

FEM Simulation of Multiple Pass Radial Forging of Pyromet 718

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ABSTRACT

Radial forging of a small diameter Pyromet 718 billet was modeled under non-isothermal and axisymmetric conditions using a finite element approach. In this model, each stroke of the radial forging tools was modeled as a separate simulation. An implicit method was developed to account for the non-contact time of the forging tools between each deformation cycle in order to improve transient temperature predictions during each pass. An improved representation of the chuckhead constraint was also developed. A three pass forging sequence using Pyromet 718 billet was conducted to validate the finite element model. Results show that deformation was generally uniform and penetrated to the workpiece center though surface strains tended to be higher. Temperature distributions show that significant differences develop between the workpiece surface and the interior and are maintained during forging. Comparison of the finite element predictions and the experimental measurements for effective strain and temperatures showed acceptable correlation.

Introduction

During the past decade, radial forging has increasingly been used by specialty metals producers for billet conversion. However, relatively little information is available regarding the thermomechanical history of the billet during multiple pass radial forging and as a result, process design remains heavily based on empiricism and trial and error. In order to analyze the radial forging process and to gain a better understanding of the material flow and temperature fields developed in the billet during forging, it is necessary to develop a process model. While some finite element modeling (FEM) work has been performed [1-3], little success has been reported in directly validating FEM temperature and strain predictions in the billet, except through comparisons with microstructure and surface temperatures [2-4].

As part of an overall study aimed at characterizing thermomechanical processing in Pyromet 718 and developing product-property relations, an effort was undertaken to develop and validate an FEM based process model. A key objective was to build a model which better represented the process characteristics and could be used to predict the thermomechanical history of the billet. In the present study, a joint effort between the Engineering Research Center for Net Shape Manufacturing at The Ohio State University and Carpenter Technology was undertaken to develop and validate an FEM based process model.

Development of the FEM Model

To perform the FEM simulations, DEFORM v3.1 was chosen because it has been developed specifically for the simulation of metal flow problems in forging. DEFORM (formerly ALPID) is an FEM code developed at Battelle Columbus Labs and is based on the "Updated Lagrangian" formulation with rigid-thermoviscoplastic material behavior.

The modeling strategy chosen for the present study was to model the process on a "stroke-by-stroke" basis using a 2-D axisymmetric model. The underlying principle being that each tool stroke may be treated as a separate simulation. The workpiece is then moved by an amount equal to the axial feed rate between each simulation to account for indexing. Due to the use of an axisymmetric model, it was necessary to introduce the following assumptions:

- 1) The small circumferential clearances between the dies are neglected
- 2) Rotational feed component of the billet is neglected
- 3) Elastic deformation of the billet in the sizing zone is neglected
- 4) The flat surfaces on the tools are approximated by semi-circular arcs

Thermal Boundary Conditions

Due to the billet geometry, heat transfer at the billet surface is essentially a one-dimensional problem. Because convective losses tend to be a small fraction of the total heat loss, heat transfer was assumed to be due to radiation only. In most radial forging analyses the effect of die chilling has been assumed to be negligible due to the relatively short time over which the die is in contact with the

workpiece [2,5,6]. It has been estimated that the tools are in contact with the workpiece for less than 10-15% of each forging cycle [7]. For a machine operating at 180-200 strokes per minute, the non-contact time for each stroke will be on the order of 0.3 seconds. While the amount of heat loss occurring between each stroke is negligible, the accumulated effect will be very important. To account for the non-contact time of the tools between each stroke, an implicit method was used to introduce a period of heat transfer equal to the dwell time between subsequent forging cycles at the start of each simulation.

Boundary Conditions at the Workpiece Ends

Under actual radial forging conditions, the trailing end of the workpiece is firmly held as it enters the forging box and may be considered as fixed. However as forging proceeds, both ends are held by the chuckheads which apply a front and back pull. Previous work has assumed that the chuckhead restraint may be modeled by fixing nodal velocities at the trailing edge of the workpiece to zero [1,8]. While the previous assumption is not strictly valid during the entire pass, it will be sufficient during the early stage of the pass when only one chuckhead is in contact with the workpiece. However, this is not a good representation of the chuckhead as it is necessary to switch the boundary conditions at mid-length. This was found to give rise to a transient in the strain field and to artificially cause deformation to penetrate to the core as the dies move towards the fixed workpiece edge.

