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Fatigue crack propagation in short-carbon-fiber reinforced plastics evaluated based on anisotropic fracture mechanics

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ABSTRACT

The influence of fiber orientation on crack propagation was studied with single edge-notched specimens cut from injection-molded plates of fiber-reinforced polyphenylene sulfide (PPS). Fracture mechanics parameters were calculated by FEM based on anisotropic elasticity. For mode I crack propagation in specimens parallel (MD) and perpendicular (TD) to molding direction, difference in crack propagation rate, dc/dN, among specimens becomes small when correlated to a crack-tip-opening radius parameter, $H_I\Delta G_I$, where H_I is a compliance parameter. Including crack propagation under mixed loading, all the data tend to merge a single relation when correlated to total energy-release-rate range divided by Young's modulus, $\Delta G_{total}/E_0$.

1. Introduction

Short-fiber reinforced plastics (SFRP) are expected to be used more widely in order to reduce the weight of ground vehicles such as automobiles. The injection molding process makes the production of SFRP components more efficient and economical. The mechanical properties of SFRP components are very much anisotropic, depending on the fiber orientation produced by injection molding. Since the applications of SFRP in fatigue-sensitive components are steadily increasing in automobile industries, the anisotropic fatigue properties should be assessed in relation to the fiber orientation.

The fiber orientation produced by injection molding has a big influence on the propagation rate and path of fatigue cracks [1–11]. The crack propagation rate perpendicular to aligned fibers is much slower than that parallel to fibers when compared at the same stress intensity range. Wyzgoski and Novak [3] proposed the range of the energy release rate as a fracture mechanics parameter which gave a unique relation irrespective of fiber orientation. Akiniwa et al. [4] proposed to use the stress intensity range divided by Young's modulus as a controlling parameter for crack propagation with different orientations. In our previous works [10,11], we also found that the relation between the crack propagation rate and the stress intensity range divided by Young's modulus are rather insensitive to fiber orientation. The effect of R ratio on fatigue crack propagation rate became minimal when correlated to the range of energy release rate divided by Young's modulus [11]. The macroscopic as well as microscopic crack path of crack propagation was influenced by the fiber orientation, and cracks often propagated under mixed mode condition even if the applied load was uniaxial.

In all of these previous works [1–11], fracture mechanics parameters such as the stress intensity range or energy release rate, were derived based on isotropic elasticity, neglecting material elastic anisotropy. Since SFRP are normally highly anisotropic, fracture mechanics approach based on anisotropic elasticity may provide deeper understanding of crack propagation mechanisms.

In the present paper, SFRP are assumed to be homogeneous and anisotropic. The energy release rate was evaluated by the modified crack closure integral (MCCI) of the finite element method (FEM) [12,13], and converted to the stress intensity factor for the cases of cracks on elastic symmetrical planes [14,15]. These fracture mechanics parameters are applied to crack propagation in polyphenylene sulfide (PPS) reinforced with 30 wt% short carbon fibers studied in our previous papers [10,11]. PPS is a versatile temperature and chemical resistant, inherently flame retardant crystalline thermoplastics [16], and a candidate material for high temperature applications in automobile components. Specimens with a 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 fiber orientation on fatigue crack propagation was evaluated from a viewpoint of fracture mechanics based on anisotropic elasticity.

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Nomenclature

a	crack length projected on the plane perpendicular to the loading direction
c	crack length measured along crack path
dc/dN	fatigue crack propagation rate
E	Young's modulus for isotropic materials
E_1	Young's modulus parallel to fiber direction
E_2	Young's modulus perpendicular to fiber direction
E_θ	Young's modulus in the direction of angle θ relative to molding (fiber) direction
F_I	correction factor for stress intensity factor of mode I
F_{xi}, F_{xj}	nodal forces in x direction at node i and j
F_{yi}, F_{yj}	nodal forces in y direction at node i and j
G_{12}	shear modulus
G_I	energy release rate for mode I
G_{Imax}	energy release rate for mode I at maximum stress
G_{Imin}	energy release rate for mode I at minimum stress
G_{II}	energy release rate for mode II
G_{total}	sum of energy release rates of mode I and II
H_I	compliance parameter for mode I
IMP	injection molded plate
K_I	stress intensity factor for mode I
K_{Imax}	maximum stress intensity factor of mode I
K_{Imin}	minimum stress intensity factor of mode I
MCCI	modified crack closure integral
PPS	polyphenylene sulfide
R	stress ratio
SFRP	short fiber reinforced plastics
SLP	skin layer plate
$u_{xk}, u_{xk'}$	upper and lower nodal displacements in x direction at node k
$u_{xm}, u_{xm'}$	upper and lower nodal displacements in x direction at node m
$u_{yk}, u_{yk'}$	upper and lower nodal displacements in y direction at node k
$u_{ym}, u_{ym'}$	upper and lower nodal displacements inyx direction at node m
W	width of specimen
Y_I	correction factor for energy release rate of mode I
Y_{II}	correction factor for energy release rate of mode II
ΔK_I	range of stress intensity factor of mode I
ΔG_I	range of energy release rate of mode I
ΔG_{II}	range of energy release rate of mode II
ΔG_{total}	sum of ranges of energy release rate of mode I and II
$\Delta\rho$	range of crack-tip opening radius
θ	angle between loading direction and fiber direction (molding direction)
ν_{12}	Poisson's ratio
ρ	crack-tip opening radius
ρ_{max}	crack-tip opening radius at the maximum stress
ρ_{min}	crack-tip opening radius at the minimum stress
σ	gross stress
σ_{max}	maximum gross stress
φ	angle between crack propagation direction and the plane perpendicular to the loading direction

