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Predictive Simulation of a Validation Forging Using a Recrystallization Model *

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ABSTRACT

Recrystallization is the process by which a strained microstructure is replaced by a strain-free set of grains through nucleation and growth. A constitutive model for recrystallization has been developed within the framework of an existing dislocation-based rate and temperature-dependent plasticity model. The theory includes an isotropic hardening variable to represent the statistically stored dislocation density, a scalar misorientation variable related to the spacing between geometrically necessary boundaries, and a variable that tracks the recrystallized volume fraction. The theory has been implemented and tested in a finite element code. Material parameters were fit to data from monotonic compression tests on 304L steel for a wide range of temperatures and strain rates. The model is then validated by using the same parameter set in predictive simulations of experiments in which wedge forgings were produced at elevated temperatures. From the forgings, tensile specimens were machined and tested. Model predictions of the final yield strengths compare well to the experimental results.

1. Introduction

During high temperature manufacturing processes, metals undergo microstructural changes that can greatly affect material properties and residual stresses. Some of the physical mechanisms that influence the strength of a material are strain hardening, recovery, recrystallization, and grain growth [1,2]. If the deformation conditions such as temperature and strain rate are not controlled properly during forging, welding, rolling, or other processes, the final part may have inadequate strength or residual stresses that could be detrimental to the life of the part [3]. In order to be able to optimize manufacturing processes using computational capabilities, it is necessary to have a physically-based constitutive model that captures the dominant strengthening and softening mechanisms. Such a model with predictive capabilities can be used in an optimization scheme to reduce the number of design iterations required to produce a part that meets all strength and microstructural requirements.

Recrystallization is a complex, inhomogeneous process in which nucleation and growth of new strain-free grains replace the worked microstructure of a strained material [4,5]. Recrystallization is due to the motion of grain and subgrain boundaries. As the boundaries move, they sweep away the dislocation structure, leaving a strain-free material with a very low dislocation density. The nucleation of a new recrystallized grain is believed to be due to

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the growth of an existing deformation-induced subgrain [6]. At elevated temperatures, a subgrain with a lower level of stored energy will preferentially expand at the expense of neighboring subgrains. The driving force for recrystallization is the difference in energy between the deformed and recrystallized state [7]. If the expanding subgrain reaches a critical size, it becomes a stable recrystallized grain.

In the current work, no critical criterion was utilized to initiate recrystallization. Rather, the kinetics of recrystallization are modeled based on the mobility of grain and subgrain boundaries under the driving force provided by the stored energy in the dislocation structure. The internal state variable theory is capable of modeling both static as well as dynamic recrystallization [8], although a simplified version is presented here since we are primarily concerned with static recrystallization for high-rate forgings. The paper is organized as follows: first, the constitutive model will be described. Next, results from parameter optimization will be presented. Finally, a comparison between model predictions and experimental results will be provided.

2. Constitutive Model

A treatment of the kinematics and thermodynamics of the model used here will be published in a future work. Here, for simplicity,we will give a condensed treatment in which we provide the set of equations for the constitutive model for the simplified case of uniaxial stress.

For uniaxial stress, let σ represent the only non-vanishing component of the Cauchy stress tensor and ε represent the axial component of the Eulerian strain tensor. After making approximations for small elastic strains, it can be shown that the model reduces to the following set of equations, written here in the current configuration:

$$\dot{\sigma} = E\left(\dot{\varepsilon} - \dot{\varepsilon}^p\right) \tag{1}$$

$$\dot{\varepsilon}^p = f(\theta)\left(\sinh\left[\left\langle \frac{\sigma}{\kappa + Y(\theta)} - 1 \right\rangle\right]\right)^{n(\theta)} \tag{2}$$

$$\kappa = \kappa_{1-X}\left(1 - X\right) \tag{3}$$

$$\dot{X} = \frac{1}{\mu\theta} e^{-\frac{c_\theta}{\theta}} \left(1 - e^{-B\bar{\zeta}_{1-X}^m}\right)\left[c_{\bar{\kappa}}\bar{\kappa}_{1-X}^2 + c_{\bar{\zeta}}\bar{\zeta}_{1-X}^2\right] X^a \left(1 - X\right)^b \tag{4}$$

$$\dot{\kappa}_{1-X} = \left[H(\theta) - R_d(\theta)\kappa_{1-X}\right]\left|\dot{\varepsilon}^p\right| \tag{5}$$

$$\dot{\zeta}_{1-X} = h_\zeta \zeta_{1-X}^{1-1/r}\left|\dot{\varepsilon}^p\right| \tag{6}$$

