2-1/2D COMPUTER MODELING AND VERIFICATION OF FORGED PYROMET 718® ALLOY INGOT

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Abstract

Finite element analysis of open-die forging as-cast Pyromet 718 alloy round ingot into octagonal shaped billet in six passes was performed using the commercial code DEFORM-PC®*. The simulation was conducted under non-isothermal conditions to predict strain, strain rate, and temperature distributions in the ingot cross section during forging. As-cast cylindrical compression specimens were subjected to the thermomechanical history of selected areas in the ingot using the Gleeble 1500 thermal-mechanical testing machine. The resulting microstructures were compared to those of a press-forged billet. A good agreement was found between the simulated and actual microstructures developed in the forged billet. The results indicate that the combined computer and physical modeling can be used effectively to predict billet microstructure in open-die forging operation.

*DEFORM is a registered trademark of Scientific Forming Technologies Corporation

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

Pyromet 718 alloy has been widely used in the manufacture of critical components of gas turbine engines, such as discs and blades, due to its excellent physical and mechanical properties especially in relatively high operating temperatures. High temperature fatigue resistance is a primary requirement for turbine discs while a high temperature creep resistance is required for turbine blade application. These applications require a strict control of microstructure as to grain size distribution and its uniformity.

The manufacture of a forged disc starts typically with the primary melting of electrode by vacuum induction melting (VIM), followed by electroslag re-melting (ESR), vacuum arc remelting (VAR), or a combination of ESR/VAR for ingot re-melting. These operations [1] are designed to provide ingots with chemistry and structure superior to those of primary electrode although the ingots in this stage usually has a coarse and non-uniform grain structure. The refinement of as-cast structure is achieved by ingot to billet breakdown by cogging usually on an open-die forging hydraulic press. The cogging procedure comprises of several forging operations to reduce the cross-section into octagonal, square or round shape by elongating the ingot. With re-heating between any two successive operations. At the disc forgers the billet is then cut into mults (preform), reheated and closed-die forged ,with a limited amount of hot work, into a disc. As it is well known, the properties of this component depends primarily on the forged billet microstructure developed during the primary ingot breakdown. Therefore, it is essential for the billet suppliers to optimize and control their primary forging operation.

In recent years, computer modeling has been increasingly used as a powerful tool to analyze and optimize the open-die forging operations instead of the classical trial-and-error approach. However, there have been few computer modeling studies starting from as-cast ingot. Axisymmetric conditions were assumed in modeling radial forging by Boyk [2], Jackman [3], and Domblesky [4]. Zaho [5] analyzed a cogging process of ingot breakdown by finite element modeling and implemented a mathematical model [6] for static recrystallization to predict microstructure evolution. Antolovich [7] presented a 3D computationally intensive finite element model and analyzed the effect of process parameters on microstructure evolution in Udimet® alloy 718.

The objective of this work was to model the breakdown of as-cast Pyromet 718 alloy ingot on an open-die forging press into an octagonal shaped billet using the finite element analysis program DEFORM-PC and predict the resulting microstructure by physical simulation on the Gleeble 1500, thermal-mechanical testing machine.

Process Modeling

As it was stated in the introduction , the modeling of the cogging process is necessary to analyze and optimize the open-die forging process instead of the trial and error approach. The understanding of the process and its variables is of great importance to develop a forging model to obtain the desired billet shape and properties. The process modeling tasks in this paper are divided into numerical modeling and physical simulation.

Numerical Modeling of Ingot Breakdown

The DEFORM-PC finite element simulation package was used to develop the forging model. Since the code is limited to plane strain and axisymmetric geometry, the transverse section of the ingot was modeled. Figure 1 shows the initial breakdown model of 508-mm as-cast Pyromet 718 alloy ingot. The forging dies are assumed to be rigid and preheated before the start of forging. The as-cast material flow at different temperatures and strain rates to describe the constitutive behavior as well as the thermophysical material properties were obtained from the literature [8,9].

