EFFECT OF HOT DEFORMATION PARAMETERS

ON THE GRAIN SIZE OF WROUGHT IN718

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Abstract

Superalloy IN718 is one of the most important aero-materials. It has been widely used to manufacture turbine discs and other important components. Because the microstructure and mechanical properties of IN718 forgings are highly sensitive to metallurgical technology and thermomechanical processing(TMP), it is very difficult to control every step of TMP to obtain most favorable mechanical properties and microstructures in IN718 forgings. In recent years, more and more attention has been paid to the hot deformation behavior and computer simulation of TMP of superalloy IN718. However, up to now, any perfect model suitable for manufacturing turbine discs has not been found. To set up such a model, it is necessary to formulate the relationship between grain size and hot deformation parameters after a constitutive relationship has been developed. In the present work, isothermal constant speed compression tests of superalloy IN718 were conducted using a computer-controlled MTS machine with temperatures from 960°C to 1040°C, initial strain rates from $0.001s^{-1}$ to $1.0s^{-1}$ and engineering strain from 0.1 to 0.7. The deformed specimens were immediately quenched in water to retain the deformation microstructures. The effect of hot deformation parameters on the grain size was analyzed. A formula was developed to express the relationship between grain size and deformation temperature, strain rate and strain.

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Introduction

IN718 is one of the nickel-base superalloys extensively used in aeronautic, astronotic, oil and chemical industry for its excellent mechanical, physical and chemical properties and accounts for about 50% of wrought nickel-base alloys[1-4]. As it is well known, it is necessary to obtain most favorable microstructure for best properties. The variation of microstructure of IN718 is very sensitive to the deformation condition. Therefore, in recent years, many material scientists studied the hot deformation behavior of IN718[4-13]. Srinivasan investigated the hot deformation behavior of fine grain IN718 in the temperature range from 871°C to 1149°C (1600F to 2100F) and strain rate range from $0.001s^{-1}$ to $10s^{-1}$. A constitutive equation which is independent of strain was developed[8]. Garcia did the similar research works in the temperature range from 900°C to 1177°C and strain rate range from $0.005s^{-1}$ to $5s^{-1}$. A similar constitutive equation was obtained[6]. Liu and Luo developed another constitutive relationship for IN718 as a function of Zener-Hollomon parameter[14]. Recently, Zhang developed a new constitutive relationship expressing the hot deformation behavior of IN718 on the basis of consideration of physics and mathematics[13]. In the area of microstructure modeling, Sellars and coworkers have done extensive work on C-Mn steels in hot rolling[15,16]. And then, many researchers did the works to different materials similar to that of Sellars did[17-22]. Many studies have been done on the microstructure characterization and recrystallization behavior of IN718[5,7,8,10-12,23-25]. However, few models suitable for the quantitative prediction of grain size of alloy 718 can be found except the relation given by Domblesky[10] to represent the ASTM grain size at the end of each simulated pass sequence for super-solvus deformation. A whole model system on the effect of hot deformation parameters on the microstructure of IN718 has not been found in literatures.

In the present work, isothermal constant speed compression tests of superalloy IN718 were conducted using a computer-controlled MTS machine with temperatures from 960°C to 1040°C, initial strain rates from $0.001s^{-1}$ to $1.0s^{-1}$ and engineering strain (reduction in height) from 0.1 to 0.7. The deformed specimens were immediately quenched in water to retain the deformation microstructures. The effect of hot deformation parameters on the grain size was analyzed. A formula was developed to express the relationship between grain size and deformation temperature, strain rate and strain.

Experiment

Slices with 300mm diameter and 35mm thickness were cut from commercially available IN718 wrought bars. And then, these slices were solutionized at 1020°C for 2 hours. Cylindrical compression specimens with diameter of 20mm and height of 30mm were machined. To minimize scatter of the initial grain size, all samples were taken from the 22mm ring-shape bands locating at the mid-radius of the billet slice. The chemical composition of the experimental material is shown in Table I. To decrease the friction between ceramic dies and specimens and to decrease the barrel effect of specimens during high temperature compression tests, a kind of powdered glass mixed with a resin was chosen as the lubricant which is very suitable for the compression of superalloy IN718[13,26].

