Deformation behaviour of GH4169 nickel based superalloy in isothermal compression

M. Q. Li*, W. B. Ju, Y. Y. Lin, X. J. Wang and Y. Niu

Isothermal compression of the GH4169 nickel based superalloy was carried out at a Thermecmaster-Z simulator at deformation temperatures of 930–1050°C at intervals of 20°C, strain rate of 0·1–50·0 s^{-1} and maximum height reduction of 60·0%. The deformation behaviour of the GH4169 superalloy in isothermal compression was characterised based on the stress–strain behaviour analysis. Constitutive equations described the flow stress as a function of strain rate, strain and deformation temperature were proposed for the isothermal compression of the GH4169 superalloy and a close agreement between the calculated and experimental stress–strain curves is achieved.

Keywords: Superalloy, High temperature deformation, Isothermal compression, Constitutive equation

Introduction

Nickel based superalloys are widely used for gas turbine applications. As one of the high temperature metallic materials, nickel based superalloys have a high potential to manufacture important components in the aerofoil blade and pancake used at the service temperature of 650°C in the aviation and aerospace industries.[1] Like other advanced metallic materials, the deformation behaviour and/or its mathematical description of a nickel based superalloy is very important to plan the forging process.

In the past several decades, much work has been done to describe the variation of flow stress with the process parameters. Among all the methods, the empirical and semiempirical equations obtained from experimental data are widely used, in which the flow stress is presented in terms of strain, strain rate and deformation temperature. The most commonly used equation is proposed by Zener *et al.*[2] and subsequently modified by Sheppard *et al.*[3] Also, Rao *et al.*[4] have developed the constitutive equation in hyperbolic sine type to describe the flow stress during high temperature deformation. In the model for a steady flow, the Zener–Hollomon parameter Z is constructed to describe the steady deformation.[5] Lately, the artificial neural network theory is introduced into materials modelling. Li *et al.*[6] has acquired the constitutive equation of a titanium alloy at elevated temperature deformation. Bariani *et al.*[7] has developed an artificial neural network model of the nickel base superalloys under hot forging. Recently, some researchers[8–13] have constructed a constitutive equation, considering the movement of dislocation, the activation process of deformation and/or the dynamic recovery and recrystallisation during deformation process.

In the present paper, isothermal compression is conducted at deformation temperatures, strain rates and height reductions and a constitutive equation is proposed based on the deformation behaviour of the GH4169 superalloy in the high temperature deformation process.

Experimental

The chemical compositions and micrograph of as received GH4169 superalloy with 46·0 mm diameter is shown in Table 1 and Fig. 1. The heat treatment before isothermal compression was as follows: heated to 980°C and held for 1 h, air cooled to room temperature, then heated to 720°C and held for 8 h and furnace cooled to 620°C at a velocity of 50°C/h and held for 8 h, then air cooled to room temperature. Cylindrical compression specimens with 8·0 mm diameter and 12·0 mm height were machined from the heat treated bar.

To investigate the effects of process parameters on deformation behaviour of the GH4169 superalloy in isothermal compression, nominal deformation temperatures ranging from 930 to 1050°C at intervals of 20°C were employed and the strain rates were 0·1–50·0 s^{-1} for each deformation temperature. Isothermal compression was performed to 60·0% of maximum height reduction at each combination of deformation temperatures and strain rates. Isothermal compression with a constant strain rates was conducted at a Thermecmastor-Z simulator. The specimens were held for 3 min at the deformation temperature. All the tests were carried out at isothermal deformation temperature being maintained within ± 1°C. The load stroke data were converted to the stress–strain curves using standard equations. The flow stress was obtained as a function of deformation temperature, strain rate and strain.

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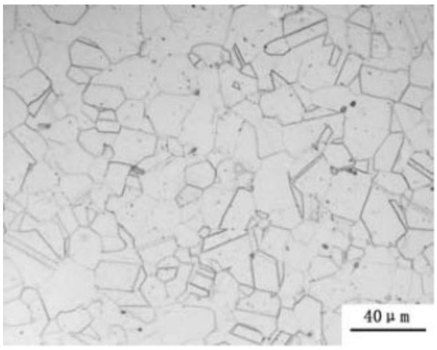
Published by Maney on behalf of the Institute
Received 2 November 2005; accepted 13 May 2006
DOI 10.1179/174328406X148769