To simulate the primary breakdown process in 2-1/2D, to account for the reduction in area in each pass, a strain rate in the direction of ingot axis was estimated using the following formula:

$$\dot{\varepsilon}_z = \frac{1}{\Delta t} \ln \frac{A_{n-1}}{A_n}$$

where: A_{n-1} and A_n are the areas of the cross section before and after the pass. Δt is the cogging time per stroke in seconds. The forging process of a 508-mm ingot into a 432-mm octagon shaped billet was simulated in a total of six passes under non-isothermal conditions, including billet cooling after forging.

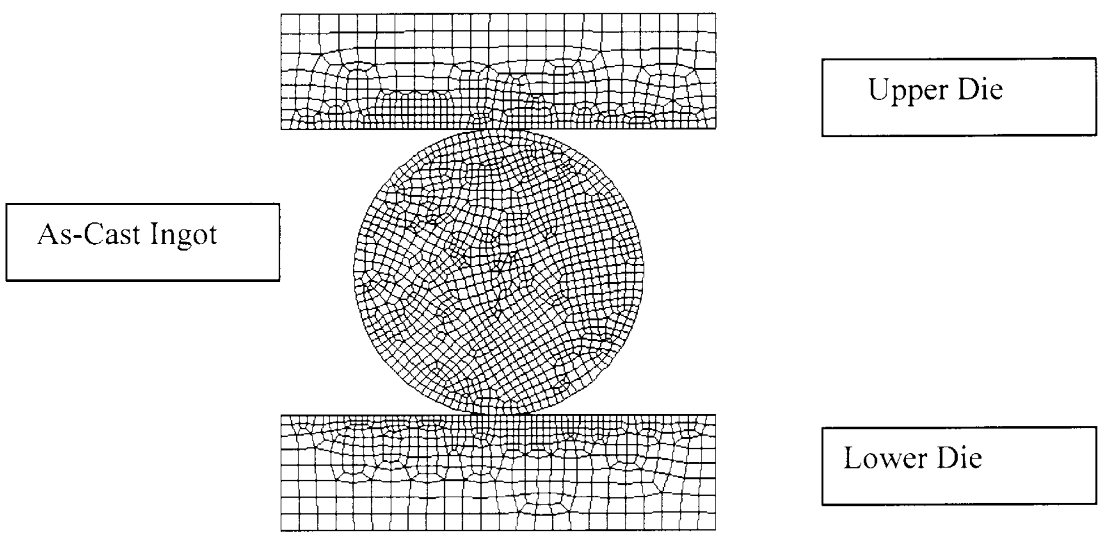


Figure 1: Initial FE Model of Ingot Cogging .

The predicted strain distribution in the billet cross-section is presented in Figure 2. As it is seen, a strain gradient is observed as in upsetting, lower strains in the areas adjacent to the dies and higher strains towards the center. The strain rate contour predicted during forging is illustrated in Figure 3. Figure 4 shows the temperature distribution in the billet cross-section with a predicted temperature gradient from the center to the billet surface.

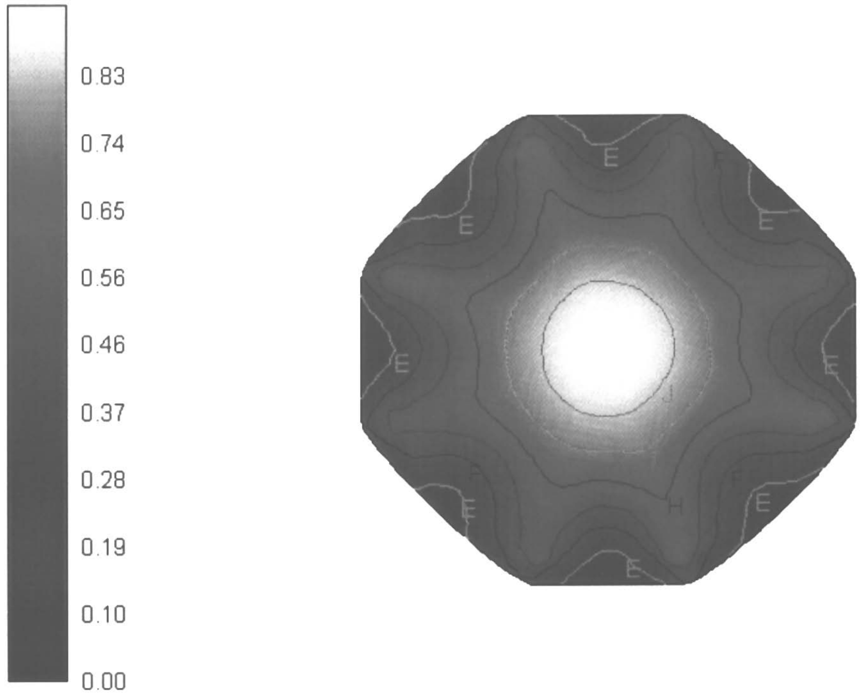


Figure 2: Effective Strain Contour in Forged Octagon.