In actuality, each chuckhead grips the workpiece at four points at the surface and allows the workpiece to move slightly in the axial direction during deformation. These intermittent motions compress springs located in the chuckhead and enable uninterrupted workpiece indexing [9]. Initially it was attempted to model the chuckhead as an elastic object but the computation time proved to be excessive. A more suitable approach was found by modeling the chuckhead as an axisymmetric ring surrounding the perimeter of the workpiece. Axial restraint was obtained by prescribing a friction factor equal to 1.0 (sticking friction) at the gripper/workpiece interface. After one-half of the pass simulation was completed, the position of the gripper was reversed. This corresponds to the point at which the gripper releases the workpiece during an actual pass.

Effect of Machine Kinematics

Depending on the type of forging machine and drive used, the die velocity profile will be quite different. Accordingly, the strain rate history of the workpiece during deformation will also be affected by the type of drive used. When forging with a mechanically driven press such as the GFM, the strain rate dependency of the flow stress necessitates using the correct stroke-velocity curve. For a mechanical drive [10], the stroke-velocity curve will follow a harmonic or sinusoidal path and may be calculated as a function of stroke using the equation:

$$V = \frac{\pi n h}{30} \sqrt{\frac{S}{h} - 1} \quad (1)$$

where: V = velocity h = distance from Bottom Dead Center
 S = total stroke n = number of strokes per minute

The total stroke of the radial forging machine was assumed to be fixed at 38.1 mm. Actual deformation will occur towards the end of the stroke with continuously decreasing strain rate. While the drive has a very high stroking rate, the strain rates experienced by the billet during radial forging are well within the range typical of mechanical presses.

Process Conditions for the Simulation Study

The steps used to model the three pass sequence used in the validation effort consisted of the same sequence of events which occur during the actual forging process. From a modeling standpoint, there are two primary events to be considered: non-isothermal deformation and heat transfer. Due to the requirement of simultaneously considering deformation, deformation heating, and heat losses, each pass was modeled using the non-isothermal mode in DEFORM. Billet transfer and inter-pass dwell periods were simulated by performing transient heat transfer analyses.

At the beginning of the simulation sequence, the billet was assumed to have just come out of the furnace at a uniform temperature of 1066 °C. A heat transfer analysis was then performed corresponding to the time required to transfer the billet from the furnace to the rotary forge. For a multiple pass sequence, deformation was modeled under non-isothermal conditions to obtain the strain and temperature history of the billet. Heat transfer occurring between consecutive forging cycles was accounted for using the method described above. Inter-pass dwell times were simulated using a transient heat transfer analysis. The temperature and strain distributions in the billet at the end of each pass were used as the initial distributions for the subsequent pass simulation.

Process Conditions for the Experimental Forging

To validate the FEM model, a three pass forging sequence was performed. The billet material was cast using VIM/VAR into a 508 mm diameter ingot which was subsequently homogenized and rotary forged into a 264.2 mm diameter preform. The preform was then machined to a 254 mm diameter preform with a length of 4.1 m. The billet was reduced using the forging schedule in Table I. The billet was assumed to have been at a uniform starting temperature of 1066 °C based on thermocouple readings taken during furnace heating. Prior to forging, the dies were heated to 426 °C which is consistent with rotary forging practice for Pyromet 718.

Table I. Pass schedule used in the forging experiment at CarpenterTechnology.

Pass Number	% Reduction in Area	Average Feed Rate
1	10.7	6.9 m/stroke
2	15.2	4.8 m/stroke
3	19.6	3.8 m/stroke

Validation Technique

Previously reported studies [2-4] have used surface temperatures and as-forged microstructure as the basis for validating the FEM model. While this type of comparison does provide an indication of the level of agreement between the model and the physical process, it is basically an indirect comparison. Even though the predicted surface temperatures may agree well with measured temperatures, it does not guarantee that the billet interior will match the predicted temperature distribution. Therefore, it is necessary to validate the model using direct measurements of billet temperature and metal flow.

