Three-Dimensional Computer Simulation of Alloy 718

Ingot Breakdown by Cogging

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Abstract

A three-dimensional finite element analysis of the breakdown of cast alloy 718 ingot by cogging using an industrial process schedule was conducted. Six cogging passes were simulated for non-isothermal conditions and the predicted loads were compared to the loads recorded during industrial cogging practice. Microstructural models were implemented to predict the resulting microstructures as a function of local temperature, strain, and strain rate. These predicted microstructure values, which included percent recrystallization and recrystallized grain size, were compared with the industrial data.

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Introduction

Properties of a forged billet are dependent on the microstructures developed during cogging of the cast ingot. In order to successfully control the microstructure of the resulting billet, an optimized cogging schedule is critical. The use of computer modeling is ever increasing as a tool to optimize forging schedules. However, very few computer simulations have been performed for ingot breakdown processes [1-3], with most of them using a number of broad assumptions. For example, when Boyko et al. [1] modeled open die and radial forging of cast alloy 718 using the finite element modeling (FEM) software DEFORM™, they assumed axisymmetric conditions. While such an approach simplified the three dimensional problem, it also represented a significant approximation. The study conducted by Jackman et al. [2] developed a 3D model for simulating round forging, but also used many restrictive assumptions in an attempt to simplify the analysis.

Recently, prediction of microstructures after forging has become a focus area of FEM applications. Domblesky et al. [3] conducted a finite element simulation of multiple pass radial forging of wrought alloy 718 billets using axisymmetric conditions. Radiation was recognized as the primary mechanism for heat loss and temperature distribution after deformation was used for verification. In a subsequent work, Domblesky et al. [4] used the following equation to predict grain size:

$$\log d_{gs} = a\sqrt{\varepsilon} + \log s$$

where d_{gs} is the ASTM grain size number, s is the starting ASTM grain size number, ε is true strain, and a, typically a value between 0.3 and 0.6, is a constant dependent on temperature and time per pass. However, the above equation was developed for wrought material, and is not appropriate for cast material going through initial ingot breakdown steps because the mechanisms for grain refinement are different.

The objective of the present work was to conduct a FEM analysis of the cogging process for cast alloy 718 using assumptions that create a close representation of the actual open die or radial forging process. In addition, microstructural models were implemented to predict the microstructure resulting from cogging, in terms of percent recrystallization and grain size.

Finite Element Modeling

A finite element model was constructed using the commercially available forming simulation package, DEFORM3D™. A quarter of the ingot was modeled taking advantage of the symmetry and using brick elements. Dies were modeled as rigid surfaces with heat transfer capability. Flow curves generated by testing the material at various temperatures and strain rates [5-6] were used to describe the constitutive behavior of the workpiece. Related thermophysical properties were either obtained from the literature [7-8] or provided by Inco Alloys International. The coupled thermomechanical simulation was conducted using a commercial forging schedule provided by Inco Alloys International. As identified in Domblesky's investigation [4], radiation was the major form of heat loss in this operation.

Figure 1 shows the die set-up and the meshed initial billet containing 1333 elements and 1804 nodes. With 10 to 15 strokes per pass and six passes in total, the modeling process was very time consuming. Typical results obtained for parameters such as temperature, strain, and strain rate are shown in Figures 2 through 4.

DEFORM and DEFORM3D are trademarks of Scientific Forming Technologies Corporation, Columbus, OH.