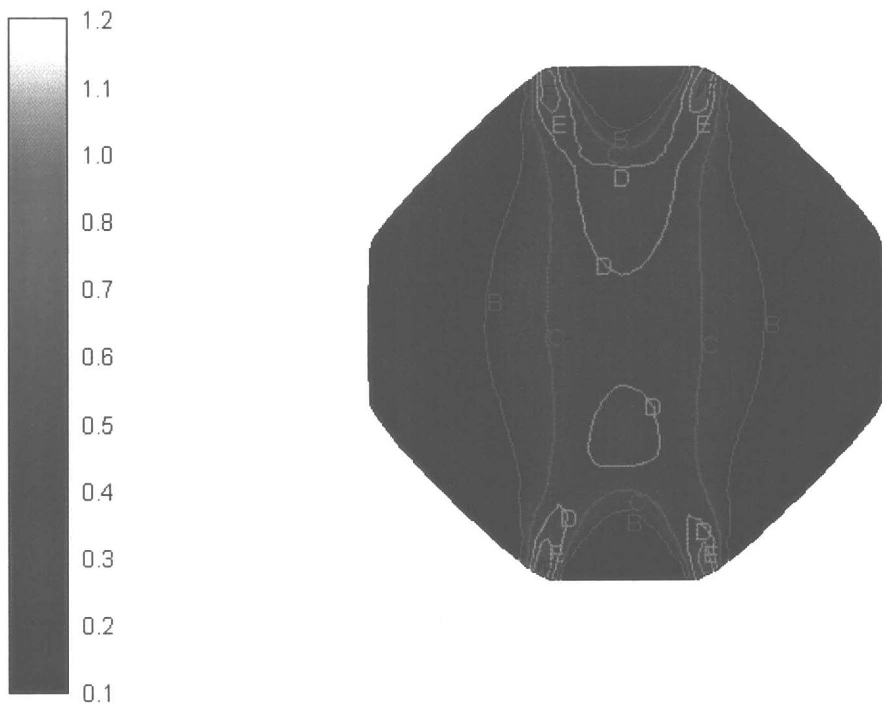


Figure 3: Strain Rate Contour in the Octagon Billet during Forging.

