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Discontinuous yielding in Ni-base superalloys during high-speed deformation

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ABSTRACT

Discontinuous yielding in Ni-base superalloy during high-speed compression has been investigated. Flow stress curves of GH4049 can be divided into two types: the first type curves display common flow behavior revealing work hardening, stable, softening and steady stages; the second type curves present abnormal flow behavior revealing discontinuous yielding feature, which were characterized by a sharp peak stress (σ_P), obvious upper yield point (σ_U) and a lower yield point. Apparent activation energies for peak values and upper values were calculated to be Q_P=1162 kJ mol^{-1} and Q_U=1106 kJ mol^{-1}, respectively. Constitutive equations represent peak stress and upper stress as functions of strain rate and deformation temperature are described. First type curves present common work hardening behavior; however, second type curves present spiral hardening behavior since discontinuous softening during high-speed deformation. When GH4049 superalloys present first type flow behavior, volume fraction of dynamic recrystallization (X_{DRX}) can be described in terms of normal S-curves revealing slow–rapid–slow property. However, when alloys present second type flow behavior, X_{DRX} can be described in terms of double S-curves exhibiting sudden–steady–rapid–slow property.

1. Introduction

Nickel-base superalloys are of great interest to aerospace industries for high temperature structural applications [1,2], such as turbine engine components, because of their unusual ability to retain excellent combinations of mechanical properties and corrosion resistance at high temperatures comparing with other materials [3,4]. Nickel-base superalloys mainly consist of γ' precipitate ($L1_2$) and γ matrix (fcc) two-phase structure, which is important for them to keep excellent high temperature properties [5,6]. GH4049 is a γ' phase strengthened wrought nickel-base superalloy with good oxidation resistance and strength at elevated temperatures [7]. This superalloy is currently used for rotor vanes, turbine blades and other high temperature load bearing components servicing at temperatures below 900 °C [8].

Turbine components operate in high temperature and high pressure gas surroundings. Their working reliability largely affects flight security. With the raising of thrust–weight ratio and gas temperature before turbine, creep, fatigue and creep–fatigue have become three main failure modes for hot section components in aeroengine [9]. To meet present requirements of favorable mechanical properties, better control of forging processes for GH4049 is rather important. However, GH4049 superalloy is rather difficult to deform because of its poor workability especially when strain rate is above 6 s^{-1}. For GH4049, the available processing data are very limited. These are far from the need for the optimization of processing parameters.

In this work, isothermal compression tests were conducted on GH4049 superalloys with strain rates ranging 0.1–50 s^{-1}. Constitutive model associating discontinuous softening feature has been proposed. Microstructure observation for hardening and softening mechanisms has been investigated. Discontinuous yielding in GH4049 superalloy during high-speed compression has also been investigated. All these studies are foundations for application of GH4049 superalloys.

2. Material and experimental procedure

The nominal composition of GH4049 superalloy is: Cr, 20.0; Nb, 1.5; Ti, 2.5; Al, 1.0; Si, 0.30; Mn, 0.30; C, 0.03; B, 0.03; Ce, 0.01. Cylindrical specimens with a dimension of ∅8 × 12 mm were machined from the pre-treated bar. A series of isothermal compression tests were conducted by using a Gleebe-3500 thermo-simulation machine at deformation temperatures (T_d) of 1060, 1090, 1120, 1150 and 1180 °C. The temperatures were controlled

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within ± 1 °C. The strain rates ($\dot{\varepsilon}$) selected in this work were 0.1, 1.0, 10 and 50 s^{-1}, and the height reductions were 10%, 30%, 45% and 60%, respectively. All of the specimens were heated at a heating rate of 10 °C/s and soaked for 3.0 min at the deformation temperature to obtain a uniform temperature distribution in the entire specimen. The strain–stress curves were automatically recorded during the compression process. Upon compression, the specimens were cooled down to room temperature by spraying of water. The samples were sectioned parallel to the compression axis, and the microstructure examination was conducted by OLYMPUS-PM3 Optical Microscope.

3. Experimental results and discussion

3.1. Abnormal flow behavior at high strain rates of 10 and 50 s^{-1}

Flow curves obtained under various compression conditions are shown in Fig. 1. It can be found that flow stress increases significantly with increasing strain rate ($\dot{\varepsilon}$) and decreasing temperature (T_d). It is also demonstrated the sensitivity of flow stress on the variation of strain rate and temperature. Summarized, flow curves of GH4049 superalloys can be divided into two types. The first type curves display a severe work hardening to a single stress peak (σ_P), and a gradually decreased flow stress. As shown in Fig. 1, red curves show four different stage, viz., work hardening stage, stable stage, softening stage and steady stage. These flow curves indicate that the softening mechanism, such as DRX, is sufficient to cancel out the work hardening [10]. For further analysis, microstructure observation should be conducted.

