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Fracture behavior of Inconel 718 sheet in thermal-aided deformation considering grain size effect and strain rate influence

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ABSTRACT

In this paper, the fracture behavior of Inconel 718 sheets in thermal-aided deformation processes is elucidated, accompanied by high-temperature fracture photography analysis, considering the effect of grain size and strain rate. Uniaxial tests were conducted under varied test conditions. A segmentation phenomenon was observed in the Hall-Petch curves for the fracture stress at lower strain rates, which disappeared at higher strain rates. Moreover, the fracture strain is predicted by the Cockcroft & Latham criterion with a modified Voce constitutive model. Based on the fracture photographs acquired by scanning electron microscopy (SEM), a two-step fracture mechanism was proposed and shown for Inconel 718 thin sheets. Furthermore, thin sheet fracture was found to be influenced by inclusions, which was verified by CAE simulations. This article thus provides an in-depth discussion of fracture behavior of Inconel 718 thin sheets, which was influenced by the comprehensive effects of the grain size distribution, strain rate influence, local element composition, and the second-phase particles or inclusions.

1. Introduction

Examination of the state of the art shows that nickel-based superalloys have received global attention in the aerospace and aviation industries because of their high corrosion and oxidation resistance, high strength and long creep life at elevated temperatures [1]. In light of the demand for miniaturization of service components that can operate at high temperatures, nickel-based superalloys have been recently introduced into microdeformation processes [2–5]. Inconel 718 has been used as the material for micro-scale heat transforming tubes for improved turbine-based combined cycle engines [6]. These Inconel 718 tubes are prepared using a micro-drawing process conducted at 800 °C with varied velocities to reduce the deformation resistance. However, the manufacturing process of Inconel 718 micro-tubes and their fracture related issues are quite different from those of macro-tubes. First, the forming force/rupture stress of the microtubes may be subject to the strong grain size effect arising from the similarity between the specimen size and grain size. A number of studies [7,8] have shown that the tensile strain leading to failure and the scatter band of ductility values clearly differ in small specimen sizes. Additionally, the fracture location, or crack occurrence time, can be particularly affected by the microstructure [9]. Moreover, inclusions play a decisive role during the deformation process of thin-walled structures. The grain size effect thus affects the fracture behavior of thin-walled Inconel 718 structures in thermal-aided deformation, which is an attractive yet challenging process for researchers in materials science.

Few reports are available about the grain size effect of Inconel 718 or other nickel-based superalloys, since the manufacturing of micro-sized parts using superalloys is relatively new compared to that using traditional metals. Accordingly, the mechanical properties of this typical face-centered-cubic alloy depend on numerous aspects of its chemistry and microstructural features, such as the grain size; γ'/γ'' size and distribution; carbides size and content; and grain boundary morphology: this makes studying the grain size effect complicated. However, Zhao [10,11] studied the influence of temperature on the grain size effect of Inconel 718, but, over the range of room temperature to 400 °C, which does not encompass temperatures encountered in high-temperature deformation processes. Liu [12] has studied the effect of grain size on the fracture behavior during axis-tensile tests performed on Inconel 718 sheets. This work explained the fracture behavior with respect to the influence of the microstructure, but the effects of the temperature and strain rates on the fracture was neglected. Qin [13] determined the mechanism of multi-scale fatigue crack propagation of Inconel 718 with different grain sizes using micro-notches. The cracks initiated and propagated in a transgranular mode, which changed to a mixed transgranular–intergranular mode with increase in number of fatigue cycles. However, the fracture behavior was scarcely mentioned