Isothermal constant speed compression tests were conducted on a computer-controlled MTS machine with a load capacity of 250KN. The deformation parameters of compression tests are shown in Table II. To obtain uniform temperature distribution, each specimen with lubricant on the ends was soaked at the test temperature for 20 minutes and then was deformed to the required engineering strain at a constant compression speed and a relevant initial strain rate.

Meanwhile, load and stroke data from the tests were acquired by a computer and latter converted to true stress and true strain. However, engineering strain will be valid in the present work since engineering strain is often used in practical forging production. Every deformed specimen were immediately quenched in water to retain the deformation microstructure. The deformed specimens were sectioned through the longitudinal axis for microstructure examination.

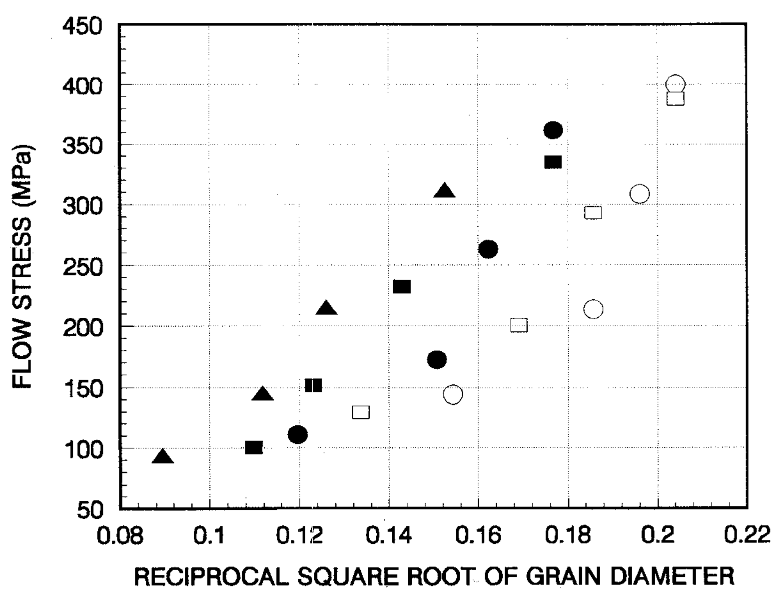
Table I Main Chemical Composition of Experimental Material

Ni	Cr	Fe	Nb	Mo	Ti
53.51	18.39	17.37	5.34	2.97	0.99
Al	Co	Si	Mn	C	Ta
0.50	0.35	0.10	0.05	0.024	0.02
N	P	B	O	S	Mg
0.008	0.006	0.004	0.001	0.0005	0.0008

Table II Deformation Parameters of Compression Test

Temperature	960°C	980°C	1000°C	1020°C	1040°C
Strain	0.1		0.4		0.7
Strain Rate	0.001 s^{-1}	0.01 s^{-1}	0.1 s^{-1}	1.0 s^{-1}	

The samples for microstructure examination were prepared using standard metallographic techniques. The photographs were taken from the center of the longitudinal section of every specimen. The determination of grain size includes two parts. First is directly measuring the diameters of 60 grains along three principal directions by intercept method and obtaining an average grain diameter. Second is comparing the photographs with ASTM standard grain charts and obtaining a nominal grain diameter. The experimental results are the average values of every set of first and second diameter.



