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CONSTITUTIVE MODELING OF FLOW BEAHAVIOUR OF Ni BASED SUPERALLOYS

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ABSTRACT
This paper examines the applicability of the proposed constitutive model to the simulation of the hot forging behavior of P/M Rene 95 in initially coarse-(50 µm) and fine-grained (7 µm) conditions. It is shown, by means of constant true strain rate compression tests, that the microstructures of the coarse and fine grained materials transform into the same equiaxed fine grained micro-duplex structure at which point their flow strengths become identical. Continued deformed at that point produces no further change in grain size or flow strength. Under this steady state regime, grain size and flow strength are independent of the initial microstructure but vary with applied strain rate and temperature.
Keywords: Ni based super alloy, constitutive modeling, hot forging, grain boundary sliding, intragranular flow

1. INTRODUCTION
The hot deformation behavior of superalloys have been characterized in the temperature range 900–1100°C and strain rate range 0.001–1.0 s^{-1} using compression tests on process annealed material, with a view to obtain a correlation between grain size and the process parameters[1]. Many studies have been made to model behavior of superalloys in hot forging operations [2,3]. Currently, material behavior is modeled through constitutive equations, taking into account only the dependence to the instantaneous values of process parameters. Even under this approximation of operating conditions, the definition of correct analytical relationships involves the clear understanding of all the phenomena occurring while deforming—such as strain hardening, dynamic recovery, dynamic recrystallization—that, particularly in hot forging, are complex and not easy to model. Some experimental results show that the deformation mechanisms in high temperature forging conditions of Ni based super alloys are primarily attributed to deformation-induced recrystallization. The deformation-induced recrystallization in superalloys under isothermal forging conditions was modeled [4,5]. It was suggested that realistic modeling requires that the contribution of each mechanism to deformation, such as intragranular flow and grain boundary sliding, be considered as a dynamic variable. The kinetics of metallurgical change during forging and the heat treatment were investigated [2] by laboratory testing of IMI834 samples. Though the relationship under the β transus temperature, the modeling of the effects of dynamic recrystallization on the stress–strain behavior and on the microstructural development is still a matter of further investigation. In a more general review on mechanical and microstructural aspects of dynamic recrystallization [6], whatever grain refinement or grain coarsening occurs during recrystallization, flow softening in the stress–strain behavior is normally produced.

The purpose of this paper is to model the flow behavior of P/M Rene 95 that has undergone dynamic recrystallization in high temperature isothermal forging. The evolution of the recrystallized grain size and its effects on the stress–strain behavior in Rene 95 are considered as an internal variable in a constitutive model that takes into account a range of deformation mechanisms.

2. EXPERIMENTAL STUDY

In order to model material behavior and microstructural evolution, some compression tests on cylindrical specimens of P/M Rene 95 with 8 mm in diameter and 13 mm in length were done at the temperatures between 1050 and 1100^{o}C with strain rates between 10^{-4} and 10^0. All specimens were compressed at three different constant temperatures and five true constant strain rates. Test specimens were induction heating to test temperatures and held constant for 20 minutes at the same temperatures to secure temperature uniformly in the samples. All the samples were quenched soon after the compression tests to freeze the microstructures.

3. CONSTITUTIVE MODELLING

Fig.1 shows the deformation map for P/M Rene 95 at isothermal forging conditions obtained by superposition of peak flow strength data at constant grain size (solid lines) and steady state data (broken line)[7].