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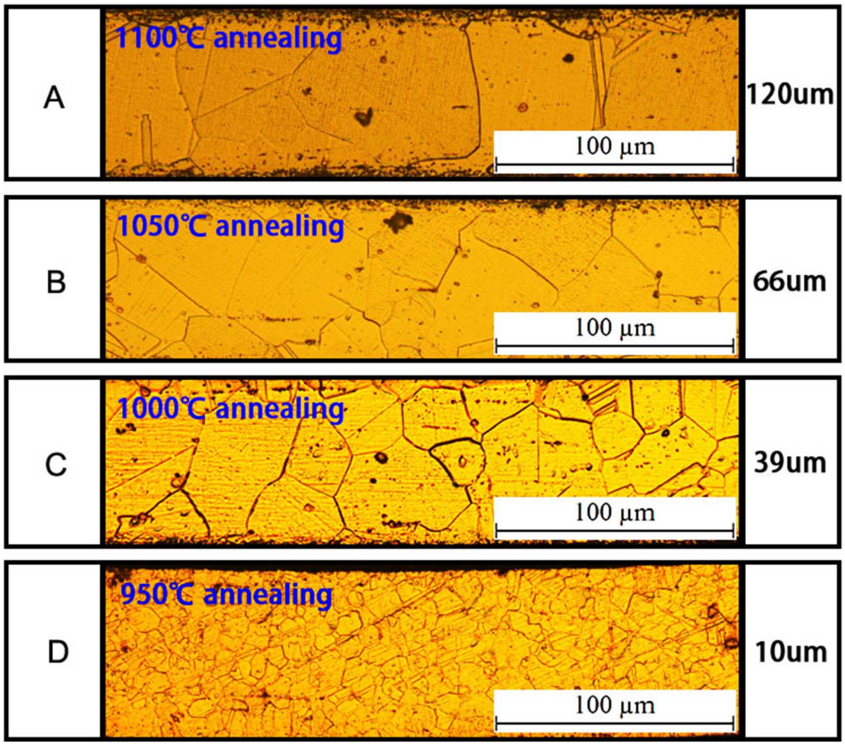

Fig. 1. Particle size distribution under various material conditions.

Table 1
Simulation parameters of the GTN model.

$q1$	$q2$	$q3$	Total volume void fraction at total failure	Critical void volume fraction	Mean void nucleation	Standard deviation	Volume fraction
1.5	1	2.25	0.06	0.04	0.3	0.1	0.21

in the article.

In addition to the grain size effect, several authors have focused on the structure-property relationships of the fracture behavior of Inconel 718. Lin [14] has studied the effects of deformation temperature and strain rate on the fracture morphology of Inconel 718 by hot uniaxial tensile tests in the temperature range of 920–1040 °C and strain rate range of 0.001–0.01 s^{-1}. The sectional fracture morphologies of the failure specimens were also taken into account to verify the ductile fracture failure by Lin's team [15]. EBSD analysis was also performed to study the evolution of dynamic recrystallization grains and the δ phase during hot compressive deformation [16]. Effects of processing routes on room-temperature tensile strength and elongation for Inconel 718 were investigated by Yung-Ta Chen [17], who observed that a good balance of ultra-high tensile strength and moderate elongation can be achieved by adjusting the processing route. A comparison of different types of fracture modes was also provided by Babout [18], where they proposed an interesting model describing the competition between interface decohesion and particle cracking. Their model was applied to analyze the dominating damage mechanism in various composite materials, however, the model needs to be tested further using other engineering materials. The influence of metallic inclusion was systematically studied by Zhou [19], and the damage mechanics were described using experiment and simulation.

In brief, prior research on the effect of grain size on fracture issues of Inconel 718 have been mainly undertaken either at relatively low temperatures, or by eliminating the strain rate influence. In addition, even though prior structure-property studies have been based on a wide range of strain rates and temperatures, a systematic elaboration is still required to summarize the interacting effects of the grain size and strain rate on fracture behaviors in thermal-aided deformation processes. With this aim, uniaxial tensile tests were conducted at 800 °C with different grain sizes under various strain rates. To avoid deviation owning to clamping of the thin wall capillary, thin sheet specimens were used instead of micro-tubes. In addition, the fracture morphology was observed and analyzed by optical microscopy and scanning electron microscopy. Thus, we undertook fundamental and crucial work to understand the fracture behavior of Inconel 718 sheets in thermal-aided deformation processes, considering the effects of grain size, strain rate and inclusion, in an attempt to meet the ubiquitous demand of manufacturing Inconel 718 capillaries.

2. Materials and experimental procedure

2.1. Sample preparation

Inconel 718 sheets (thickness: 0.12 mm) were used to prepare the specimens in this experiment. The specimen dimensions and heat treatment steps were similar to those employed in a previous study [11]. Metallographic observations were made and grain size distribution of both the surface and the central part was obtained by microscopy (Leica DM2700 in BUAA University), the results are shown in Fig. 1. The average grain size was calculated by Heyn's method. Only 3 or 4 grains were found across the thickness of sample type “A,” while the number of grains across the thickness increased from specimen type “A,” to specimen type “B,” “C,” and “D”.

2.2. Uniaxial tensile tests

Uniaxial tensile tests were carried out in a programmable MTS testing machine at 800 °C at strain rates of 0.001 s^{-1}, 0.01 s^{-1}, and 0.03 s^{-1}. During the process, strain rate variation was conducted by changing the cross-head speed. The same experiments were done three