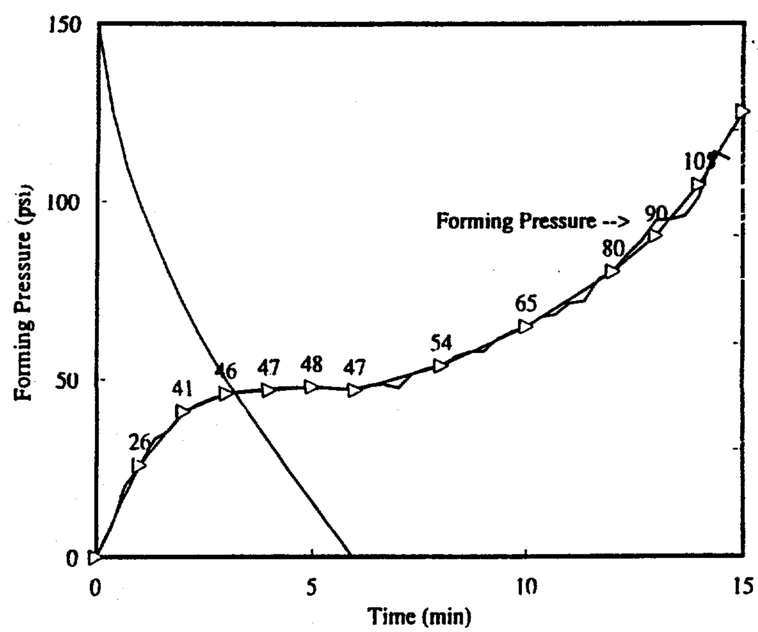

Figure 3. P/t curve including stress correction.

or the inclusion of the stress correction factor, could introduce about 17% error in the forming time. This trend was also consistent with longer forming times as the sheet formed into the corners of the die. However, even after stress corrections, the predicted forming times were much faster than the actual experimental forming times. The PNL research has attributed the observed differences to the constitutive model used in the PNL study as well as to potential errors in the testing procedure for the materials database.

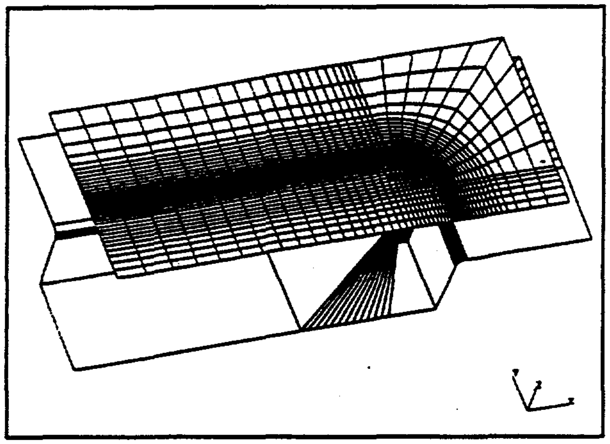

Figure 4. PNL structural fine mesh model.

A comparison of the pressure schedule used in the PNL experiments and the analytical pressure schedule obtained at ORNL using the model based in the constitutive relation given by Eq. (6) is shown in Table 4.

The calculated pressure curve is very close to the prescribed pressure used in experimentally forming the component at PNL. Table 5 presents analytical results of forming simulations performed at ORNL using the LS-DYNA3D program. The data presented include "bulge depth" that represents deformation of the blank relative to the initial state (undeformed). The second column presents data calculated in a mode in which the forming pressure is prescribed to the analysis. No optimization of this pressure was performed (the pressure schedule is the one used at PNL). The third column presents these data for the case when the forming pressure is optimized, so that the peak strain rate in the blank material does not exceed the prescribed value of strain rate (0.001/s). The fourth column represents bulge data measured from the experiments performed at PNL.

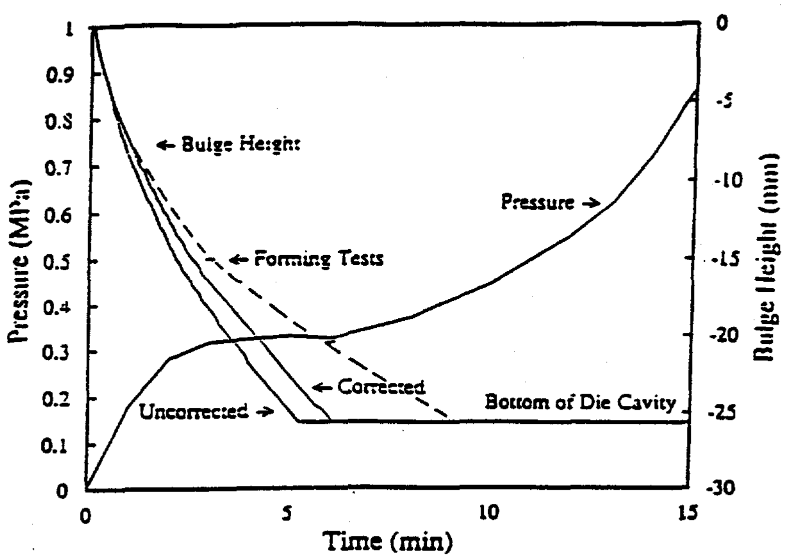

Figure 5. Comparison of bulge height versus time for test results and model predictions.

