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Influence of grain size on fatigue crack propagation and acoustic emission features in commercial-purity zirconium

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ABSTRACT

The influence of grain size on fatigue and corresponding acoustic emission (AE) features in commercial-purity zirconium were investigated. Fatigue crack propagation tests were conducted at room temperature with AE monitored simultaneously. The fatigue properties and AE sources were discussed combined with the microstructural and fractographic observations. The results showed that the increased grain size affected the fatigue crack stable propagation rate slightly, but it resulted in a significant increase of the AE counts rate. During the crack stable propagation, for the specimens with small-sized grains and medium-sized grains, the relationships between AE counts rate and fatigue stress intensity factor range were both generally according with the Pairs law, except some local fluctuations due to the regional occurrence of deformation twins. Especially, for the specimen with large grains, higher AE counts rate presented persistently, which were caused by twins appearing continuously at the edge of the crack. These results suggest that as the grain size increased in commercial-purity zirconium, twin became more frequent and made a more important contribution to the fatigue process, and the AE technique was sensitive to the crack propagation and the twin incidents during fatigue crack growth.

1. Introduction

Owing to its remarkable corrosion resistance, good mechanical properties and machinability, zirconium and zircaloy have been increasingly used in pressure vessels and pipelines for chemical industry. On account of the cyclic loading and potential fatigue damage, it is essential to monitor the safety situation of these equipments. However, because of its complex deformation mechanism due to the hexagonal-close-paced (*hcp*) lattice structure, the fatigue behavior of zirconium is still not clearly understood. Over the past decades, a lot of work has been concerned with the effect of environmental factors on fatigue-crack initiation or total life, such as loading mode [1,2], temperature [3–5], corrosive conditions [6,7], and so on, whereas variations in material parameters would also alter the fatigue property. With the hydrogen content increasing in nuclear grade zirconium, the fatigue crack growth rate enhanced [8,9]. Different composition of zirconium alloys changed the fatigue behavior under certain strain amplitude and temperature [4,10]. However, the influence of grain size on fatigue crack propagation behavior has been seldom researched.

Acoustic emission (AE) has been confirmed to be an effective nondestructive evaluation method to monitor growing flaws. For further exploring the AE source, some investigations associated AE signals with micro-structures or micro-damage events in material. Studied the influences of equiaxed and lamellar micro-structures of titanium alloy, Kohn et al. [11] concluded that more interfaces and larger grain size in the lamellar one accounted for the more cleavage and intergranular fractures and the greater amount of AE. In fracture toughness test, Mashino et al. [12] observed that the AE events stemming from the microcracks generation, were larger in the α-titanium alloy with acicular microstructure than those of the equiaxed one. For Zr–2.5Cb alloy, the increased AE energy per load cycle was found to be in a power law relationship with fatigue crack growthrate, and the AE signal propagation was insensitive to the surrounding medium [13]. Although AE application to fatigue appears promising, the AE source mechanism is still not clearly understood.

Since the crack stable propagation occupies most of the fatigue life, the purpose of the present work was to investigate the grain size effect on fatigue crack stable growth behavior in zirconium. The AE signals generated during fatigue test were compared and analyzed. Complemented with the micro-structural and fractographic observations, the AE source mechanisms were discussed.

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2. Material and experiments

2.1. Material and specimens

Hot-rolled polycrystalline commercial-purity zirconium (code R60702) was used, which contained impurities of 0.01C, 0.1 (Fe+Cr), 0.005H, 0.004N and 1.0 Hf (wt%). The four-point bending fatigue specimens were machined parallel to the rolling direction, and the dimensions are shown in Fig. 1. The following annealing treatments under high vacuum conditions ($<10^{-5}$ Torr) were given to the specimens to produce two grain sizes different from the as-received one: (a) annealed at 923 K for 2 h and air-cooled to room temperature; (b) annealed at 1093 K for 12 h and furnace-cooled. All the investigated specimens exhibited nearly equiaxed grains in a single α-phase without twin. The mechanical properties of the three conditions from tensile tests are given in Table 1.

2.2. Fatigue test and AE monitoring

Fatigue crack propagation tests were conducted at room temperature (300 K) using a servo-hydraulic testing machine (Model: 8801, Instron Ltd., Britain). A sinusoidal cyclic loading at a frequency of 10 Hz was employed, with the load ratio of 0.1 and the peak load of 8.6 kN. A standard crack tip opening displacement (CTOD) gage was used to measure the crack length with the accuracy of 0.01 mm. At least three specimens were tested for each condition to confirm the regularity. After the crack growing to an a/W of 0.7 (a is the crack length and W is the width of the specimen), the tests were terminated. Then, the specimens were sectioned parallel to the major plane of the plate for microstructure examination, and the fatigue-fracture surfaces were observed by scanning electron microscope (SEM, Model: JSM-5800, JEOL, Japan).

