Hot Compression Deformation Characteristics of Nimonic Alloy as-forged

WU Chunchun1,a*, JIN Keyu2,b and CHEN Gang3,c
1Shanghai Soonv Special Alloy Co., Ltd. Shanghai 201700, China
2Zhejiang Boteli Technology Co.,Ltd. Wenzhou 325100 ,China
3Ningbo Branch of Ordnance Science Institute of China, Ningbo 315103, China
ajames.wu@soonv.com, bjkwywz@126.com, ccg661231@163.com

Abstract. Hot Deformation Behavior and Constitutive Model of the nickel-base alloy Nimonic Alloy as–forged are investigated by hot compression tests in the ranges of strain rate (0.001-1s⁻¹) and temperature 1323-1423K, at intervals 50K. During the process of compression deformation, with the increase of true strain, the flow stress first increases rapidly to the peak value. Then, the flow stress decreases with the increase of true strain. Flow curves show dynamic recrystallization occurs at low strain rate (0.001-0.1 s⁻¹) and temperature (1323-1423K). The softening mechanism at high strain rate (1 s⁻¹) is dynamic recovery. According to the values of the ture stress and strain, the material constants of constitutive model are calculated and Arrhenius-type equation is given.

1. Introduction
Nickel base alloys are widely used to manufacture key parts of equipment such as turbine blades, discs, ring sections, bolts and fasteners in aerospace, nuclear engineering, energy and power, petrochemical, metallurgy and other industries due to their high performance, for example good oxidation resistance and corrosion resistance[1-3]. Nimonic alloy is a typical nickel-cobalt-chromium-base Superalloy strengthened by additions of molybdenum, aluminum and titanium. It has been developed for service up to 950°C, and combined the high strength of the age-hardening nickel-base alloys with good creep resistance. The alloy is widely used for making components in above mentioned industries. Many products are generally manufactured using different hot plastic deformation methods such as forging, rolling, upsetting and extrusion to obtain the best microstructure and mechanical properties [4-7]. Therefore, it is very necessary to study its hot deformation characteristics in order to optimize process parameters and predict forming defects in forming process using simulation technology[8,9].

In addition, it is well known that the constitutive equation including temperature, strain rate and stress is the basis and premise of numerical simulation for further study on the deformation stage. Therefore, constitutive equations for studied alloy has been commonly applied to steels with the objective of calculating forging forces[10,11].

In this study, a number of compression deformation tests have been carried out in different strain rates and temperature to obtain the rheological behavior and establish the constitutive model of the tested alloy as-forged. Firstly, the characteristics of flow curves under different deformation conditions are analyzed. And then, the material parameters in the constitutive model are obtained according the obtained true stress-true strain data values. At last, the validity of descriptive results based on the proposed constitutive equation is also investigated.
2. Experiment

| C  | Cu  | Si  | Mn  | P   | S   | Al  | Cr  | Ni  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.1500 | 0.055 | 0.009 | 0.012 | 0.003 | 0.005 | 4.79 | 14.76 | 63.87 |
| Fe | Mo  | Ti  | B   | V   | Nb  | W   | Co  |
| 0.09 | 4.996 | 1.3 | 0.0069 | 0.037 | 0.003 | 0.36 | 19.38 |

The study alloy is Nimonic alloy. The chemical composition (wt%) of the alloy is listed in Table 1. Firstly, the alloy with 100 mm diameter as cast is forged to be 45x45 square billet at initial and final forging temperature are 1393K and 1273K respectively. And then, cylindrical samples with a diameter of 10 mm and a height of 15 mm were machined from the square billet flowing the procedure showing in Fig.1.

![Fig.1 Sample processing procedure](image)

The compression tests were carried out on the Gleeble-3500 thermo-mechanical simulator in a range of temperatures (1323-1423K, at intervals 50K) and strain rates (0.001, 0.01, 0.1 and 1s⁻¹). Prior to hot compression tests, the heating rate of the compressed sample is set to be 10 °C/s. The holding time is set as 180 s at the different deformation temperature, respectively. During the tests, the flow curves of true strain VS. true stress were collected by the simulator. The reduction in the height of specimens was 70%. The microstructure under different deformation parameters was analyzed by modern metallurgical technology.

3. Results and Discussion

3.1. True stress-true strain curves
The curves between true stress and true strain of the studied alloy at true strain 0.7 obtained from the tests are given in Fig. 2. During the process of compression deformation, with the increase of true strain, the flow stress first increases rapidly to the peak value with the increase of strain. Then, the flow stress decreases with the increase of true strain. All the curves show dynamic recrystallization characteristics occurs at low strain rates which can be seen in Fig.2(a), (b) and (c). In Fig.2(d), the same flow stress changing trend can be observed in the initial deformation stage as the curves in other conditions. However, after the flow stress reaches the peak value, the flow stress keeps stable with the increase of true strain, and then shows a weak decreasing trend. It shows typical dynamic recovery curve characteristics. The characteristic of rheological curves can be proved by the characteristic of microstructure. Take the microstructure of deformation samples under different strain rates for example.

