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Use of instrumented micro-indentation to study the mesoscopic elasto-plastic behavior of GH4145/SQ superalloy during high-temperature cyclic straining

Duyi Ye[a,*], Lei Xiao[a], Haibo Cha[a], Ping Xu[b], Yuandong Xu[a]

[a] Institute for Process Equipments, Zhejiang University, 38 Zheda Road, Hangzhou 310027, China
[b] Institute of Applied Mechanics, Zhejiang University, 38 Zheda Road, Hangzhou 310027, China

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ABSTRACT

In this paper the instrumented micro-indentation testing (IIT) was used to study the mesoscopic elasto-plastic behavior of nickel-base superalloy GH4145/SQ subjected to cyclic straining at an elevated-temperature. For this purpose, a series of experiments including high-temperature low-cycle fatigue tests, instrumented micro-indentation measurements and OM (TEM) examinations were carried out. The characteristic parameters of indentation (C, h_{max}, S, h_r, W_e and W_P) during high-temperature fatigue failure process were determined from the experimental indentation load–depth (P–h) curves. The fatigue mesoscopic elasto-plastic properties such as E, σ_y and n were estimated using Dao et al.'s analysis algorithm [19], combined with the indentation characteristic parameters, and their distribution patterns were verified in a statistical sense. Microstructural examinations using both OM and TEM were performed to provide the micromechanisms for the fatigue mesoscopic elasto-plastic behavior of the superalloy during high-temperature low-cycle fatigue.

1. Introduction

In order to overcome the inherent ambiguities in macro-modeling of fatigue damage mechanics behavior in classical approaches to fatigue design, which is mainly based on experimental data and empirical rules, meso-damage mechanics (MDM) incorporating local material properties and microstructural features into the constitutive relation and damage evolution law has been developed over the last decades [1–3]. This meso-based approach to study fatigue damage mechanics behavior provides a promiseful way to deal with microstructure-sensitive damage evolution process, such as fatigue micro-crack initiation and growth. As it has been indicated [1,2], using MDM to model the fatigue damage mechanics behavior of polycrystalline solids, some knowledge regarding the local elasto-plastic properties of materials such as Young's modulus, flow stress and strain hardening capacity as well as their statistical distributions during fatigue damage process would be necessary. To date, a variety of methods for mesoscopic mechanics measurement have been developed [4–8], among which the instrumented micro-indentation technique, developed in recent decades, has received increasing attention in practical applications due to its simplicity, convenience and relatively non-destructive nature for characterizing various mechanical properties including hardness, elastic modulus, yield strength, strain hardening exponent, fracture toughness, etc., of small volumes of materials or thin solid films [8,9].

GH4145/SQ is a precipitation-strengthened nickel-based superalloy with good high-temperature strength and oxidation resistance. This alloy is currently used for the fabrication of elevated-temperature load-carrying components in high-capacity steam turbines in power plant. Most of these load-carrying elements undergo a typical combination of alternating loadings and elevated-temperature exposure in real service conditions and, therefore, high-temperature fatigue damage analysis becomes an important aspect in their safe designing against fatigue failure. Although the macroscopic fatigue mechanics behavior of GH4145/SQ superalloy has been investigated extensively in the last two decades [10–13], relatively few studies have been focused on the mesoscopic fatigue mechanics behavior of this material. In our recent research work [14], the instrumented micro-indentation testing (IIT) was introduced to study the mesoscopic mechanical properties of fatigue fracture specimens of GH4145/SQ superalloy. This study exhibited a preliminary success of IIT in measuring the mesoscopic mechanical properties of polycrystalline metals. In the present work, the instrumented micro-indentation testing will be further applied to study the mesoscopic elasto-plastic behavior of GH4145/SQ superalloy during high-temperature low-cycle fatigue. The main purpose of the present study is to provide more systematic experimental understandings of the mesoscopic fatigue mechanical behavior of GH4145/SQ superalloy for establishing a

* Corresponding author. Tel.: +86 571 88869213; fax: +86 571 88869213.
E-mail address: duyi_ye@zju.edu.cn (D. Ye).

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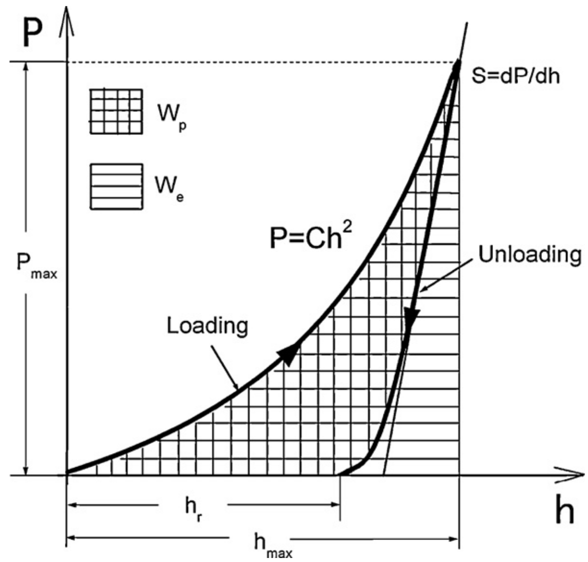

Fig. 1. A typical indentation load–depth (P–h) curves for loading and unloading.

meso-based fatigue damage mechanics model for predicting crack-initiation life of elevated-temperature load-carrying components.

