

A modified Zerilli–Armstrong model for alloy IC10 over a wide range of temperatures and strain rates

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ABSTRACT

IC10 is a newly developed Ni₃Al-based superalloy. To investigate its flow behaviors, tensile experiments were conducted over a wide range of temperatures (293–1073 K) and strain rates (10^{-5} – 10^{-2} s⁻¹) on Material Test System. Experiments show that: (1) flow behaviors are not sensitive to strain rates at room temperature; (2) flow behaviors varies slightly with the temperature at the same strain rate. Z–A model, one of the most widely used models, is employed in describing the flow behaviors of IC10. Normally, the parameters in Z–A model are regarded as constants at various conditions and whole deforming process, which do not agree with the actual process and will decrease its predicted accuracies. In order to improve the predicted accuracies, Z–A model is modified by adding the functions to consider the effects of temperature, strain rate and deforming process on certain parameter. The modified model is used to predict flow behaviors of IC10 at different experiment conditions. Compared with the predicted data of original Z–A model and the experimental data, it is found that the predicted accuracy of the modified Z–A model is improved obviously. The max average relative error decreased from 6.37% to 3.86%.

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1. Introduction

In recent years, ordered Ni₃Al-based intermetallic compounds have been intensively studied as potential high temperature structural materials in the aerospace applications, e.g. turbine engine components. Such materials have the features of high specific moduli, high yield strength, fairly good ductility from room temperature to elevated temperature, high incipient melting temperature, excellent oxidation resistance and high creep resistance over a wide range of temperatures [1].

Alloy IC10, one of the newly developed Ni₃Al-based alloys, can be used as the material for advanced aero-engine fan with a service temperature up to 1373 K [2]. By now, there are great deals of studies related to the applications of alloy IC10. However, the studies on the flow behaviors and the constitutive equations for alloy IC10 are still lacking for design requirement.

During the past several decades, studies were made in characterizing material behaviors through both phenomenological and physically based models. In order to clarify the anomalous thermo-mechanical properties of Ni₃Al alloys, various mechanistic modes have been proposed successfully, such as TK model [3], PPV model

[4], ELU model [5], Hirsch's model [6,7] and Choi's model [8], etc. But these models focus on the anomalous properties of Ni₃Al alloys, negligible modeling research has been focused on the behaviors after yielding. The internal variable constitutive models, such as Miller's model [9], Bonder and Partom's model [10,11] and Chaboche's model [12], etc., have achieved great successes in practice. However, there are many material parameters contained in these models. As a result, a large number of independent tests are needed to identify them. J–C model proposed by Johnson and Cook [13] is adopted widely in practice, due to its simple formulation and few parameters. And it is modified by Zhang [14,15] successfully to describe the flow behaviors of alloy IC10. But J–C model is an empirical equation and has not considered the coupling effect of temperature and strain rates. As a matter of fact, the material behavior depends to a high degree on the rate of deformation and temperature. Various models which consider the coupling effect of temperature and strain rates have been proposed. Voyiadis et al. [16–20] proposed coupled temperature and strain rate microstructural physically based models and yield functions based on the concept of thermal activation analysis as well as dislocation interaction mechanisms. Zerilli and Armstrong [21,22] used the dislocation mechanics concept to develop a constitutive model (Z–A model) that accounts for strain, strain rate and temperature dependence in a coupled manner. As the material behavior depends on the material crystal structure, these models consider two different forms for the two different classes of metals: BCC and FCC.

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Table 1

Nominal composition of alloy IC10/wt%.

C	Co	Cr	Al	W	Mo	Ta	Hf	B	Ni
0.07–0.12	11.5–12.5	6.5–7.5	5.6–6.2	4.8–5.2	1.0–2.0	6.5–7.5	1.3–1.7	0.01–0.02	Bal.
2	5	5	2	2	0	5	7	2	

Z–A model is considered as one of the most widely used models that have been used by many authors in different types of low and high strain rates and temperature-related applications. A lot of authors reviewed and evaluated the predicted inaccuracies as well as the inconsistencies of the Z–A model when compared to experimental results for different BCC and FCC metals. These inconsistencies are attributed to certain assumptions used in the Z–A model formulation. The assumption, that the parameters of Z–A model are regarded as constants at various conditions and the whole deforming process, do not agree with actual process. As a key point, the assumption should be modified. Abed and Voyiadjis [23] modified Z–A model by introducing a new definition for activation area which is both temperature and strain rate related. However, the parameters in modified model are still constants at the whole deforming process. Zhu et al. [24] modified the Z–A model by considering the evolution of the microstructure of the deforming metals and the variation of density of mobile dislocation. But the effects of the temperature and strain rate are not considering in the variation of dislocation density. In this paper, on the basis of the investigations on the physical interpretations of these parameters, Z–A model was modified by adding the functions to consider the effects of temperature, strain rate and deforming process on certain parameter.