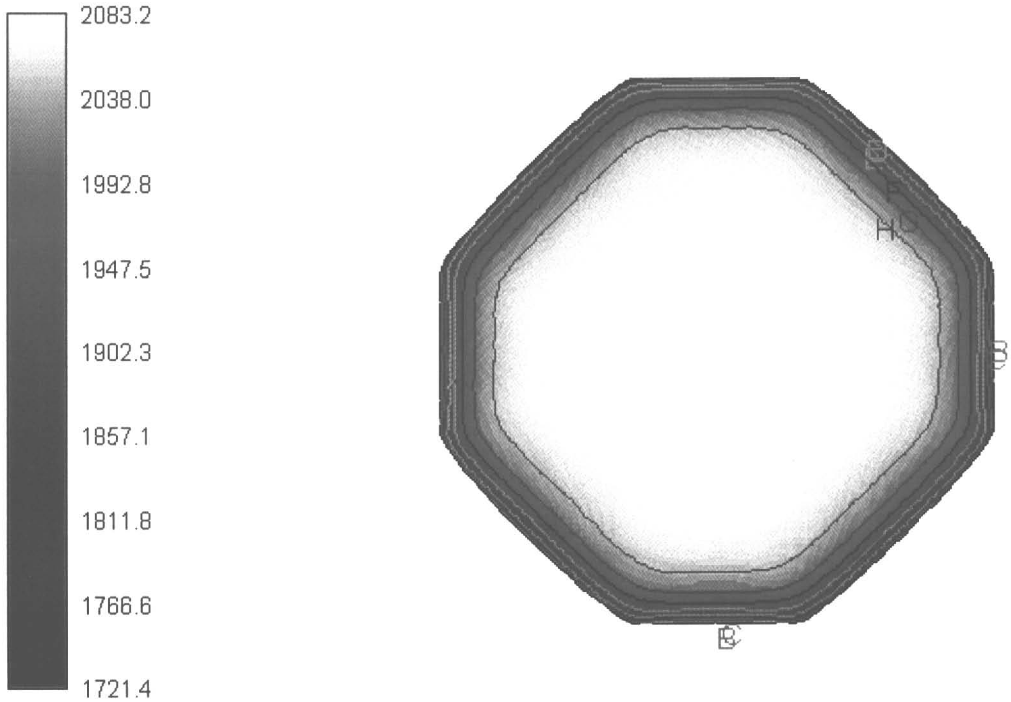


Figure 4: Temperature Distribution in the Forged Billet.

Physical Simulation on the Gleeble 1500

The experimental primary open-die forging operation of as-cast Pyromet 718 alloy, 508 mm round ingot, was physically simulated on the Gleeble 1500 thermomechanical testing machine. Square cross-section 15 mm x 15 mm x 100 mm blanks were cut in the radial direction from the as-cast Pyromet 718 alloy disc. The blanks were subjected to a proprietary homogenization cycle used at Carpenter Technology Corporation. After cooling to room temperature, the blanks were machined to provide compression samples of 10 mm diameter x 15 mm long with its axis coinciding with the ingot radial direction subjected to open-die forging. Platinum-platinum rhodium thermocouple 0.254 mm diameter wires were percussion welded at mid-length of the specimen to monitor and control the temperature during physical simulation of the ingot breakdown.

Since the compression specimen is resistance-heated on the Gleeble by a flowing electric current, an isothermal plane across the diameter is maintained during heating or cooling, but a longitudinal temperature gradient exists along the specimen with higher temperature at sample's mid-length. To reduce this temperature gradient, a set of ISO-T^{TM} anvils developed by Dynamic Systems Inc. was used in this simulation. To reduce friction and minimize the sample barreling during the course of simulation, a graphite foil was placed between the tungsten carbide anvils and the specimen. The simulation was carried out on the Gleeble under argon protective atmosphere.

The thermomechanical history of points at the billet's center, mid-radius, and surface was generated using the point tracking feature of DEFORM-PC post processing. The thermal history of the selected points includes billet cooling to 954 ^{O}C to simulate grain growth after cogging [10].

Breakdown Experiment

Vacuum Induction Melted followed by Vacuum Arc Remelted 508 mm (20 inch) diameter Pyromet 718 alloy ingot was used in this investigation for the cogging experiment. The chemical composition is given in Table I.

Table I

Typical Chemical Composition of Pyromet 718® alloy in Wt. %

Element	Wt. %
C	0.035
Cr	18.30
Mo	3.05
Cu	0.04
Al	0.48
Ti	0.98
Cb+Ta	5.20
Fe	18.90
Ni	Balance

The ingot was homogenized according to a proprietary Carpenter heating practice before cogging. The 3000-Ton hydraulic press was used to forge the ingot into an intermediate 432-mm octagonal shaped billet in 6 passes. At the end of each pass, the ingot was turned 45 or 90° by means of a manipulator until the octagon billet was formed. The depth of penetration during ingot forging was between 12.5 to 76 mm, while the longitudinal ingot advance varied from 178-203 mm between each bite. After forging, the ingot was air cooled to room temperature.

Microstructure Verification

Two 125-mm thick discs were cut from the octagonal billet for macrostructure and microstructure evaluation. The first disc was cut 100 mm from the toe end and the second was 500 mm from the same end. Macrostructure evaluation revealed that most of the cross section had recrystallized, while the billet area near the surface was only partially recrystallized. This is mainly due to the existence of temperature and strain gradients from the center to the surface. The temperature at the center of the billet exceeded the initial ingot temperature due to the adiabatic heating generated during forging, while the surface temperature decreased due to radiation heat loss.