To validate the FEM model, a controlled forging experiment was designed and carried out at Carpenter Technology to measure the billet temperature profile and material deformation. The surface temperatures were measured during each pass at 1.0 second intervals using optical pyrometers mounted at the entry and exit of the forging box. Surface temperatures are normally measured during forging and permit direct comparison with the DEFORM predictions for nodal temperatures at the surface. To measure the billet temperature profile after forging, a pyrometer was positioned adjacent to the abrasive cut-off saw as shown in Figure 1. Due to the possibility of the abrasive wheel fracturing during cutting, the pyrometer system was triggered from a remote location. Immediately after the workpiece end was cut off, the newly exposed surface was scanned by the pyrometer. The temperature profile was then stored using a data acquisition system to electronically record the temperature data.

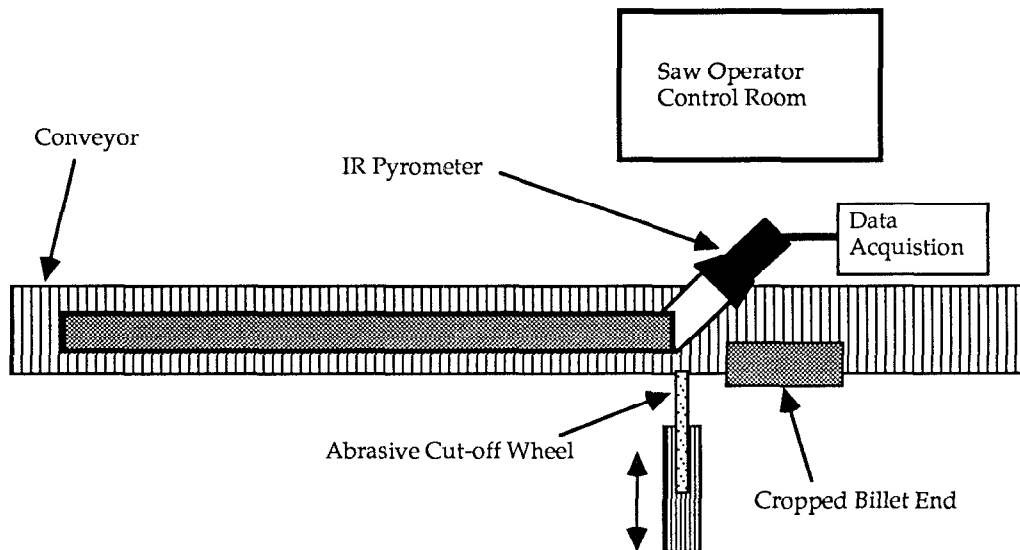


Figure 1. Pyrometer location for measuring the billet temperature profile after forging.

To measure the material deformation at the end of the third pass, two 25.4 mm diameter Pyromet 718 (Pyromet) rods which had been doped with a refractory based tracer material were press fit into the billet at 90 degrees to one another. To prevent the rods from shifting during forging, the surfaces of both inserts were

welded to the billet surface. In order to eliminate transient effects due to deformation at the billet ends, the rods were placed 1.06 and 1.21 m from the leading billet end. After forging and cooling to room temperature, the billet was ultrasonically scanned to locate the position of the deformed rods. The segment containing the deformed rods was removed from the billet and sectioned to characterize the shape of the plugs and to measure the average effective strain as a function of radial position.

Results

In simulating a multiple pass sequence, one of the difficulties encountered was the large number of man-hours required to simulate a single pass. Due to the large number of simulations which were required to model each pass, an automated routine was developed to significantly reduce the engineering time required for pre-processing. The routine enabled simulations to be run sequentially with no user interface time required for pre-processing. Results from the three pass forging sequence which was simulated are shown below. The simulations were performed on an IBM 340 Workstation running under AIX (UNIX) Operating System. Each simulation required approximately 6-8 minutes of CPU time to perform.

Effective Strain

The effective true strain prediction along the radial direction for the location corresponding to the first Pyromet insert is shown in Figure 2 for each of the three passes simulated. The highest strains predicted were near the billet surface while the lowest strains were predicted in the workpiece core.

