DEVELOPMENT OF A FINITE ELEMENT

MODEL FOR RADIAL FORGING OF SUPERALLOYS

Laurence A. Jackman, M.S. Ramesh and Robin Forbes Jones
Teledyne Allvac
Monroe, NC

Erik G. Thompson
Colorado State University
Fort Collins, CO

Shesh Srivatsa
G.E. Aircraft Engines
Cincinnati, OH

Abstract

Establishing and optimizing radial forging procedures by empirical means to meet stringent microstructural requirements can be time consuming and expensive. Therefore, a three dimensional finite element model has been developed to predict temperature and strain distributions during radial forging. The model applies a quasi-steady-state approach that reduces computation time and simplifies the presentation of results. Temperatures and strains are presented as contour plots of longitudinal and transverse cross sections and by three dimensional perspective views. Values predicted by this model show good agreement with experimental results based on temperature measurements and microstructure evaluation for Alloy 718.

Superalloys 1992
Edited by S.D. Antolovich, R.W. Stusrud, R.A. MacKay,
D.L. Anton, T. Khan, R.D. Kissinger, D.L. Klarstrom
The Minerals, Metals & Materials Society, 1992

Introduction

During radial forging, adiabatic heat is generated by the rapid stroke rate. This helps provide an opportunity to meet stringent grain size and other structural requirements needed by forgers and end users such as aircraft engine builders. However, establishing a procedure for radial forging a given product entails selecting values for a number of parameters such as furnace temperature, axial feed rate, reduction per pass, reheat sizes, die geometry, and billet length. Selection of these process parameters has traditionally been expensive and time consuming; it has been governed by empiricism, trial and error, designed experiments, and operator experience. Therefore, analytical methods to predict process parameters are highly desirable. Such methods are very useful for conducting "what-if" parametric studies to investigate relationships between process variables and their effects on final products.

Review of the literature revealed that an adequate model for predicting process parameters during radial forging of solid workpieces did not exist. Therefore, a program was undertaken to develop a three dimensional (3-D) finite element model for radial forging solid work-pieces with the GFM Machine at Teledyne Allvac.

Radial Forging Process

Radial forging is an open-die process for converting ingots to billets, reducing cross sections of billets, and forging shafts and axles. The radial forging machine at Teledyne is a Model SXP-55 GFM (Gesellschaft fur Fertigung und Maschinenbau). Round, square, and rectangular shapes can be produced; also, hollow shafts can be forged. The workpiece is deformed by four hammer dies arranged radially around the work piece. Four die configurations are used: universal, round, rectangular, and hollow. The configuration for round dies is shown in Figure 1. Dies are activated by connecting rods driven by eccentric shafts which generate a stroke rate of 200 strokes per minute. For different size machines the stroke rates would be different. After each forging blow, the workpiece is fed axially (1-8 m/min) toward the entrance of the dies. The workpiece is held at each end by chuckheads, which are track bound manipulators. When producing round products, the chuckheads rotate the work piece between blows to obtain a uniform forged surface.

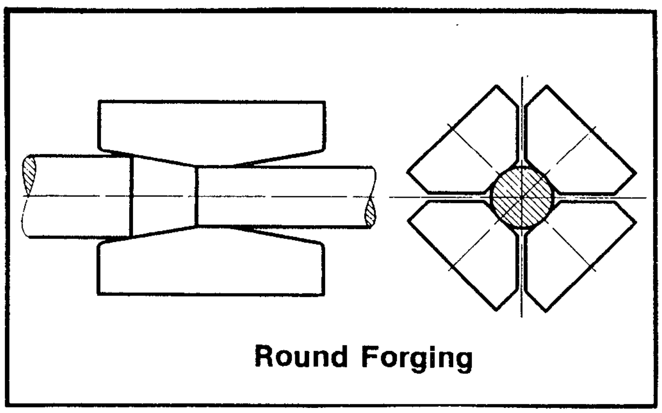


Figure 1. Radial forging with round dies.

