**10th International Research/Expert Conference**
**"Trends in the Development of Machinery and Associated Technology"**
**TMT 2006, Barcelona-Lloret de Mar, Spain, 11-15 September, 2006**

# CHARACTERISTIC BEHAVIOURS OF NI BASED SUPERALLOYS UNDER ISOTHERMAL HOT FORGING CONDITIONS

**M.Oktay Alniak**
**Bahcesehir Unviversity**
**Engineering Faculty**
**34538 Istanbul**
**Turkey**

**J.P. Immarigeon**
**N. Aeronautical Establishment**
**M13-M14 Lab. Directory**
**NRC Ottawa**
**Canada**

**Fevzi Bedir**
**S.Demirel University**
**Dept. of Mechanical Eng.**
**32260 Isparta**
**Turkey**

## ABSTRACT
*Thermomechanical behaviors of superalloys at high temperatures, constant strain rates related dynamic microstructural changes are studied in this article by means of the commentaries of thermomechanic graphs and microdublex changes. Thermomechanic and microdynamic deformation characteristics based on test data are presented by a methodology for superalloys which are consolidated by hot isostatic pressure (HIP) operation. It is assumed that true stress caused deformation changes depending on thermomechanical behaviors such as; strain, strain rate, absolute temperature, activation energy, diffusion mechanism, grain size, microdynamic behaviors and structural parameters of the material. In this study, a detailed investigation of thermomechanical and microdynamical behaviors of P/M Rene 95 is carried on by the attribution of experimental data.*
**Keywords:** superalloys, microstructure, Rene 95, thermomechanical and microdynamical behaviors

## 1. INTRODUCTION
Ni based superalloys are most important materials and extensively used in the aeronautics and astronautics industry [1,2]. The alloys contain different alloying elements, which give rise to the difficulties in forging with controlled microstructures. To control every step of thermomechanical processing to obtain the most favorable mechanical properties including strength, creep, and low cycle fatigue crack initiation and crack propagation characteristics [3] has been paid to the hot deformation behavior. Post-heat treatment which is normally used for conventional metal forging is not used to control the grain size of forging superalloys parts. Grain size optimization and control through thermomechanical processing is thus one of the primary goals in the forging of Ni based superalloys. In this investigation, microstructural evaluation of Rene 95 during forging has been analysis. The variation of microstructures due to dynamic recrystallization, as well as grain growth has been consider to asses microstructural variation of Alloy Rene 95 forged specimens.

## 2. EXPERIMENTAL STUDY
To investigate the material flow and microstructural evolution, compression tests on cylindrical specimens 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. RESULT AND DISCUSSION
### 3.1. Flow behavior
The typical flow behavior of Rene 95 under various test conditions is presented in Fig.1. The shape of the flow curves depends on the strain rate and temperature. The flow curves show a prominent peak

stress when the strain rate is above $10^{-2}$ $s^{-1}$ regardless of the test temperature. After the initial peak stress, the flow curves continuously decrease and essentially reach a saturation stress. The stress softening after the peak stress can be attributed to dynamic recrystallization.

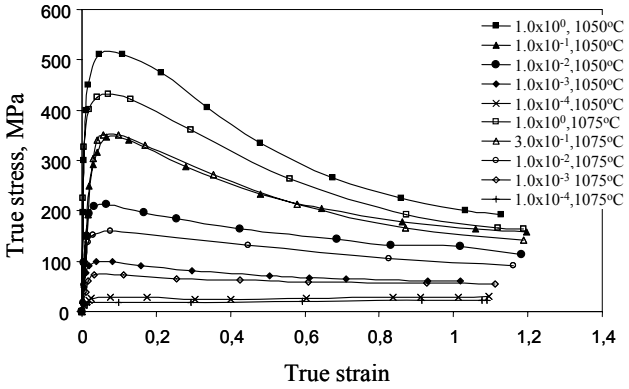


*Figure 1. Flow behavior of Rene 95.*

Dynamic recrystallization occurs typically near grain boundaries, forming a necklace microstructures [4] for different superalloys as shown in Fig. 2.

