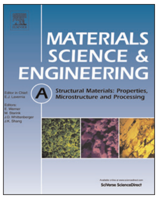
Materials Science & Engineering A 647 (2015) 277–286

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea



Necking characteristics and dynamic recrystallization during the superplasticity of IN718 superalloy

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ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form
8 September 2015
Accepted 9 September 2015
Available online 11 September 2015

Keywords:
IN718
Superplastic deformation
Necking
Dynamic recrystallization
Grain size

ABSTRACT

The necking extent of the superplasticity of IN718 alloy is difficult to quantificationally evaluate because of its point fracture (with extreme small final fracture area) after failure. In this investigation, we have defined a necking angle to donate the necking extent after failure and systematically investigated the superplastic behavior of the alloy at temperatures between 935 °C and 1010 °C in strain rate range 5×10^{-4}–$10^{-2}\ s^{-1}$. In the temperature range 935–980 °C, the elongation was found to decrease with the increasing strain rate while the necking angle (extent) increased because softening source provided by the dynamic recrystallization increased with the increasing strain rate at necking zone. In contrast, at 1010 °C, due to a good balance between the grain refinement by recrystallization and the dynamic grain growth, a peak elongation of 225% was obtained at $10^{-3}\ s^{-1}$. Our study has emphasized the vital role of the dynamic recrystallization during the superplasticity of IN718 alloy.

1. Introduction

Superplastic forming has been widely used to manufacture complex-shaped components in industry due to its low applied force and energy cost [1]. Grain boundary sliding is one of the most popular deformation mechanisms for superplasticity, and during which the processes of hardening and softening are generally absent. Therefore, a stable plastic flow with a high strain rate sensitivity (>0.5) is usually achieved without necking during deformation [2,3]. However, apparent necking can be observed in some other superplastic alloys with the superplastic deformation mechanism of dislocation motion or dynamic recrystallization, which are closely related to hardening and softening. For instance, the localized necking in the gauge length was observed during the superplasticity of a spray-cast Al-7034 alloy with an initial grain size of ~2.1 μm at 400 °C [4], where the dislocation glide was predicted to be the dominant rate-controlling flow mechanism. The dynamic recrystallization was detected at the localized necking zone in the superplasticity of ZK60 Mg alloys at 177 °C, and finally the failure was caused by necking [5]. Park et al. [6] attributed the high strain rate superplasticity of a Sc-added 5083 Al alloy to the combined effects of dynamic recrystallization and preservation of fine recrystallized grains by the presence of Sc. Also the necking was visible in the alloy of 0.3 μm grain size at 500 °C and above $10^{-2}\ s^{-1}$ in the alloy.

IN718 superalloy is widely used in aerospace, nuclear and petrochemical industries due to its superior mechanical properties, excellent weldability and relatively low cost [7–9]. However, as a high-alloyed material, complex-shaped components of IN718, e.g., fuel manifold, are difficult to produce using conventional mechanical techniques [10]. Thus, a great number of investigations have been performed on its superplastic deformation [10–12]. Ceschini et al. [13] predicted the occurrence of the dynamic recrystallization by the presence of a peak point followed by a decreasing flow stress on the true stress–true strain curve. Han et al. [14] believed that the superplasticity of the alloy was based on the dislocation proliferation and movement. Besides, an obvious necking was observed simultaneously during its superplastic deformation [14–16]. Recently, we have systematically investigated the microstructural evolution of IN718 alloy during the superplasticity and deem that the discontinuous dynamic recrystallization is the main deformation mechanism for the superplasticity [16]. Furthermore, our investigation has shown that the necking development is closely related to the difference of the dynamic recrystallization extent in various regions of the gauge section during the superplastic test [17]. Interestingly, for those superplastic alloys exhibiting obvious necking, the desirable ductility would still be achieved as the strain after necking can still contribute much to the total elongation.

However, it is worth noting that the fracture morphology obtained after failure in these superplastic alloys is usually point-shape (fracture with extreme small area) [14]. The point fracture makes it difficult to evaluate the necking extent or demonstrate its connection with the microstructure and elongation. Within this

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http://dx.doi.org/10.1016/j.msea.2015.09.040
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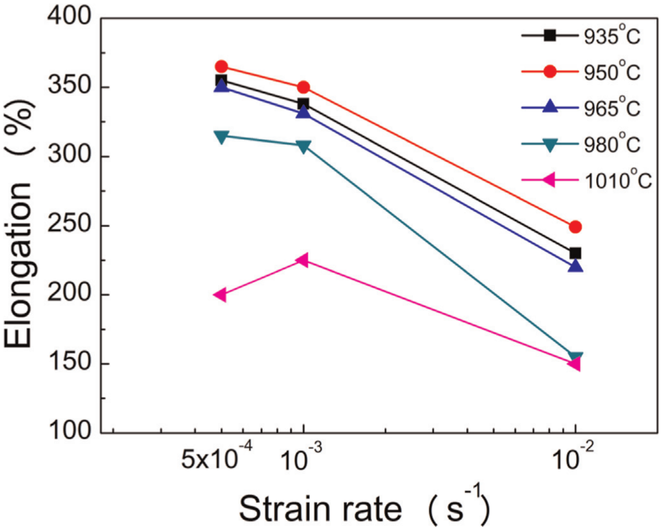

Fig. 1. Variation of elongation to failure with the strain rate at temperatures from 935 °C to 1010 °C.

context, we have systematically investigated the issues below: (i) define a necking angle to evaluate the necking extent quantitatively; (ii) how the deformation temperature and strain rate influence the necking extent and the final elongation; (iii) the microstructure evolution for different necking extents.