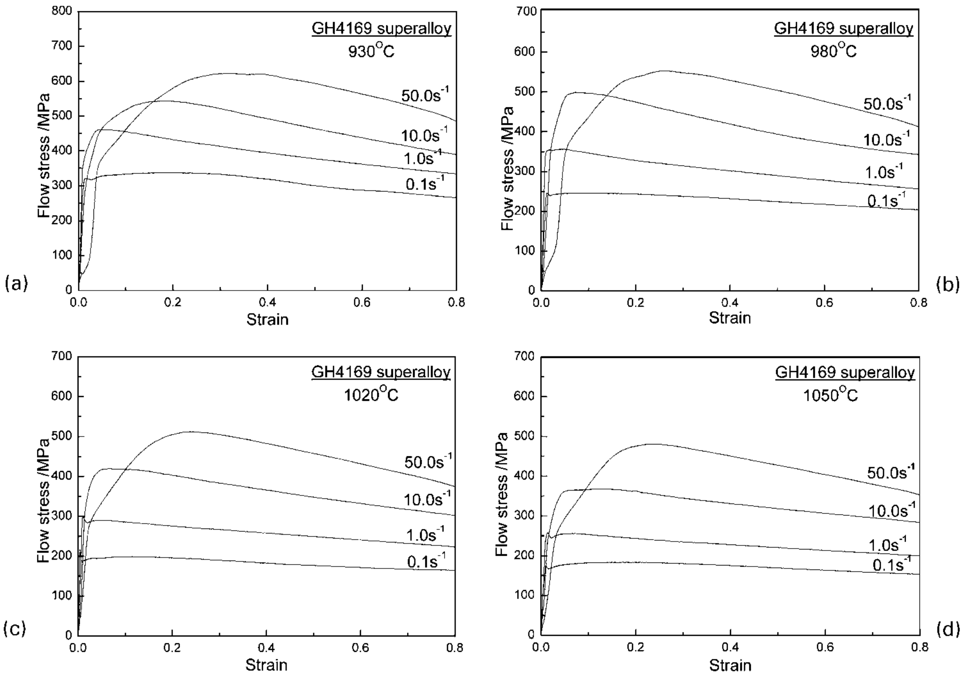


1 Micrograph of as received GH4169 superalloy before isothermal compression

Results and discussion

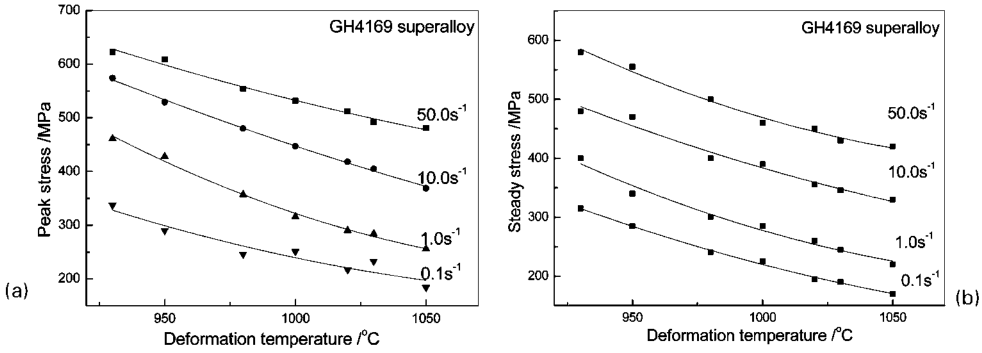
Flow stress

Typical stress–strain curves of the GH4169 superalloy at deformation temperature of 950 and 1060°C at different strain rates are shown in Fig. 2. As can be seen in Fig. 2, the curves exhibit flow softening behaviour in which the flow stress reaches a peak at a critical strain and then decreases with further straining. The critical strain from the peak stress to the steady flow increases with increasing strain rate. The peak stress in the isothermal compression of the GH4169 superalloy is shown in Fig. 3*a*. From Fig. 3*a*, effect of deformation temperature on peak stress is more evident at the testing strain rates. The peak stress of this alloy has a slope drop and then maintains a steady flow above the deformation temperature 1030°C, which results from the dynamic