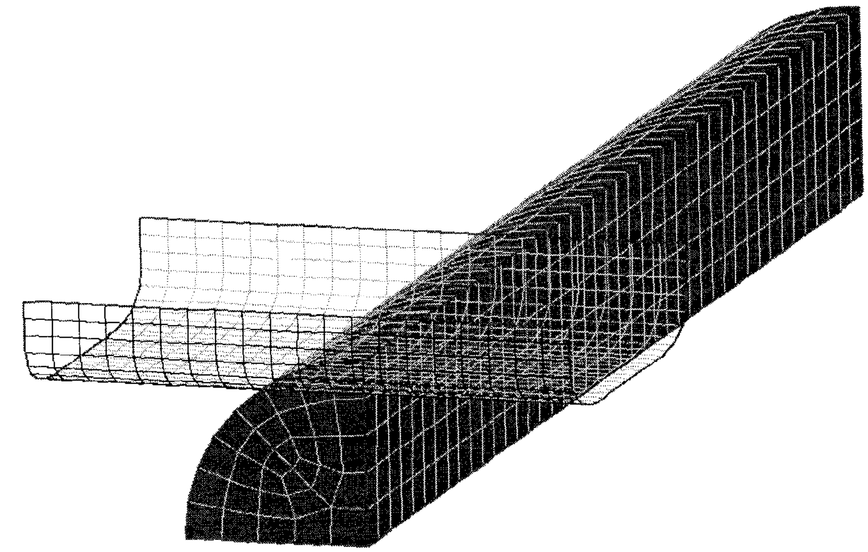

Figure 1 - The initial mesh and die set-up for cogging of alloy 718.

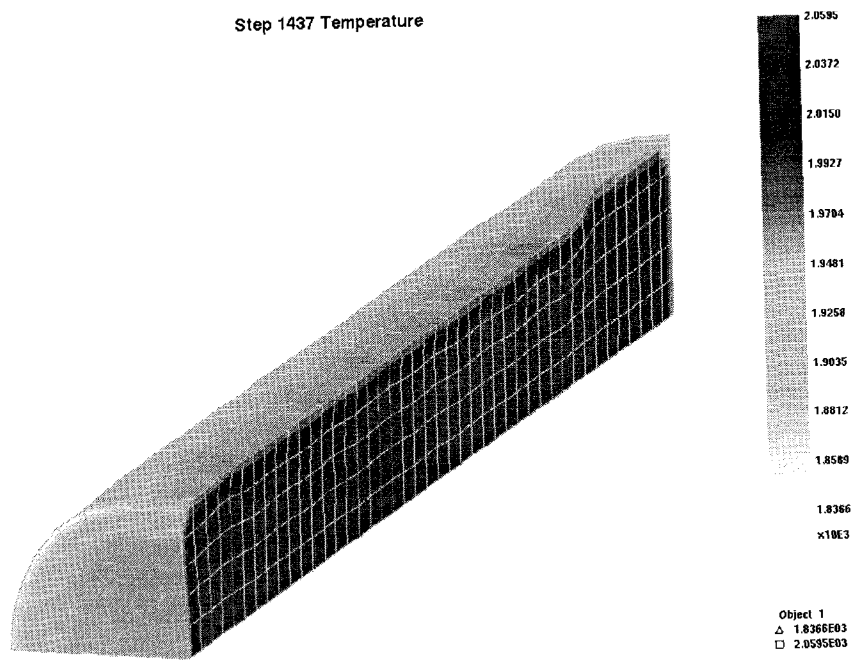

Figure 2 -Temperature contour in the workpiece at Step 1437.

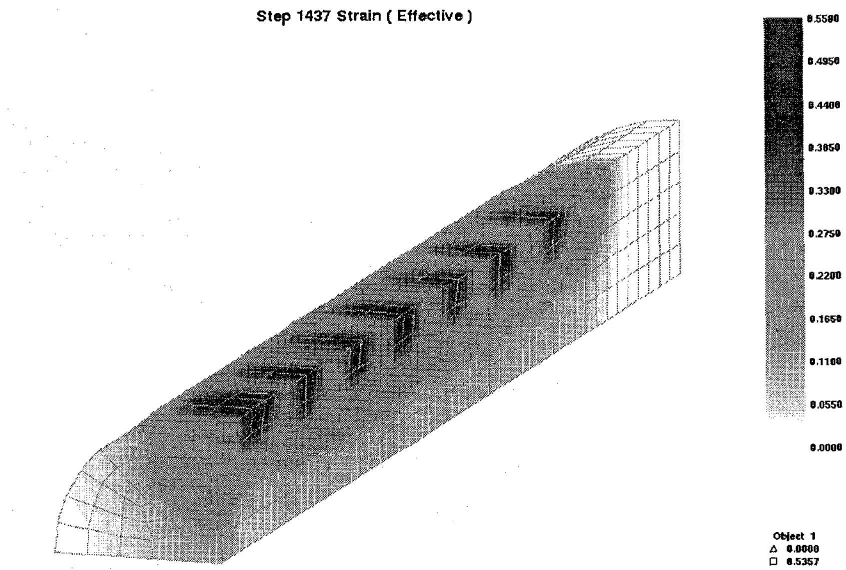

Figure 3 - Equivalent strain contour in the workpiece at Step 1437.