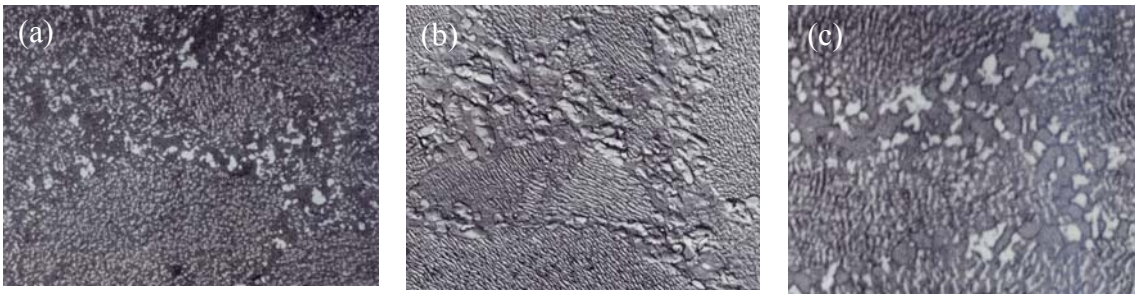


*Figure 2. Example of necklace microstructures (a) P/M Rene 95, (b) P/M Mar M200 and (c) P/M 713LC compacts showing partial dynamic recrystallization of initially coarse-grained microstructure after isothermal forging sub-solvus temperatures.*

The variations of the volume fraction of dynamically recrystallized and unrecrytallized regions is written as, $\dot{\varepsilon} = F\dot{\varepsilon}_S + (1-F)\dot{\varepsilon}_H$ where the rate equations for the soft and hard regions, $\dot{\varepsilon}_S$ and $\dot{\varepsilon}_H$ may be viewed as constitutive relations that relate flow strength to strain rate and temperature within each region. Both relations are of the general form

$$\dot{\varepsilon} = A\,\lambda^{P}\,(\sigma-\sigma_0)^{1/m}\exp\left(\frac{-Q}{RT}\right) \qquad (1)$$

where A is material constant, $\lambda$ is the grain size, $\sigma$ is the flow stress, $\sigma_0$ is a microstructure dependent parameter, p and m are numerical exponents that depend on the mechanism of deformation , Q is the activation energy for the deformation mechanism, T is the absolute temperature and R is the gas constant. The volume fraction F of recrystallized material is described in the proposed model by an Avrami type relation of the form, $F = 1-\exp(-C(S,\dot{\varepsilon})\,t^n)$ where C is a parameter conditioned by the instantaneous microstructure and strain rate, t is the time and n is a numerical exponent. The model has been shown to be consistent with the forging behaviour of both coarse and fine-grained P/M 713LC compacts [5]. Dynamically recrystallized grain size was expressed as a function of Zener–Holloman parameter as suggested by Shen et al. [6]. Fig.3 summarizes the flow behavior in the step compression tests. The hardening is possibly due to rapid grain growth due to the prominent dynamic recrystallization, which would result in fine microstructures. The effects of strain rate, $\dot{\varepsilon}$ on the peak flow strength, $\sigma_P$, of the fine-grained as hipped material are illustrated in Fig.4. A

discontinuity in the strain rate sensitivity m, the slopes of the isothermal curves in Fig. 4 where occurs at intermediate strain rates between $10^{-3}$ and $10^{-2}$ $s^{-1}$ at all test temperatures.

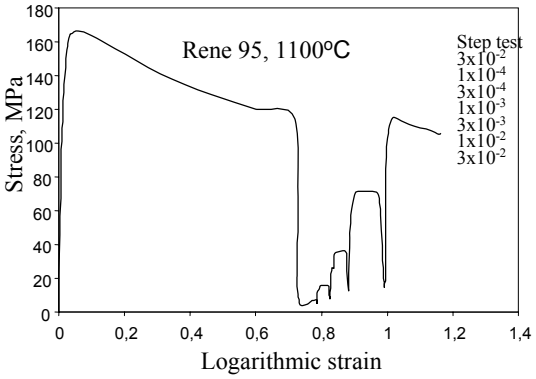


*Figure 3. Effects of the variation of test conditions on the flow behavior.*

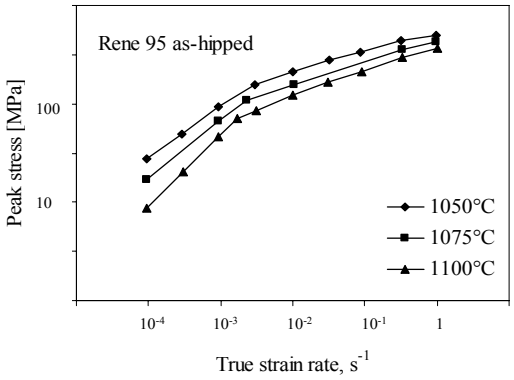


*Figure 4. Variation in the peak flow strength of the hipped P/M Rene 95 fine grained compacts as a function of strain rate (log-log plot).*

