Flow Stress Evolution of P/M Nickel-base Superalloy During High-temperature Plastic Deformation

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Abstract. In this work, the use of scanning electron microscopy, transmission electron microscopy, electron backscatter diffraction technique and experimental study of the nickel-base superalloy FGH96 recrystallization behavior of alloy. Through experimental study found that the thermal deformation, FGH96 alloys under different plastic deformation at high temperature deformation process parameters, mainly dynamic softening and strain hardening in two stages.

1. Introduction
Turbine disks of current combustion turbines are generally made from nickel-base superalloys because of the need for high temperature strength along with high creep, corrosion, and fatigue resistance. Turbine engine manufacturers produce polycrystalline disk alloys with well-controlled chemistry, grain structure, and mechanical properties in order to extend operational lifetimes and increase engine efficiency[1-3]. However, the complications of grain structure control and its resultant influence on design and processing of disk materials makes optimization of current and new disk materials time consuming and expensive.

The alloy of interest in this study is a powder metallurgy turbine disk alloy developed by Beijing Institute of Aeronautical Materials named FGH4096, which is similar to the Rene 88DT produced by GE Aviation[4-5]. The Thermocmaster-Z hot working simulation test machine was used to perform high temperature uniaxial compression deformation test on FGH96 alloy to obtain the true stress-true strain curve of FGH96 alloy under different plastic deformation process parameters. Observe the evolution of flow stress in true stress-true strain curve Law.

2. Experimental
The chemical composition of the FGH96 alloy selected for the test material is listed in Table 1.

| Element | Cr  | Co  | Mo  | W  | Ti  | Al  | C   | Ni              |
|---------|-----|-----|-----|----|-----|-----|-----|-----------------|
| Content, wt% | 15.94 | 12.90 | 4.10 | 4.00 | 3.62 | 2.22 | 0.042 | Remaining |

The sample size of the uniaxial compression deformation test is Φ10 × 15mm. The process map of the deformation test is shown in Figure 1.

3. Results and Discussion
Figure 2 is the true stress-true strain curve of FGH96 alloy during high temperature uniaxial compression deformation under the conditions of deformation temperature of 1000°C~1100°C,
deformation rate of 0.001~1s⁻¹, and strain value of 0.9, at different deformation temperatures. Under the condition of deformation rate and deformation rate, the basic common feature is that as the strain value increases, the flow stress increases rapidly. First, the minimum stress value and the corresponding strain value required for the recrystallization to start nucleation are first broken, namely the yield stress σc and Yield strain εc; thereafter, the flow stress continues to increase until it reaches a peak, and the corresponding stress value and strain value are the peak stress σp and the peak strain εp. After exceeding this peak strain εp, as the strain value increases, the rheology. The stress shows a certain downward trend until it reaches a minimum value. The corresponding stress and strain values are the steady-state stress σss and the steady-state strain εss. After a certain degree of strain accumulation, the flow stress continues with the strain value. Increase and continue to rise, this rising trend continues to the final strain value of the experimental design, the corresponding stress value is defined as the end stress σfinal, it should strain value of 0.9.

Figure 1. Uniaxial compression deformation routing

Figure 2. True stress-true strain curve of FGH96 alloy during uniaxial compression deformation

Regarding the above phenomenon, it is generally believed that this is the result of the combined effect of dynamic softening and strain hardening during high-temperature plastic deformation [6-7], but the effect of dynamic softening and strain hardening is slightly different under different plastic deformation process parameters. There are differences, and the influencing factors of the two affect each other.