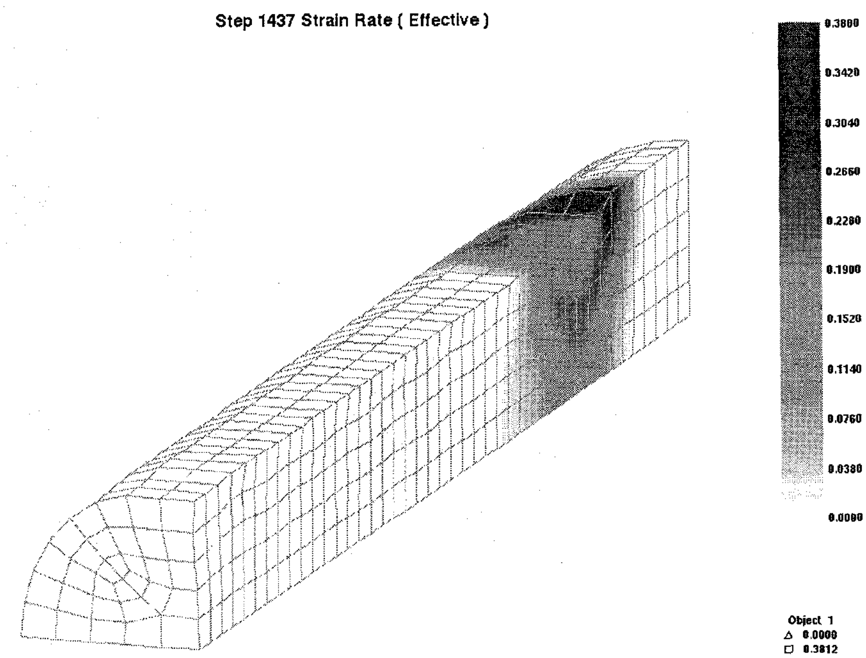

Figure 4 - Strain rate contour in the workpiece at Step 1437.

A software called TMP Viewer was developed in-house (Concurrent Technologies Corporation) to interpret and display FEM results. Equations describing the microstructural evolution of cast alloy 718 during cogging [5] were implemented in TMP Viewer with data interface to DEFORM3D™. Using this software, the microstructural features, such as grain size and percent recrystallization, could be visualized by interpreting the post-processing results from the FEM simulations. Figure 5 shows grain size prediction on a cross section of the forged ingot, which was located 1016 mm from the toe end.