Table 4. Pacific Northwest Laboratory pressure used in experiment and Oak Ridge National Laboratory calculated pressure

Time (s)	Calculated pressure (psi)	Prescribed pressure (psi)
0.0	0.00	0.0
60.2	26.06	26.0
120.2	40.15	41.0
180.2	39.93	46.0
240.2	36.10	47.0
300.2	40.02	48.0
360.2	43.90	47.0
420.2	53.17	
480.2	62.41	54.0
540.2	68.80	
600.2	72.97	65.0
660.2	81.05	
720.2	82.03	80.0
780.2	98.65	90.0
840.2	109.5	105.0
900.2	125.2	135.0
960.2	131.1	

Preliminary comparisons of the thickness distributions predicted by the model were made at bulge heights equal those measured in the PNL interrupted tests. PNL research indicates that the local thinning is dominated by the co-efficient of friction. Figures 6, 7, and 8 show thickness contours at 2.66, 4.33, and 6 min. from initiation of simulation; this corresponds to 44.33, 72.17, and 100% of the time at which the blank makes initial contact with the bottom of the die. The data in this figures gives bulge heights in the model that are equal to that observed in the 3, 6, and 9 min. in the forming tests. The comparisons with experimental results are, in general, inconclusive due to minimal experimental data. The values were limited to thicknesses at three locations, at three intermediate stages. Thickness values near the corners, which experienced large plastic deformation, were not available. In order to make a definitive comparison, a more detailed experimental study must be performed.

Table 5. Bulge depth for ORNL analyses and PNL experiment

Time (s)	ORNL model prescribed pressure (in.)	ORNL model calculated pressure (in.)	PNL experiment (in.)
0.0	0.0	0.0	
49.75	-0.0488	-0.0488	
99.75	-0.2097	-0.2097	
149.75	-0.4149	-0.4119	
180.00	--	--	-0.590
199.75	-0.5815	-0.5652	
249.75	-0.6652	-0.6290	
299.75	-0.6845	-0.6483	
349.75	-0.7185	-0.6811	
360.00	--	--	-0.890
399.75	-0.7508	-0.7150	
449.75	-0.7902	-0.7611	
499.75	-0.8228	-0.8131	
540.00	--	--	-1.000
549.75	-0.8558	-0.8571	
599.75	-0.9046	-0.9118	
649.75	-0.9514	-0.9673	
699.75	-0.9985	-0.9995	

Results obtained from the ORNL analysis are shown in Figs. 9, 10, and 11, which correspond to the stages in the forming process in Figs. 6, 7, and 8 of the PNL analysis. The final configuration of the formed pan, for the ORNL analysis is shown in Fig. 12. The thickness profile of the formed pan, at the time when full contact between the part and the die is reached, is shown in Fig. 13. Maximum thinning occurs at the corners of the pan (0.033 in.) which is equivalent to 42% of the original blank thickness. The ORNL calculated thickness of the pan at the same stages of forming, compared to the PNL analytical results, is consistently about 10% higher. The ORNL maximum peak strain rate during the forming process is given in Fig. 14, the target value specified is 0.001 in./in./s. The time required for forming the pan, calculated by the ORNL analysis, is 1600 s compared with 1200 s for the PNL model.

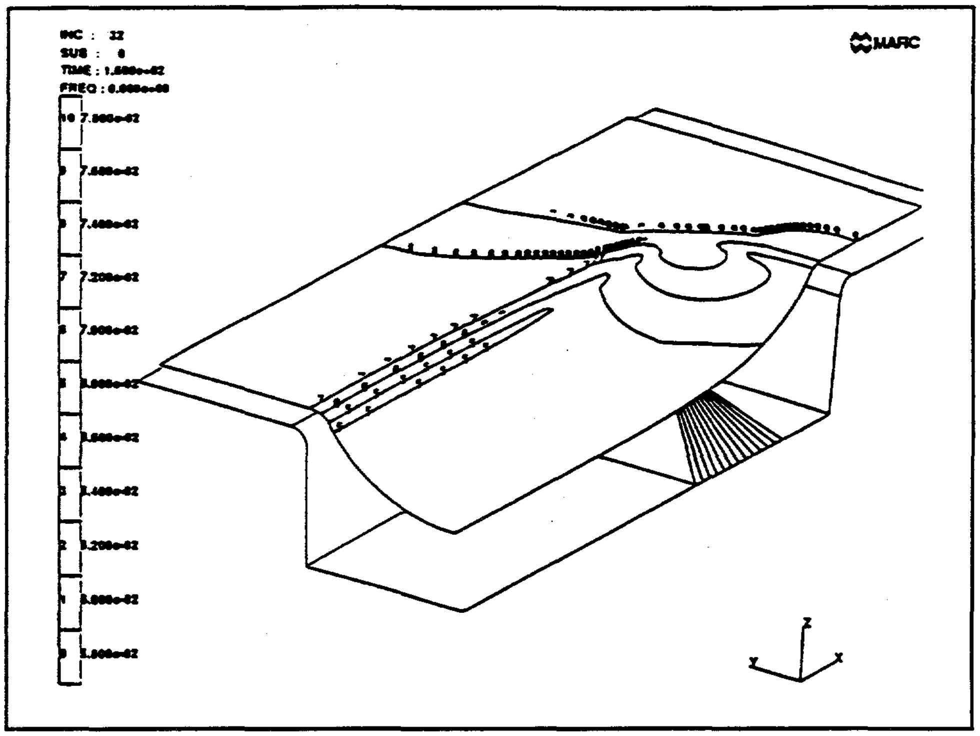

Figure 6. PNL thickness contours at 2.66 minutes.