An excessively fast deformation rate (generally greater than 1s⁻¹) can lead to deformation temperature rise, which in turn affects the microstructure. The temperature data collected by the hot
working simulation test machine cannot truly reflect the deformation temperature rise of the sample [8], so Formula method to calculate deformation temperature rise during plastic deformation [9]

\[ \Delta T = \eta \beta \frac{\sigma_{\text{ave}} \Delta \varepsilon}{\rho c} \]  \hspace{1cm} (1)

\[ \sigma_{\text{ave}} = \frac{1}{\Delta \varepsilon} \int_{\varepsilon_0}^{\varepsilon_{\text{p}}} \sigma d\varepsilon \]  \hspace{1cm} (2)

In the formula, \( \Delta T \) is the temperature change caused by the heat generated by plastic deformation, \( \sigma_{\text{ave}} \) is the average flow stress in the range of \( \Delta \varepsilon \), \( \rho \) (8.33 g/cm\(^3\)) and \( c \) (0.5421 ~ 0.5769 J/(g·K)) are the density and specific heat melting of FGH96 alloy under different deformation temperature conditions, \( \beta \) is the thermal work conversion coefficient, and \( \eta \) is the adiabatic factor. The values suitable for isothermal uniaxial compression deformation of small samples are 0.97 and 0.9, respectively, by formula (1) and (2), you can calculate the deformation temperature rise of the sample under different plastic deformation process parameters, as shown in Figure 3, which is the calculation result of the deformation temperature rise under different plastic deformation process parameters. As the deformation rate increases, the deformation temperature rises gradually. When the deformation rate is 0.001 s\(^{-1}\), the average temperature rise under different strain values is less than 10\(^\circ\)C. When the deformation rate is 1 s\(^{-1}\), the average temperature rise is between 50 and 70\(^\circ\)C.

![Figure 3. Temperature rise in different plastic deformation parameters](image)

According to the Avrami kinetic principle of the dynamic recrystallization process [10], the true stress–true strain curve obtained from the uniaxial compression deformation test of FGH96 alloy was fitted with a 7-degree polynomial. From the fitted curve, Read the peak stress \( \sigma_p \), peak strain \( \varepsilon_p \), yield
stress $\sigma_c$, yield strain $\varepsilon_c$, steady state stress $\sigma_{ss}$, steady state strain $\varepsilon_{ss}$, and end stress $\sigma_{final}$. Using the fitting method described above, the 16 true stress-true strain curves in Figure 3 were fitted with a 7-degree polynomial, and the peak stress $\sigma_p$, yield stress $\sigma_c$, steady-state stress $\sigma_{ss}$ and the final stress $\sigma_{final}$, as listed in Table 2, except for the protruding stress value (deformation temperature of 1100°C and deformation rate of 0.001 ~ 0.01s$^{-1}$), under the same deformation rate, the same type of rheology. The stress values decrease with the decrease of the deformation temperature; under the same deformation temperature conditions, the flow stress values of the same category all increase with the increase of the deformation rate.

**Table 2.** $\sigma_p$, $\sigma_c$, $\sigma_{ss}$ and $\sigma_{final}$ in different plastic deformation parameters

| Deformation temperature, °C | 1000 | 1050 | 1070 | 1100 |
|-----------------------------|------|------|------|------|
| $\varepsilon = 0.001s^{-1}$  | $\sigma_p$ | 62.81 | 30.07 | 23.89 | 42.90 |
| $\varepsilon = 0.01s^{-1}$   | $\sigma_c$ | 38.03 | 21.93 | 16.18 | 26.23 |
| $\varepsilon = 0.1s^{-1}$    | $\sigma_{ss}$ | 38.63 | 29.20 | 23.83 | 39.89 |
|                             | $\sigma_{final}$ | 51.98 | 35.95 | 33.99 | 43.519 |
| $\varepsilon = 1s^{-1}$     | $\sigma_p$ | 174.91 | 108.57 | 87.94 | 77.06 |
|                             | $\sigma_c$ | 104.42 | 65.09 | 52.17 | 47.20 |
|                             | $\sigma_{ss}$ | 96.75 | 64.50 | 57.95 | 61.02 |
|                             | $\sigma_{final}$ | 123.99 | 70.08 | 68.933 | 70.44 |
| $\varepsilon = 0.1s^{-1}$   | $\sigma_p$ | 312.96 | 169.04 | 134.37 | 125.58 |
|                             | $\sigma_c$ | 187.93 | 101.32 | 80.64 | 75.02 |
|                             | $\sigma_{ss}$ | 206.76 | 140.44 | 111.36 | 106.62 |
|                             | $\sigma_{final}$ | 216.57 | 164.92 | 130.16 | 130.15 |
| $\varepsilon = 1s^{-1}$     | $\sigma_p$ | 473.38 | 291.21 | 267.99 | 229.92 |
|                             | $\sigma_c$ | 285.52 | 174.16 | 160.53 | 137.84 |
|                             | $\sigma_{ss}$ | 236.12 | 177.25 | 163.93 | 145.71 |
|                             | $\sigma_{final}$ | 247.45 | 194.73 | 178.29 | 166.43 |

