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Hot working characteristics of nickel-base superalloy 740H during compression

Jue Wang*, Jianxin Dong, Maicang Zhang, Xishan Xie

School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

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ABSTRACT

The hot deformation behavior of nickel-based superalloy 740H has been investigated by hot compression experiments. The tests were carried out in the temperature range of 1050–1200 °C with strain rates of 0.1–20 s^{-1} to a total strain of 0.6. True stress–true strain curves and deformation microstructures were studied. The results show that dynamic recrystallization, which is the principal softening mechanism in the hot working of 740H, determines the shape of flow curves. The fraction of DRX grains at the strain of 0.6 is increased by deformation temperature while at a particular temperature, it is lower at strain rate of 1 s^{-1} than at other strain rates. A hyperbolic-sine type equation has been established between peak stress and deformation conditions through Z parameter, giving activation energy value of 357.3 kJ/mol. The hot working windows of alloy 740H was briefly discussed using the processing map. Temperature range of 1160–1200 °C with strain rate larger than 10 s^{-1} is the probable domain for hot extrusion of 740H.

1. Introduction

In order to increase the thermal efficiency of power plants and reduce CO_2 emission, several projects have been conducted to improve steam parameters up to 700 °C/35 MPa in pulverized coal-fired boilers [1–4]. Considering the long life request of components, the most critical issue of these projects is to find materials which can be used in the severe conditions for a long time (longer than 100,000 h) and manufactured smoothly. As conventional ferritic and austenitic stainless steels could not meet the requirement, the application of Ni-base superalloys becomes essential [1]. Age hardening nickel-based superalloy 740H is designed for manufacturing superheater tubes and header pipes utilized in advanced ultra-supercritical (AUSC) steam boiler applications. Compared with its prototype, alloy740, 740H has a more excellent weld ability and microstructural stability by adjusting Al/Ti ratio and reducing Si content. According to Zhao's research [5], η phase, which is detrimental to alloy's creep properties, is not observed neither at the grain boundaries nor in the grains after aging at 760 °C till 1000 h for 740H. It is reported that after composition modifications for alloy740 (i.e.740H), micro-fissures are absent in the heat affected zone (HAZ), indicating insusceptibility to liquation cracking in thick section weldments [6], which is the main limitation in application of alloy 740.

Favorable microstructure and required properties are largely restricted by alloy's work ability in manufacture process. Hot working of 740H mainly contains billet forging of casting ingot, extrusion of superheater tubes and thick section header pipes. Thus, it is necessary to investigate the hot deformation characteristics and workability of this new alloy. In the past decades, the hot working behaviors of several superalloys, both solution strengthening and precipitated strengthening, have been systematically studied by physical simulation system (e.g. hot compression and torsion tests) [7–10]. In the hot working of superalloys, work hardening, which is caused by increase of dislocation density, coincides with dynamic softening, i.e. dynamic recovery (DRV) and dynamic recrystallization(DRX). By thermal activation, dislocations annihilate through climb and cross slip to form cells and sub-grains in the parent grains(i.e. dynamic recovery). In contrast, accumulation of dislocations at boundaries and triple junctions of prior grains due to the strain incompatibility can cause nucleation of DRX grains with few dislocations [7,9,11,12]. New grains grow with the migration of high angle grain boundaries. During the DRX process, deformed grains are gradually replaced by refined equiaxial DRX grains, which is beneficial to the mechanical properties of alloys [13,14]. The two softening processes are responsible for the decrease of dislocation density and flow stress during compression. However, in the nickel base superalloys, DRX is considered to be the critical mechanism [7,10]. It is generally accepted that the processing parameters, i.e. deformation temperature, strain rate and strain, have a crucial importance on the hot working behavior of a material. As 740H is

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* Corresponding author. Fax: +86 10 62332884.
E-mail address: wangjue_sor@126.com (J. Wang).

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manufactured mainly by forward hot extrusion, it is reasonable to combine the deformation characteristics of material with the feature of extrusion process, i.e. large strain with high temperature and high strain rate. Besides the influence of extrusion parameters on microstructure and properties of the extrudate, extrusion force should also be considered for the load capacity of equipments.

Recently, much attention has been paid to the creep, corrosion resistant properties and weldability for alloy 740 and 740H [4–6,15]. However, there is few report on the hot working behaviors of this new alloy, which is the foundation of application. In this study, the hot deformation characteristics of alloy 740H is investigated by hot compression tests on a Gleeble1500 thermo-mechanical simulator. The dependence of flow behavior and microstructural evolution on strain rate and temperature was established by Zener–Hollomon parameter. The probable hot working windows are briefly discussed by processing map.

