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Effect of fiber orientation on fatigue crack propagation in short-fiber reinforced plastics

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ABSTRACT

The influence of the fiber orientation on the crack propagation behavior was studied with single edge-notched specimens which were cut from an injection-molded plate of short-fiber reinforced plastics (SFRPs), at five fiber angles relative to the loading axis, i.e. $\theta = 0°$ (MD), 22.5°, 45°, 67.5°, 90° (TD). Macroscopic crack propagation path was nearly perpendicular to the loading axis for the cases of MD and TD. For the other fiber angles, the crack path was inclined because the crack tended to propagate along inclined fibers. In the relation between the crack propagation rate and the stress intensity factor range, ΔK, the propagation rate of fatigue cracks was slowest for MD, and increased with increasing fiber angle. When the crack propagation rate was correlated to $\Delta K/E$ (E = Young's modulus), the relations for different orientations merged into a single relation. Based on the results of stress-ratio effect, it was concluded that the crack propagation rate was mainly controlled by ΔK at low rates and by the maximum stress intensity factor K_{max} at high rates. For injection molded plates, the existence of the core layer accelerated crack propagation in MD direction, and decelerated in TD direction. Mechanisms of crack propagation were discussed based on microscopic observation of the near crack-tip region and fracture surfaces.

1. Introduction

Short-fiber reinforced plastics (SFRPs) are expected to be used more widely to reduce the weight of ground vehicles, and the injection molding process makes high-rate and economical production possible. Their application in fatigue-sensitive components has steadily increased in vehicle industries. Under cyclic loading, fatigue cracks may be formed relatively early in some components and the propagation stage occupies the most part of the fatigue life.

The propagation behavior of fatigue cracks is highly anisotropic, depending on the fiber orientation [1–7]. The crack propagation rate and path are influenced by fiber orientation. The rate of crack propagation perpendicular to aligned fibers is much slower than that parallel to fibers when compared at the same stress intensity range. Wyzgoski and Novak [2] proposed the energy release rate as a fracture mechanics parameter which gave a single relation irrespective of fiber orientation. Akiniwa et al. proposed to use the stress intensity range divided by Young's modulus as a controlling fracture mechanics parameter [3]. Most of the past work on fatigue crack propagation of injection molded SFRP has been polyetheretherketone (PEEK) [1,4], polyamides [2], polycarbonate [3], polypropylene [5,6], and polyphenylenesulphide (PPS) [7] systems reinforced

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Nomenclature

a	crack length
da/dN	fatigue crack propagation rate
E	Young's modulus
E_1	Young's modulus parallel to fiber direction
E_2	Young's modulus perpendicular to fiber direction
$F(a/W)$	correction factor for stress intensity factor
G_{12}	shear modulus
IMP	injection molded plate
K	stress intensity factor
K_c	critical stress intensity factor for unstable fracture
K_{eq}	equivalent stress intensity factor
K_{max}	maximum stress intensity factor
m	exponent of Paris law
R	stress ratio
SLP	skin layer plate
W	width of specimen
γ	parameter indicating the contribution of maximum stress intensity factor
ΔK	range of stress intensity factor
$\Delta K/E$	range of stress intensity factor divided by Young's modulus
ΔK_{eq}	range of equivalent stress intensity factor
θ	angle between loading direction and fiber direction (molding direction)
ν_{12}	Poisson's ratio
σ	applied gross stress
φ	angle between crack propagation direction and the plane perpendicular to the loading direction

with either glass or carbon fibers. The effects of the fiber orientation, frequency and stress ratio on fatigue crack propagation may depend on material systems. PPS is a versatile temperature and chemical resistant, inherently flame retardant crystalline thermoplastics [8], and a candidate material for high temperature applications in automobile components. Mandel et al. reported excellent fatigue properties of PPS reinforced with carbon fibers [9], indicating a high retardation effect of carbon fibers on crack propagation. The effect of the fiber orientation on the fatigue crack propagation behavior of PPS reinforced with carbon fibers is not yet explored.

In the present paper, the crack propagation behavior was studied with PPS reinforced with 30 wt.% carbon fibers. Specimens with single edge notch were cut at different orientation angles with respect to the molding flow direction from plates made by injection molding. Fatigue crack propagation tests were conducted at stress ratios of 0.1 and 0.5. The influence of the fiber orientation on the crack path and crack propagation rate was studied from a viewpoint of fracture mechanics. Mechanisms of crack propagation was discussed on the basis of microscopic observation of the near crack-tip region and fracture surfaces by scanning electron microscopy (SEM).

2. Material and experimental procedure

2.1. Materials and specimen

The test material is a crystalline thermoplastics PPS reinforced with 30 wt.% carbon fibers. The glass transition temperature is around 360 K. Fatigue specimens were cut from an injection-molded plate with the in-plane dimensions of 80×80 mm and the thickness of 1 mm as shown in Fig. 1. The molding flowed uniformly downward, and the crack propagation behavior was examined in the central region of injection-molded plates. Fig. 2 shows the shape and dimensions of test specimens which has a single edge notch of length 2 mm and width 0.3 mm. The angle between the longitudinal direction of specimens and the molding flow direction (MFD) was set to be five values: $\theta = 0°$ (named MD), 22.5°, 45°, 67.5°, 90° (named TD) as shown in Fig. 1. Since the fiber direction of the skin layer of injection-molded plate is nearly along MFD, the angle θ indicates the angle between the fiber direction and the loading axis. In the following, the angle θ is called the fiber angle. The fiber length distribution was determined by means of optical microscopy, after burning off the matrix at about 800 °C. The mean fiber length was 189 μm. The mean diameter of fibers was 6.12 μm, so the aspect ratio was 30.8.

Injection-molded plates have a three-layer structure where two skin layers sandwich the core layer [8]. Fig. 3 shows the micrographs of the cross sections perpendicular and parallel to MFD. The fiber direction is parallel to MFD in skin layers,