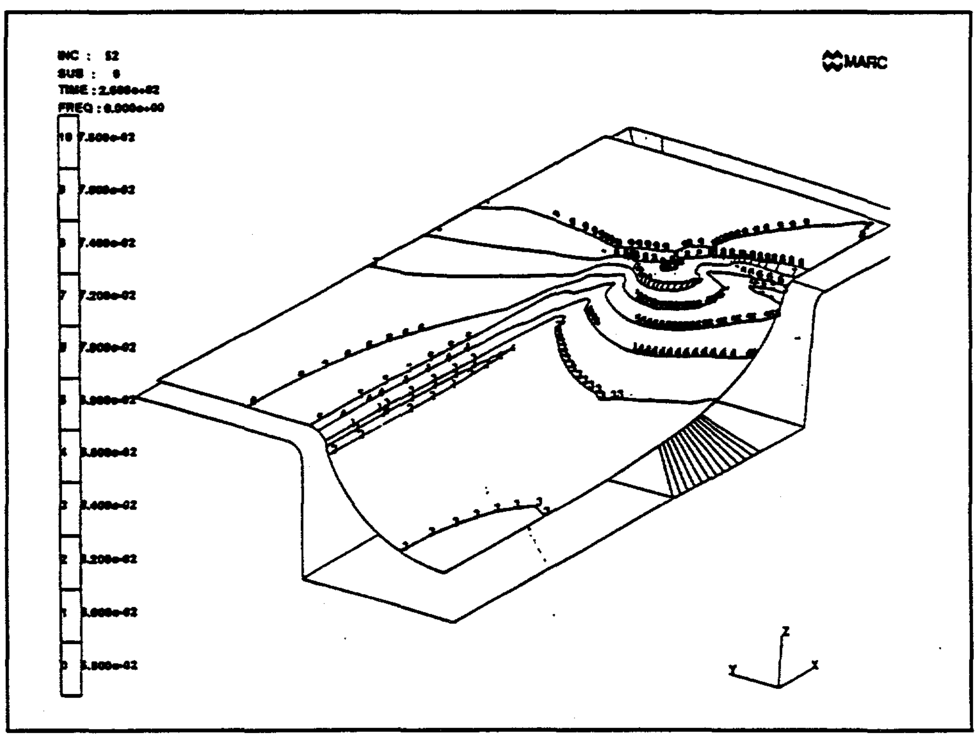

Figure 7. PNL thickness contours at 4.33 minutes.

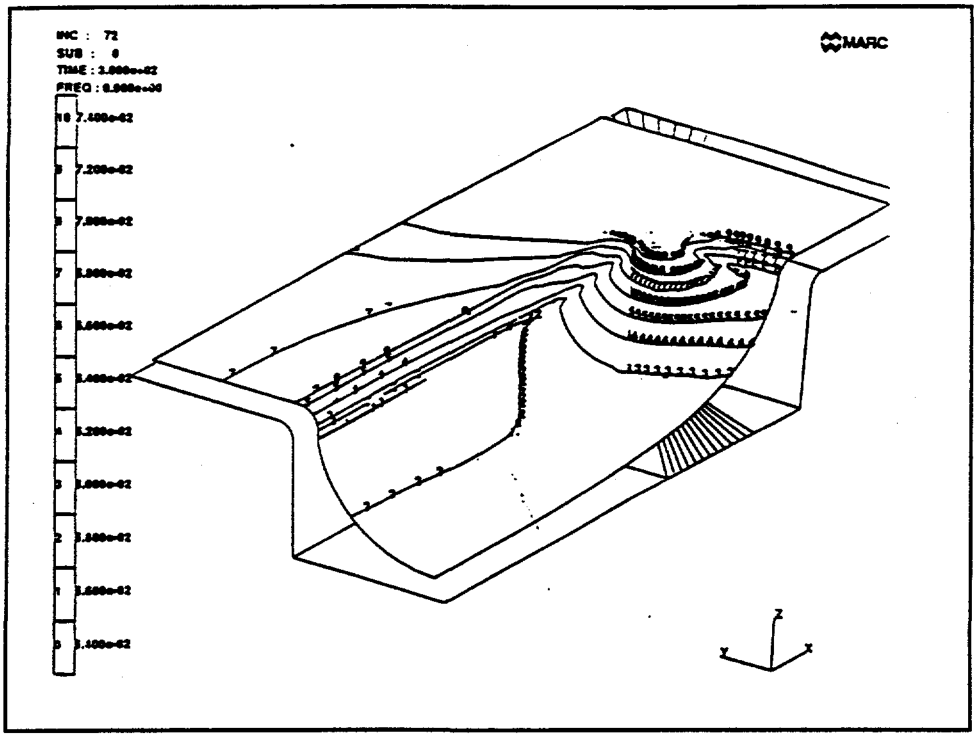

Figure 8. PNL thickness contours at 6 minutes.

