

## ANALYSIS OF HOT DEFORMATION OF NIMONIC 80A USING PROCESSING MAP

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### Abstract

The hot deformation behavior of NIMONIC 80A was studied in the temperature range of 900 - 1200 °C by employing the hot compression tests with the strain rates varying between 0.02 - 20 s<sup>-1</sup>. The results showed that the strength during hot compression increased with increasing the strain rate and decreasing temperature. Hot deformation of NIMONIC 80A was well-described by the sinh creep law with the stress exponent of 4.4 and the activation energy of 424 kJ/mol. Processing maps were also constructed on the basis of a dynamic material model. At low strains, the processing map of NIMONIC 80A did not reveal any instability domain regardless of the strain rate and temperature. However, at high strains, the processing map exhibited an instability domain at low strain rates of 0.02 - 0.2 s<sup>-1</sup> and within a temperature range of 900 - 1000 °C. In the instability domain, no or partial recrystallization occurred and the deformed microstructure exhibited shear bands and carbide precipitation while full recrystallization occurred in the safe domain.

**Keywords:** NIMONIC 80A, hot working, constitutive equation, processing map

### 1. INTRODUCTION

NIMONIC 80A is the representative age-hardenable Ni base superalloy for high temperature use such as gas-turbine components, tube supports in nuclear generators, and exhaust valves in internal combustion engines, etc. Such components are generally fabricated by employing the near net shaping technology to save production time and cost. Particularly, the near net shaping processes such as radial forging, roll forming, etc are adequate for the large product with complex shape [1]. Such processes usually involve several repetitive steps for shaping under non-isothermal conditions. Moreover, non-uniform stresses are applied depending on the local shape and dimension for a complex shaped product [2]. In order to fabricate the sound components under non-isothermal and non-uniform stress conditions, it is important to determine the range of the processing variables (temperature, stress, strain rate, etc) in which plastic instability do not occur. The present study was performed to determine the safe range of the processing variables for net shaping process of NIMONIC 80A under non-isothermal and non-uniform stress conditions. For this purpose, with the results of uniaxial hot compression tests of NIMONIC 80A, the constitutive expression of the alloy for high temperature deformation was obtained and then the processing map was constructed. The validity of the processing map was examined by observing the microstructures developed in the safe and unsafe regions of the processing map.

### 2. EXPERIMENTAL

NIMONIC 80A was supplied in the form of extruded bars of 12 mm diameter - the composition is listed in **Table 1**. The bars were solutionized at 1066 °C for 20 min and air-cooled. The grain size was ~100 μm. The cylindrical specimens of 10 mm diameter and 12 mm height were machined from the air-cooled bar for hot compression tests. A series of hot compression tests was carried out on a Gleeble 3800 machine up to true strain of 1.1 in the strain rate range of 0.02 - 20 s<sup>-1</sup> with one order interval and the temperature range of 900 -1200 °C with 100 °C interval. The heating rate was 5 °C/s and the specimen was maintained for 5 min at the testing temperature before deformation. After deformation, the specimens were water quenched. The deformed

specimens were mechanically ground, polished, and etched with a mixture of C<sub>2</sub>H<sub>5</sub>OH (100 ml) + HCl (25 ml) + FeCl<sub>3</sub> (8 g) for microstructural observation. The peak stresses of the true stress-strain curves obtained from the compression tests were used to build the constitutive equation. The processing map was constructed at different strain levels by superimposing a power dissipation map and an instability map as described elsewhere.

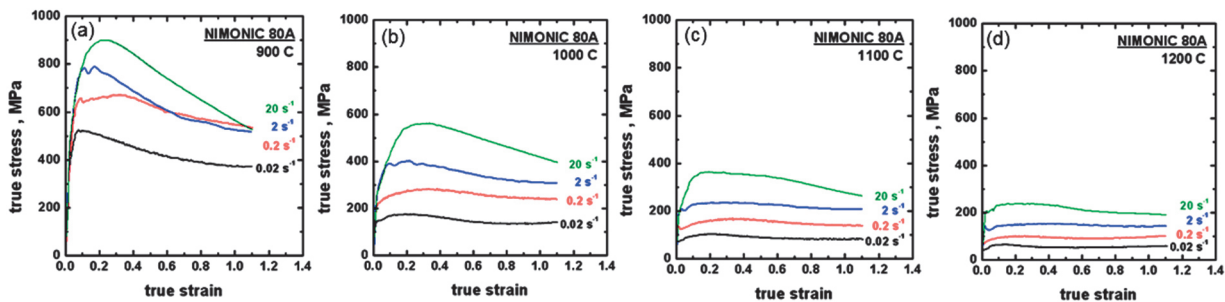
**Table 1** Chemical composition (in wt.%) of the present NIMONIC 80A