a 930°C; *b* 980°C; *c* 1020°C; *d* 1050°C

2 Flow stress–strain curves in isothermal compression of GH4169 superalloy

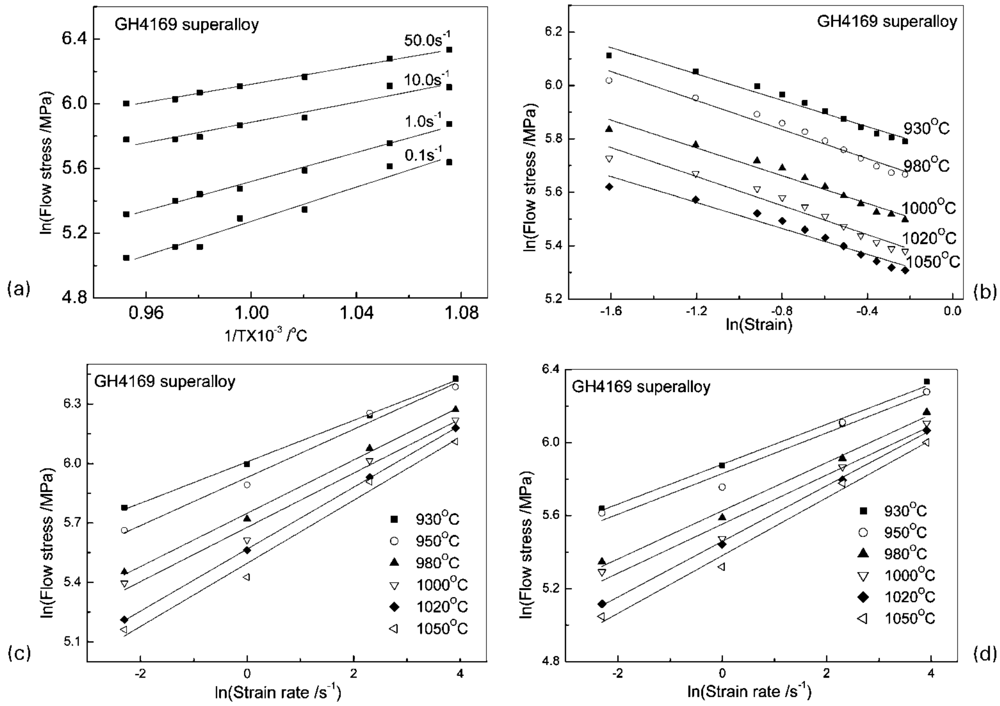


a peak stress; *b* steady stress

3 Peak and steady stress in isothermal compression of GH4169 superalloy

Table 1 Chemical compositions of GH4169 superalloy, wt-%

Element	C	Cr	Nb	Ni	Mn	Mo	Al	Ti	Si	Fe
Content	⩽0·08	17·0–21·0	4·75–5·50	50·0–55·0	⩽0·35	2·80–3·30	0·30–0·70	0·75–1·15	⩽0·35	Bal.



***a* deformation temperature; *b* strain; *c* ε=0·4; *d* ε=0·6**

4 Variation of flow stress with process parameters

recrystallisation. The steady stress in isothermal deformation of the GH4169 superalloy is shown in Fig. 3*b*. From Fig. 3*b*, steady stress in the isothermal compression of nickel based superalloy is sensitive to strain rate.

Constitutive equation for plastic deformation

In general, flow stress depends on the chemical composition, strain rate, strain and deformation temperature. Figure 4 is the variation of flow stress with the process parameters. Figure 4*a* is the variation of flow stress with deformation temperature at different strain rates, Fig. 4*b* is the variation of flow stress with strain at different deformation temperatures and Fig. 4*c* and *d* is the variation of flow stress with strain rates at different strains and deformation temperatures. The steady state rate equation in high temperature deformation relates flow stress to deformation temperature, strain rate and strain as[2]

$$\varepsilon^{m}\dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)=A\sigma^{n} \qquad (1)$$

where A is a constant, $\dot{\varepsilon}$ is the strain rate (s^{-1}), σ is the flow stress (MPa), ε is the strain, Q is the activation energy of deformation (kJ mol^{-1}), R is the gas constant (kJ mol^{-1} K^{-1}), T is the absolute deformation temperature (K), n is the stress exponent and m is the strain exponent.

By taking logarithm, equation (1) can be written as follows

$$\ln\sigma=-\frac{\ln A}{n}+\frac{1}{n}\left(\ln\dot{\varepsilon}+\frac{Q}{RT}\right)+\frac{m}{n}\ln\varepsilon \qquad (2)$$

where A, B and C are the material constants.

The temperature compensated strain rate parameter or the Zener–Hollomon parameter Z is defined as

$$Z=\dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \qquad (3)$$

Introducing the Zener–Hollomon parameter into equation (2), it can be modified as

$$\ln\sigma=A+B\ln Z+C\ln\varepsilon \qquad (4)$$

where A, B and C are the material constants.

In order to describe the deformation behaviour of nickel based superalloy in isothermal forging accurately, equation (4) is improved as

$$\ln\sigma=B_0+B_1\ln Z+B_2(\ln Z)^2+B_3(\ln Z)^3+B_4\ln\varepsilon \qquad (5)$$

where B_0, B_1, B_2, B_3 and B_4 are the material constants.

The nickel based superalloy is very sensitive to strain rate, therefore the material constants in the constitutive equation (5) should be different in different strain rate regions. By regression analysis to equation (5) according to the present experimental results of the GH4169 superalloy at different strains, material constants are determined and shown in Table 2.

By substituting the material constants in Table 2 into equation (5), the flow stress can be calculated at different deformation conditions. A comparison of calculated and experimental flow stress of the GH4169 superalloy shows that the mean difference between the calculated and the experimental flow stress is 8·0%.

Conclusions

During isothermal compression of the GH4169 superalloy, deformation behaviour is affected significantly by

Table 2 Material constants of GH4169 superalloy in equation(5)

Strain rate, s^{-1}	B_0	B_1	B_2	B_3	B_4
⩽10·0	1·1935	66·4765	100·189	31·0953	−0·1637
>10·0	0·0	−229·8438	105·2526	−11·8337	−0·196

deformation temperature, height reduction and strain rate. Deformation temperature and strain rate affect the peak and steady stress in isothermal compression of nickel based superalloy greatly. The peak and steady stress decrease with increasing deformation temperature and decreasing strain rate. The mean difference in the calculated flow stress though the present constitutive equation based on the Zener–Hollomon parameter with the experimental flow stress is $\leqslant 8{\cdot}0\%$.

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