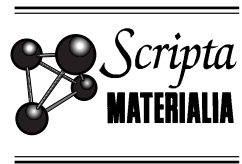




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ACTIVATION ENERGY FOR SUPERPLASTIC DEFORMATION OF IN718 SUPERALLOY

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Introduction

IN718 superalloy is reported [1–5] to exhibit superplasticity in the temperature range of 1173–1273 K. Superplastic behavior is characterized by high strain rate sensitivity index ($m \geq 0.3$) and low activation energy (Q), which is generally comparable with that for grain boundary diffusion. However, the stress (σ) – strain (ϵ) curves obtained under superplastic condition are known [6] to exhibit strain hardening and/or strain softening, especially, in the early part of deformation. Under such non-steady state flow condition, the values of m and Q can vary with strain [6–7], making them as the non-unique parameters of the constitutive relationship [8] for high temperature deformation. Fortunately, the σ – ϵ curves for a large number of superplastic materials [7] exhibit steady state flow behavior subsequent to the large initial transient stage of strain hardening/softening and concomitant microstructural evolution. Hence, the stress (σ)–strain rate ($\dot{\epsilon}$) data obtained [9] beyond a certain strain level represent a reasonable steady state condition. Therefore, the aim of the present work was to evaluate the m and Q parameters, of the constitutive relationship for superplastic deformation of IN718 superalloy after such prestraining.

Experimental

IN718 superalloy of superplastic forming (SPF) grade was obtained in the form of 1.3 mm thick sheet. The analyzed composition of the alloy is given in Table 1.

Tensile specimens with gage length and width of 20 mm and 5.3 mm, respectively, were machined and tensile tested by Instron Universal Testing Machine. Test temperatures were controlled to an accuracy of ± 1 K, and the specimens were soaked at the test temperature for 30 min. prior to deformation. Metallographic samples were prepared by mechanical polishing followed by and electrolytic etching with 10% oxalic acid in water. Grain size was measured by mean-linear intercept method and the error in the grain size data reported here were within $\pm 5\%$.

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TABLE 1
Chemical Composition of the IN718 Superalloy

Constituent	C	Cr	Ni	Mo	Nb	Al	Ti	Cu	Fe
Wt.(%)	0.034	17.4	52.9	3.11	4.99	0.48	1.07	0.19	19.4

Results

Five tensile specimens, whose initial microstructure has been presented elsewhere [5], were deformed to true strains of 0.10, 0.30, 0.50, 0.70 and 1.00 at a true constant strain rate of $1 \times 10^{-4} \text{ s}^{-1}$ and the temperature of 1248 K. The grain sizes attained at these strain levels were 6.9, 7.9, 7.9, 8.0 and 8.2 μm , respectively. This suggests that the microstructure remained reasonably stable beyond the strain of 30%. Therefore, the prestraining of $\varepsilon = 0.30$ was assumed to provide steady state flow during subsequent tests, as supported by the σ - ε data to follow.

Another tensile specimen was prestrained to $\varepsilon = 0.30$ under the same condition of strain rate and temperature as above, and then subjected to differential strain rate tests at a series of cross-head speeds, viz. 0.05, 0.002, 0.005, 0.01, 0.02 and 0.05 cm/min which resulted in strain rates in the range $\sim 1 \times 10^{-5}$ to $3 \times 10^{-4} \text{ s}^{-1}$. The first and the last cross-head speeds were selected to be the same in order to check if there occurred strain hardening or strain softening in the course of deformation during the ascending order of strain rate changes used in this investigation. Such differential strain rate tests were performed at various temperatures, viz. 1248, 1238, 1228, 1218, 1208, 1198, 1188, 1173 and 1248 K. During the adjustment to the new test temperatures in this sequence, the specimen was unloaded within the furnace and reloaded in 10 min for further differential strain rate test. At the termination of the final differential strain rate test, no necking was noticed in the sample.