Cr	Ti	Al	Fe	Co	Si	C	Mn	Cu	Ni
19.25	2.41	1.47	0.79	0.32	0.06	0.05	0.03	0.03	balance

### 3. RESULTS AND DISCUSSION

#### 3.1 Constitutive behavior

**Fig. 1** shows the true stress - strain curves of NIMONIC 80 A under the hot deformation conditions described above. In all cases, the peak stresses appeared obviously showing strain softening. The peak stress decreased with increasing temperature and strain rate. However, the rate of strain softening became faster with decreasing temperature.



**Fig. 1** True flow curves of NIMONIC 80A obtained from uniaxial hot compression tests; (a) 900 °C, (b) 1000 °C, (c) 1100 °C, (d) 1200 °C

In order to examine the constitutive behavior of NIMONIC 80A under the present deformation conditions, the sinh law of Eq. 1 was employed [3].

$$\dot{\epsilon} = A \sinh(\alpha \sigma)^n \exp(-Q/RT) \quad (1)$$

where  $\dot{\epsilon}$  is the strain rate,  $\sigma$  is the stress,  $n$  is the stress exponent,  $Q$  is the activation energy for deformation,  $\alpha$  is the constant and others have the usual meaning. From Eq. (1), it is straightforward that

$$n = \frac{\partial \ln \dot{\epsilon}}{\partial \ln [\sinh(\alpha \sigma)]} \quad (2)$$

$$Q = n R \frac{\partial \ln [\sinh(\alpha \sigma)]}{\partial (1/T)} \quad (3)$$

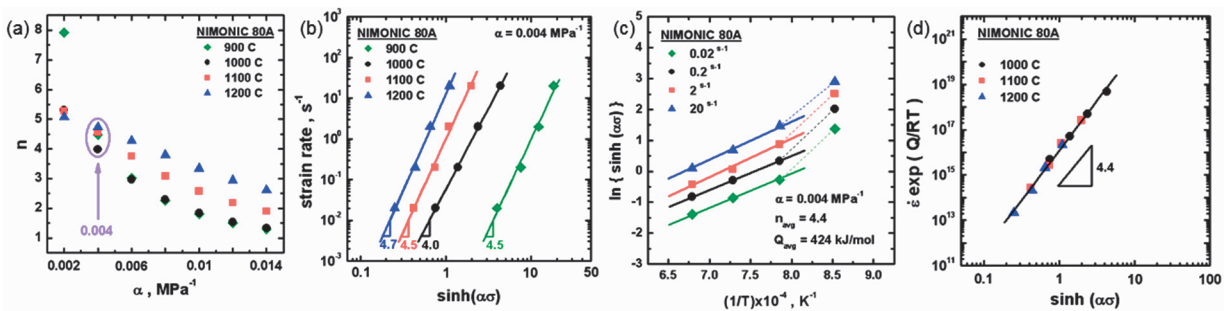
To apply Eqs. (1) - (3), the value of the constant  $\alpha$  should be first determined such that the  $n$  value at each temperature exhibits the least scattering. As shown in **Fig. 2a**,  $\alpha$  showing the least scattering of  $n$  was 0.04 MPa<sup>-1</sup>. With  $\alpha = 0.04$  MPa<sup>-1</sup>, the average  $n$  was ~ 4.4 (**Fig. 2b**). It is noticed that data at 900 °C stood apart from those of other temperatures in spite of the similar  $n$  value.  $Q$  was estimated as ~424 kJ/mol (**Fig. 2c**). In

the estimation of  $Q$ , the data at 900 °C were excluded since they were not fitted into a linear relationship between  $\ln \sinh(\alpha\sigma)$  and  $(1/T)$  predicted by Eq. (3).