The radial forging process can be fully automated, which results in excellent product consistency and makes rotary forging a good candidate for modeling.

Radial Forging Model

Quasi-Steady-State Approximation

The metal forming industry has made extensive use of the finite element method to conduct both transient and steady-state analyses of forming processes. When appropriate, steady-state analyses are usually desirable. In general, they are numerically more accurate, computationally less expensive, and easier to interpret than results obtained from transient analyses. But, radial forging is inherently a transient process. As the billet moves through the forge, it is subjected to cyclic loadings from the hammers. However, evaluation of surface temperatures, forces, and microstructures led the authors to investigate the use of a quasi-steady-state (QSS) formulation for the analysis of radial forging.

An important aspect of the quasi-steady-state approach is the concept of a control volume. This represents a section of the billet in the near vicinity of the hammers. It provides the shape of the billet just prior to being struck by the hammers as shown in Figure 2 where the mesh is superimposed on the control volume. With the quasi-steady-state approach, it is necessary to work only with the control volume rather than the entire billet.

Input for Material Properties

Before an analysis can be performed on a given alloy, certain material properties for that alloy must be put into the computer. These include the following:

- Flow stress as a function of temperature, strain, and strain rate
- Specific heat vs temperature
- Thermal conductivity vs temperature
- Density

Compression testing has been used to acquire flow stress data now in the computer.

Input for Problem Definition

At the beginning of an analysis, the following parameters are inputed:

- Furnace temperature
- Feed rate
- Die set
- Die temperature
- Coef. of convective heat transfer to air
- Coef. of convective heat transfer to dies
- Coef. of convective heat transfer from furnace to forge
- Work to heat ratio
- Emissivity
- Starting billet diameter
- Billet diameter after first pass

For subsequent passes before reheating, the parameters below must be provided:

- Elapsed time from when the cross section of interest leaves the control volume to when that same cross section enters the control volume for the next pass.
- Billet diameter before the pass
- Billet diameter after the pass.

Mesh

Figure 2 illustrates the mesh used for the 3-D finite element analysis - it contains 2418 nodes and 1900 elements. A coarser mesh is available for reducing analysis time. An axisymmetric 2-D mesh is also available for even faster calculations.

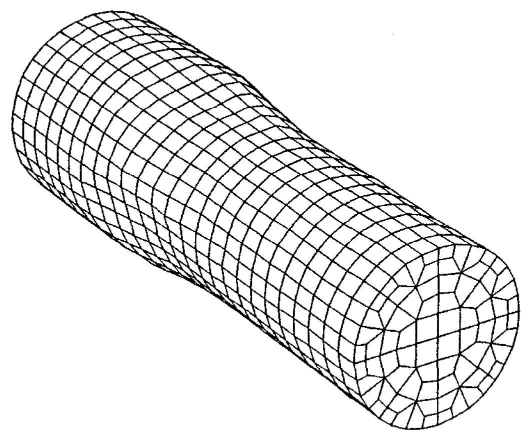


Figure 2. Control volume and finite element mesh

Analysis

An analysis of a scheduled-forging operation begins with the billet temperature assumed uniform and equal to the known furnace temperature. A transient thermal analysis is then conducted to account for temperature changes which take place during the transfer of the billet from the furnace to the forge. It is assumed that the temperature changes are the same throughout the length of the billet; hence, the analysis is conducted on a typical cross section of the billet. The simulated time used for the analysis is the time between the removal of the billet from the furnace and the entrance of material into the control volume used for the analysis.

Once the transient, thermal analysis is completed, the QSS analysis is begun with the billet entering the control volume having the temperature distribution obtained from the transient analysis. The QSS analysis then provides the temperature distribution throughout the billet occupying the control volume.

For subsequent passes of the workpiece through the forge, the temperature distribution in the cross-section of the billet leaving the control volume is used as the initial temperature for a transient, thermal analysis. The simulated time for this analysis is the time that a cross section leaves the control volume to the time that same cros section enters the control volume for the next QSS analysis. Note that the thermal changes which take place within the billet between the time the material enters the control volume and leaves the control volume is accounted for in the QSS analysis; hence, this period of time is not part of the transient analysis. With the initial temperatures for the next pass thus obtained, a new QSS analysis is conducted. The procedure is continued until the entire forging schedule has been simulated.