The second type curves are characterized by a sharp peak stress at a lower strain with an obvious upper yield point and a lower yield point, which is usually called discontinuous softening. Previous research reported that discontinuous softening always occurred at higher temperatures during hot processing with high speed strain rates [11–14]. In this work, discontinuous softening is observed for GH4049 superalloys processing with high strain rates of 10 and 50 s^{-1} at all deformation temperatures except 1060 °C. As blue curves shown in Fig. 1, four stages are exhibited for discontinuous softening curves. Firstly, the flow stress increases severely to a peak value (σ_P). And then, a sharp drop of flow stress occurs until reaching the lower value (σ_L). After the lower stress, the flow stress increases slowly to an upper value (σ_U), and then followed by a continuous decrease. The severe increase of flow stress is due to the rapid proliferation of movable dislocations. The critical density of dislocations is obtained in local deformed region, and local dynamic recrystallization results in the sharp drop of flow stress. The slow increase of flow stress is mainly associated with the interaction of strain hardening and softening mechanism. As the strain increases, the second peak value, named upper value (σ_U), is reached, and the softening mechanism plays a dominant role. The microstructure observations indicate that the softening mechanisms for GH4049 superalloys present discontinuous softening are considered as discontinuous dynamic recrystallization (DRX). Peak value (σ_P), upper value (σ_U) and lower value (σ_L) can also be seen in Fig. 2, which also gives processing conditions associated with discontinuous DRX. Based on flow behavior analysis and microstructure observation, the second flow behavior associated with discontinuous DRX occurred at deformation temperatures of 1090–1180 °C with high strain rates of 10–50 s^{-1}.

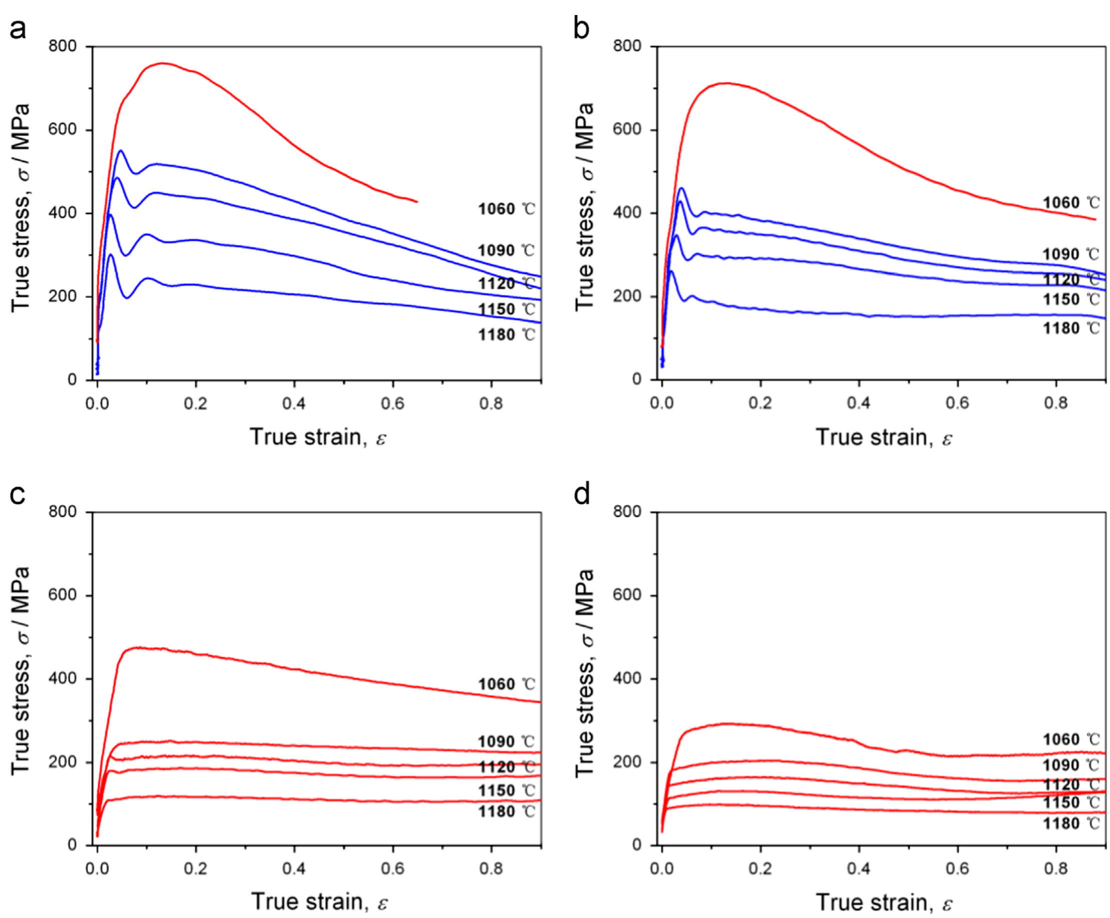

Fig. 1. Flow curves of GH4049 superalloys compressed with strain rates of (a) 50, (b) 10, (c) 1 and (d) 0.1 s^{-1}, in which blue curves reveal discontinuous softening feature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)