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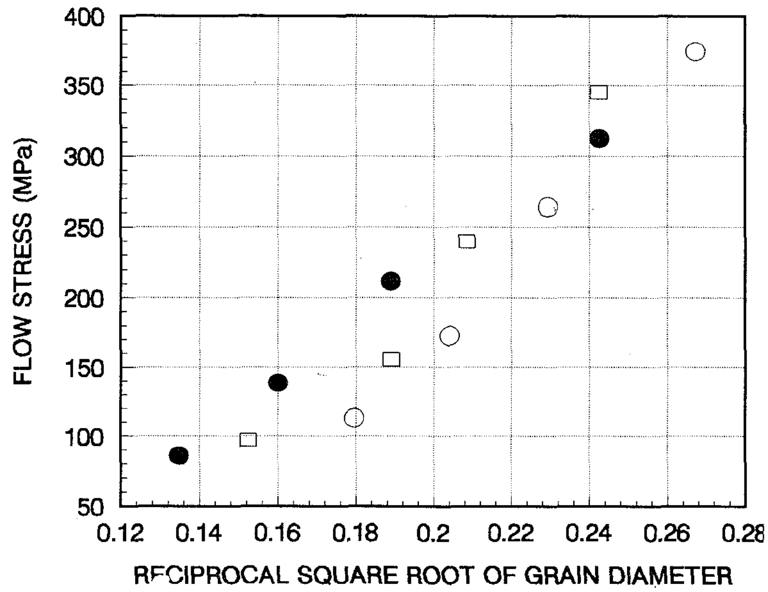

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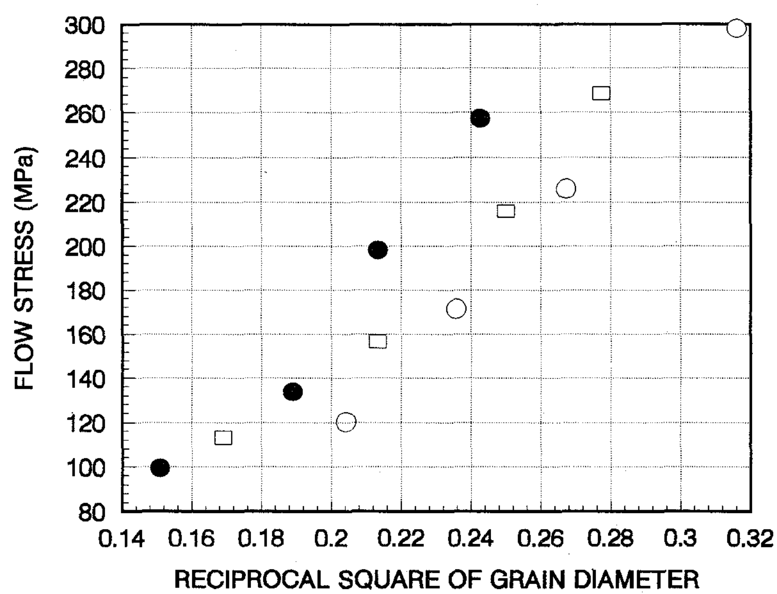
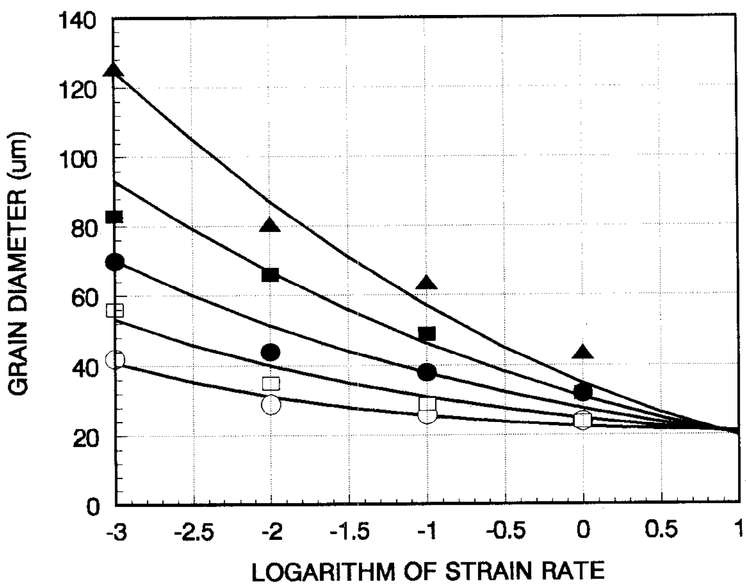


(c)

Figure 1 - The experimental relationship of grain size and flow stress when strain is 0.1(a), 0.4(b), 0.7(c) and temperature is
(a) 960° C (full triangle), 980° C (full square), 1000° C (full circle), 1020° C (empty square), 1040° C (empty circle)
(b) and (c) 1000° C (full circle), 1020° C (empty square), 1040° C (empty circle)