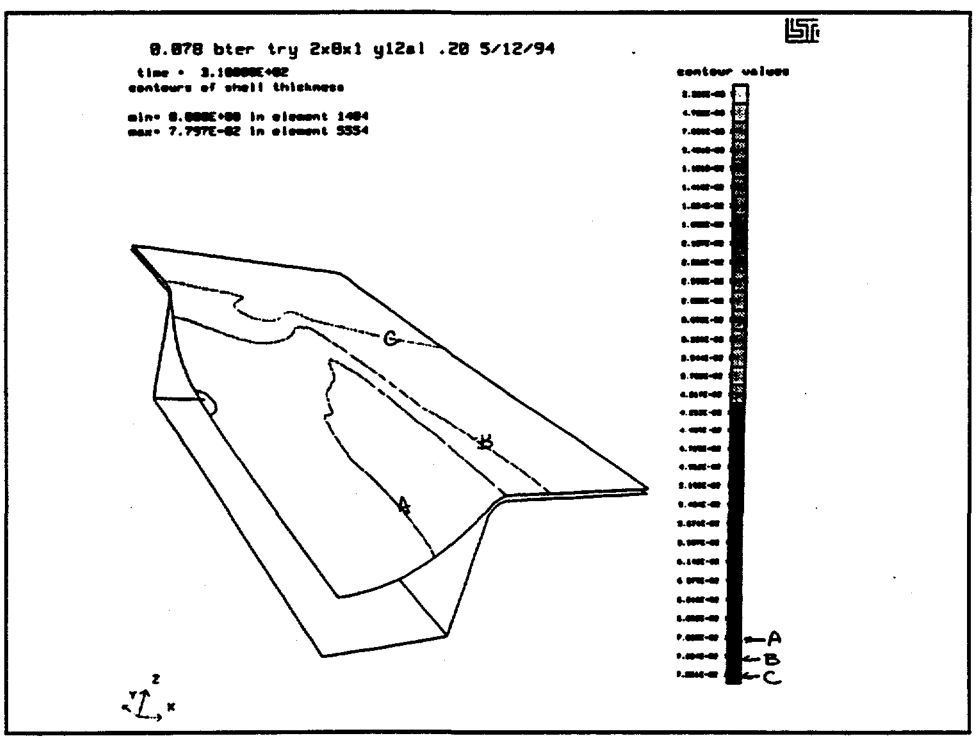

Figure 9. ORNL thickness contours at 44.33% of initial contact.

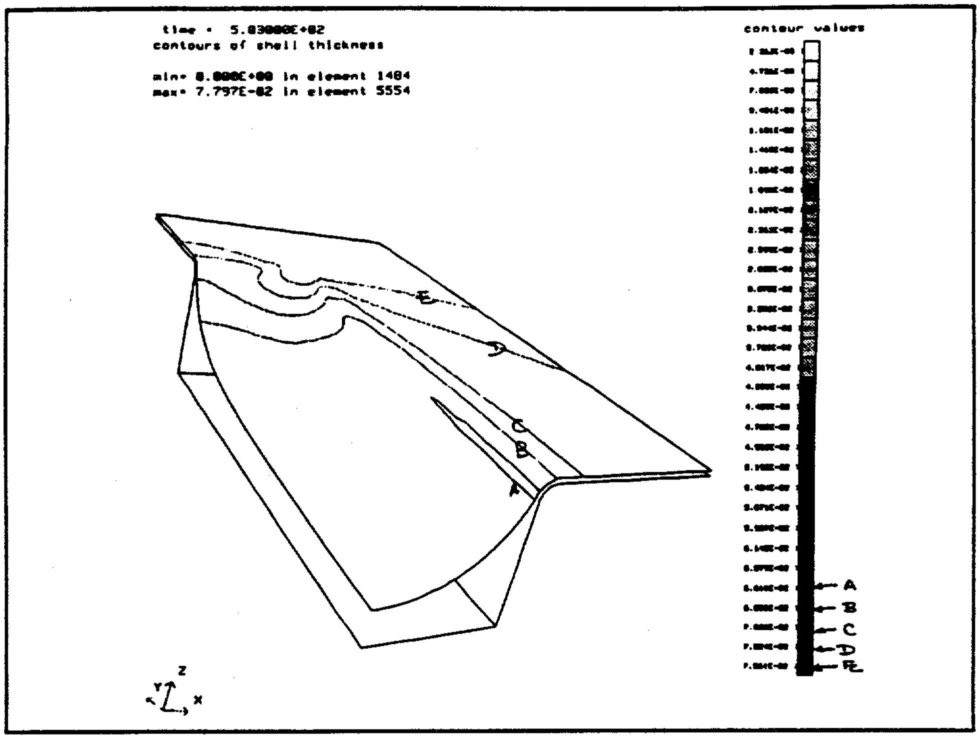

Figure 10. ORNL thickness contours at 72.17% of initial contact.

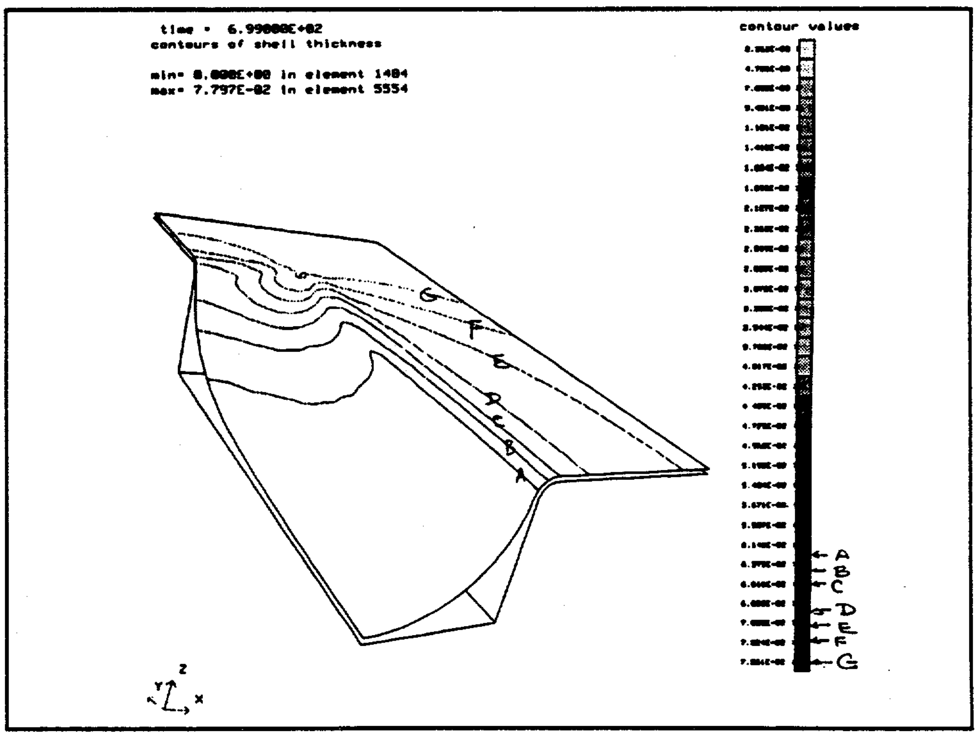

Figure 11. ORNL thickness contours at initial contact.