The microstructures from the experimental cogged billets were compared to the physically simulated samples on the Gleeble 1500 thermomechanical testing machine. Figure 5 shows the initial microstructure of the as-cast homogenized Pyromet 718 alloy Gleeble sample. Figures 6, 7, and 8 represent the actual billet microstructure at the center, mid-radius, and surface, compared to those predicted by physical simulation. As can be seen from these figures, there is a good agreement between the actual billet microstructures and those predicted by physical simulation on the Gleeble 1500. It is also observed that the forged billet center has recrystallized extensively compared to its surface which is partially recrystallized. This can be explained by the results of finite element modeling, which predicted higher strain generated at the center compared to the surface.

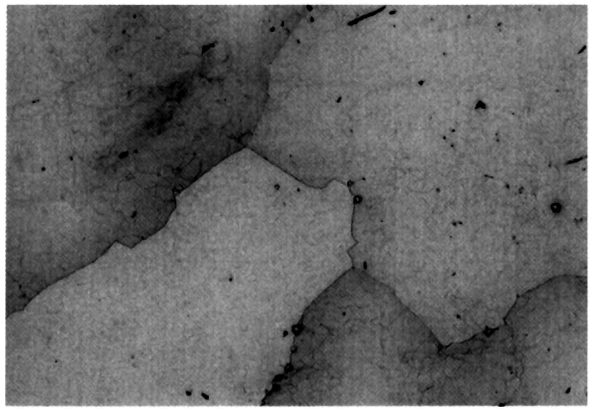
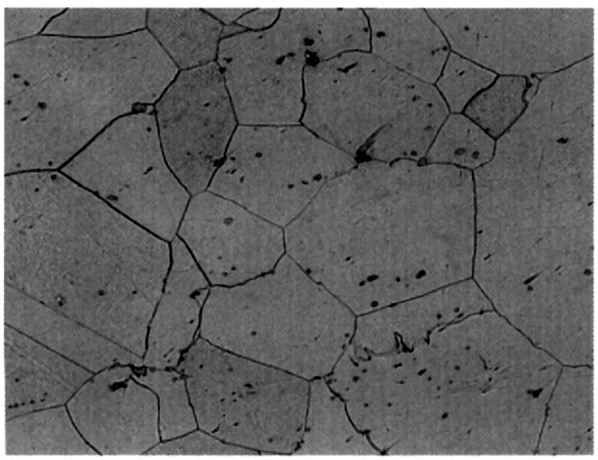


Figure 5: Microstructure of as-cast homogenized Pyromet 718 Alloy Compression Specimen.



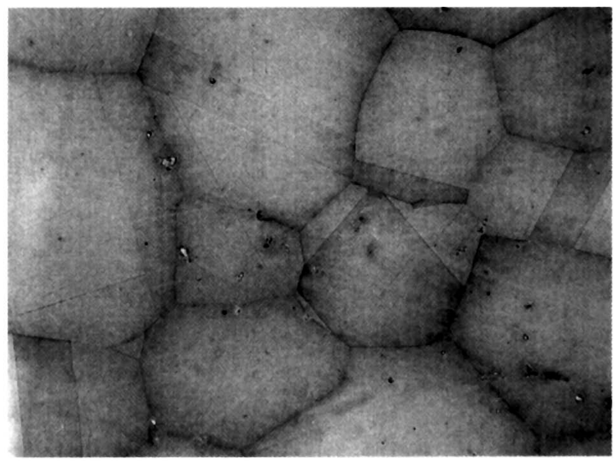
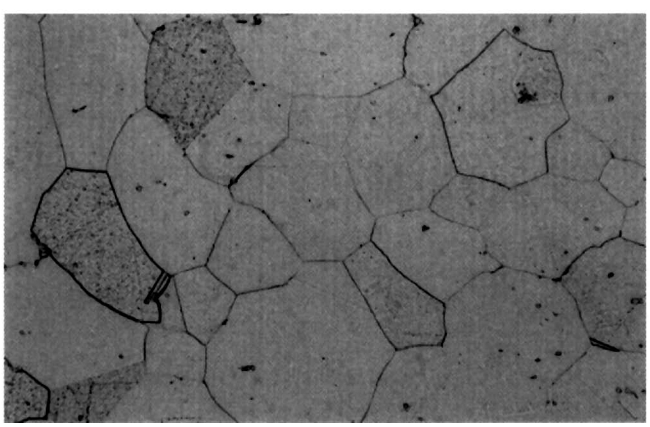


Figure 6: A comparison Between (A) Simulated Gleeble Specimen Microstructure and (B) Actual Microstructure of Billet Center.



