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An indentation fatigue depth propagation law

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Using both experimental and numerical studies, we show that, upon cyclic indentation with a flat cylindrical indenter, the steady-state rate of indentation depth propagation can be well characterized by a simple power-law function of the stress intensity range and the maximum stress intensity, which is qualitatively similar to the steady-state growth of a fatigue crack. The simple law of indentation fatigue has the potential to extract the fatigue properties of materials with small volumes and clarify the fatigue crack mechanisms.

Keywords: Indentation fatigue experiment; Finite element analyses; Indentation depth propagation; Fatigue crack growth; Stress intensity

When a metal is subjected to cyclic uniaxial loading, a fatigue crack initiates and grows with the number of cycles. The intermediate region of the fatigue crack growth of many metallic materials can be described by the well-known Paris equation [1,2], where the crack growth rate is a power-law function of the nominal stress intensity factor range, $\Delta K = K_{\max} - K_{\min}$, with $K_{\max}$ and $K_{\min}$ denoting the maximum and minimum stress intensity factors, respectively. Recent studies have shown that another important driving force for fatigue crack propagation is $K_{\max}$, especially for the relatively more brittle materials. For example, Liu and Chen [3] and Dauskardt et al. [4] explored the competition between the intrinsic mechanism of crack advance ahead of the crack tip and the extrinsic mechanism of crack tip shielding behind the tip. From extensive experiments, they proposed the following phenomenological law for the fatigue crack growth rate:

$$\mathrm{d}a/\mathrm{d}N = C(K_{\max})^n(\Delta K)^m \tag{1}$$

Here, ΔK and $K_{\max}$ represent the intrinsic and extrinsic mechanisms of fatigue crack growth, the dominances of which are denoted by the power indices m and n, respectively. m, n and C are empirical constants that depend on the material and microstructure, fatigue frequency, loading mode and environment, etc. In other words, there are various intrinsic and extrinsic factors that could either promote or impede the fatigue crack growth in ductile or brittle materials, yet their fundamental roles are still not yet sufficiently understood [5,6].

Meanwhile, with the wide applications of small material structures, including nano-/micro-electromechanical systems (N/MEMS) and thin films [7,8], there is an increasing practical need to understand the fatigue properties of materials of very small volumes. Note that these small material structures often exhibit properties distinct from their bulk counterparts, and it is challenging to measure their fatigue characteristics using conventional uniaxial testing methods. The development of an alternative testing technique could help to address both the fundamental and the practical challenges described above.

Instrumented indentation is widely used to measure the mechanical properties of material structures at various nanoscopic, microscopic and macroscopic scales [9–11]. Its popularity arises in that it is easy to conduct, only minor preparation (if any) of the tested material is needed, and the tests are inherently simple, fast and precise. The tests can be conducted at various working temperatures and in a range of environments, and measurements close to in situ conditions are possible thanks to the small penetration needed in most cases. Therefore, it is a very attractive alternative testing technique for small material structures [12–14].

Upon cyclic indentation loading, also known as the indentation fatigue test, an early study by Li and Chu

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on β-tin single crystal samples showed that the indenter could continuously sink into the specimen with applied cycles [15], thus the evolution of indentation depth can be used as a characteristic measure of the indentation fatigue properties. They further pointed out that the behavior of indentation fatigue depth propagation was qualitatively similar to that of fatigue crack propagation under over- and underloading conditions [16,17]. Similar findings were reported from recent indentation fatigue experiments on polycrystalline copper specimens [18,19]. Despite such similarities, a quantitative analysis of the depth propagation of indentation fatigue is still lacking, and it has not yet been compared with the crack growth characteristics of a conventional fatigue test.

Indentation fatigue and fatigue crack propagation both show stress singularity. Upon static indentation using a rigid flat cylindrical indenter, the stress singularity at the rim of contact is similar to that of a semi-infinite circumferential crack in a vertical cylindrical rod under model I loading (see Fig. 1), from which the stress intensity factor near the contact rim can be obtained as [20]:

$$K_I = \frac{P}{2a\sqrt{\pi a}} \tag{2}$$

where a is the radius of the flat cylindrical indenter. By applying this relationship to the flat cylindrical indentation fatigue (with indentation load range ΔP and the maximum load $P_{\max}$),

$$K_{\max} = \frac{P_{\max}}{2a\sqrt{\pi a}}, \Delta K = \frac{\Delta P}{2a\sqrt{\pi a}} \tag{3}$$