In the following sections, the flow behaviors of alloy IC10 were investigated firstly based on the results presented by the tensile tests over a wide range of temperatures (293–1073 K) and strain rates (10^{-5} – 10^{-2} s $^{-1}$). Then, the modified Z–A model was developed. At last, the effectiveness of modified Z–A model was verified by extensive experiments on IC10 before a summary.

2. Experimental procedures

A Ni₃Al-based alloy IC10, which is provided by Beijing Institute of Aeronautical Materials (BIAM), is a directional solidification material in [001] orientation, with its nominal composition listed in Table 1.

The master alloy ingot of IC10 was first prepared by a vacuum induction furnace. Then the master alloy ingot was cut to several smaller ingots with its weight of 4 kg. And the smaller ingots were processed to directional solidification bars of Φ 15 mm in [001] orientation in directional solidification vacuum induction furnace. Then, the as-cast bars were heat-treated as the following processes: (1) homogenized at 1453 K for 2 h, and increased the temperature to 1543 K for 2 h, followed by air-cooling to room temperature; (2) increased the temperature to 1323 K for 4 h, and air-cooling to room temperature; (3) increased temperature to 1143 K for 16 h, followed by air-cooling. The columnar tensile specimens with dimension of Φ 10 mm $\times$ 50 mm were machined from the bars.

The size of the tensile specimens was 10 mm in diameter and 50 mm in gauge length. Fig. 1 shows the typical microstructures of alloy IC10. As seen in a SEM micrograph in Fig. 1a, there are some unsolved γ/γ' eutectic and resolved MC. This is because that the initial melting temperature of γ' is lower than its total melting temperature caused by the existence of the trace elements, such as B, Hf and C, etc. As seen in Fig. 1b, the size of γ' particles ranges from 0.2 to 0.6 μ m. By image analysis the volume fraction of γ' phase was found to be about 65%.

In order to investigate flow behaviors of IC10, two types of tensile tests were completed as follows: (1) at four different strain

rates (10^{-2} , 10^{-3} , 10^{-4} and 10^{-5} s $^{-1}$) under room temperature; (2) at three different temperatures (873, 973 and 1073 K) with the same strain rate of 10^{-4} s $^{-1}$. All tests were conducted on Material Test System (MTS809), a computer-controlled, servo-hydraulic tensile torsion machine. The experimental data were collected and stored by a computer with the signal automatism gather system of MTS809.

3. Experimental results

Fig. 2 shows the stress–strain curves of alloy IC10 at ambient temperature for different strain rates. It is shown that work hardening behavior of the alloy is obvious and insensitive to strain rates during the whole deformation under room temperature.

Fig. 3 shows the stress–strain curves of the IC10 at different temperatures (293, 873, 973 and 1073 K) with the same strain rate of 10^{-4} s $^{-1}$. As shown in Fig. 3, there is still work hardening behavior during the whole deformation in the curves at high temperature. It is similar with the hardening behaviors at ambient temperature. In addition, the work hardening rate varies a little with temperature.

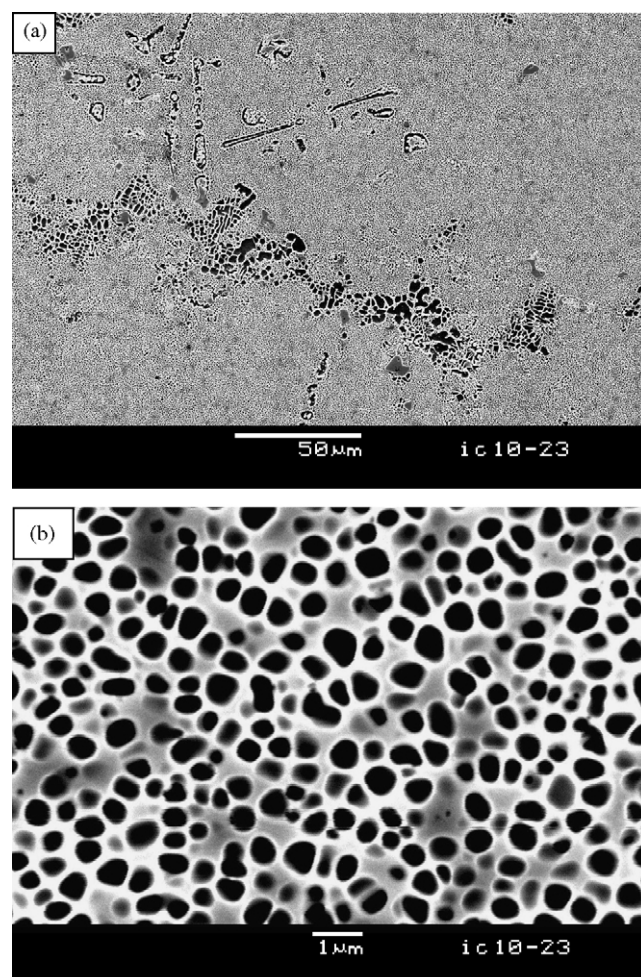


Fig. 1. Typical microstructures of alloy IC10 after heat treatment (a) morphology of unsolved γ/γ' eutectic and resolved MC; (b) spherical γ' phase.

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