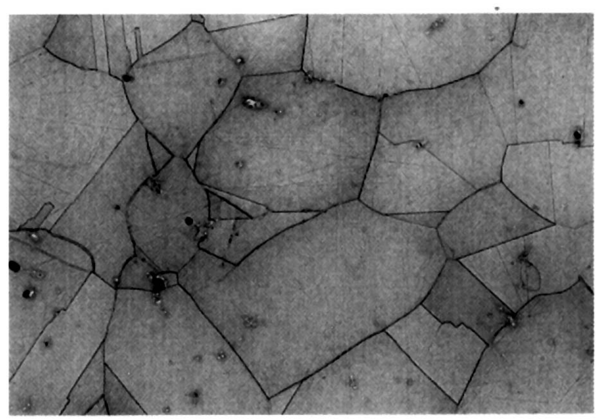


Figure 7: Microstructure of (A) Gleeble Specimen Simulating mid-radius location Compared to (B) Actual Cogged Billet .

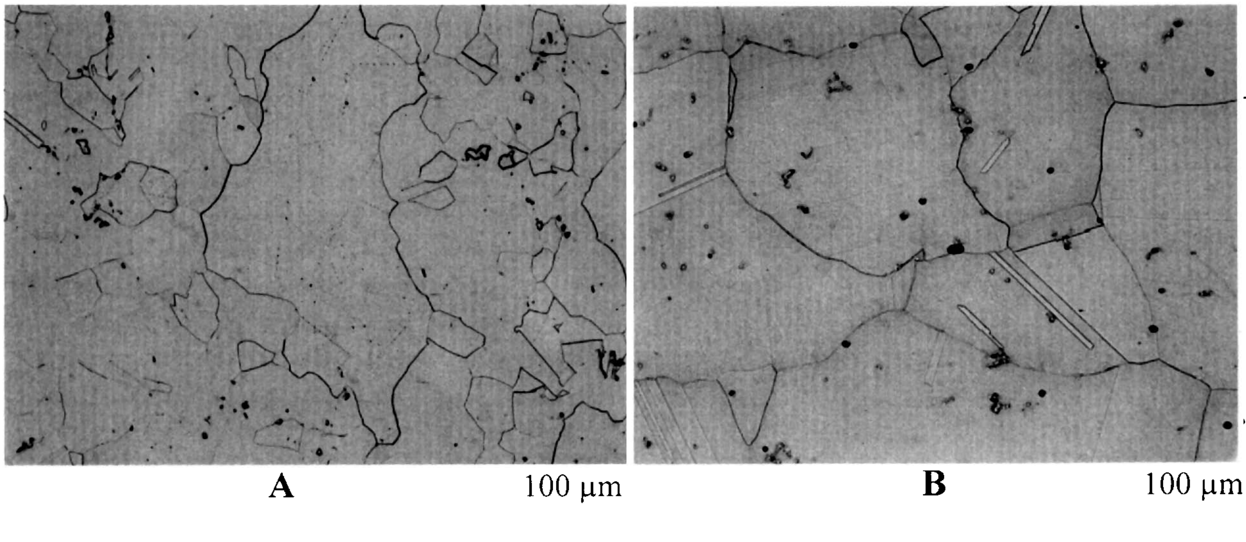


Figure 8: Predicted Surface Microstructure (A) Compared to Actual Surface Location on the Cogged Billet (B).

CONCLUSIONS

This work has demonstrated that the breakdown of as-cast round ingot into an octagonal shaped billet can be numerically modeled in 2-1/2 D by assuming a strain rate value in the direction of ingot axis to account for ingot area reduction. By using the thermomechanical history of selected areas of interest in the cogged billet and starting with as-cast homogenized cylindrical specimens, the microstructure evolution can be simulated successfully on the Gleeble 1500. A good agreement was observed between the simulated and actual billet microstructures.

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