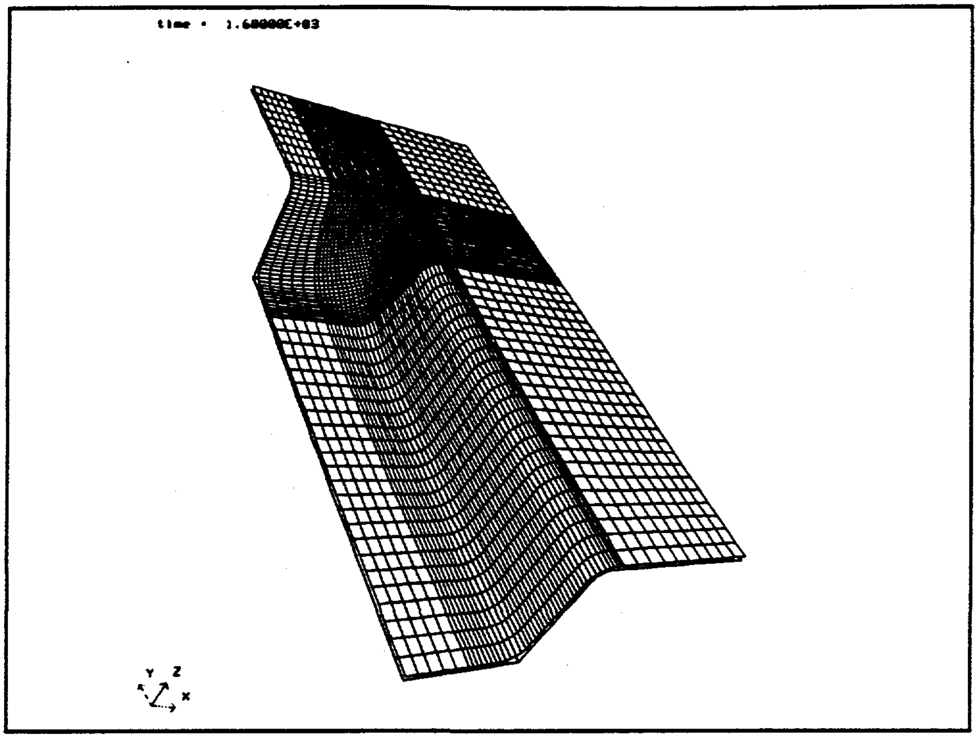

Figure 12. ORNL form fully tucked in die.

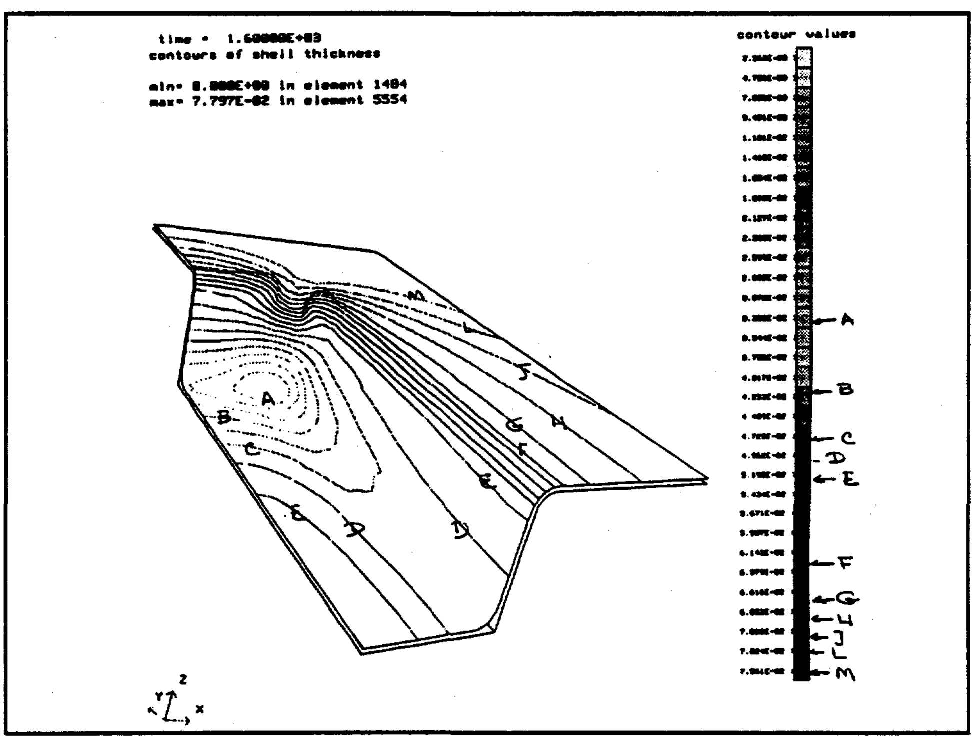

Figure 13. ORNL thickness contours of formed pan.