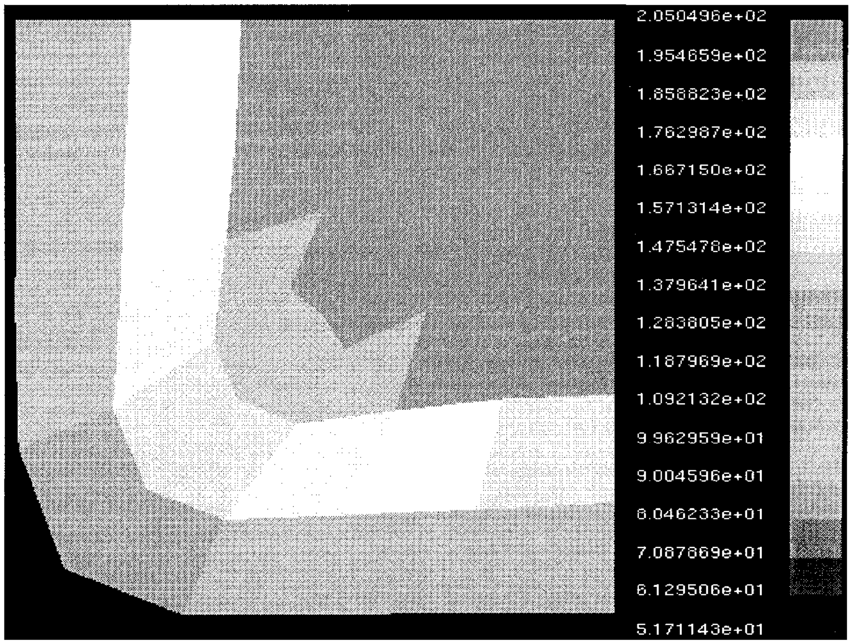

Figure 5 - Prediction of grain size on a cross section of the forged ingot, located 1016 mm from the toe end.

Experimental Validation

The results from the modeling work carried out in this study were validated by a full-size ingot cogging operation performed using an industrial process schedule. The cogging procedure, results, and their comparison to the model predictions are described in this section.

Cogging Practice

The cogging operation was performed by Inco Alloys International in Huntington, West Virginia. A cast alloy 718 ingot of 2159 mm length and 508 mm diameter was forged into a billet of 2971 mm length and 381 mm Round-Cornered Square (RCS) section in six passes. A discussion on the starting microstructure of a typical ingot is beyond the scope of this paper and can be found elsewhere [5-6].

A 5,000-ton hydraulic press was employed for the cogging operation. A manipulator was used at each end to handle the ingot during cogging. The ingot, which was heated to 1120°C, experienced a proprietary homogenization treatment before forging. During cogging, the workpiece was turned 90 degrees between each pass. The bite ranged from 14 to 72 mm, and the stroke along the piece ranged from 203 to 229 mm. Ram velocity was maintained at 76 mm/s and the dwell time between passes at 3 s. In order to maintain consistency, the forging passes always started from the toe end of the ingot.

Microstructural Results

After forging, the ingot was cut at three sections; nominally located at 1020 mm (Section M) and 130 mm from the toe end, and 230 mm from the head end. Macrostructural and microstructural examinations were performed on these sections. The examinations showed similar trends for all three sections. However, the values of parameters such as grain size were different. Figure 6 shows a macrograph for Section M. The outer layer of the ingot (about 20-25 mm in depth) was only partially recrystallized, while most of the interior had completely recrystallized (as shown in a sketch in Figure 7), mainly due to friction and temperature gradient. Deformation heating also contributed to this temperature gradient. The temperature at the center sometimes exceeded the initial holding temperature before cogging due to the adiabatic heating effect as predicted by the numerical simulation. Figure 8 shows the micrographs taken at four different locations of Section M. It illustrates the fact that recrystallized grain size increased from the surface to the center, in agreement with the formulation established in a companion paper [5], indicating that grain size increases with increasing temperature.

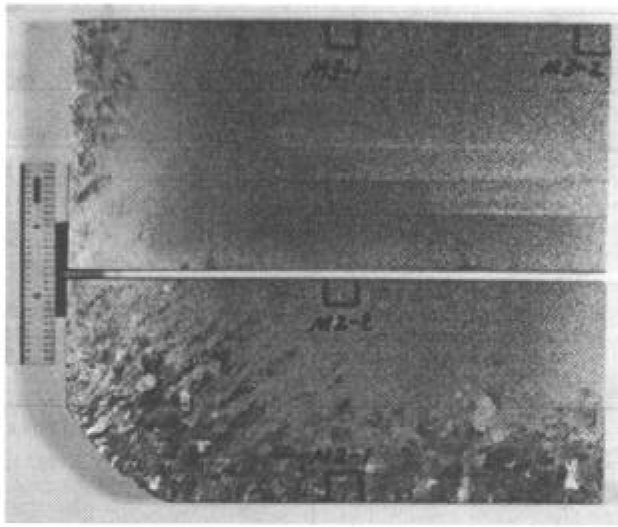

Figure 6 - Macrograph for Section M, located 1016 mm from the toe end of the ingot.

