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Time dependent fatigue crack growth behavior of silica particle reinforced epoxy resin composite

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ABSTRACT

The fatigue crack growth behavior in a silica particle reinforced epoxy resin composite was investigated under two levels of constant K_{max} with various stress ratios R and frequencies, where the ranges of R and frequency were from 0.05 to 0.7 and from 0.1 to 10 Hz, respectively. The crack growth rate da/dt under a constant K_{max} was almost constant regardless of R and frequency, which clearly confirmed that the crack growth behavior of the present epoxy resin composite was K_{max}-controlled and time-dependent. The crack path and fracture surface observations revealed that the crack propagated mostly in the matrix: even for the crack propagation along the boundary between silica particle and matrix, the crack propagated in the matrix near the boundary.

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1. Introduction

Epoxy resin composites are now increasingly employed in a wide range of engineering components and structures, which are served under various loading, temperature and environment conditions. For safety design, it is particularly important to understand fatigue and fatigue crack growth characteristics of these composites [1].

There are lots of reports on fatigue crack growth behavior of monolithic polymers [2–5] and polymer composites reinforced by second phase particles [6–10]. Almost all reports have concluded that the fatigue crack growth rate increases with increasing stress ratio and with decreasing loading frequency or strain rate for both monolithic and composite. In their reports, the stress intensity factor range ΔK was adopted as the fracture mechanics parameter to control the fatigue crack growth behavior without detailed confirmation of its effectiveness. However, Kanchanomai and Tammaruechuc [5] for monolithic epoxy resin have discussed in detail about the controlling parameter and concluded that the maximum stress intensity factor K_{max} controls fatigue crack growth behavior of the monolithic epoxy, while the creep fracture mechanics parameter C^* will be the controlling parameter when the large scale creep deformation occurs at the crack tip. It is known that there are two typical modes of fatigue crack growth behavior depending on material, loading and environmental conditions [11,12]. One is the cycle-dependent crack growth behavior, where a crack propagates based on repetition of the loading cycle. The controlling fracture mechanics parameter and crack growth rate for this mode are given by ΔK and the crack growth rate da/dN, respectively, where da/dN is the fatigue crack increment per one cycle. The other is the time-dependent crack growth behavior, where a crack propagates based on the time elapsed. The controlling fracture mechanics parameter and crack growth rate for this mode are given by K_{max} and the crack growth rate da/dt, respectively, where da/dt is the crack growth increment per unit time. Consequently, the cycle-dependent crack growth behavior and the time-dependent crack growth behavior are expressed by the $\Delta K - \mathrm{da/dN}$ curve and the $K_{max} - \mathrm{da/dt}$ curve, respectively.

In the previous paper [9], the conventional ΔK increasing fatigue crack growth tests under various stress ratios at a constant frequency were carried out to clarify the effect of stress ratio on fatigue crack growth behavior of the silica particle reinforced epoxy resin composite. From the results, it was speculated that the fatigue crack growth behavior of the same composite would be not cycle-dependent but rather time-dependent, while the parameter ΔK used to be adopted in Refs. [2–4,6–8], as mentioned above, without clear confirmation of cycle-dependent crack

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growth behavior. In the previous experiment, the suggested time-dependent crack growth behavior was not always obvious because the K_{max} value was varied during the ΔK increasing test and the loading frequency was constant and not varied.

In the present study, to clearly confirm the time-dependent crack growth behavior of the silica particle reinforced epoxy resin composite, the K_{max} constant fatigue crack growth test with decreasing ΔK was carried out. The reason for adopting this test is that the resultant crack growth rates should be constant under the K_{max} constant condition if the crack growth behavior is not cycle-dependent but time-dependent. At the same time, the same experiments were conducted under various frequencies for further confirmation of time-dependent crack growth behavior. Crack growth path as well as fracture surface have been observed in detail by using a scanning electron microscope (SEM) to investigate the influence of frequency on crack growth mechanism. Based on the results, the reason for time-dependent crack growth behavior of the present composite has been discussed.