Results and Discussion

Among all microstructure parameters, grain size has a most direct and obvious relationship with mechanical properties. Hence, the model for simulating the deformation behavior of an alloy should be developed as a function of grain size. According to the experimental results, as shown in Figure 1, the reciprocal square root of grain size after hot deformation has a linear relationship with the flow stress. The relationship is similar to Hall-Petch formula, as shown in equation (1). Both the first term σ_0 and the coefficient K are a function of hot deformation parameters. In general, it is believed that the first term σ_0 in equation (1) indicates the inner state of grains, such as crystal structure and density of various defects. The second term $K \cdot d^{-\frac{1}{2}}$ mainly shows the outer characteristics of a grain, such as grain shape, grain size and grain boundary structure. Both of them will depend on the deformation parameters.



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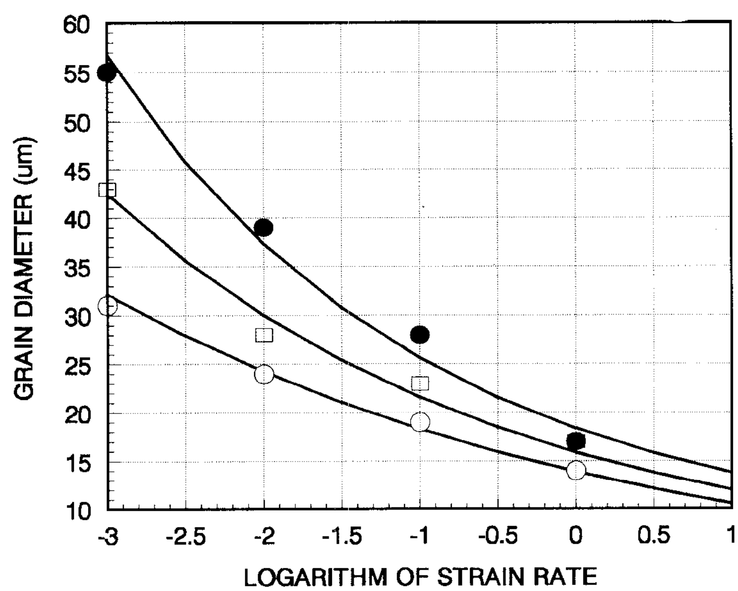