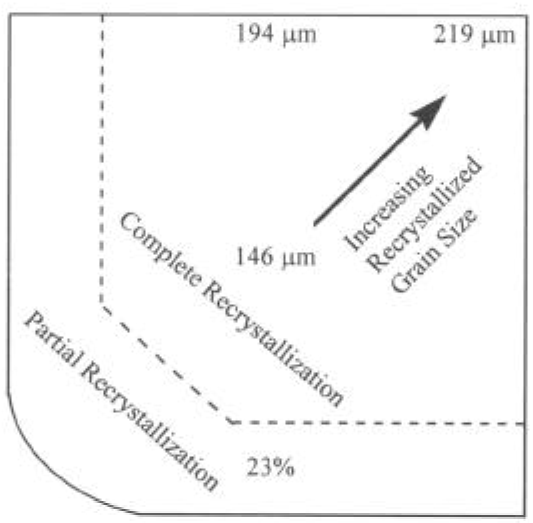

Figure 7 - A sketch of the grain size results for Section M.

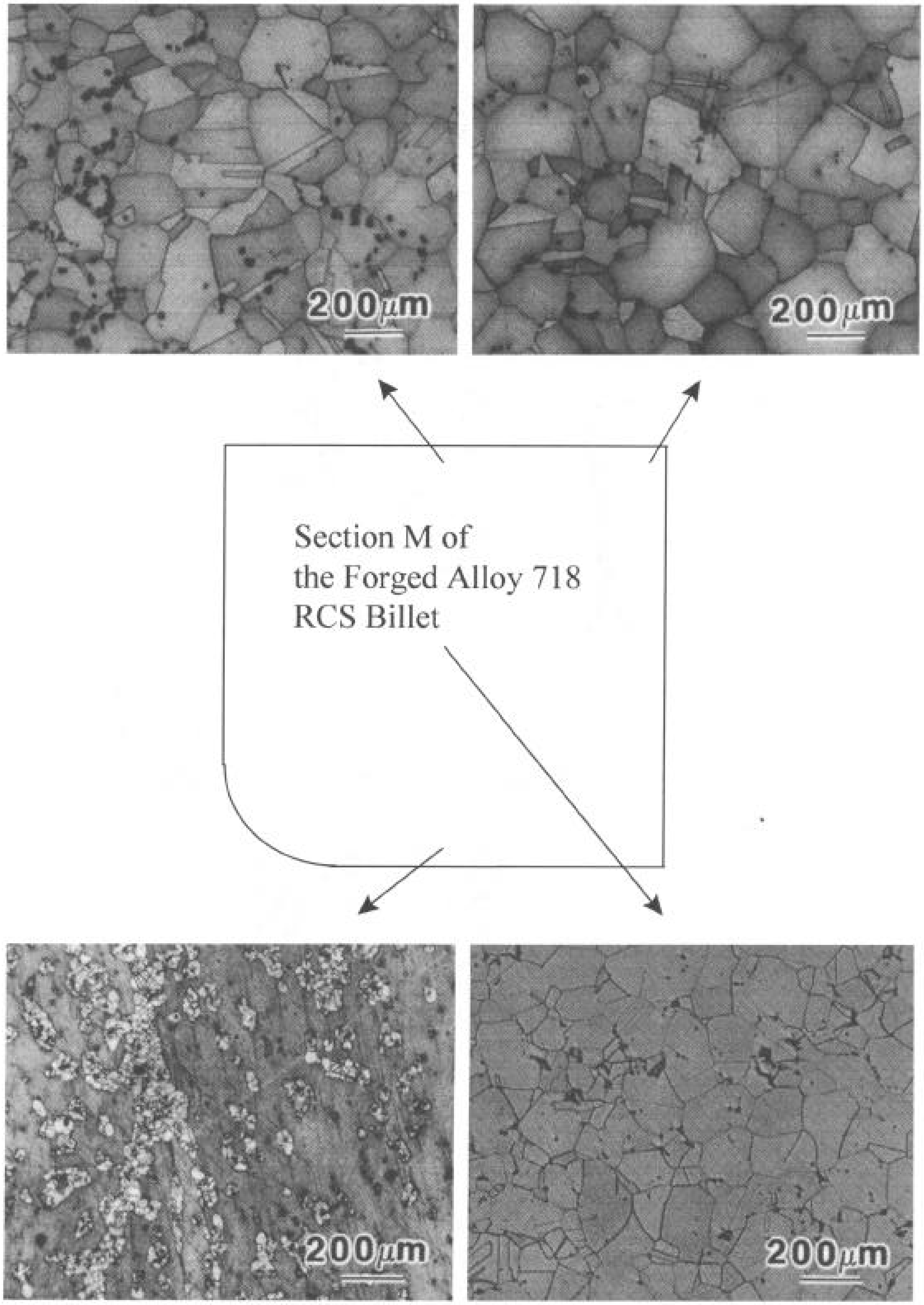

Figure 8 - RCS billet microstructures at four different locations on Section M.

Comparison of Experimental Cogging Results and Computer Predictions

During the cogging experiment, the maximum load for each pass was recorded. Figure 9 shows how these loads compared to the FEM-predicted loads. The variation seen in the comparison could be due to the procedure used to collect data for