Output

Results from an analysis are presented as contour plots of temperature and contour plots of strains for the control volume. These contours can be lines or enclosed regions can be color coded. They can be displayed for longitudinal cross sections, transverse cross sections, or three dimensional perspectives. The model also has the capability of providing strain rate information.

Application of Radial Forging Model

Forging Small Diameter 718

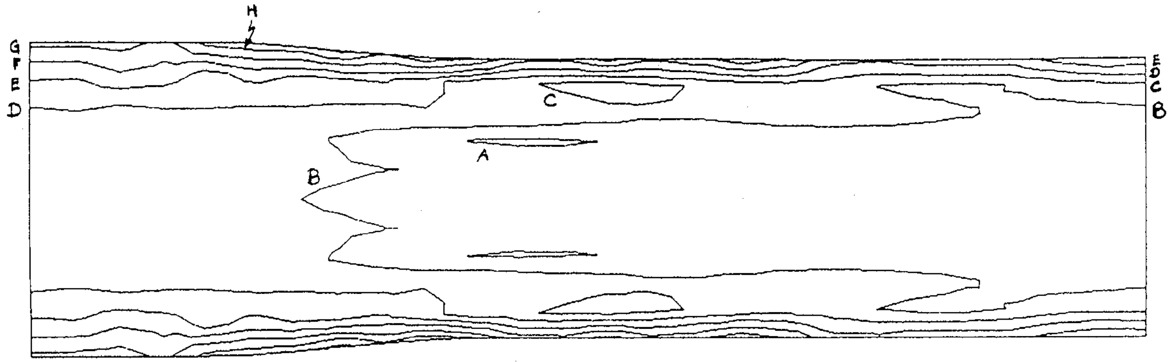
As part of the verification process, a billet six inches (152 mm) in diameter was radial forged to four inches (109 mm) in three passes following the forging schedule shown in Table I. Temperature contours for Passes 1 and 3 generated by the model are presented in Figures 3 and 4, respectively, for longitudinal and transverse cross sections and for a perspective view. The volume shown represents the control volume and the transverse cross-section corresponds to the extreme exit end of the control volume. The model allows any cross section through the control volume. Effective true strain contours are shown for Pass 3 in Figure 5 for longitudinal and transverse cross-sections.

Table I. Schedule for Forging 718 Billet 3.91m Long from 1900°F with Round Dies.

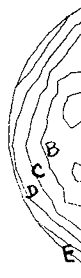
Pass	Cool Down (sec)	Diameter (mm)		R.A. Speed	
		In	Out	%	(mm/sec)
1	86.7	152.0	136.0	19.9	75.0
Pass Thru					
2	100.2	136.0	121.0	20.8	75.0
Pass Thru					
3	109.7	121.0	109.0	18.9	93.3

The surface spiral pattern evident in Figures 3 and 4 is related to rotation of the workpiece. It is also visible in practice, which indicates agreement between the model and actual practice. Adiabatic heating is also evident.

Surface temperatures were measured by infrared pyrometers mounted on both the entrance and exit sides of the forging box. These agree well with model predictions for all three passes as shown in Figure 6 and Table II. Predicted temperatures in the center of the billet are presented in Figure 7 and Table II. Experiments are underway to measure internal temperatures for comparison with model predictions. An indication of agreement

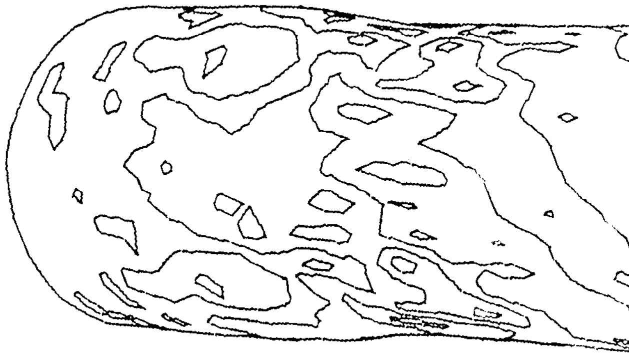


Longitudinal Section



Tran

KEY:
A 1950°F
B 1900°F
C 1850°F
D 1800°F
E 1750°F
F 1700°F
G 1650°F
H 1600°F
I 1550°F



Perspective View

Figure 3. Temperature Contours for Pass 1.