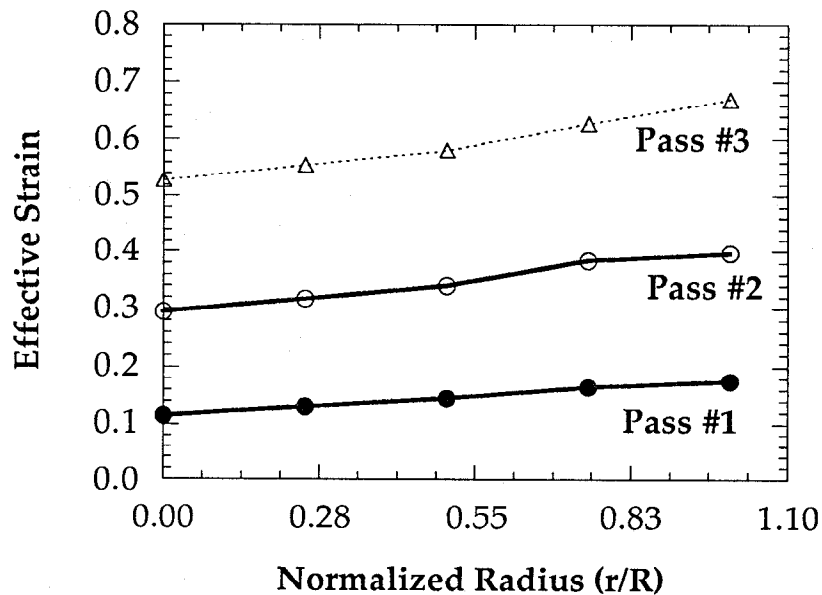


Figure 2. Predicted effective strains at elements corresponding to the location of the Pyromet rods (strains are cumulative).

The accumulated strain in the billet after the third pass is shown in Figure 3. With the exception of the billet ends, the variation in effective strain along the billet length is predicted to be negligible which is consistent with the steady-state nature of radial forging.

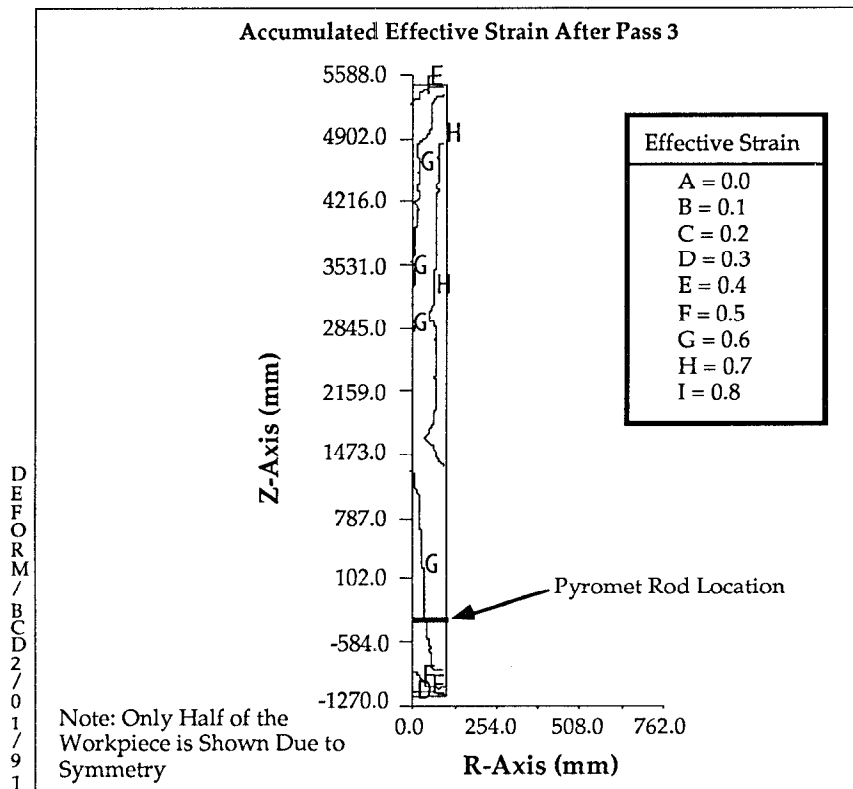


Figure 3. DEFORM predictions of accumulated effective true strain in the forged billet after three passes.