the material model development. Single-hit tests conducted on the as-cast material were used to collect the required material information. However, during the cogging operation recrystallization eventually occurs, resulting in flow softening. This softening may not be accounted for fully by the material flow data, which would explain the over-estimates of the load by the model for the last three passes.

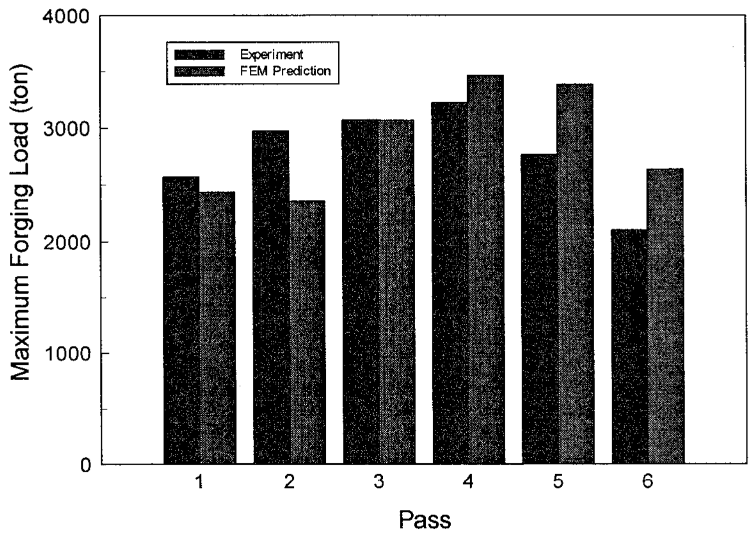

Figure 9 - Comparison of maximum load from the FEM prediction and the experiment.