2. Materials and experimental procedures

2.1. Materials

An IN718 superalloy ingot was produced through vacuum induction melting and vacuum arc remelting and its chemical compositions in wt% are given as follows: Ni 52.65, Nb 5.20, Mo 3.12, Cr 18.77, Al 0.48, Ti 1.05, C 0.027, P 0.022, B 0.010, Fe balance. The ingot was homogenized, cogged and hot close-die forged into a cake-like forging. The fine-grained samples used in this paper were cut from the cake-like IN718 forging with an average grain size of 7.9 μm.

2.2. Tensile test

To investigate the superplastic behavior of the alloy, tensile experiments were carried out on the round specimen with the gauge length 10 mm and diameter 5 mm using a Shimadzu DCS-25T servo-hydraulic machine by a constant cross-head speed. In the electrical resistance furnace with the temperature controlled in three zones (an error less than 3 °C), the tensile specimens were held at the test temperatures for 20 min prior to deformation at nominal strain rates spanning the regime of 10^{-2}–$5\times10^{-4}\ \mathrm{s}^{-1}$. In order to achieve good superplasticity of IN718, deformation temperatures (935–1010 °C) were set in the range for the dynamic recrystallization, which acts important role during the deformation [16]. True stress–true strain data was calculated from the load–displacement measurements based on the assumption of volume constancy [18], though it is known that the assumptions is not actually true in the whole tensile process [19]. Specimens were water quenched immediately after the tension tests in order to retain the deformed microstructure.

2.3. Microstructure

Microstructural characterization was performed on the longitudinal section parallel to the loading axis via optical microscope (OM) and scanning electron microscope and electron backscatter diffraction (SEM; Hitachi S-3400N). Metallographic samples were mechanically polished and then, electrolytic etched at room temperature in a solution of 10 g oxalic acid in 90 ml water at an applied potential of 6 V for 6 s. Grain boundary can be deeply etched using this method, making the grain size easily measurable. The average grain size was measured in digital image analysis software SISC IAS V8.0 with OM images by using the linear intercept method counting over 400 grains for each specimen so as to ensure the measurement accuracy. Transmission electron microscope (TEM) was employed to examine the dislocation and recrystallization on a JEOL 2010 TEM operated at 200 kV. TEM specimens were prepared by mechanically grinding sample slices to 50 μm thick and twin-jet electropolishing in a mixture of 90% alcohol and 10% perchloric acid at −20 °C under 24 V.

3. Results

3.1. Superplastic behavior

Fig. 1 shows the variation of the elongation with the strain rate at different temperatures. It is obvious that the alloy shows desirable superplastic ductility, exceeding 150% under all

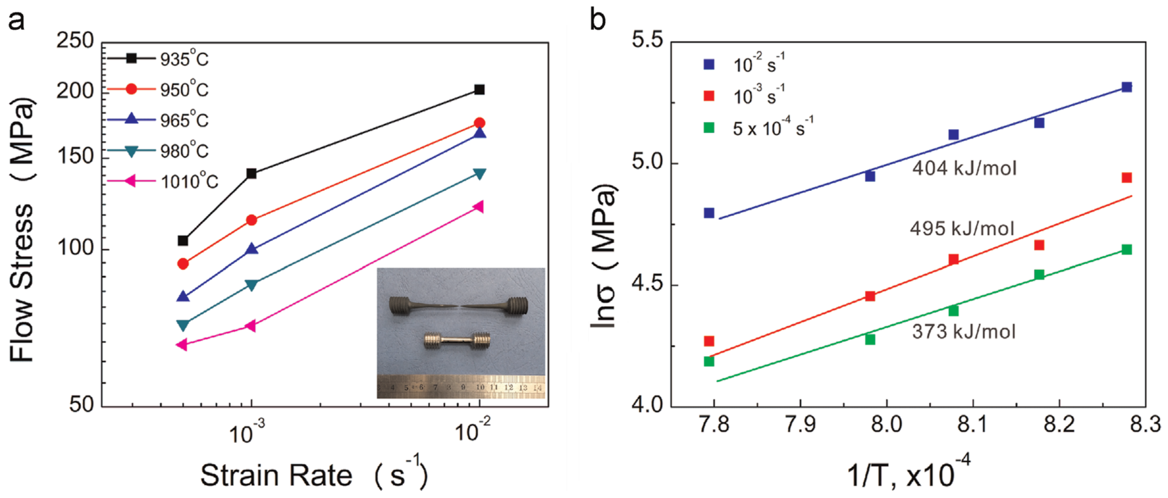

Fig. 2. (a) Flow stress as a function of strain rate at various temperatures, the appearance of the specimen before and after failure at 950 °C and $5\times10^{-4}\ \mathrm{s}^{-1}$ was inset; (b) ln σ as a function of reciprocal temperature. Note that the stresses at the strain of 0.1 were used as the flow stress.