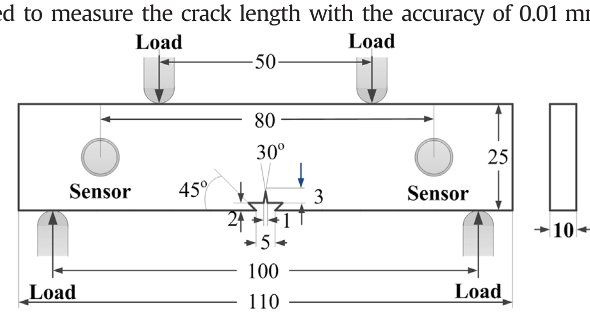

Fig. 1. Details of four-point bending fatigue specimen (unit, mm).

AE signals generated during the fatigue tests were recorded by a DiSP-4/PCI AE system (Physical Acoustic Corp., USA). Two broad-band AE sensors with a flat response from 100 kHz to 900 kHz were placed on the specimen (Fig. 1). Two preamplifiers with 40 dB gain and a band pass filter in the range of 100–1200 kHz, were used. To make sure the obtained signals are from the crack area and to avoid the environmental noise, determined by a dummy specimen without a slot, an AE energy threshold of 1 mV · μs, a average frequency threshold of 35 kHz, and a linear AE source location were set, which were the same acquisition setup with the previous study in our lab [14].

3. Results and analysis

3.1. Fatigue crack propagation

A fatigue crack growth can be divided into three stages: (1) the crack initiation, (2) the crack stable propagation, and (3) the crack rapid growth. For stage 2, the crack propagation obeys the Paris law

$$da/dN = M(\Delta K)^n, \quad \text{or } \log(da/dN) = \log M + n\log(\Delta K) \qquad (1)$$

where a is the crack length, N is the number of fatigue cycle, ΔK is the stress intensity factor range, and M and n are constants for a particular material. The relationships between the fatigue crack growth rates (da/dN) and the stress intensity factor ranges ΔK are plotted on the double logarithmic axes in Fig. 2. During stage 2, they all obeyed the Paris law and the da/dNs of the three conditions were almost overlapped. But in the middle and late of

Table 1
Mechanical properties of three grain?sizes.

	Average grain size, D [μm]	Yield stress [MPa]	Ultimate tensile stress [MPa]	Elongation [%]	Area reduction [%]
As received	22	344.9	417.7	29.4	48.9
Heat treatment					
(a)	38	316.1	393.9	24.3	46.5
(b)	74	298.5	373.5	26.5	32.1

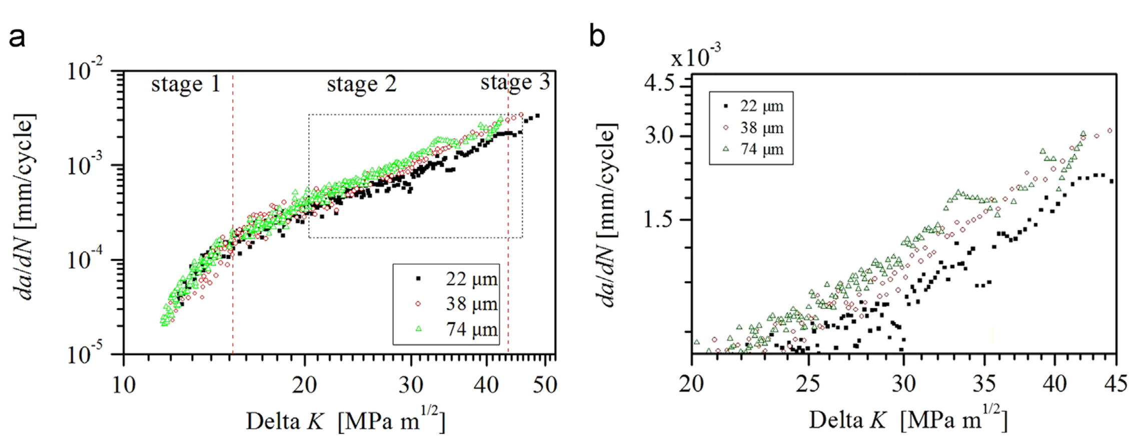

Fig. 2. Relationships between da/dN and ΔK for three grain sizes.