A comparison of the predicted and experimentally obtained effective strains after the third pass are shown in Figure 4. Reasonable agreement between the FEM model predictions and the experimentally measured strains may be seen between the predicted and experimental results. The strains in both rods were found to be equivalent at each radial location. From Figure 4 it may be seen that the DEFORM model slightly over predicts strain at the billet center and under predicts strain at the surface. This result is to be expected given the use of an axisymmetric deformation model where the material spread between the tools is neglected. Due to the fact that the tools are assumed to totally enclose the workpiece surface, the model will predict higher penetration at the billet core. The experimentally measured billet strains verify previous FEM predictions that the strain in the billet varies as a function of radial position. As seen in Figure 4, the effective strain is maximum at the surface and decreases towards the center of the workpiece. An indication of the uniformity of the strain imposed during radial forging is also evident from Figure 4. The effective strain measured at each of the inserts may be seen to be very close at each radial location.

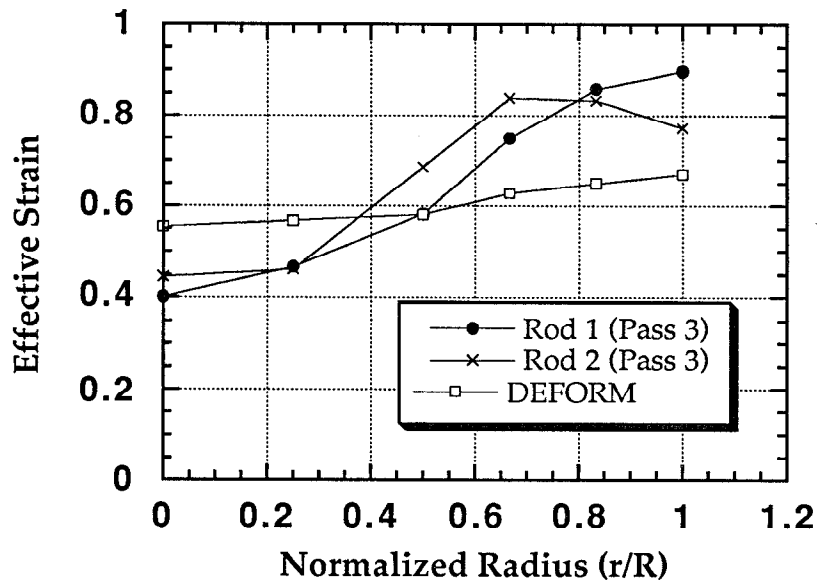


Figure 4. Comparison of predicted and measured strains in the forged billet.

Temperature

A comparison of surface temperatures predicted by DEFORM and the average surface temperatures entering and exiting the forging box is shown in Figure 5.

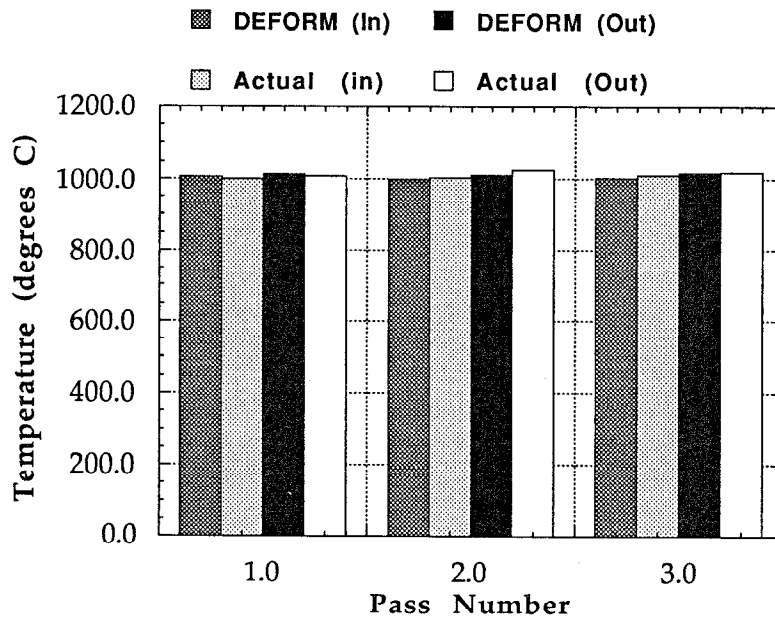


Figure 5. Comparison of predicted and measured surface temperatures of the billet during forging.