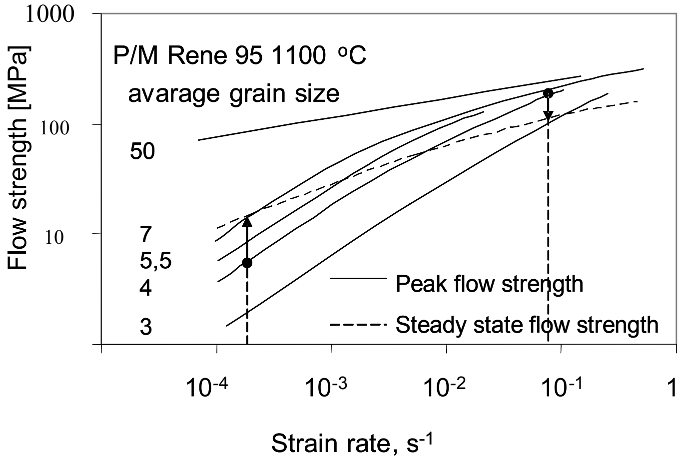

Figure 1. Deformation map for P/M Rene 95

The grain size of the as-hipped (7 μm) and grain coarsened (50 μm) compacts are refined, and their flow strength is reduced at all rates of interest to isothermal forging. In order to model these deformation-induced changes in flow strength and microstructure as a function of deformation conditions, it is necessary to predict the flow strength. Following the model for deformation induced recrystallization in P/M 713 LC [8], the partially recrystallized P/M Rene 95 compacts can be viewed as composite materials consisting of soft recrystallized grains and hard unrecrystallized regions. As the volume fraction of the recrystallized material increases with strain, the flow strength of the compacts is increasingly influenced by flow localization within the fine recrystallized regions. The contribution from grain boundary sliding towards overall deformation becomes increasingly prominent and ultimately dominates once the transformation is complete. The rate equation for peak flow strength prior to the onset of grain refinement in both coarse and fine grained compacts can be written in terms of those for grain boundary sliding, (gbs) and intragranular flow, (mdg) as:

$$\dot{\varepsilon} = \dot{\varepsilon}_{gbs} + \dot{\varepsilon}_{mdg} \tag{1}$$

where $\dot{\varepsilon}$ is the applied strain rate and $\dot{\varepsilon}_{gbs}$ and ε_{mdg} are the strain rates due to gbs and mdg respectively. In the coarse grained compacts, the strain contribution from gbs re initially small because of a large initial grain size and the rate equation reduces to $\dot{\varepsilon} = \dot{\varepsilon}_{mdg}$.

In the fine grained compacts, the contribution from each deformation mechanism depends on the initial grain size and the applied strain rate. At slow strain rates, the contribution from gbs dominates whereas at high strain rates it becomes negligible. At high strain rates, the rate equation for the fine grained material also reduces to Eq.1 while at low strain rates it reduces to $\dot{\varepsilon} = \dot{\varepsilon}_{gbs}$. At strain rates of interest to isothermal forging both gbs and mdg contribute to the deformation and the rate equation is that given by Eq.1. The $\dot{\varepsilon}_{mdg}$ component in Eq.1 can be represented by a dislocation glide/climb controlled creep equation of the form

$$\dot{\varepsilon}_{mdg} = A' \frac{D_v \mu b}{kT} \left(\frac{\sigma - \sigma_0}{\mu}\right)^4 \tag{2}$$

where σ_0 is a back stress due to intragranular γ' precipitates, A' is an experimentally determined material constant and other symbols have their usual meaning.

The $\dot{\varepsilon}_{gbs}$, component in Eq.1 can be represented by atomistic models for describing superplastic flow where sliding along the grain boundaries may be controlled by diffusion flow accommodation within the grain interiors, as in Ashby and Verrall's model [9], or by dislocation climb within the boundary planes, as in Gittus's model [10].

In the case of Ashby and Verrall's model the rate equation is given by:

$$\dot{\varepsilon}_{gbs/AV} = \frac{100\Omega}{kt\lambda^2}\left(\sigma - \frac{0.72\Gamma}{\lambda}\right) D_V \left(1 + \frac{3.3\delta}{\lambda}\frac{D_B}{D_V}\right) \tag{3}$$

whereas for Gittus's model:

$$\dot{\varepsilon}_{gbs/G} = 53.4 \frac{D_B \mu b}{kT} \left(\frac{b}{\lambda}\right)^2 \left(\frac{\sigma - \sigma_i}{\mu}\right)^2 \tag{4}$$

where λ is the grain size, Γ is the grain boundary energy and $0.72\Gamma/\lambda$ and σ_i are threshold stresses arising from fluctuations in the grain boundary area and grain boundary ledges respectively [10].

Predictions of peak flow strength in P/M 713 LC compacts of different grain sizes, based on the superposition of a dislocation creep model (Eq.2) with the Gittus model for grain boundary sliding (Eq.4), have been shown to closely approximate the experimental data at 1050°C [11] and correctly predict the strain rate sensitivity of flow strength (m=0.5) at slow strain rates. In P/M Rene 95, the superposition of these two equations also describes peak flow strength and its strain rate sensitivity (m=0.5) at 1050°C reasonably well as shown in Fig.2a. However, at 1100°C, this superposition does not adequately predict the peak flow strength or its strain rate sensitivity at slow strain rates. In this case, the strain rate sensitivity m is greater than 0.5, of the order of 0.66.