Inspired by such similarity between the crack and indentation stress singularity, here we show that a simple indentation fatigue depth propagation law exists. When a specimen subjects to a cyclic indentation load using a cylindrical flat punch, the relationship between the indentation load (P) and depth (d) can be recorded as a function of number of cycles (N). We propose that the steady-state rate of indentation depth propagation $(\mathrm{d}d/\mathrm{d}N)_s$ can be described quantitatively by the following simple law:

$$(\mathrm{d}d/\mathrm{d}N)_s = C_i K_{\max}^{n_i} \Delta K^{m_i} \tag{4}$$

where $K_{\max}$ and ΔK are obtained from Eq. (3) (despite the fact that no apparent crack is generated from such

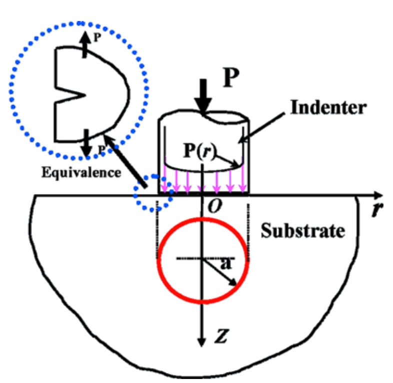

Figure 1. Schematic illustration of a flat cylindrical indenter on a semi-infinite substrate. The singular stress distribution at the rim of contact is analogous to the stress intensity at a crack tip.

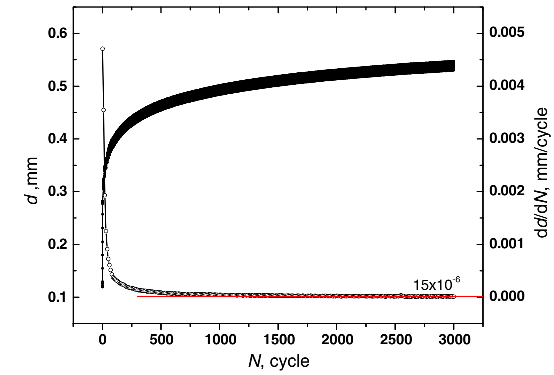

Figure 2. For the flat cylindrical indentation fatigue experiment on a polycrystalline copper, the evolution of the indentation depth d and indentation depth rate $\mathrm{d}d/\mathrm{d}N$ are given as variations of the applied fatigue cycle number. $K_{\max} = 485.26$ and $\Delta K = 469.12$ MPa mm$^{1/2}$.

indentation fatigue experiment known to the authors), and C_i, n_i, and m_i are constants of indentation fatigue, which depend on material/microstructure and testing environments.

In this study, we validate the critical relationship in Eq. (4) by a series of numerical simulations, and an experiment on a polycrystalline copper (with 0.0262% Zn, 0.0145% P, 0.003% Pb and 0.1266% Fe) at room temperature. The details of finite-element simulations of indentation fatigue can be found in Ref. [18]. The experiment is performed using a customized load cell of Instron 8871 testing system; the flat cylindrical indenter is a high-strength alloy with $2a = 0.991$ mm. Detailed information of the sample preparation and experimental setup can be found in our previous work [19]. The cyclic load varies in a sinusoidal manner.

We first look at the typical experimental behavior of indentation fatigue depth propagation. For representative values of $K_{\max} = 485.26$ and $\Delta K = 469.12$ MPa mm$^{1/2}$,[1] Figure 2 shows the evolution of indentation depth d with the number of cycles N observed in the experiment, where the increment of d with N can be divided into two stages: a primary stage, during which the indenter sinks quickly into the specimen; followed by a steady-state stage, where the indentation depth increases at almost a constant rate. This is in fact quite analogous to the first two stages of fatigue crack growth. In essence, within a indentation cycle, upon unloading the negative dislocation may be activated due to either the retraction of the dislocation into the source or the negative stress concentration caused by the shielding effect (the width of band in the curve of d vs. N in Figure 2 roughly represents the elastic deformation of the cycles); during the loading half cycle, more dislocations will be emitted by the renewed stress concentration to advance the plastic zone propagation. After a certain number of cyclic indentations, the emission and retraction of dislocation reach a balance, which results in an apparent steady-state propagation of the indentation fatigue depth, d [19]. From the comparison, the evolution mechanisms

[1] These numbers are not integers since it is much more straightforward to control $P_{\max}$ and ΔP during an experiment. All findings in this paper are not affected by such non-integer values of $K_{\max}$ and ΔK.