The inconsistency of 900 °C data will be discussed later in terms of microstructures developed during deformation. The present  $Q$  value agrees well with that reported by Jeong et al. (426 kJ/mol) [4] but higher than that reported by Bombač et al. (380 kJ/mol) [5]. It is worth noting that Ni base superalloys are reported to exhibit a wide range of  $Q$  between 400 - 1500 kJ/mol [6]. **Fig. 2d** shows the Zener - Hollomon plot of the sinh law for 1000 - 1200 °C. All data for 1000 - 1200 °C are well fitted into a single straight line with the slope of 4.4.

Accordingly, the constitutive behavior of the present NIMONIC 80 A can be explicitly expressed as

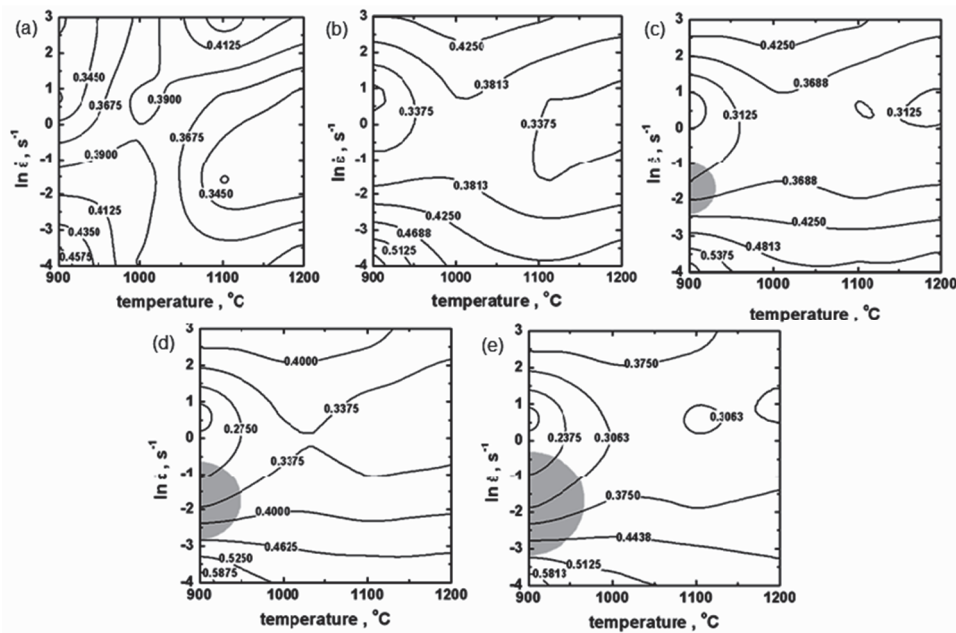
$$\dot{\epsilon} \exp(424000/RT) = 1.17 \cdot 10^{16} \sinh(0.04 \sigma)^{4.4} \quad (4)$$



**Fig.**

2 (a) variation of  $n$  with  $\alpha$  for the sinh law, (b) a plot of  $\dot{\epsilon}$  against  $\sinh(\alpha\sigma)$  in a double logarithmic scale, (c) a plot of  $\ln[\sinh(\alpha\sigma)]$  against  $(1/T)$  for estimation of  $Q$ , (d) the Zener - Hollomon plot (the 900 °C data were excluded in Figs. 2c and 2d)

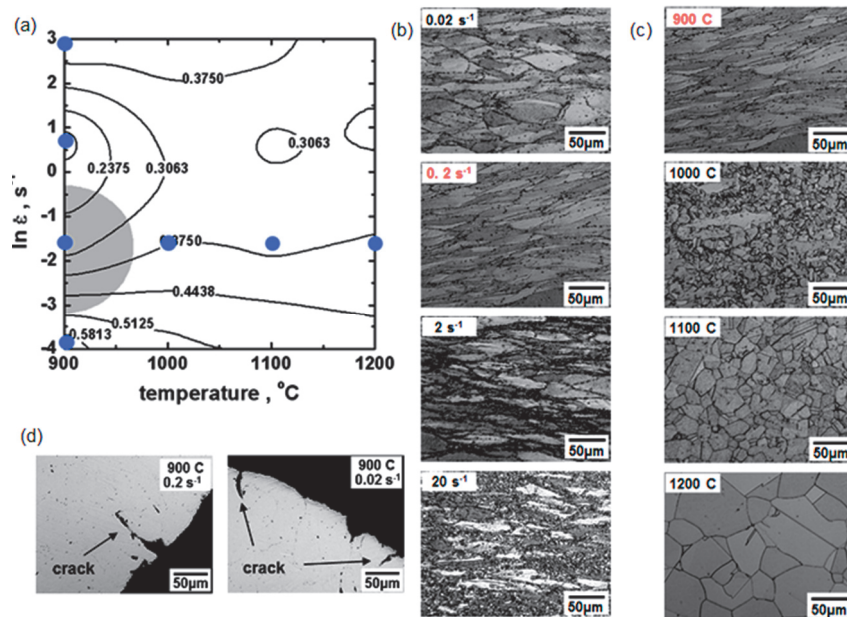
### 3.2 Processing map and deformed microstructure



