EVALUATION OF AN INCONEL® ALLOY 718

MICROSTRUCTURAL EVOLUTION MODEL

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Abstract

The purpose of this study was to evaluate a 2D finite element forge model. The code incorporates a microstructural model for prediction of recrystallized volume fraction and recrystallized grain size. Because the model assumes plane strain deformation, flat rolling provides a potential method for evaluating the microstructural model. Pilot mill rolling experiments were conducted with deformation temperatures ranging from 925°C (1700°F) to 1150°C (2100°F) and a maximum draft of ~75%. The analysis of results focused on the onset of recrystallization and predictions for partial recrystallization in INCONEL® alloy 718. The model predicts the onset of recrystallization reasonably well for most temperatures. An accelerated recrystallization rate to a fully recrystallized structure is predicted compared to experimental results.

Introduction

A model for predicting the microstructural evolution of INCONEL® alloy 718 during thermo-mechanical processing would provide a valuable tool to industries supplying material or manufacturing gas turbine engine components. Alloy 718 applications require stringent control of microstructure with an emphasis on grain size and uniformity. Often it is difficult to impart the required microstructure in the later stages of component processing due to the complexity of the final shape. Consequently, the required grain size must be generated during primary or intermediate processing. Therefore, the suppliers of alloy 718 stock are increasingly required to supply material which meets microstructural specifications.

In an attempt to meet these requirements, one can employ process models to provide a method for optimizing process parameters to produce the desired microstructure. The forging process represents a challenging task for developing a process model for microstructural predictions. During forging, the material is deformed over a range of strains, temperatures and time between deformations, leading to complex time-temperature-deformation histories. The deformation path can vary with location and is not conducive to generating a uniform microstructure. Finite element methods can address the thermo-mechanical analysis of the process. However, a coupled thermo-mechanical-microstructure model is a current topic being investigated by several researchers [1-6].

One such effort is being conducted at the Interdisciplinary Research Centre, located at the University of Wales Swansea, U.K. Inco Alloys International (IAI) is supporting this effort to develop a microstructural evolution model tailored for the forge process. Currently, a 2D model which assumes plane-strain deformation has been developed. Because the plane-strain assumption is not valid for the shapes involved with the forge process, flat rolling provides an alternative process for evaluating model predictions. In this paper, the results of flat rolling experiments will be presented and compared to predictions generated by the microstructural model.

Hot Rolling Experiments

Material used in this investigation came from two alloy 718 vacuum induction melted and subsequently vacuum arc remelted ingots. Chemical composition for each ingot is given in Table I. Homogenized ingots were hot rolled to a 152mm (6 in.) x 203mm (8 in.) billet. Material for the hot rolling experiment was cut from the billets and heat treated at 1120°C (2050°F) for 2 hours. The resulting microstructure had a uniform equiaxed grain size of ASTM ½. Figure 1 shows the microstructure of the heat treated material. Coupons for hot rolling were approximately 102mm (4 in.) wide by 152mm (6 in.) long with the initial thickness in the range of 25mm (1 in.) to 38mm (1.5 in.).

Hot rolling experiments were performed on a pilot mill in IAI's Technology Processing Center (TPC). Coupons were soaked at temperature for approximately 90 minutes prior to rolling. Preheat temperatures ranged from 925°C (1700°F) to 1150°C (2100°F). The percent reduction in thickness varied from as small as 13.3% to a maximum of 75.8%. Depending upon the total reduction in thickness, the number of deformation passes required ranged from 1 to 5. The as-rolled coupons were air-cooled. The coupons were sectioned and metallographic examination was performed via optical microscopy on the longitudinal surface.

Table I - Composition of alloy 718 Ingot Material

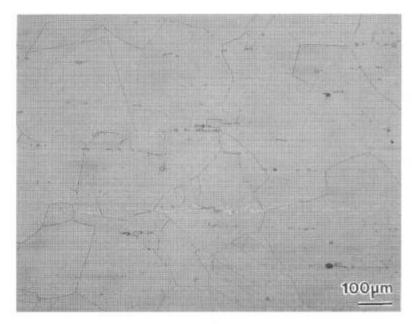| Element	Heat A Composition in Weight Percent	Heat B Composition in Weight Percent
Ni	53.44	53.68
Cr	18.31	18.38
Fe	18.36	18.07
Cb	5.1	5.1
Mo	2.92	2.93
Ti	0.96	0.96
Al	0.52	0.5
Co	0.13	0.1
C	0.03	0.03
Mn	0.06	0.07
Si	0.07	0.1
B	0.003	0.003
Cu	0.08	0.06
Ta	0.01	0.01