The stress-strain rate data, obtained from differential strain rate tests over the range of strain rates and temperatures covered, are plotted in log-log scale in Fig. 1. The σ - ε data repeated at the highest strain rate at each temperature and the entire differential strain rate test repeated at 1248 K showed an absence of strain hardening/softening in the course of entire test, thus suggesting that steady state condition was established. For the sake of clarity in Fig. 1, the σ - ε data corresponding to the repeated tests are not presented here. While the σ - ε data in Fig. 1 suggest straight lines for 3–4 data points towards the lower strain rates at each temperature, the data at the highest strain rate employed suggest a curvature with lower slope, which is a measure of m . The values of m were obtained by applying regression analysis to only those data points that were suggestive of clear straight lines. Strain rate sensitivity index thus calculated was found to increase linearly from 0.37 at 1173 K to 0.58 at 1248 K, as shown in Fig. 2.

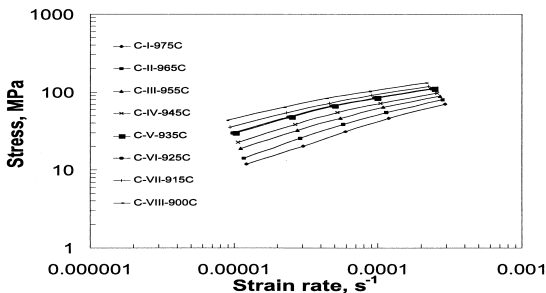


Figure 1. Stress-strain rate plot obtained from differential strain rate tests conducted at various temperatures (in descending order from 1248 to 1173 K).

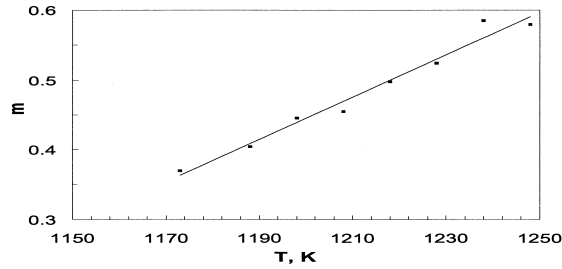


Figure 2. Variation in strain rate sensitivity in superplastic region as a function of test temperature.

The flow stresses at a constant strain rate of $5 \times 10^{-5} \text{ s}^{-1}$ were taken from Fig. 1 for the Arrhenius plot of $\ln(\sigma)$ vs $1/T$ in Fig. 3 to evaluate the activation energy for superplastic deformation using:

$$Q = nR \left(\frac{\partial \ln \sigma}{\partial (1/T)} \right)_\varepsilon \quad (1)$$

where $n = 1/m$ is the stress exponent, T the absolute temperature and R is the gas constant. For all the data points considered together and by taking the average $n = 2.28$, based on the regression analysis of σ - ε data within the superplastic region, Q is estimated to be 241.1 kJ/mol (broken line in Fig. 3). The regression coefficient r^2 was 0.94. However, the close examination of the data points in Fig. 3 suggests a possibility of bi-linear relationship instead of single straight line through all the data points. The slope of the straight line at higher temperatures (1218–1248 K) is seen to be greater than that at lower temperatures (1173–1218 K). Also, the linear regression analysis supporting the bi-linearity improves the values of r^2 better than 0.99 in both the temperature regimes. The activation energies for superplastic deformation, by using equation (1) and the respective average values of n in the relatively lower and higher temperature regimes, were determined to be 179.3 and 345.4 kJ/mol, respectively.

Discussion

It is to note here that, in spite of the small change in temperature (1173–1248 K with an interval of 10 K), m was found to increase from 0.37 to 0.58 with temperature. The earlier investigations on superplasticity of this material exhibited the maximum value of m to be 0.90, with the most common values being between 0.50–0.63 [1–5]. Based on the stability of grain size obtained here beyond $\varepsilon = 0.30$, to which the tensile specimen was prestrained, the variation in m with temperature appears to be a result of direct thermal effect, rather than the indirect effect through grain growth or recrystallization.

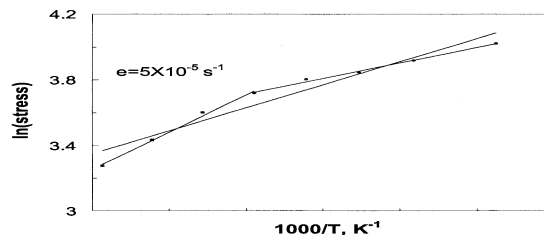


Figure 3. Arrhenius plot to determine activation energy for superplastic deformation. The data suggest bi-linearity (solid line) rather than a single line (broken line).