Under the same deformation rate, as shown in Figure 4, as the deformation temperature increases, the strain value required for the true stress-true strain curve to reach the peak stress $\sigma_p$ gradually decreases. This is because as the deformation temperature increases, the mutual coordination between the original grain slip systems is promoted, and grain twisting and grain boundary slipping become relatively easy, which leads to a reduction in the critical shear stress of the plastic deformation of the grains, thereby promoting recrystallization nucleation.

**Figure 4.** Evolution tendency of $\varepsilon_p$ in different plastic deformation parameters
Under the same deformation temperature condition, with the increase of the deformation rate, the strain value required for the true stress-true strain curve to reach the peak stress $\sigma_p$ is slightly reduced, but the change is not large. Although under the condition of high deformation rate, it will cause a larger degree of deformation temperature rise is shown in Figure 4, but the test results have not been affected much, and because the test conditions are adiabatic and isothermal, the effect of the deformation temperature rise caused by the deformation rate on the microstructure is instantaneous, and there is no cause long-term effects.

Under different plastic deformation process parameters, the evolution law of the strain value required for the true stress-true strain curve to reach the steady-state stress $\sigma_{ss}$ is similar to that of the peak strain $\varepsilon_p$. As shown in Figure 5, the steady-state strain $\varepsilon_{ss}$ can be considered Strain hardening began to dominate the beginning, and it can be seen that most of the steady state strain values are concentrated between 0.6 and 0.7.

![Figure 5. Evolution tendency of $\varepsilon_{ss}$ in different deformation parameters](image)

Figure 6 is the statistics of the time ($\sigma_p-\sigma_{ss}$) and the time ($\sigma_{final}-\sigma_{ss}$) required to reduce the flow stress under different plastic deformation process parameters. When the deformation rate is 0.001s$^{-1}$ and the deformation temperature is 1050 ~ 1100 °C, during most of the plastic deformation process, the flow stress is gradually increasing, that is, strain hardening dominates, and under the other plastic deformation process parameters, dynamic softening occupies the main plastic deformation time. As the deformation rate increases, strain hardening gradually weakens, which indicates that the formation of microstructures that cause strain hardening takes a certain amount of time. As the deformation temperature increases, strain hardening gradually increases, which indicates that the microstructures that cause strain hardening follow deformation. Increasing temperature gradually became apparent.
4. Conclusions

FGH96 alloy undergoes high-temperature plastic deformation under different plastic deformation process parameters (1000 ~ 1100 °C, 0.001 ~ 1s-1, ε = 0.1 ~ 0.9), and there will be two stages of dynamic softening and strain hardening. When the deformation rate is 0.001s-1 and the deformation temperature is 1050 ~ 1100 °C, the flow stress gradually increases during most of the plastic deformation time, that is, the strain hardening plays a dominant role, and under the remaining plastic deformation process parameters, Dynamic softening predominates. As the deformation rate increases, strain hardening gradually decreases, and as the deformation temperature increases, strain hardening gradually increases.

5. References

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