Figure 1. Starting microstructure for hot rolling experiments. (Grain Size ASTM ½)

Forge Model Methodology

Thermo-mechanical Analysis

The model used in this work was developed at the University College of Swansea by Evans [7]. The current version represents an intermediate stage in the development of a 3D forge model for predicting microstructural evolution. The less complex 2D model applies a plane strain

assumption for deformation. The applied finite element method utilizes a rigid-viscoplastic flow formulation to solve for nodal velocities. This type of finite element formulation is common in modeling deformation of metals [8,9] and has been proven to predict metal flow accurately. A coupled thermal analysis is performed which accounts for adiabatic heating during deformation and heat transfer from billet to tooling and surrounding environment. Contact between the billet and tooling is modeled using Coulomb friction.

Constitutive Equations

Constitutive relationships for modeling microstructure are given forms which best reproduce experimental data. Equation parameters are determined via hot compression of cylindrical specimens. The stress-strain curves are defined by four characteristics: 1) initial yield stress, 2) peak stress and the 3) associated strain, and 4) a large strain stress level. Nomenclature is described below:

σ - stress ε - strain $\dot{\varepsilon}$ - strain rate T - temperature

R - gas constant Δt - time increment α,A,n,B,m,D,q,Q,H,G - material constants

Each of the defined stress values are related to the strain rate and temperature by a hyperbolic sine function shown in equation (1).

$$\sigma = \frac{1}{\alpha}\sinh^{-1}\left[\left\{\frac{\dot{\varepsilon}}{A}\exp\left(\frac{Q}{RT}\right)\right\}^{\frac{1}{n}}\right]$$

(1)

The strain at peak stress is given a dependence on strain rate and temperature as shown in equation (2).

$$\varepsilon_{peak} = B\dot{\varepsilon}^{m}\exp\left(\frac{H}{RT}\right)$$

(2)

Although the path dependence for varying strain rate and temperature is not described, Evans [7] notes that experiments validate the use of strain as a variable of state.

The microstructure is defined by volume fraction recrystallized and the recrystallized grain size. Because strain replaced structural terms in the mechanical equation of state, empirical relations are determined for the microstructural evolution. The onset of recrystallization is set equal to the strain at peak stress and the rate of recrystallization is given a dependence shown in equation (3).

$$\dot{r} = \frac{dr}{d\varepsilon} = D\dot{\varepsilon}^{q}\exp\left(\frac{G}{RT}\right)$$

(3)

Using equation (3), the volume fraction recrystallized is calculated incrementally for each time step by equation (4).

$$X_2 = 1-(1-X_1)\exp(-\dot{r}\dot{\varepsilon}\Delta t)$$

(4)

Here X_1 is the volume fraction recrystallized at the start of an increment and X_2 is volume fraction at the end. The volume fraction recrystallized during the increment will have a grain size which is assumed independent of strain and given a strain rate/temperature dependence similar to the form found in equation (2). The grain size distribution is then updated for each time step.

The described model has been implemented into a computer program for simulating the forge process. Because the model is tailored for forging, manipulation of tooling and billet is somewhat limited. In the following section, the method for applying the model to flat rolling is discussed.

Simulation of Flat Rolling

To evaluate predictive capabilities of the model, flat rolling was identified as an approximate method for reproducing plane strain deformation. Because the geometry and motion of tooling for the two processes is different, a methodology for generating approximately equivalent deformation conditions is required. In this section, the method and assumptions for performing simulations are presented.

By analyzing the motion and geometry of rolling, approximations can be made for strain rate based on the length of the deformation zone and contact time. Strain can be approximated from the draft and to simulate the deformation, forge model inputs were used. The die movement is governed by a displacement and a velocity. For a deformation pass, the displacement is input to duplicate the draft for a roll pass. The die velocity is found by dividing the die displacement by the contact time. In effect, the model is simulating plane strain compression. Although the deformation paths for the two processes are dissimilar, these differences are considered negligible. An example of the model geometry is shown in Figure 2.
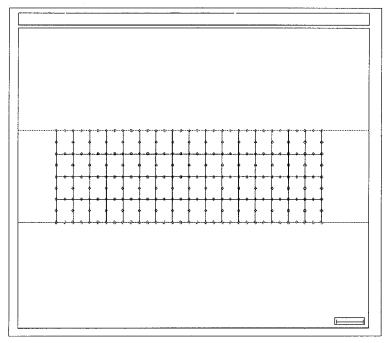

Figure 2. Typical forge model mesh of workpiece between dies.