Khaleel et al. [6] included the analysis for a more complex part with number of steps, which has hitherto not been simulated. Since then, we have compared the results of the PNL model with that of ORNL. The comparison of the pressure schedule shows reasonable overall agreement, considering that two different material models have been used in the analysis. The ORNL analysis showed that the forming pressure, Fig. 15, monotonically increases to a peak value of 217 psi at 1600 s which is the time at which the pan is fully tucked in the die. There is a 0.125-in. radii at the intersection of the die base and the die vertical walls. The PNL calculated pressure schedule is shown in Fig. 16, this pressure profile shows an almost monotonic increase in pressure from start to a peak pressure of 300 psi at 1200 s. The thickness profiles for the analysis show qualitative agreement. However, the location, where maximum thinning occurs, appears to be inconsistent with the ORNL analysis as well as prior experimental observations on similar parts. Typically, it is our experience that the part fails at the corner due to overthinning. The ORNL analysis was performed using a 1/4 model consisting of 5554 Belytchko-Tsay shell elements and 5761 nodes.

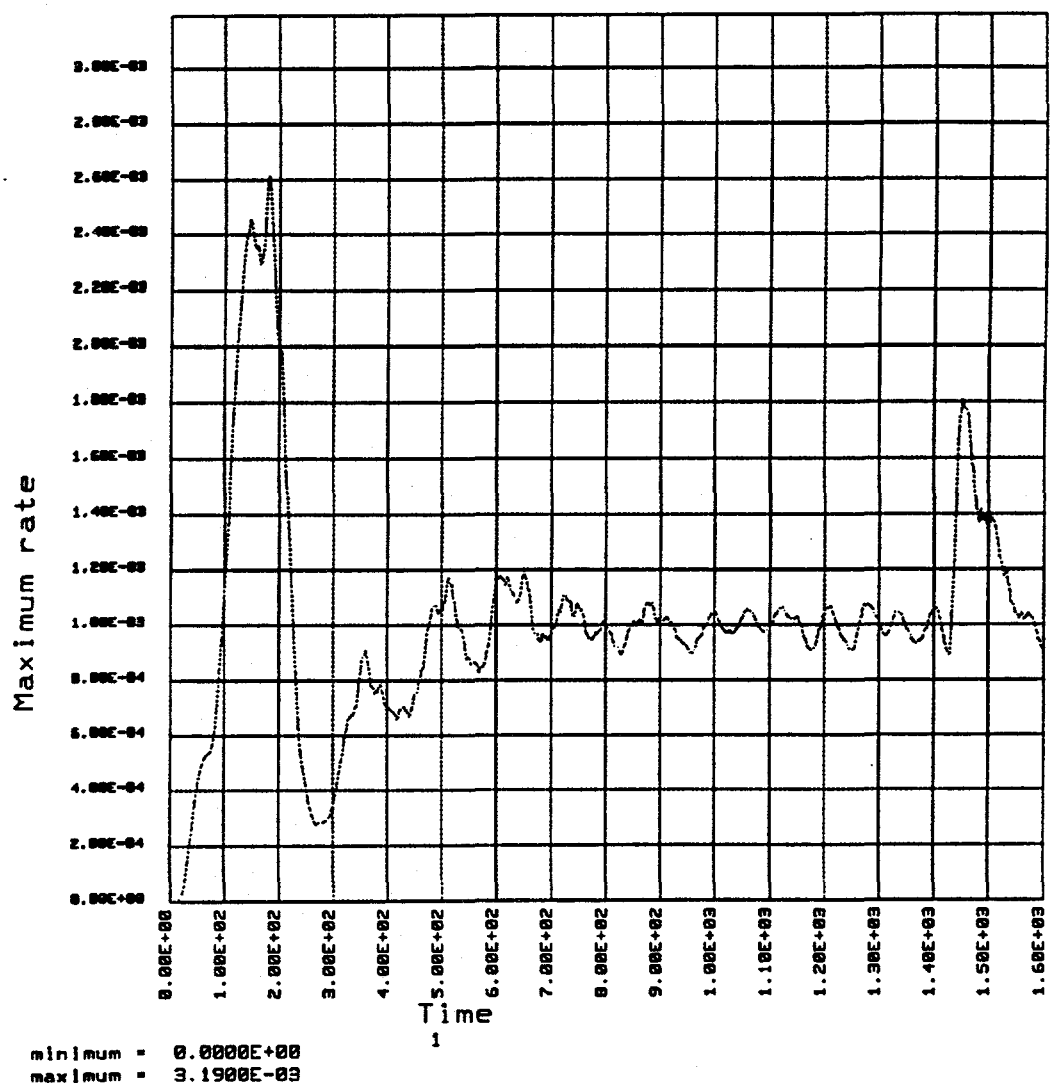

Figure 14. ORNL computer peak strain rate during forming.