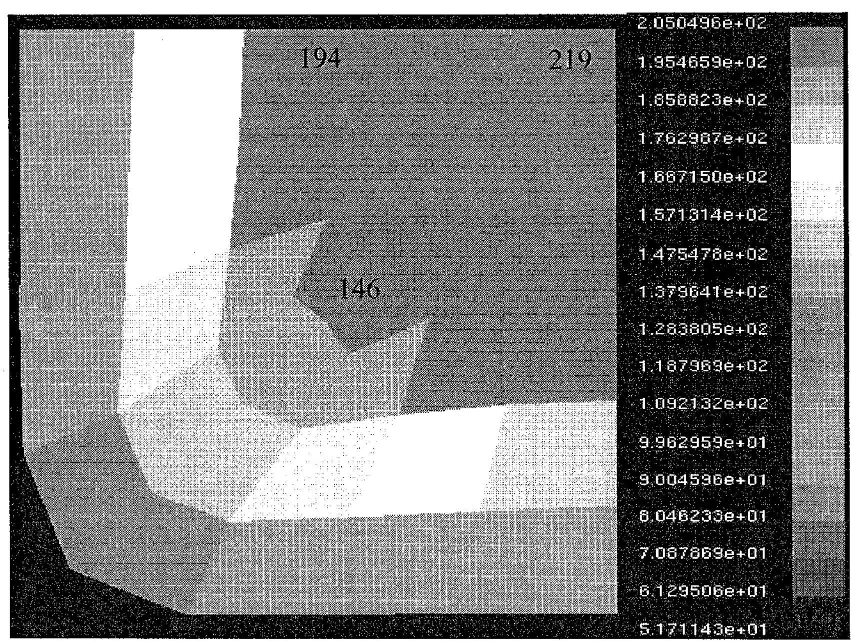

Figure 10 - The grain sizes predicted based on the finite element simulations (shown as contours) and the experimental results (shown as numbers) for Section M.

The microstructures in the cogged ingot were compared to those predicted by computer simulation. Figure 10 shows the grain size predicted by finite element simulation (shown as contours) and the experimental results (shown as numbers) for Section M. The grain size at the center is predicted to be on the order of 200 microns, in general agreement with the experimental observation. At the border between the fully and partially recrystallized region (identified by a dotted line), the predicted grain size ranges from 118 to 147 microns, again in reasonable agreement with experimental observation. Figure 11 shows that the FEM simulation correctly predicts the existence of the partially recrystallized outer layer. In addition, it predicts a percentage of recrystallization of 18 to 31 % in that layer, in general agreement with the measured 23%.

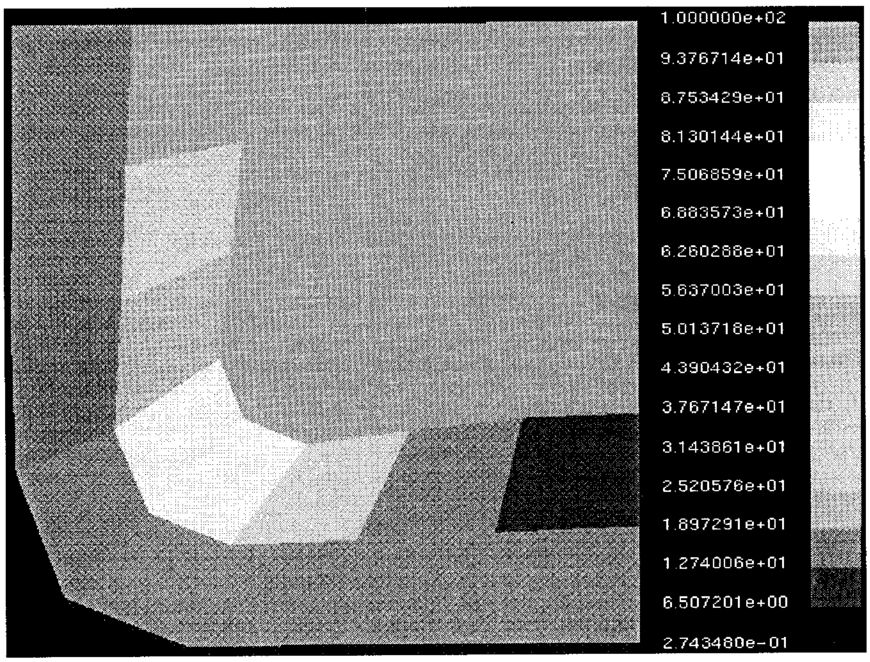

Figure 11 - The percent recrystallization predicted by the computer, showing similar results as in Figure 7, with a partially recrystallized outer layer.

Summary and Conclusions

A cogging process for ingot breakdown of alloy 718 has been analyzed numerically using the finite element modeling technique. Mathematical models describing the static recrystallization process of cast alloy 718 ingot were implemented by interfacing them with the finite element modeling package, allowing visualization of predicted microstructural features, such as percent recrystallization and recrystallized grain size. The predicted forging loads and microstructures were in good agreement with the results obtained from the cogged billet.

Acknowledgment

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