**Fig. 3** Processing maps of NIMONIC 80A at different strain levels; (a)  $\epsilon = 0.2$ , (b)  $\epsilon = 0.3$ , (c)  $\epsilon = 0.4$ , (d)  $\epsilon = 0.5$ , (e)  $\epsilon = 0.6$  (The shaded area indicates the plastic instability region)

Based on the constitutive behavior of NIMONIC 80A under the present deformation conditions, the processing maps were constructed at different strain levels; the construction procedure of the processing map on the basis of the dynamic material model is well described elsewhere [7], so it is not described here.

As shown in **Fig. 3**, the instability region (the shaded area in **Fig. 3**) does not appear up to the strain of 0.3. At the strains of 0.3 - 0.4, the instability region begins to appear at temperatures around 900 °C and the strain rates of  $\sim 0.1 \text{ s}^{-1}$ . Then, the instability region expands with increasing the strain. The maximum efficiency of the power dissipation is predicted to be achieved below  $0.05 \text{ s}^{-1}$  and below 1000 °C regardless of the strain level.



**Fig. 4** (a) Processing maps of NIMONIC 80A at  $\epsilon = 0.6$ ; the blue dots indicate the strain rate and temperature at which deformed microstructures were observed, (b) microstructures deformed at various strain rates at 900 °C, (c) microstructures deformed at various temperatures at  $0.2 \text{ s}^{-1}$ , (d) cracks developed in the plastic instability region of 900 °C and  $0.02 \text{ s}^{-1}$

In order to examine the validity of the present processing map, the microstructures deformed to  $\epsilon = 0.6$  were observed and compared with the corresponding processing map as seen in **Fig. 4**. For 900 °C deformation, no dynamic recrystallization (DRX) occurred at the low strain rates but partial DRX occurred at high strain rates (**Fig. 4b**). Full DRX was observed in the specimens deformed at  $0.2 \text{ s}^{-1}$  above 1000 °C (**Fig. 4c**). As shown in **Fig. 4d**, macro cracks were developed at  $0.02 \text{ s}^{-1}$  and  $0.2 \text{ s}^{-1}$  for 900 °C deformation. These deformation conditions belong to the plastic instability region of the corresponding process map (**Fig. 4a**). Accordingly, the present analysis shows that the present processing map based on the dynamic material model along with the sinh law is valid for prediction of hot working of NIMONIC 80A. As described in **Figs. 2b** and **2c**, 900 °C deformation exhibited the higher  $Q$  than deformation at other higher temperatures. As seen in **Figs. 4b** and **4c**, no DRX or partial DRX occurred at 900 °C while full DRX occurred at higher temperatures, indicating the higher  $Q$  for 900 °C deformation is closely associated with no DRX or partial DRX structure [5, 8].

## CONCLUSIONS

- Hot deformation of NIMONIC 80A was well-described by the sinh creep law with the stress exponent of 4.4 and the activation energy of 424 kJ/mol in the strain rate range of  $0.02 - 20 \text{ s}^{-1}$  and the temperature range of 1000 - 1200 °C. Dynamic recrystallization fully occurred under these deformation conditions.

- 2) For 900 °C deformation, no or partial dynamic recrystallization occurred. Accordingly, the activation energy for 900 °C deformation was higher than that for deformation at higher temperatures.
- 3) Processing map based on the dynamic material model along with the present constitutive behavior predicted the plastic instability region at 0.02 - 0.2 s<sup>-1</sup> and 900 - 1000 °C above  $\epsilon = 0.4$ . In the specimens deformed in the plastic instability region, macro cracks were observed.

## ACKNOWLEDGEMENTS

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