Below the transition strain rates, m is high, while above the transition strain rates, it is low and is not as nearly dependent on temperature as it is below the transition strain rates. This behavior is generally consistent with fine grain superplasticity and can be attributed to a change in deformation mechanism as the strain rate is raised from below to above the transition strain rate [7,8].

The temperature sensitivity of the peak flow strength ($d\ln\sigma_p/d(1/T)$) obtained by plotting log flow stresses at constant strain rates against the inverse of the absolute temperature exhibits a discontinuity which shifts to higher temperatures as the strain rate is increased, as shown in Fig.5. This discontinuity is consistent with the change in deformation mechanism indicated by Fig.4. Activation energies for the respective mechanisms can be calculated on the basis of the data contained in Fig.9 from the relation $Q = \frac{R}{m}\frac{d\ln\sigma_p}{d(1/T)}$. The significance of these calculated quantities is however questionable since the $\gamma'$ volume fraction is not constant over the range of temperature considered and therefore the microstructure varies from one temperature to another. True activation energies require that calculations be made based on constant structure data and this is not the case for the data shown in Fig.5.

### 3.2. Microstructure Dependence of Flow Strength

It was found that, at all strain rates and temperatures, the difference in flow strength between the coarse and fine grained compacts gradually decreased as the amount of applied strain was increased.

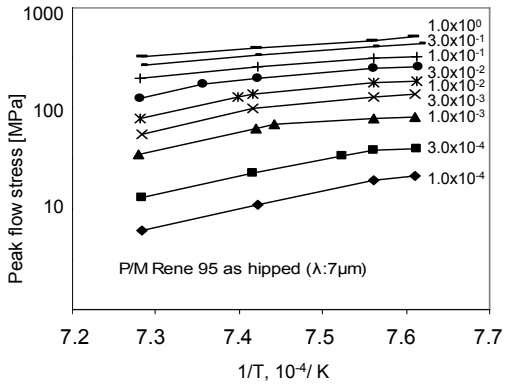


*Figure 5. Temperature dependence of peak flow strength at constant strain rates for the hipped P/M Rene 95 fine grained compacts*

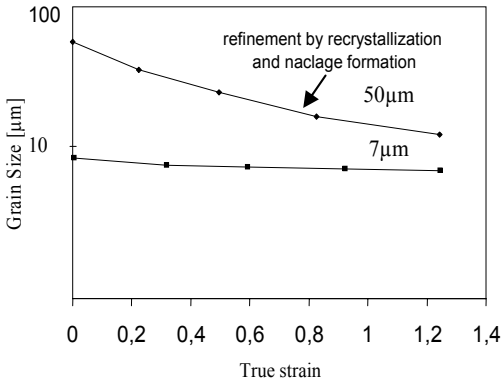


*Figure 6. Comparison of the flow curves for initially coarse and fine grained compacts of hipped P/M Rene 95 deformed under the same revealed by metallography*

For instance, at 1100°C and $10^{-3}$ $s^{-1}$ the peak flow strength for the 50 μm grain size material was roughly three times higher than that for the 7 μm grain size compact, Fig.6. However, after a strain of 1.2, the difference in flow strength for the two materials was reduced to less than 20%. This

convergence of flow strength with increasing strain can be attributed to the microstructure evolving in each case towards the same fine grained microduplex structure[9], as indicated by Fig.6. This is clearly demonstrated in Fig.7 which shows the as-worked microstructure after a true strain of 1.2 at 1100°C and $10^{-3}$ $s^{-1}$. The initially coarse grained material shows partially recrystallized regions of fine microduplex grains, Fig.7, of a size similar to that observed in the as-worked fine grained (7 μm) compact. It was also noted that a regime of deformation develops at high strains during which there is no further change in the microduplex grain size with continued straining at constant strain rates and temperature. The grain size depends very much on the test temperature and strain rate for the given test conditions. Fig.8 shows that the dynamically recrystallized grain size varies consistently with the Zener–Hollomon (Z–H) parameter given by $\dot{\varepsilon}\exp(Q/RT)$ . The grain size of dynamically recrystallized grains decreases consistently with increasing of the Z–H parameter

It is to be noted that the grain size does not depend on the Z–H parameter to a similar extent to that of dynamically recrystallized grain sizes, but depends very much on the initial grain size as well as the applied strain. This trend indicates that the dynamic recrystallization is simply given by the function of strain rate and temperature, but the meta-dynamic recrystallization is rather a function of grain size and strain instead of process parameters such as temperature and strain rate.