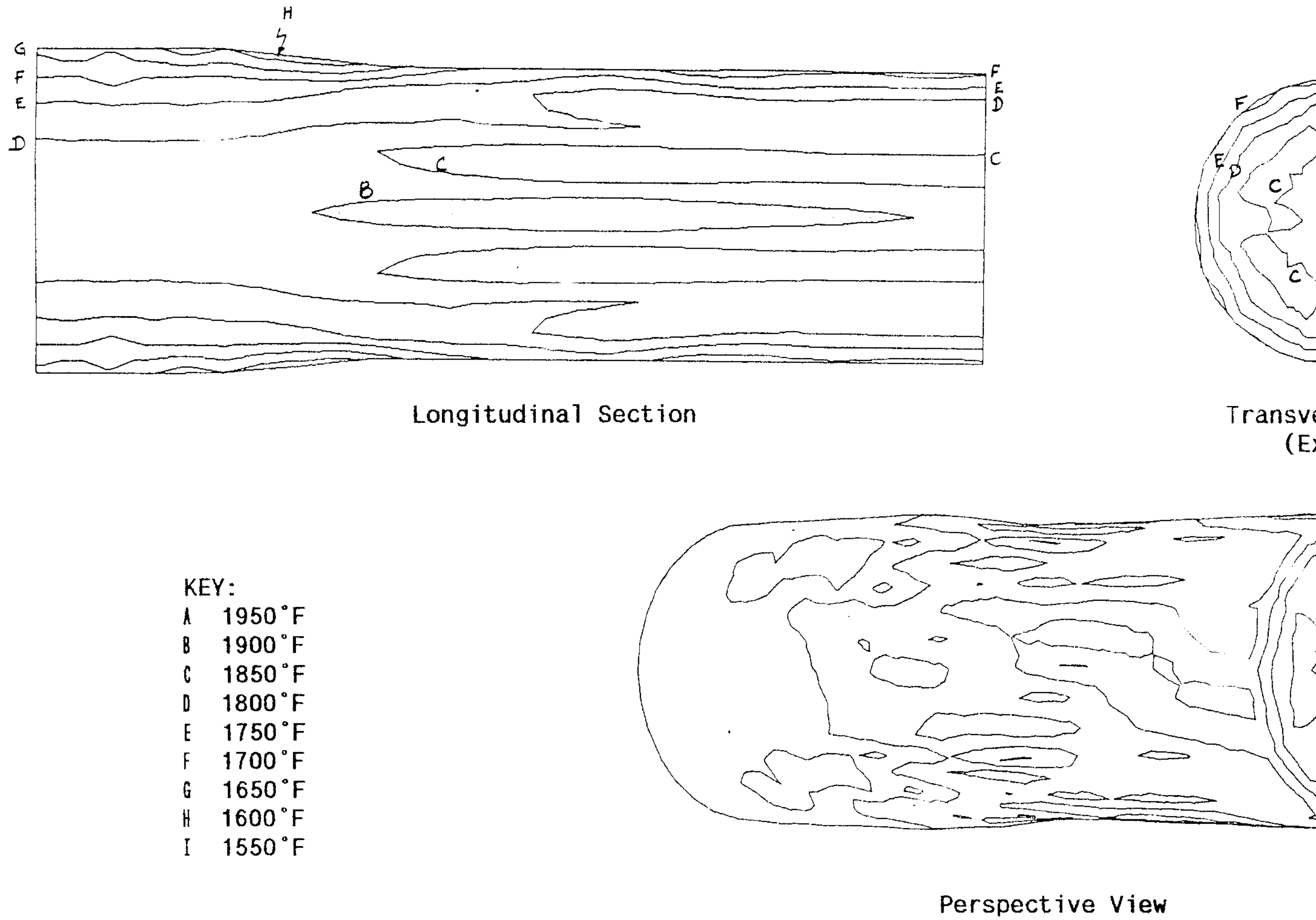
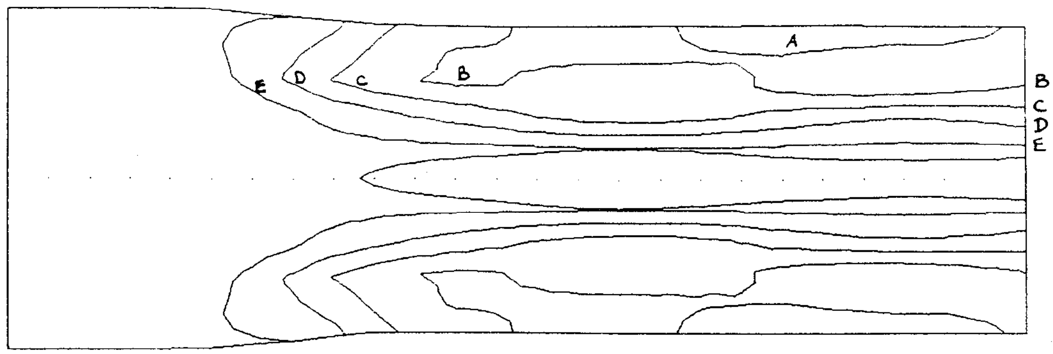