2. Determination of the elasto-plastic properties from the indentation load–depth curve

A typical loading and unloading response of an elasto-plastic material to a sharp indentation is shown schematically in Fig. 1. From this indentation load–depth (P–h) curve, the following characteristic parameters of indentation can be extracted, i.e. the peak load, P_{max}, the maximum penetration depth, h_{max}, the indentation curvature, C, the initial unloading slope, $S(= dP/dh\big|_{h_{max}})$, the residual depth of penetration after complete unloading, h_r, the recovered elastic work, W_e, and the residual plastic work, W_p. As indicated [15,16], C is a measurement of the resistance to indentation, S characterizes the stiffness property of the indented material, h_r represents the ability of a material to change its shape, i.e. plasticity in a wide interpretation of this term, and W_p denotes the ability to dissipate the plastic work during indentation. The local elasto-plastic behavior of an indented material can thus be evaluated comprehensively in terms of the above characteristic parameters of indentation.

As seen in Fig. 1, h_{max}, h_r, W_e and W_p can be extracted directly from the indentation response curve, while determination of C and S needs to further provide the description of the loading and unloading curves. Generally, in the case of sharp indenter as Vickers the loading curve can be expressed in the form of a parabolic relation known as Kick's law [9], $P = Ch^2$, while the unloading curve is usually described by a power-law relation suggested by Oliver and Pharr [9]: $P = B(h - h_r)^m$, where B and m are empirically determined fitting parameters. Thus C and S can be expressed, respectively, in the following forms,

$$C = \frac{P_{max}}{h_{max}^2} \tag{1}$$

$$S = \left(\frac{dP}{dh}\right)_{h=h_{max}} = Bm(h_{max} - h_r)^{m-1} \tag{2}$$

A number of recent investigations [15–19] indicated that, through the combined use of the above characteristic parameters of indentation and simple principles of analysis based on elastic and elastic–plastic contact theory, some basic mechanical properties of materials, such as Young's modulus, E, yield stress, σ_y, and strain hardening exponent, n, can further be deduced. In order to determine the mechanical properties from the indentation load-depth (P–h) curve, several analytical approaches have been proposed in recent years [15–19], among which a representative method was developed by Dao et al. [19]. In Dao et al's method, a set of universal dimensionless functions that relate the characteristic parameters of indentation to the mechanical properties (E, σ_y and n) obtained from the stress–strain curves was proposed. Fig. 2 illustrates the flow chart of Dao et al's analysis algorithms, where the dimensionless functions (Π_1, Π_2, Π_4 and Π_5) can be expressed concretely in the following forms,

$$\prod\nolimits_1\left(\frac{E^*}{\sigma_{0.033}}\right) = \frac{C}{\sigma_{0.033}} = -1.131\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right]^3 + 13.635\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right]^2 - 30.594\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right] + 29.267 \tag{3}$$

$$\begin{aligned}\prod\nolimits_2\left(\frac{E^*}{\sigma_{0.033}}, n\right) = \frac{S}{E^* h_{max}} &= (-1.40577n^3 + 0.77526n^2 + 0.15830n - 0.06831)\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right]^3 \\ &+ (17.93006n^3 - 9.22091n^2 - 2.37733n + 0.86295)\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right]^2 \\ &+ (-79.99715n^3 + 40.55620n^2 + 9.00157n - 2.54543)\left[\ln\left(\frac{E^*}{\sigma_{0.033}}\right)\right] \\ &+ (122.65069n^3 - 63.88418n^2 - 9.58936n + 6.20045)\end{aligned} \tag{4}$$

$$\prod\nolimits_4\left(\frac{h_r}{h_{max}}\right) = \frac{F_{av}}{E^*} \approx 0.268536\left(0.9952495 - \frac{h_r}{h_{max}}\right)^{1.1142735} \tag{5}$$

$$\prod\nolimits_5\left(\frac{h_r}{h_{max}}\right) = \frac{W_p}{W_t} = 1.61217\{1.13111 - 1.74756^{[-1.49291(h_r/h_{max})^{2.535334}]} - 0.075187(h_r/h_{max})^{1.135826}\} \tag{6}$$

In above equations, E^* denotes the reduced Young's modulus and can be written as, $E^* = S/c^*\sqrt{A_{max}}$, where A_{max} is the projected area of the contact, and c^* is a constant that depends on the geometry of the indenter. As suggested by Dao et al., two sets of indentation characteristic parameters, (C, h_r, h_m and S) or (C, W_p/W_t, P_m and S), can be chosen as input data for the above analysis algorithm.

In the present work the method proposed by Dao et al. will be used to estimate the local elasto-plastic properties of a polycrystalline solid subjected to low-cycle fatigue loading at an elevated temperature.

3. Experimental procedures

The material used in this study was GH4145/SQ superalloy supplied in the form of 30 mm diameter hot forged bars. Its chemical