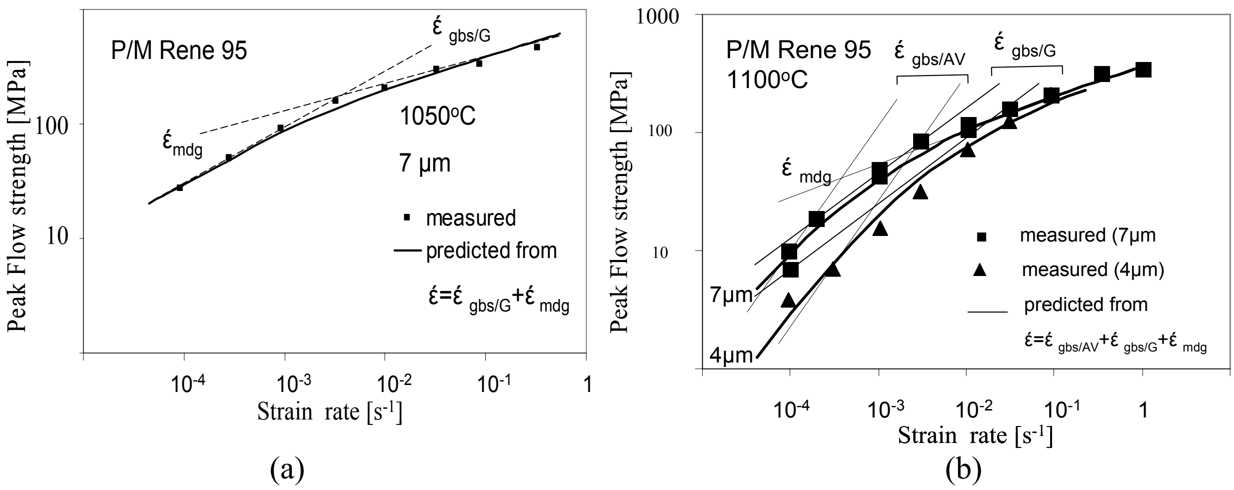

Figure 2. Comparison of experimentally established peak flow strengths for the as-hipped P/M Rene 95 compacts

It has however been suggested that superplastic flow can arise from the simultaneous operation of a number of mechanisms. It is therefore quite possible that at 1100°C both the Ashby and Verrall and the Gittus mechanisms are contributing to flow at the lower strain rates. This is not totally unexpected since the contribution from diffusional flow accommodation in the grain interiors can be expected to increase as the forging temperature is increased from 1050°C to 1100°C. Therefore, it is suggested that at 1100°C, the variation in peak flow strength can be described by superposition of $\dot{\varepsilon} = \dot{\varepsilon}_{mdg}$, $\dot{\varepsilon} = \dot{\varepsilon}_{gbs}$ and Eq.2 where

$$\dot{\varepsilon} = \dot{\varepsilon}_{mdg} + \dot{\varepsilon}_{gbs/G} + \dot{\varepsilon}_{gbs/AV} \tag{5}$$

That this is indeed the case is shown in Fig.2b where the magnitude of peak flow strength and its strain rate and grain size dependences are closely approximated by Eq.5. The parameters and constants used in calculating the peak flow strength values in Fig.2. In the discussion that follows on deformation at 1100°C, any reference to $\dot{\varepsilon}_{gbs/AV}$ will be assumed to represent a combination of $\dot{\varepsilon}_{gbs/AV}$ and $\dot{\varepsilon}_{gbs/G}$.

4. CONCLUSIONS

This paper has shown that a recently proposed methodology for modelling forging deformation and microstructural evolution in P/M superalloys under isothermal forging conditions is applicable to P/M Rene 95 compacts. This methodology assumes that several mechanisms contribute towards overall deformation and uses established models for each of the mechanisms to formulate a rate equation for predicting flow strength. It also uses an Avrami type relationship, with steady state flow data as boundary conditions, to predict changes in microstructure as a function of initial microstructure and applied strain rate. The rate equation in combination with the Avrami type relationship forms a microstructure dependent constitutive relation which can be used to predict microstructural gradients within forgings.

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