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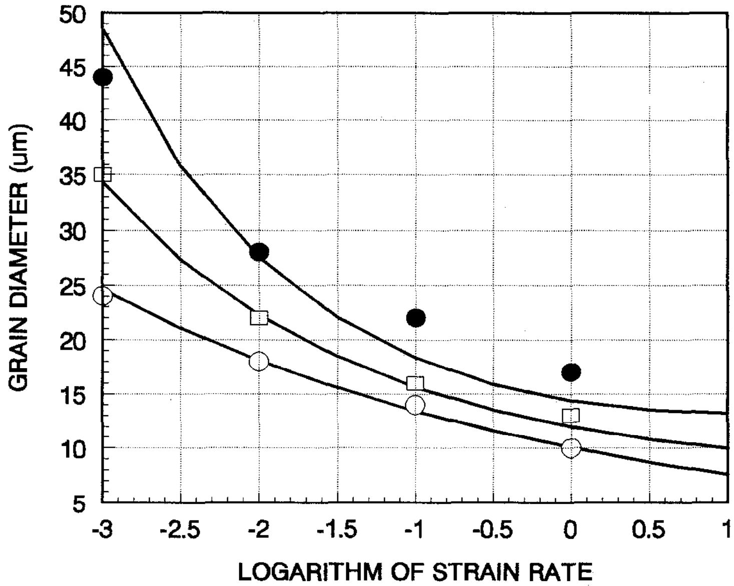
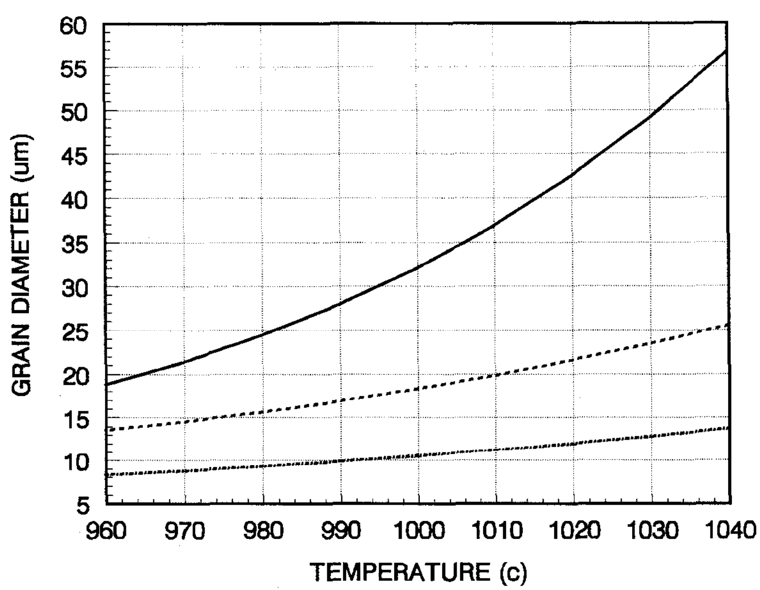
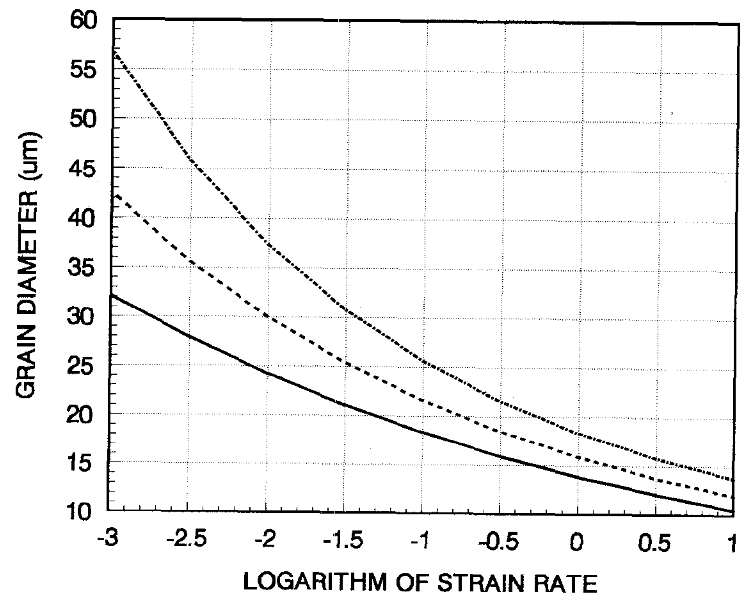


(c)

Figure 2 - Comparison of experimental grain sizes (shown by a symbol) with those calculated from equation (1)(shown by solid line) when strain is 0.1(a), 0.4(b), 0.7(c) and temperature is
(a) 960° C (empty circle), 980° C (empty square), 1000° C (full circle), 1020° C (full square), 1040° C (full triangle)
(b) and (c) 1000° C (empty circle), 1020° C (empty square), 1040° C (full circle)



(a)