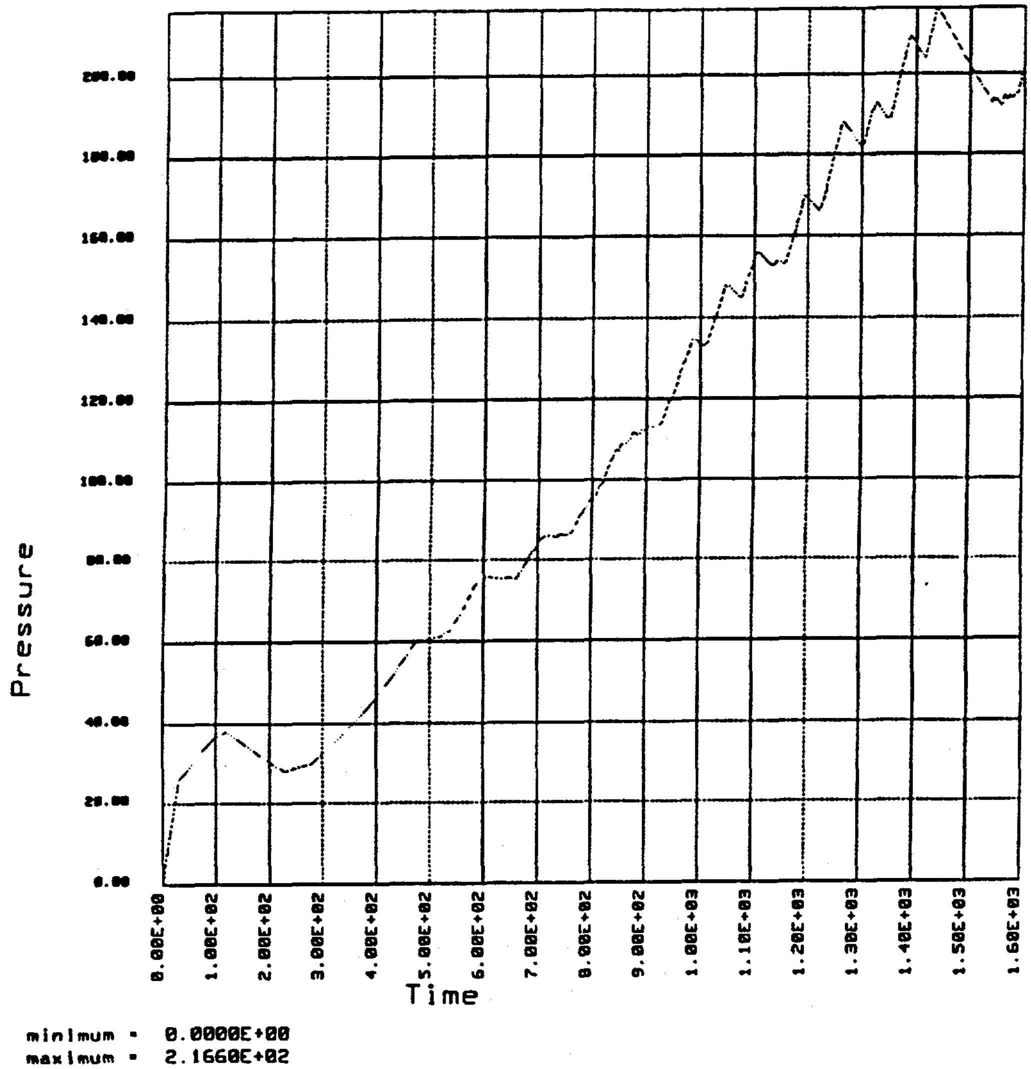

Figure 15. ORNL calculated forming pressure.

MASSIVELY PARALLEL COMPUTING

High-performance computing and simulation are expected to play a key role in supporting the improvements required in advanced simulation techniques for superplastic forming. Superplastic formability and service properties are strongly affected by strain rate, and the resulting distribution of thickness in the formed part is dependent on the part geometry and friction. Because of the high sensitivity to variations in strain rate, it is important to use a pressurization schedule during forming which will lead to acceptable formability. Mathematical models of the superplastic forming process are used to predict the pressure scheduling that will result in optimum superplastic formability. This is accomplished by maintaining the peak strain rate in the forming part at or near the optimum superplastic strain rate of the material in the superplastic region, and to predict the distribution of thickness in the formed part so that reproducibility can be assessed. Modeling also yields an estimate of forming time, which is needed to estimate the cost of operation.

Until recently, only simple shapes such as long (plane strain) and axi-symmetric pans could be easily analyzed. The corners of square and rectangular pans take an extensive amount of time to completely fill the die cavity. Depending on the complexity of the problem, these analyses may require an inordinate amount of computational time. Even on current supercomputers, some of these relatively small problems can be intractable. The computational requirements for a single Belytschko-Tsay shell element with five integration points through the thickness are on the order of 3500 floating point operations per time step and 602 words of memory. Forming models currently use 50,000 elements and run for about 100,000 time steps.

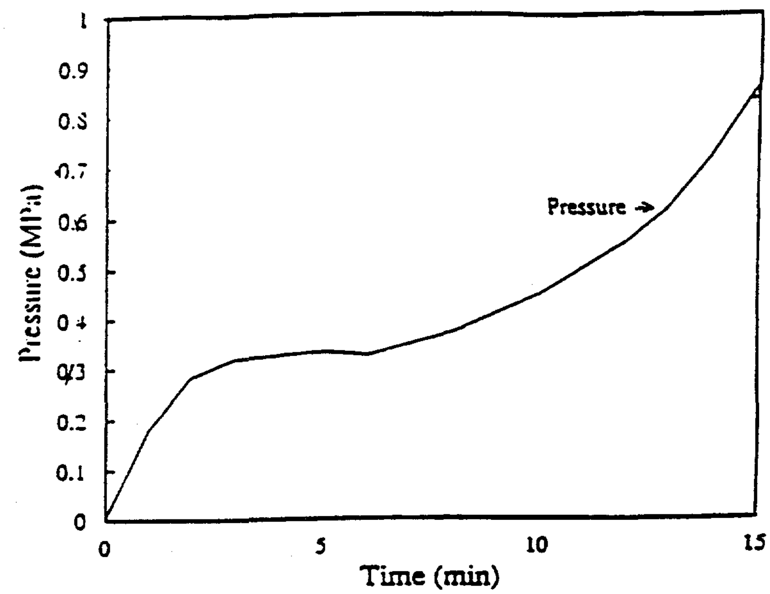

Figure 16. PNL calculated forming pressure.