2. Experimental procedures

2.1. Material

The material used in this study was the same material used in the previous work [9]: an epoxy resin composite reinforced with crushed silica particles, which was fabricated by casting process. Detail of the fabrication process was indicated in Ref. [9]. Microstructure of the material is shown in Fig. 1. As seen from the figure, pre-existing cracks in the larger silica particles were often observed, which would be induced by the crushing process of silica particles. The histogram of particle size based on the cross-sectional observation is shown in Fig. 2, which indicates rather wide distribution of particle size with average particle size of 20–30 μm.

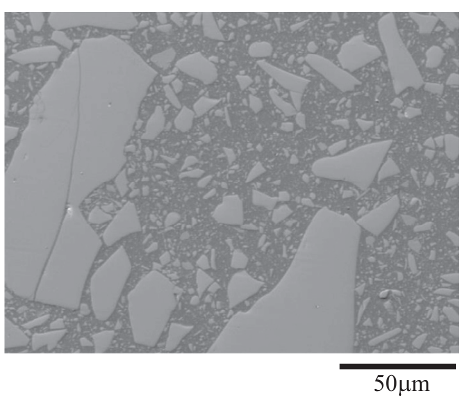

Fig. 1. Microstructure of the silica particle reinforced epoxy resin composite.

2.2. Fatigue test specimen

A single edge notch tension (SENT) specimen was used for the fatigue crack growth test as well as for the in situ observation of crack path. The specimens were machined from the cast block of epoxy resin composite reinforced with crushed silica particles. A notch with 0.1 mm width and 0.5 mm depth was introduced by using a metal slitting saw blade with the V-shape tip. Shape and dimensions of the SENT specimen are shown in Fig. 3. Prior to the fatigue crack growth test, specimen surfaces were coated by Au with a thickness of 2×10^{-3} μm for surface crack path observation in an SEM. A fatigue pre-crack of 0.5 mm length as the starter crack for the fatigue crack growth test was then introduced at the notched tip by a servo-hydraulic fatigue machine under a frequency of 10 Hz at a stress ratio R of 0.05.

2.3. Fatigue crack growth test

Fatigue crack growth experiments were conducted in tension–tension mode using a servo-hydraulic fatigue testing machine with a load cell of 2 kN capacity under a controlled temperature of 20 °C and a relative humidity of 55%. Fatigue crack growth tests were conducted using a sinusoidal wave form under a constant K_{max} with various stress ratios R, as schematically shown in Fig. 4. Two levels of K_{max} value, 0.9 MPa$\sqrt{m}$ and 1.4 MPa$\sqrt{m}$, and three levels of frequency, 0.1, 1 and 10 Hz, were used in the fatigue crack growth tests for more detailed discussion about the time-dependent crack growth behavior.

Stress intensity factor, K, for an SENT specimen was calculated according to the equation proposed by Brown–Srawley [13]:

$$K_I = \sigma\sqrt{\pi a} \cdot F_I(\alpha) \quad (1)$$

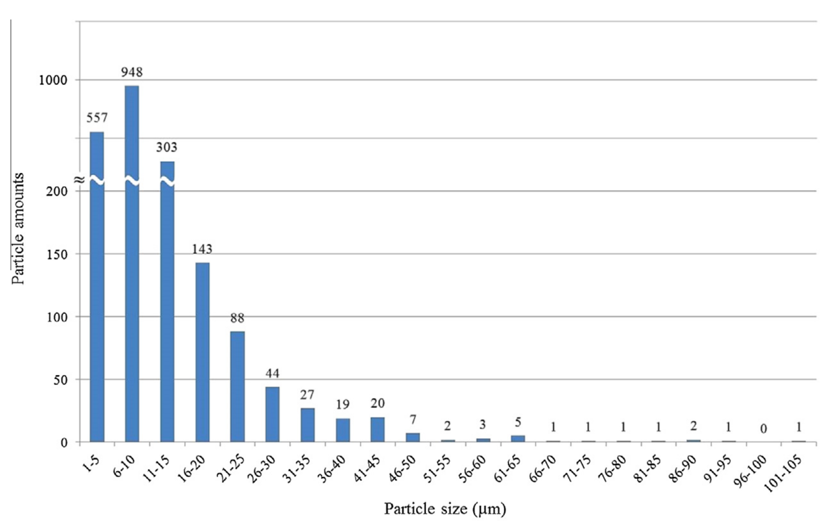

Fig. 2. Silica particle size distribution of the silica particle reinforced epoxy resin composite.

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