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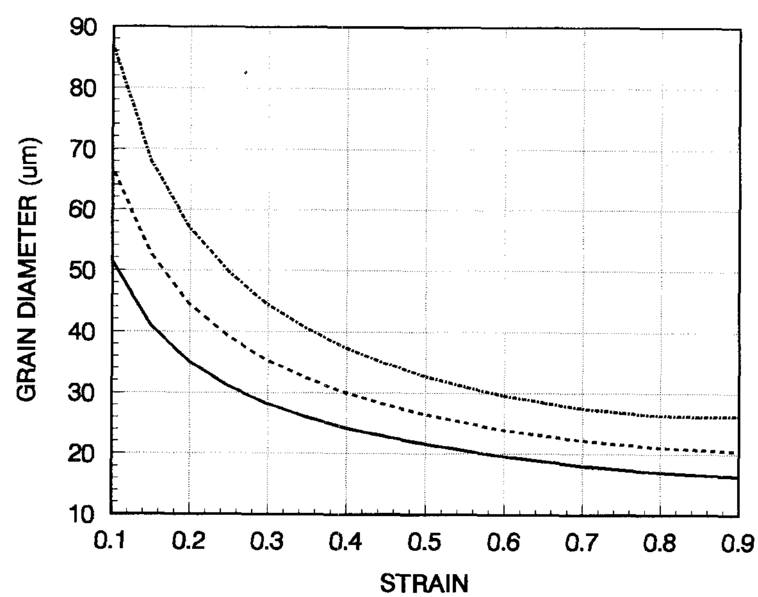

(c)

Figure 3 - The relationship between grain size and temperature(a), strain rate(b), strain(c) when (a) strain is 0.4, strain rate is 0.001 s^{-1} (solid line), 0.1 s^{-1} (dashed line), 10.0 s^{-1} (dash dotted line)
(b) strain is 0.4, temperature is 1000° C (solid line), 1020° C (dashed line), 1040° C (dash dotted line)
(c) strain rate is 0.01 s^{-1}, temperature is 1000° C (solid line), 1020° C (dashed line), 1040° C (dash dotted line)

$$\sigma = \sigma_0 + K \cdot d^{-\frac{1}{2}} \qquad (1)$$

Hall-Petch formula generally shows the relationship between yield stress and grain size of a metal or an alloy at room temperature[27]. At some sense, flow stress is the yield stress of a material at high temperature. Thus, it must have a relationship similar to Hall-Petch formula with grain size. From the results calculated from equation (1), as shown in Figure 3, it can be seen that the results are satisfactory. Therefore, it can be concluded that flow stress of IN718 during hot deformation has a linear relationship similar to Hall-Petch formula with grain size.

During hot deformation, two possible phenomena will appear in a hot deformed material. They are work hardening and dynamic softening. Both of them can be shown by flow stress. Flow stress is always correlative to a certain grain size. Thus, the variation of flow stress and grain size will be the results of hot deformation parameters affecting the material deformation behavior.

From equation (1), the relationship between grain size and σ, σ_0 and K can be written as

$$d = \left(\frac{K}{\sigma - \sigma_0} \right)^2 \qquad (2)$$

σ is a function of hot deformation parameters[13]. σ_0 and K are also related to hot deformation parameters. Therefore, grain size is a function of hot deformation parameters. When temperature increases, flow stress will decrease[13], which means dynamic softening will play the main role in the metal deformation. From equation (2), grain size will increase(Figure 3a). It can be concluded that coarse grain will be correlated to the dynamic softening. When strain rate increases, flow stress will increase[13], which means work hardening is the main deformation behavior of metal deformation. From equation (2), grain size will decrease (Figure 3b). It can be obtained that fine grain will certainly exist in deformed specimen when work hardening is the main behavior. When strain increases, grain size will extremely decrease first and then will be a constant when strain is larger than a certain value(Figure 3c). Therefore, it can be concluded that when strain is small enough the deformation material will characterize an obvious work hardening behavior. When strain reaches a certain value, an equilibrium between work hardening and dynamic softening will exist. The grain size will not further change with the increasing of strain. This may be the reason why flow stress is a constant with the increasing of strain when strain is larger than a certain value and strain rate and temperature reach favorite values[6,8,26].

Conclusions

1. The relationship between flow stress and grain size in superalloy IN718 is similar to Hall-Petch formula. Comparing with experimental ones, the calculated results from the developed model are satisfactory.

2. Grain size is a function of hot deformation parameters. The variation of grain size is correlative to the behavior of work hardening and dynamic softening in the hot deformation material. When temperature increases, the dynamic softening will occur and grain size will increase. When strain rate increases, work hardening will exist and grain size will decrease. When strain increases, work hardening will appear and then an equilibrium between work

hardening and dynamic softening will exist. Grain size will extremely decrease first and then will be a constant after strain is larger than a certain value.

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