Equations (1) and (2) provide the elasticity relation and the flow rule for the plastic strain rate. Equation (3) averages the isotropic hardening variable, κ, between the unrecrystallized and recrystallized volume fractions, where the isotropic hardening variable in the recrystallized volume fraction is assumed to be zero. Equation (4) describes the kinetics of recrystallization through a variable, *X*, that represents the volume fraction of recrystallized material. Equation (5) is the evolution equation for the isotropic hardening variable in the unrecrystallized volume fraction, which has a hardening minus recovery format based on [9]. The last equation, based on [10], tracks a misorientation variable, ζ_{1-X}, in the unrecrystallized volume fraction. ζ_{1-X} is inversely related to the average spacing between geometrically necessary boundaries. The stored energy due to the dislocation structure, represented by κ_{1-X} and ζ_{1-X}, drives the recrystallization kinetics. The mobility of subgrain boundary motion increases with misorientation angle, which increases as the spacing between geometrically necessary boundaries decreases.

The model in this form is only valid for static recrystallization, where the isotropic hardening variable in the recrystallized volume fraction is assumed to be zero. For dynamic recrystallization, the recrystallized material will continue to harden with increased strain. For a treatment of the model form capable of both static and dynamic recrystallization, see [8].

3. Model Performance

Material parameters were fit to data from monotonic compression tests on 304L steel for a wide range of temperatures and strain rates. Three types of test data were included in the set used for parameter optimization. Stress-strain data from single-stage compression at constant strain rate and temperature is shown in Figure 1. It should be noted that although the nominal temperature is held constant, the specimen will heat somewhat due to plastic dissipation. This effect is neglected in the work presented here, but will be included in future work. Figure 2 shows stress-strain data from two-stage compression tests in which the first stage was performed at elevated temperature, followed by a quench after approximately five seconds, and then the second stage was done at room temperature. Figure 3 contains recrystallized volume fraction data from single-stage compressions tests followed by various hold times before quenching. The data was determined from microstructure from etched samples of the compression specimens.

Sixteen parameters were optimized. The results from the parameter optimization for the three types of data are shown in Figures 1 through 3. The model captures the material response quite well over the full range of temperatures and strain rates.