TABLE 2
Activation Energies of Some Constituents Present in IN718 Superalloy [14, 20]

Diffusing Species	Lattice Diffusion		Grain Boundary Diffusion	
	Temp. Range (K)	Activation Energy (kJ/mol)	Temp. Range (K)	Activation Energy (kJ/mol)
Self Diffusion				
Ni	813–1673	278.2/357.4*	1123–1373	118.2
γ -Fe	1443–1634	264.3	1196–1289	163.4
Nb	1353–2693	349.9/438.7*	—	—
Diffusion in γ -Fe				
Cr ⁵¹	1073–1153	292.0	885–995	217.6
Ni ⁶³	1203–1323	280.7	1273–1473	173.6
Nb ⁹⁵	1433–1563	344.8	—	—
Diffusion in Ni-Cr System				
Cr	1133–1433	310.0	1133–1433	180.0/320.0*
Ni	1111–1565	259.0	1111–1565	209.0/317.0*
Diffusion in Fe-Cr-Ni System				
Fe	870–1306	263.6	870–1306	177.8 (45 wt% Ni) 148.5 (55 wt% Ni)
Diffusion in Fe-Cr-Ni-C System				
Cr	1073–1323	255.2	1073–1323	188.6
Ni	1073–1323	278.2	1073–1323	155.7–167.6
Activation Energy for Superplastic Deformation (Present work)				
	1218–1248	345.4	1173–1218	179.3
(Transition Temperature = 1218 K)				

* Arrhenius plots exhibited two distinct curvatures.

The activation energies for superplastic deformation are determined to be 179.3 and 345.4 kJ/mol at relatively lower (1173–1218 K) and higher (1218–1248 K) temperatures, respectively. To our knowledge, the activation energy for superplastic deformation of this material is reported in a limited way [5]. However, several studies on hot compression and creep tests reported [10–13] the values of activation energy to be ranging from 400–483 kJ/mol. Chen and Chaturvedi [13] found that such a large value of activation energy could be reduced to 248.1–250.8 kJ/mol on considering the effective stress instead of applied stress.

The survey of activation energy values [15] for superplastic deformation of a wide range of materials show them to be comparable with that for grain boundary diffusion in the majority of cases. However, there appear a few exceptions, where the activation energy for superplastic deformation is comparable with that for lattice diffusion. The attempts to resolve such a variation in activation energy for superplastic deformation, in fact, delineated two distinct values of activation energy for the same material, e.g. Zn-Al eutectoid [16], Pb-Sn eutectic [9] and Al-Cu eutectic [17], with a transition temperature of $\sim 0.8 T_m$, where T_m is absolute melting point. From the various theories for high temperature deformation and their presentation in the form of deformation mechanism maps [18], it is established that, closer to melting point, it is the lattice diffusion which is rate controlling, and below $0.8 T_m$, the grain boundary diffusion becomes rate controlling. Similar variation in the mechanisms for superplastic deformation was postulated by Hayden et al [19]. Superplastic deformation is known to occur by grain boundary sliding, but it requires accommodation which is provided by diffusion according to the various models and experimental measurements. Therefore, it is important to compare the present two values of activation energy for superplastic deformation of IN718 superalloy with the relevant activation energies reported [14, 20] for various elements and alloys of interest, as listed in Table 2. The comparison of activation energies in Table 2 leads to a suggestion that, for superplastic

deformation of IN718 superalloy, the grain boundary diffusion is rate controlling below the critical temperature of 1218 K ($0.79 T_m$) whereas lattice diffusion becomes a rate controlling step at higher temperatures.

Conclusions

The study of flow behavior of IN718 superalloy over the strain rate range of $\sim 1 \times 10^{-5}$ – $3 \times 10^{-4} \text{ s}^{-1}$ and the temperature range of 1173–1248 K leads to the following conclusions.

1. Log (σ)–log (ϵ) plot delineates predominantly superplastic region over the entire temperature range, with the strain rate sensitivity index increasing from 0.37 at 1173 K to 0.58 at 1248 K.
2. The Arrhenius plot reveals two values of activation energy for superplastic deformation with the transition temperature being at 1218 K ($0.79 T_m$). The activation energy of 179.3 kJ/mol below 1218 K is comparable with that for grain boundary diffusion whereas 345.4 kJ/mol at higher temperatures is comparable with the activation energy for lattice diffusion.

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