2. Experimental procedure

The nominal chemical composition(wt%) of 740H used in the study was shown in Table 1. The material in the present work was manufactured by vacuum induction melting(VIM) followed by homogenization at 1200 °C for 16 h. The ingot was rolled into a Φ15 mm bar at 1150 °C to remove the casting structure. After annealing treatment at 1150 °C for 30 min, almost all the precipitates dissolved, leaving austenitic matrix with equiaxial grains of 20 μm in size.

Cylindrical compression specimens of 8 mm in diameter and 12 mm in height were machined from the rolling bar. Hot compression tests were carried out on a Gleeble-1500 thermo-mechanical simulator at constant strain rates of 0.1, 1, 10 and 20 s^{-1}, with temperatures of 1050, 1100, 1150 and 1200 °C, respectively. All specimens were heated to test temperature at a heating rate of 20 °C/s and held for 240 s to ensure temperature uniformity before deformation. A mica sheet was used as lubricant between specimen and compression dies. Each specimen was deformed to a nominal strain of 0.6 and water quenched to freeze the microstructure. The true stress–strain data were obtained from the controlling computer with an automatic data acquisition system. The deformed specimens were cut parallel to the compression axis and mechanically polished. The cut surfaces were boiled in the solution of 2.5 g $KMnO_4$+10 ml H_2SO_4+90 ml H_2O for optical metallographic examination. Electro-etching with a solution of 170 ml H_3PO_4+10 ml H_2SO_4+15 g CrO_3 was used to reveal the microstructure for SEM investigation. The average grain size was determined using the line intercept method.

Table 1
Chemical composition(wt%) of alloy 740H.

C	Cr	Co	Al	Ti	Nb	Mo	Ni
0.03	25	20	1.5	1.5	2.0	0.5	Bal

3. Results and discussion

3.1. Flow behaviors

3.1.1. True stress–true strain curves

Fig. 1 shows the true stress–true strain curves of alloy 740H compressed at temperatures from 1050 to 1200 °C with various strain rates from 0.1 to 20 s^{-1}. In the investigations of flow curves, the influence of adiabatic heating could not be neglected. It is reported that temperature rise due to adiabatic heat during compression will cause a flow stress decrease compared to ideal isothermal deformation condition [8,16]. Thus, the temperature change is calculated and the stress is converted to an isothermal value for 740H using the following equations [16,17]:

$$\Delta T = \eta\beta\frac{\sigma_{ave}\Delta\varepsilon}{\rho c} \tag{1}$$

$$\sigma_{ave} = \frac{1}{\Delta\varepsilon}\int_{\varepsilon_0}^{\varepsilon_0+\Delta\varepsilon}\sigma d\varepsilon \tag{2}$$

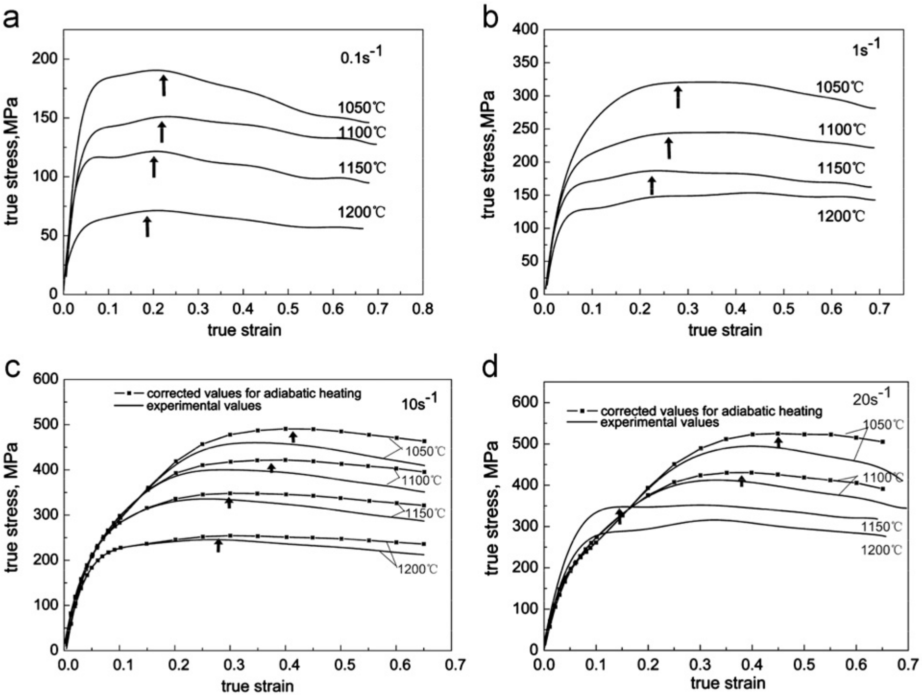

Fig. 1. True stress–strain curves for 740H under different strain rates. (a) 0.1 s^{-1}, (b)1 s^{-1}, (c)10 s^{-1} and (d)20 s^{-1}.