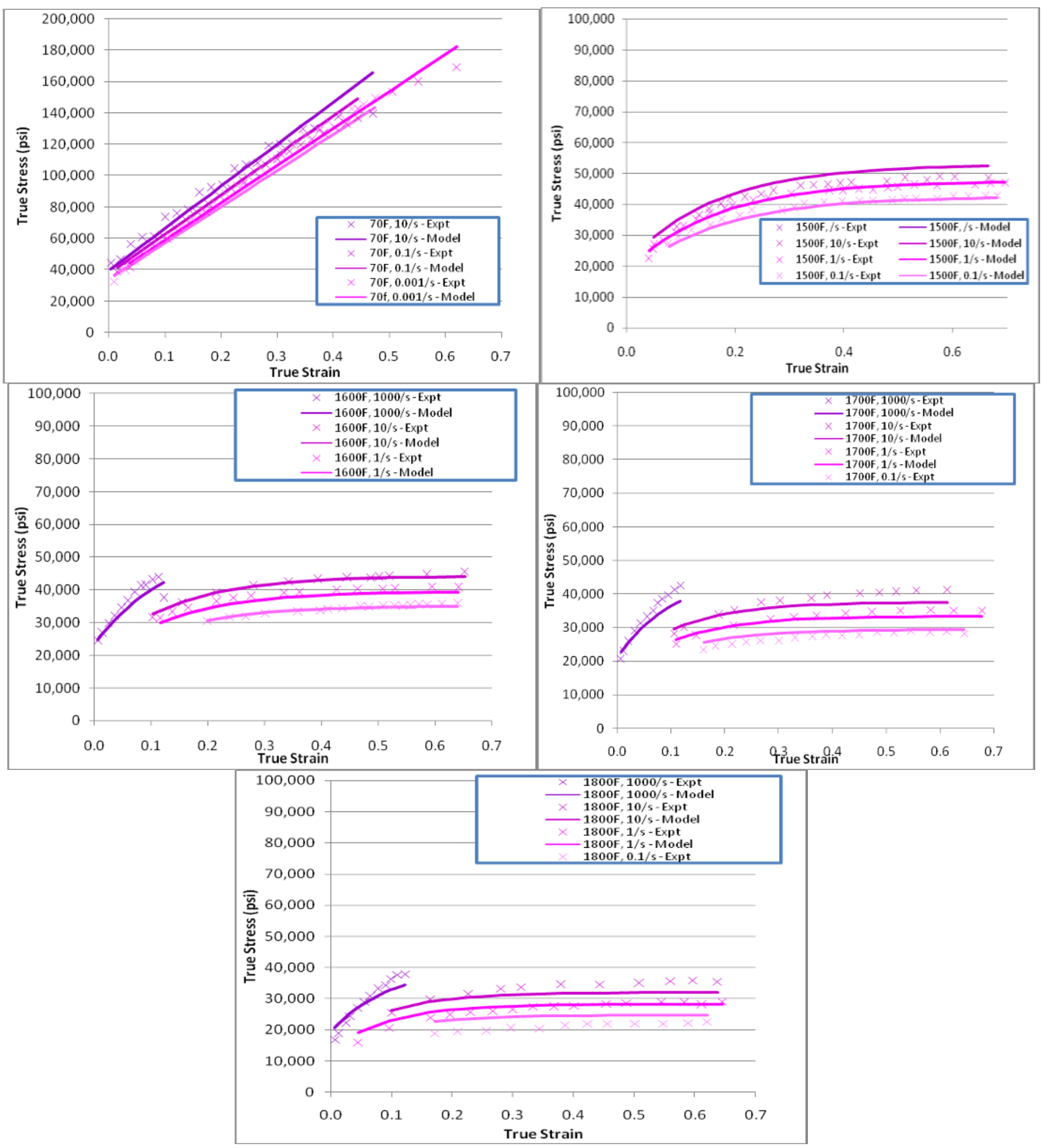

Figure 1. Stress-strain data from single-stage compression tests.

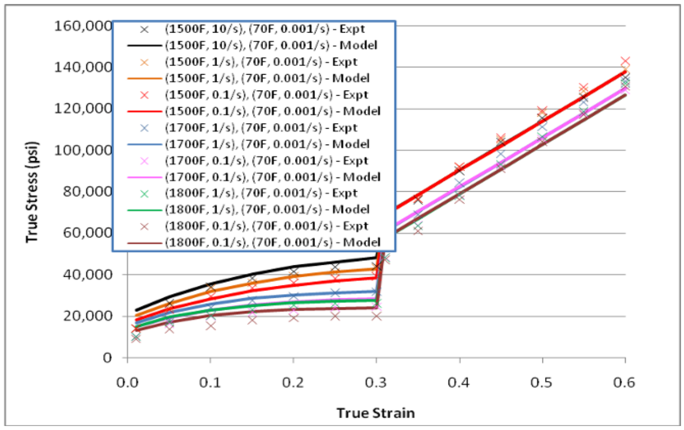

Figure 2. Stress-strain data from two-stage compression tests.

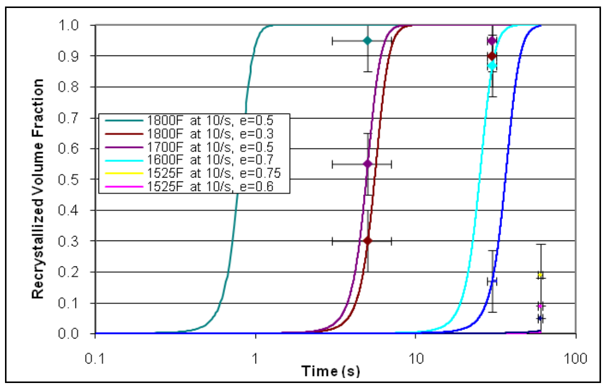

Figure 3. Recrystallized volume fraction data from compress-and-hold tests.

4. Validation

The theory has been implemented and tested in Adagio, Sandia's implicit mechanics code [11]. The model is then validated by using the same parameter set in predictive simulations of experiments in which 304L stainless steel wedges were forged with a HERF machine at Precision Metal Products, Inc. The wedge was held at 1600F, compressed to a final height of one inch by a platen traveling at a rate of approximately 20 ft/s, and then quenched to room temperature. From the flattened forgings, tensile specimens were machined and tested. Figure 4 shows the wedge specimen dimensions.

In the simulation, we assumed a coefficient of friction of 0.1 between the wedge and the platens. Figures 5 and 6 show the evolution of plastic strain and recrystallized volume fraction as the wedge is compressed between the two platens and then held at temperature for 20 seconds. Figure 7 compares the model predictions of the final yield strengths to the initial yield strengths found experimentally. Due to uncertainty in how long the wedge was held at temperature before it was quenched, results are shown for three different hold times.