The forge model accounts for surface effects such as heat transfer and friction between workpiece and tooling. For this work, the friction coefficient is set equal to zero. The no-stick condition is conducive to homogeneous deformation. Interface heat transfer coefficients are set internally by the forge model. Die temperature is set constant at 200°C (392°F).

Parameters to be investigated were starting temperature, number of passes, and final thickness. The time between passes and strain rate were assumed to be approximately constant for all conditions. For coupons that required more than one deformation pass, the time between passes was approximately three seconds. Estimates for strain rates ranged from 1 s^{-1} to 2 s^{-1}.

Results and Discussion

To critically evaluate the predictive abilities of the model, experimental results will focus on partially recrystallized microstructure. These results will identify model capabilities and limitations. Before proceeding with this section, it is important to define the results of the model and their relation to the experimental results. The model defines the microstructure at a point which is assumed to represent a local average of microstructural characteristics. The explicit morphology and arrangement of the microstructure in this local region is not described. For this work, the material at or near the center of the workpiece will be considered. The experimental microstructures are assumed to represent a local region of homogeneous deformation and temperature which can be related to a similar region represented by a point in the model.

For the high temperature 1150°C (2100°F), single pass at 16% draft, the model predicts a completely recrystallized microstructure. The experimental result showed a partially recrystallized structure with recrystallized grains nucleated at prior grain boundaries. Figure 3 illustrates the rolled microstructure.
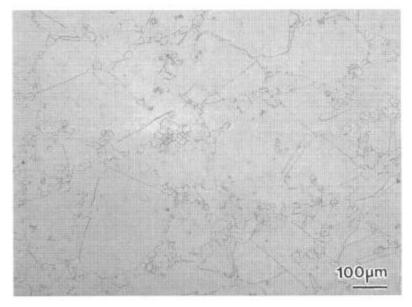

Figure 3. Partially recrystallized microstructure for material rolled at 1150°C (2100°F), 16% draft.

Other results obtained for 1150°C (2100°F) showed varying versions of duplex microstructure. Low strain samples exhibited the "necklace" structure while high strain samples contained a bimodal recrystallized grain size.

At 1093°C (2000°F),the model predicts a transition from worked structure (0% recrystallized) for a single pass 16% draft to a fully recrystallized (100%) structure for the single pass 27% draft. The experimental results for these conditions have various levels of partially recrystallized "necklace" structure. The worked structure (0% recrystallization) predicted by the model reasonably approximates the 16% draft microstructure shown in Figure 4.
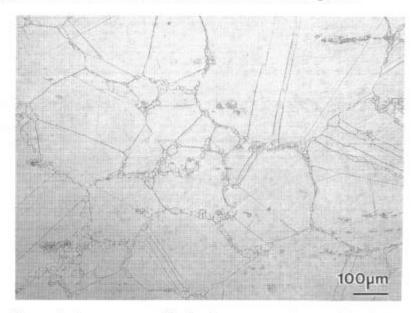

Figure 4. Sparse recrystallized microstructure for material rolled at 1093°C (2000°F), 16% draft.

The predictive ability of the model begins to improve for the 1038°C (1900°F) deformation temperature. For the single pass 26.5% draft, the model predicts a 14% recrystallized structure. This predicts the experimental result for this condition reasonably well as shown in Figure 5.
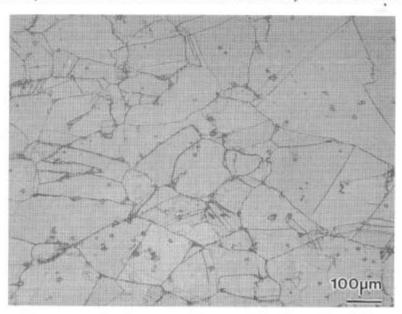

Figure 5. Microstructure for material rolled at 1038°C (1900°F), 26.5% draft.