Microstructure of deformation samples under different strain rates at 1273K are given in Fig. 3. It can be seen that the dynamic recrystallization phenomenon is can be found in the deformed microstructure at low strain rates (0.001s-1 and 0.01s-1), which belongs to the typical dynamic recrystallization structure, while the dynamic recrystallization at high strain rates (0.1s-1 and 1s-1) is not obvious, especially the microstructure at strain rate 1s-1 is the typical dynamic recovery structure. In addition, at 1273K, the change trend of grain size in the microstructure shows that with the increase of strain rate, the proportion of dynamic recrystallization decreases and the degree of recrystallization weakens. This is consistent with the change trend of rheological curve. The change characteristics of microstructure are consistent with the change characteristics of rheological curve, which generally reflects the trend of dynamic recrystallization and dynamic recovery curve under different deformation conditions. In general, the studied alloy is a strain rate sensitive alloy. The main softening mechanism of the alloy are dynamic recrystallization at low strain rate and dynamic recovery at high strain rate, respectively.
3.2. Constitutive model

The Arrhenius Constitutive equations is a typical constitutive model for describing the relationship between stress, temperature and strain rate. The relationship, especially at high temperatures, could be widely expressed by Arrhenius type equation which is expressed as Eq. (1)-(4) [12,13].

\[
\dot{\varepsilon} = A_f(\sigma)\exp(-Q/RT) \\
\dot{\varepsilon} = A_1\sigma^n\exp(-Q/RT) \quad \text{for} \quad \alpha < 0.8 \\
\dot{\varepsilon} = A_2\exp(\beta\sigma)\exp(-Q/RT) \quad \text{for} \quad \alpha > 1.2 \\
\dot{\varepsilon} = A_3[\sinh(\alpha\sigma)]^n\exp(-Q/RT) \quad \text{for all} \quad \sigma
\]  

Where R is 8.314J/mol, Q is the activation energy. $A_1, A_2, A_3, n, n_1, \alpha$ and $\beta$ are experimentally determined constants, $\alpha = \beta/n_1$, and $\sigma$ is the flow stress.

All the Constants mentioned above can be calculated according to the peak stress-strain data obtained from compression tests.

Taking logarithm of both sides of Eq. (2) yields linear relationships between ln(strain rate) and ln(stress) as Eq.(5).

\[\ln\dot{\varepsilon} = \ln(A_1) + n_1\ln\sigma - Q/RT\]  

Fig. 3 Microstructure of deformation samples under different strain rates (1273K)
Fig. 4 Linear relationships between ln(strain rate) and ln(stress)

Furthermore, the corresponding fitting linear graph can be drawn as Fig.4. The average value of slope is n1(5.1049).

Fig. 5 Linear relationships between ln(strain rate) and stress

Taking logarithm from both sides of the Eq. (3), linear relationships between ln(strain rate) and stress can be obtained shown as Eq.(6). And the corresponding diagram is also given as Fig.4.

\[
\ln \dot{\varepsilon} = \ln(A_2) + \beta \sigma - \frac{Q}{RT}
\]

The average value of slope is β. Furthermore, α is also can be calculated by α=β/ n1.

\[
\ln \sinh(\alpha \sigma) = \frac{1}{n} \ln \dot{\varepsilon} + \frac{Q}{nRT} - \frac{\ln(A_2)}{n}
\]

Taking logarithm from both sides of the Eq. (4). The linear formula can be expressed as Eq.(7). Bring (ασ) into Eq.(7), and the corresponding diagram are given as Fig.6 and Fig.7. According the values of the average slope values, then, Q and ln(A3) values are calculated. All material constants are given in Table 2.

Table 2. Material constants

| constants | β     | α     | n      | Q (KJ/mol) | lnA3   |
|-----------|-------|-------|--------|------------|--------|
| value     | 0.04537 | 0.008888 | 3.622838 | 634.997    | 60.0539 |
4. Summary

In general, the studied alloy is a strain rate sensitive alloy. During the process of compression deformation, with the increase of true strain, the flow stress first increases rapidly to the peak value. Then, the flow stress decreases with the increase of true strain. The main softening mechanism of the alloy are dynamic recrystallization at low strain rate (0.001s-1-0.1 s-1) and dynamic recovery at strain rate 1s-1, respectively. The change characteristics of microstructure are consistent with the change characteristics of flow curves. there are typical dynamic recrystallization structure and dynamic recovery structure in the microstructure of tested samples.

The flow stress data obtained from the tests in a wide range of temperatures (1323-1423K, at intervals 50K) and strain rates (0.001, 0.01, 0.1 and 1s-1) were used to study on the material constants to Arrhenius-type constitutive model. The materials constants are obtained by drawing and calculating. The values of \(Q\) and \(n\) are 634.997 KJ/mol and 3.622838, respectively.

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