The difference between the predicted and measured surface temperatures for the second and third passes appears to be due to a decrease in the total emissivity of the billet after deformation. For the simulation, the total emissivity was assumed to remain constant at 0.4. The apparent change in emissivity may be the result of the oxide layer which initially forms during furnace heating being removed as a result of deformation. Removal of the oxide layer will change the surface condition and result in a lower emissivity until the oxide layer has had sufficient time to reform.

Temperatures along the radial direction were observed to increase during each subsequent pass for the pass schedule which was employed. The temperature profile in the billet after the third pass is shown in Figure 6. With the exception of the workpiece ends, little variation in temperature was predicted along the length of the billet. A comparison of the predicted and measured billet temperature profile at the cut-off saw is shown in Figure 7. Based on the results obtained, the model is seen to predict higher temperatures in the billet. The accuracy of the model formulation and the thermal data was verified by simulating the furnace heating cycle and comparing the predicted thermal profile to the thermocouple data. Predicted temperatures were found to be in excellent agreement with the thermocouple readings indicating that the pyrometer readings taken at the cut-off saw may be too low as a result of the rapid cooling of the end on being cut, incorrect emissivity setting on the pyrometer, or the change in emissivity of the newly generated surface.

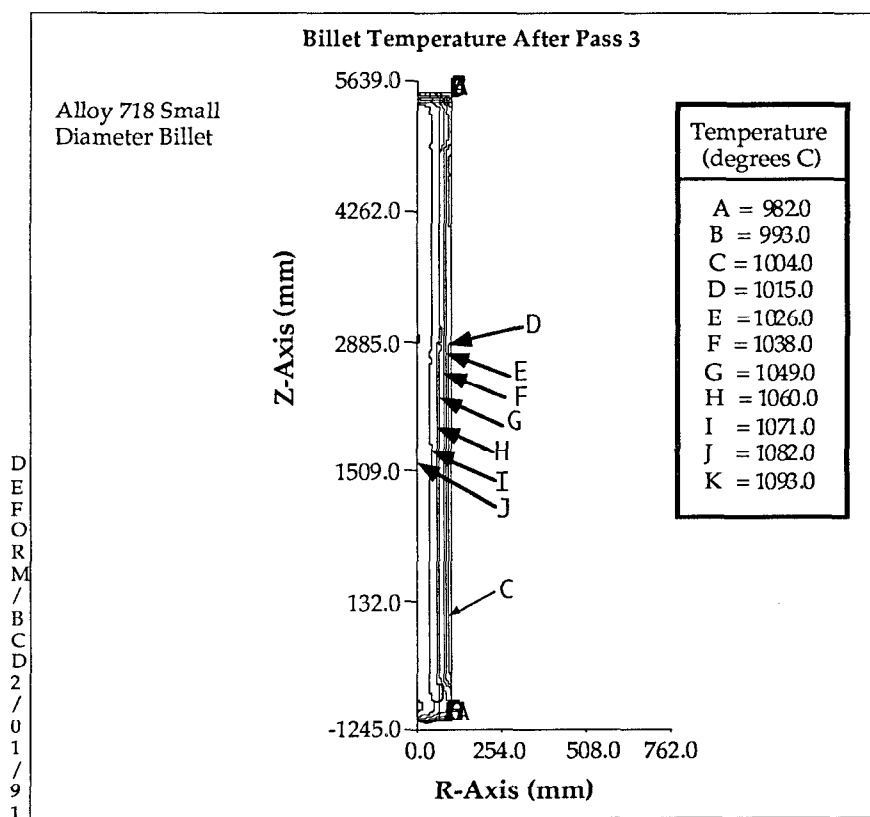


Figure 6. Predicted temperature profile in the billet after three passes.