Again, experiment and model deviate for the subsequent deformation level (39% draft, 1038°C (1900°F)). The model predicts complete recrystallization while actual results show partial (<50%) recrystallization. For the 982°C (1800°F),single pass 37% and single pass 50% draft conditions, the model predicts 21% and 95% recrystallized structure, respectively. The corresponding experimental results are shown in Figure 6.
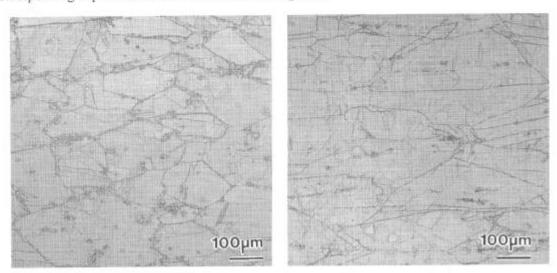

Figure 6. Microstructure for material rolled at 982°C (1800°F),(left) 37% and (right) 50% draft.

Figure 7 depicts the two pass 59% draft at the 982°C (1800°F) condition. The fully recrystallized structure shows model and experiment agreement. Note: experiment material processed at this temperature exhibited high visibility prior grain boundaries. It has been speculated that this is the result of δ-phase precipitation [10] during the 90 minute preheat. Further analysis is required to determine if δ-phase precipitation is the constituent. However, it does not appear that the recrystallization was effected by the presence of this phase.
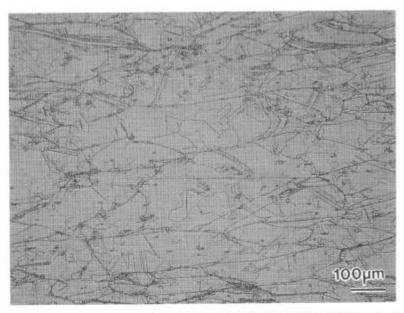

Figure 7. Microstructure for material rolled at 982°C (1800°F), 59% draft, single pass.

For the lowest experimental temperature 925°C (1700°F), the model predicts partial recrystallization (64%) for a 60% draft (3 passes). The corresponding experimental microstructure is worked with no recrystallization. Although the model accounts for heat transfer, the validity of the low temperature condition is questioned because of the multiple passes used. The potential for thermal gradients could affect the experimental results.

A major contributor to the differences between the predicted and observed volume fractions recrystallized is likely to be the initial starting grain size. Work on alloy 718 material has indicated that the initial grain size has little effect on the values of the constants in equations (1) and (2) so that the flow properties of the material are grain size independent. Since the strain to peak stress (equation 2) is an indicator of the commencement of dynamic recrystallization, grain size independence is true of the onset of recrystallization. However, the model parameters corresponding to equations (3) and (4) are strongly grain size dependent. The model currently carries constants measured for wrought stock where the initial grain size was between ASTM 3 and 6 for decreasing soaking temperature between 1150°C (2100°F) and 925°C (1700°F). The current experimental stock has a grain size of ASTM ½. Observations indicate that dynamic recrystallization is a grain boundary phenomenon and it is unlikely that the nucleation rate per grain boundary area will be affected by grain size. However, for given conditions during rolling the large grain size material will have fewer grain boundary nucleation sites per unit volume simply because of the reduction in grain boundary area. The overall recrystallization rates might then be slower than model prediction by an amount approximately proportional to the relative grain boundary areas of initial stock and the wrought stock which was used for the model constants determination. More work is required to verify that the explanation of lower observed volume fractions lies here and some testing is being undertaken to establish the correct values of the constants in equations (3) and (4) for large grained cast material.

In general, the model predicts the onset of recrystallization with a reasonable degree of accuracy. However, the rate of recrystallization is accelerated compared to experimental results. This discrepancy is probably related to the strain rate and temperature dependence set forth in equations (3) and (4). It is not obvious how the effect of strain is accounted for. However, other factors such as deformation mode (forging vs. rolling) or initial grain size could contribute to the variation.

Conclusions and Future Work

1) The model predicts the onset of recrystallization reasonably well for most deformation temperatures with an exception for the high 1150°C (2100°F) and low 925°C (1700°F) extremes of the experimental range.

2) The model consistently predicts an exaggerated rate of recrystallization compared to experimental results. In other words, a completely recrystallized microstructure is not achieved experimentally as quickly as simulations predict.

Overall, the model represents a reasonable initial attempt at a microstructural model. A base has been developed to which enhancements and modifications may be incorporated. Two items are identified as possible future enhancements. First, the incremental method for determining the volume fraction recrystallized should be revised to more accurately account for the effects of strain. Second, efforts to fit model parameters using as-cast microstructures as starting material would make the model more applicable to industrial forging.

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