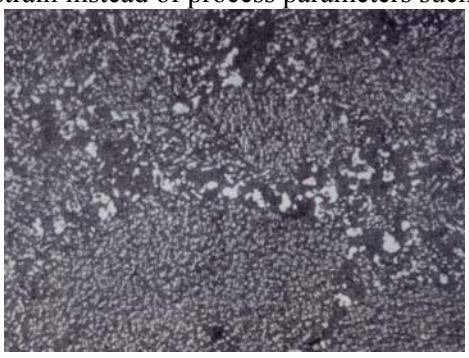

*Figure 7. Microstructures after deformation to a strain of 1.2 at 1100°C and $10^{-3}$ $s^{-1}$ in initially coarse-grained.*

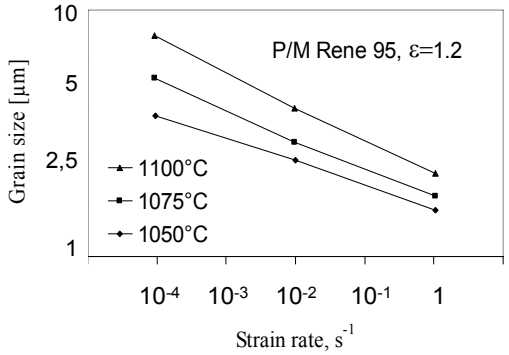


*Figure 8. Variation in as-worked microduplex grain size as a function of strain rate at the three test temperatures after a true strain of 1.2.*

## 4. CONCLUSIONS

Dynamic recrystallization can be used to control the grain size in Rene 95 for the given test conditions. The flow behavior signifies the dependence of dynamic recrystallization on the strain rate and temperature, and the dependence of on the initial grain size and applied strain. The effects of strain rate, $\dot{\varepsilon}$ on the peak flow strength, $\sigma_P$, of the fine-grained as hipped material are expressed as a function of m parameter. When the strain rate sensitivity is higher than that of the above transition strain rate this behavior can be attributed to a change in deformation mechanism.

## 5. REFERENCES


[1] Park NK., Kim IS., Na YS., Yeom JT.,: Hot forging of a nickel-base superalloy, Journal of Materials Processing Technology Volume 111, Issues 1-3 , 25 April 2001, Pages 98-102

[2] Zhao D, Tuler FR., :Effect of particle size on fracture toughness in metal matrix composites, Engineering Fracture Mechanics Volume 47, Issue 2 , January 1994, Pages 303-308

[3] Brooks JW., : Forging of superalloys, Materials and Design 21 2000 297-303

[4] Na YS., Yeom JK., Park NK., Lee JM., :Simulation of microstructures for Alloy 718 blade forging using 3D FEM simulator, Journal of Materials Processing Technology 141 (2003) 337–342.

[5] Koul AK., Immarigeon JP., :Modelling of Plastic Flow in Coarse Grained Nickel-Base Superalloy Compacts under Isothermal Forging Conditions, Acta Metallurgica, 35-7,(1987), 1791-1805.

[6] Shen G., Rollins J., Furrer D., :Microstructure modeling of forged waspaloy discs, in: R.D. Kissinger (Ed.), Superalloys 1996, TMS, Warrendale, PA, 1996, pp. 613–620.

[7] Edington JW., Melton KN., Cutler CP., :Superplasticity, Progress in Material Science, 21 (1976) 61-158.

[8] Alniak MO., Bedir F., : Modelling of deformation and microstructural changes in p/m Rene 95 under isothermal forging conditions, Mat.Sci.Eng:A,(2006) article in press.

[9] Alniak MO., Bedir F., : Change in grain size and flow strength in p/m rene 95 under isothermal forging conditions, Mat.Sci.Eng:B,(2006) article in press.