2. Experimental procedure

2.1. Specimens

The experimental material is semi-crystalline brittle thermoplastics, PPS, reinforced with carbon fibers. The amount of fiber content was 30 wt%. Fatigue specimens were cut from an injection-molded plate (IMP) with the in-plane dimensions of 80 × 80 mm and the thickness of 1 mm [10,11]. Fig. 1 shows the shape of test specimens which has a single edge notch of length 2 mm, the length of 80 mm, and the width of 20 mm. The region of length 15 mm was used for chucking to the testing machines through aluminum tabs. A fatigue crack was started from the initial notch, and extended in the direction φ as shown in Fig. 1. The angle between the molding direction and the longitudinal direction of specimens was set to be five values: $\theta = 0°$ (MD), 22.5°, 45°, 67.5°, 90° (TD).

IMP have a three-layer structure where two skin layers sandwich the core layer [10,11]. The thickness of the core layer of the present plates was about 0.15 mm, which is 15% of the plate thickness. The crack propagation behavior will be controlled by the skin layer. The fiber direction on the skin layer of injection-molded plates is nearly along the molding flow direction (MFD), and that of the core layer is perpendicular. The angle θ means the angle between the fiber direction in the skin layer and the loading axis. In the following, the angle θ is called the fiber angle.

The core layer may influence the crack propagation behavior of IMP. To evaluate its influence, specimens made of only skin layer were manufactured by thinning the 1 mm thickness to 0.4 mm from the one side of plates only for cases of MD, TD, and 45°. The layer was carefully removed by milling machines. The surface of the machined layer was polished by emery paper to eliminate damages due to machining. In the following, specimens made of skin-layer are called SLP.

Experimental values of anisotropic elastic constants of IMP and SLP are summarized in Table 1, where suffix 1 indicates the molding direction and 2 the perpendicular direction [10]. The equality of $\nu_{12}/E_1 = \nu_{21}/E_2$ is nearly satisfied for both IMP and SLP. The E_1 value is higher for SLP and the E_2 is lower, indicating SLP with higher anisotropy. The core layer of IMP reduced E_1 value and increased E_2 value. Using these values, Young's modulus E_θ for the specimen with fiber angle θ is given by [17]

$$\frac{1}{E_\theta} = \frac{\cos^4\theta}{E_1} + \frac{\sin^4\theta}{E_2} + \cos^2\theta\cdot\sin^2\theta\left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right) \tag{1}$$

Table 2 shows the calculated results. Specimens made of only the matrix resin PPS were also made from the injection-molded plate with thickness 1 mm. They are isotropic having Young's modulus of 4.45 GPa and Poisson's ratio of 0.368.

2.2. Fatigue crack propagation tests

Fatigue crack propagation tests were performed with a tension–compression electro-servo-hydraulic testing machine. Fatigue testing was done in air at room temperature under load-controlled conditions with the stress ratio R of 0.1 and 0.5 for IMP, and 0.1 for SLP. The waveform of the cyclic load was triangular and the frequency was between 2.5 and 8 Hz to maintain a strain rate at around 1%/s. No measurable temperature increase was observed near the crack by an infrared radiation thermometer in all the present experiments [10,11]. PPS is brittle at room temperature [18,19] and there was no frequency effect on crack propagation [11]. This shows a good contrast to ductile thermoplastics such as polyamide [2,18,20], polycarbonate [4], and polypropylene [8]. In these materials, a considerable crack-tip heating due to viscoelasticity was reported and the frequency influences fatigue crack propagation.

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