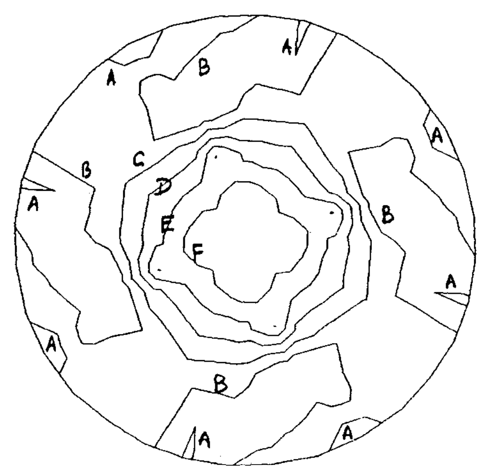
Figure 4. Temperature Contours for Pass 3



Longitudinal Section

KEY:
A 0.50
B 0.40
C 0.30
D 0.20
E 0.10

KEY:
A 0.50
B 0.43
C 0.36
D 0.29
E 0.21
F 0.14



Transverse Section
(Exit End of Control Volume)

Figure 5. Effective True Strain Contours for Pass 3.

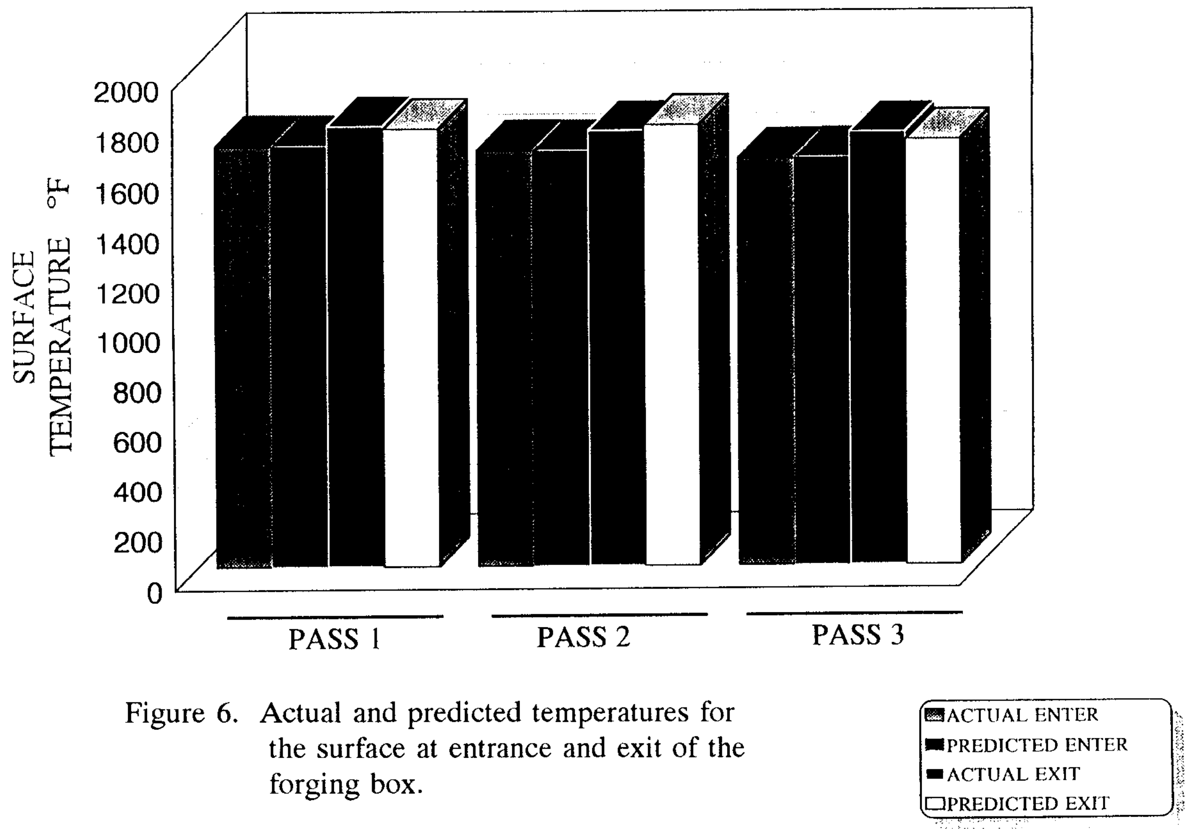


Figure 6. Actual and predicted temperatures for the surface at entrance and exit of the forging box.