The model does a fairly good job of predicting the final strength, although it slightly underpredicts the peak strength. This may be due to the fact that the model parameters were determined using compression data, whereas the validation data is from tension tests; stainless steel 304L has a lower yield strength in compression [12]. There is uncertainty in the simulation predictions due to the fact that we do not know for sure how long the wedge was held at temperature before it was quenched. For this reason, we show the results for hold times of 10, 15, and 20 seconds. The most accurate predictions are seen at a hold time of 10 seconds, but the most accurate profile shape is at 15 seconds. At 15 and 20 seconds, the right side of the wedge has started recrystallizing, which decreases the final yield strength.

Future work includes performing uncertainty quantification on the most important simulation parameters, doing mesh and time step convergence studies, and including the effects of conduction and heat generation due to plastic dissipation in coupled thermal-mechanical simulations.

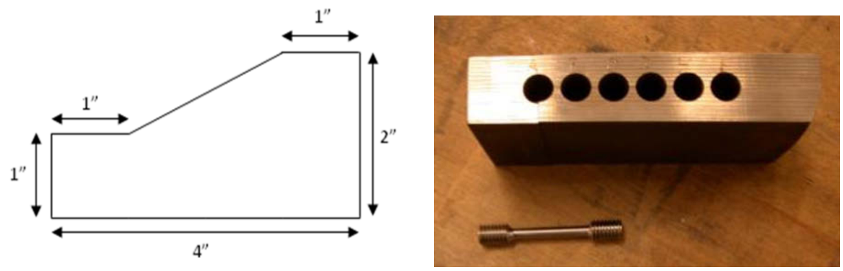

Figure 4. Wedge specimen dimension and machined tensile specimens.

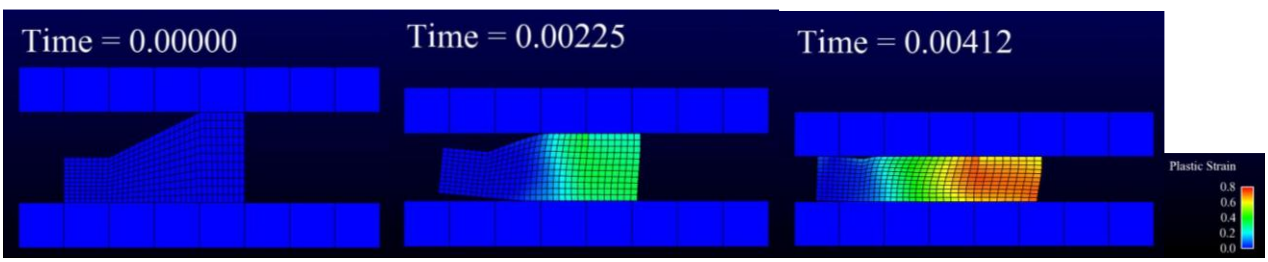

Figure 5. Evolution of plastic strain as the wedge is compressed between the two platens.

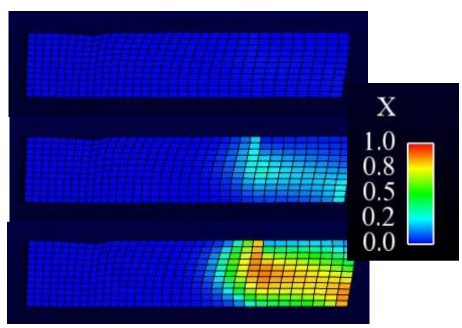

Figure 6. Recrystallized volume fraction at 10, 15, and 20 seconds hold time.

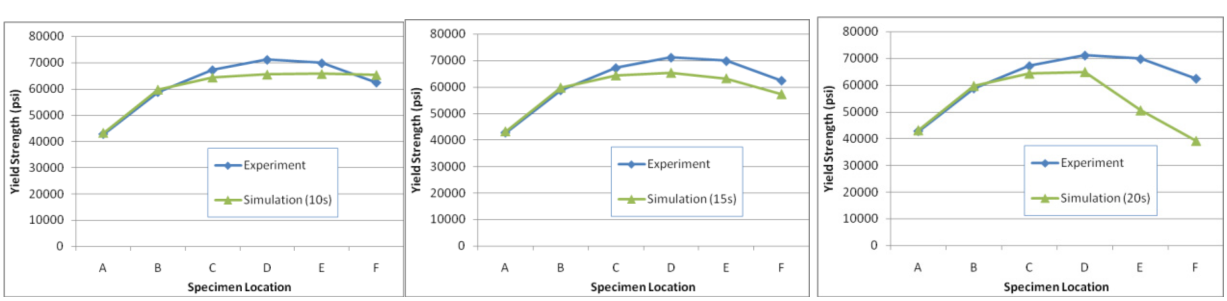

Figure 7. Comparisons between predictions and experimental results.

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