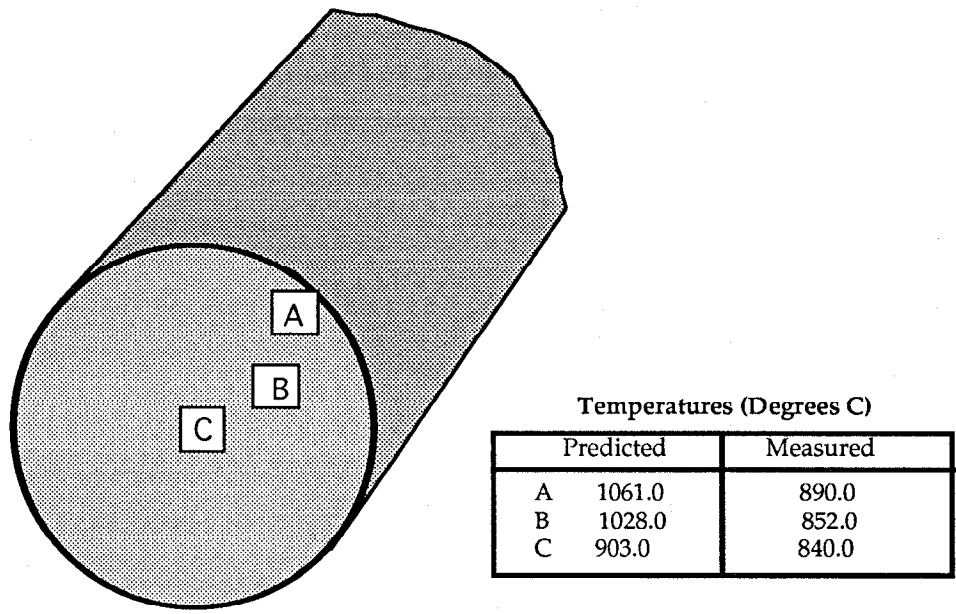


Figure 7. Comparison of measured and predicted billet temperatures at the cut-off saw.

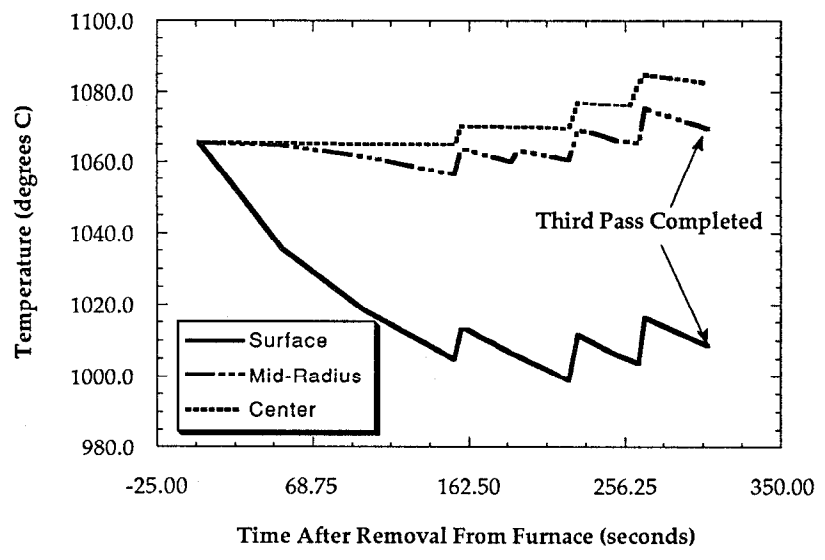


Figure 8. Predicted temperature history of nodal points corresponding to the location of the Pyromet rods during forging.

The above results also provide some insight into how microstructural gradients develop during forging. It has been reported that the as-forged grain size may vary in the radial direction [4]. Some insight to this may be obtained by examining Figure 8 which shows the temperature history of the billet after being removed from the furnace. For the billet simulated, the temperature predictions

show that a significant gradient is formed along the radial direction. It is also evident from the heat retained in the billet after forging that grain growth may occur during air cooling.

Conclusions

In forging of small diameter Pyromet 718 billet, the following observations can be made based on results of a FEM study and an experimental validation of radial forging:

- 1) With the exception of the billet ends, deformation is uniform along most of the billet length
- 2) The model validation confirms that the maximum deformation occurs at the billet surface with decreasing deformation in the billet core
- 3) Heating due to deformation is dominant in the billet core
- 4) Two-dimensional axisymmetric models underestimate strain at the surface and overestimate strain at the center of the billet
- 5) Deformation varies primarily as a function of radial position in the forged billet

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