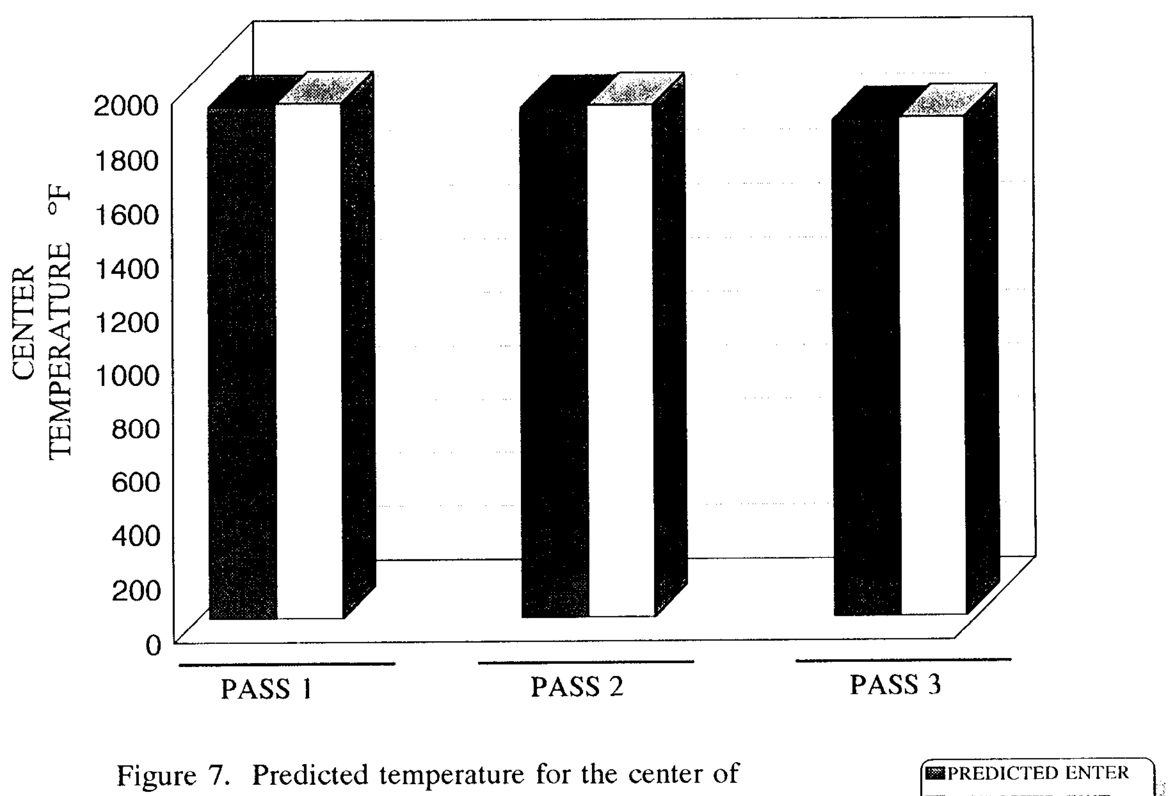
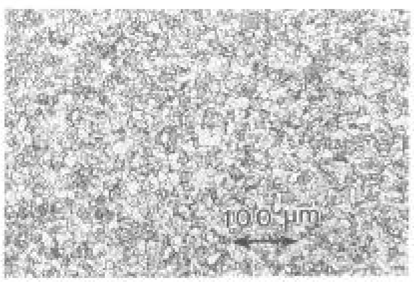


Figure 7. Predicted temperature for the center of entrance and exit of the forging box.

at internal locations can be achieved by observing microstructures. For example, final grain size for the surface of the billet forged in this study was ASTM 10 with ALA (As Large As) grains up to 2 compared to the surface which was ASTM 8 with ALA grains to 2. These grain sizes are consistent with the temperatures and strains predicted by the model. Microstructures are shown in Figure 8 for surface and center locations.

Table II. Actual and Predicted Temperatures (°F) for the Billet at Entrance and Exit of the Forging Box

Location	Pass 1		Pass 2		Pass 3	
	Entrance	Exit	Entrance	Exit	Entrance	Exit
Surface Actual	1685	1765	1665	1743	1630	1735
Surface Predicted	1688	1752	1665	1764	1634	1703
Center Predicted	1895	1908	1890	1899	1841	1850



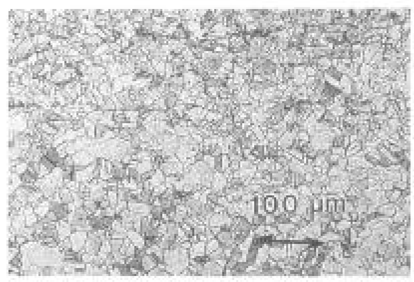


Figure 8. Microstructure of Billet After Pass 3 for the Surface (L) and Center (R).

Conclusions

A 3-D finite element model has been developed which accurately predicts temperature and strain distribution for radial forging. The model applies a quasi-steady-state approximation to generate temperatures and strain contours that can be presented as lines or colored regions. By running successive analyses, a complete forging schedule can be analyzed without excessive computational time.

References

1. G.D. Lahoti and T. Altan, "Analysis of the Radial Forging Process for Manufacturing Rods and Tubes," Journal of Engineering for Industry, p265, February 1976.

2. K. Lange, "NC-Radial Forging - A New Concept in Flexible Automated Manufacturing of Precision Forgings in Small Quantites," Proceedings of 1st International Machine Tool Design and Research Conference, Birmingham, p63-72, April 1985.

3. R. Paukert, "Investigations Into Metal Flow in Radial Forging," Annals of the CIRP, Vol 32, p211-217, 1983.