The emerging massively parallel high performance computers present the potential to solve complex models in reasonable time to support production. For instance, using a massively parallel version of LS-DYNA3D in the analysis of the superplastic forming process, the model performed very well, exhibiting linear increase in computational speed for the 128 ipsc-nodes available for computation. From a practical point of view, the simulation of the superplastic forming process of the butter-tray model, using an SGI (Silicon Graphics) ONYX class parallel computer operating under system ULTRIX 6.0.1 with R8000 chips, results in execution times shown in Table 6. The solution times given in Table 6 are based on the use of LS-DYNA3D version 936.0. The solution times are obtained in an environment in which the computer is shared with other users.

Table 6. Computer utilization as function of number of processors

Number of processors	CPU[a] Solution Time (min)
1	84
2	57
4	37

[a]CPU=central processing unit.

Finally, an analysis of superplastic forming of a mock-up panel similar to an automotive component was also performed to evaluate the scalability of the numerical model for real-life applications. The analysis was performed for the Y-12 Plant processed aluminum 5083 alloy. The one-fourth scale model shown in Fig. 2 has 26,986 nodes and 26,567 shell elements. The blank has 22,116 Belytchko-Tsay shells; the remaining shells belong to the rigid die. The boundaries of the blank are fully constrained. The calculated thickness profiles indicate that the minimum thickness in the part was about 26% of the nominal thickness of the blank.

CONCLUSIONS

The bulge height prediction is reasonable. The thickness distribution is inconclusive. The ORNL model used material properties for the Y-12 Plant processed aluminum alloy 5083 instead of the PNL alloy, since the material property data were not available in a form that was usable. The calculated pressure and forming time were in reasonable agreement with experimental observations. The PNL model underpredicted the time to form the pan, while the ORNL model overpredicted the time to form the pan. Differences in the results are likely due to inaccuracies in the constitutive relations. A more detailed and thorough comparison is necessary to evaluate the models fully.

The constitutive relations used in the PNL study were derived by Prof. Hamilton[5,6] at WSU and relied on material property data from open literature. However, PNL has identified some inaccuracies in the model. A new model that accounts for the deficiencies in the current model was not studied due to the limited scope of the current project.

ORNL is currently investigating the CGBS model and its relevance to optimal structural superplasticity. Detailed experiments are being performed to characterize Al 5083 alloys for evaluation of the current power-law plasticity model to the CGBS model.

Frictional effects on the forming pressure and thickness distribution profile of the formed sheets were investigated. Simulations were performed using coefficients of friction of 0.2 and 0.5. In the case of the higher friction, the thickness profiles shows more thinning in the tray section and less in the skirt region.

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APPENDIX A

PROPOSED FOLLOW-ON PROJECT

Joint Modeling of Superplastic Forming

The purpose of the proposed work is to improve superplastic forming of aluminum alloys by comparing and enhancing the different numerical simulation methods employed by the Oak Ridge National Laboratory (ORNL) and the Pacific National Laboratory (PNL). Initially, through this joint effort, both ORNL and PNL performed analyses of a long, rectangular tray section. Direct comparisons between the two analyses were made difficult due to the use of different constitutive models at ORNL and PNL during baseline modeling simulation. Also, correlations between modeling predictions and actual forming were affected by inaccuracies found in testing methods used in developing the data for constitutive models. PNL has identified significant inaccuracies in the tensile test methods commonly used to develop data for constitutive models for superplasticity. These inaccuracies result from the short tensile test specimens typically used, where end effects and material flow from the grips result in slower strain rates than would be predicted assuming no flow from the grips and a constant strain rate throughout the gage section. PNL currently uses a 1-in.-long gauge section. PNL has suggested a joint effort to develop constitutive relations based on the more accurate testing procedures.

Initial fiscal year (FY) 1994-95 comparisons were made difficult by the need to use different constitutive models at ORNL and PNL during baseline modeling simulation. Also, the correlation between the model predictions and actual forming were affected by inaccuracies found in the testing methods used in developing the constitutive model. More recently, PNL's testing, modeling, and forming comparisons on modified aluminum alloy have shown excellent comparison between model predictions and forming.

PNL has identified significant inaccuracies in the short tensile test specimen commonly used to develop the materials database. The material flow from the grips results in slower strain rates than would be predicted assuming no flow from the grips and a constant strain rate through the gage section. The work at PNL suggests that a 1-inch gage section will minimize the end effects. Since the materials database is key to any constitutive model developed, and therefore the accuracy of the simulation, it is important that ORNL and PNL use constitutive relations based on accurate testing procedures.

FY 1996 tasks

The specific tasks of the proposed joint research are:

1. To make model versus model comparisons and model versus actual forming comparisons. ORNL and PNL will use and implement the same constitutive relations. PNL will provide ORNL with constitutive data compatible with the power constitutive relations used in LS-DYNA. PNL will provide ORNL with the values of the coefficients K, m, and n in table format. PNL will implement the constitutive relations used by ORNL in their simulation codes. Both models will then be used to simulate thickness profiles, bulge height history, and strains using a pressure time history derived using a constant

strain rate. The results of the analysis using both codes will then be compared with actual forming results.

2. ORNL and PNL will investigate control algorithms for applied pressure to optimize the forming cycle and avoid part thinning. The first control algorithm will be based on maintaining the maximum strain rate averaged over a certain number of elements, and another will use a variable strain rate path as the target strain rate. Finally, a hybrid control algorithm based on both strain rate and strain rate gradient will be implemented to optimize forming and minimize thinning.

3. ORNL and PNL will study the different pressure time histories resulting from the use of these control algorithms based on selecting a control region in the tray.

4. ORNL and PNL will perform sensitivity studies to investigate the effect of mesh refinement, contact tolerance, friction coefficient, and other friction parameters on optimum pressure time history.

ORNL Cost and Schedule

1 year, $75,000

PNL Cost and Schedule

1 year, $50,000

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