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Geometry effects on fracture trajectory of PMMA samples under pure mode-I loading

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A B S T R A C T

Mode-I fracture strength and crack growth trajectory of polymethylmethacrylate (PMMA) samples have been investigated experimentally and theoretically for five different cracked specimens. Although all the specimens have been tested under pure mode I loading conditions, the crack growth paths and the values of apparent fracture toughness have been found to be significantly different. The crack trajectory and the fracture strength can be estimated theoretically by using a modified form of the strain energy density criterion. The observed differences in the crack trajectory and the fracture strength of different specimens have been found to be related to the magnitude and sign of the T-stress.

1. Introduction

Brittle fracture is a major mode of failure in cracked brittle materials like PMMA. In many practical applications related to brittle materials, such as material cutting processes and hydraulic fracturing, the fracture strength is an important material property. Moreover, for applying the crack growth retardation methods an estimate of the direction of the fracture initiation and early propagation is required. Hence, the investigation of the fracture trajectory is an interesting topic for researchers involved in the field of fracture mechanics of brittle and quasi-brittle materials. Under pure mode-I loading conditions, cracks sometimes grow along curvilinear paths and not necessarily along the direction of the initial cracks [1–5]. This happens when the value of the *T*-stress is considerably high. It is possible to include the *T*-stress contribution in the fracture criteria by considering higher order terms of Williams' series expansion. Different researchers have proposed several fracture criteria based on the leading terms of series expansion governed by the stress intensity factors (SIFs) K_I and K_{II} combined with the *T*-stress. It has been shown that the consideration of *T*-stress effects provides a more reliable fracture assessment in the case of brittle materials [6–10]. Cotterell [11] considered the second, third and fourth terms of Williams' series solution and reported that the second and third terms of Williams' series control the stability of crack direction and crack propagation.

Smith et al. [7] suggested a generalized maximum tangential stress (GMTS) criterion and studied the effect of *T*-stress in mixed mode brittle fracture. It was shown that mixed mode brittle fracture is significantly influenced by *T*-stress values. As originally proposed, the GMTS criterion cannot consider the influence of *T*-stress in the case of pure mode-I loading. However, several researchers have shown that there is a considerable difference between the experimental results in terms of mode-I fracture strength, and these differences are influenced by the shape of the tested specimen [12–18]. Some previous

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Nomenclature

a	crack length
B	biaxiality ratio
dW/dV	The strain energy density function
E	axial modulus of elasticity
G	shear modulus of elasticity
h	height of cracked specimen
h_1	minor height of TDCB cracked specimen
h_2	major height of TDCB cracked specimen
K_I	mode-I stress intensity factor
K_{Ic}	mode-I fracture toughness
K_{If}	critical mode I SIF
K_{II}	mode-II stress intensity factor
K_{eff}	effective stress intensity factor
F	applied load
F_c	fracture load
r, θ	polar coordinates with the origin located at the crack tip
r_c	critical distance
S	strain energy density factor
S_{cr}	critical value of the strain energy density factor at the critical distance
t	thickness of cracked specimen
T	T-stress
W	width of cracked specimen
x, y	Cartesian coordinate components with the origin located at the crack tip
Δa	crack growth incremental length
θ_0	the angle between the initial direction and the direction of new crack growth increment
κ	elastic constant introducing the stress state in the model
$\sigma_{ij}(i,j = r,\theta,z)$	stress components
σ_t	ultimate strength
ν	Poisson's ratio
α	dimensionless form of the critical distance
ASED	average strain energy density criterion
ASTM	American society of testing materials
CT	compact tension specimen
DCB	double cantilever beam specimen
TDCB	tapered double cantilever beam specimen
GMTS	generalized maximum tangential stress criterion
GSED	generalized minimum strain energy density criterion
LEFM	linear elastic fracture mechanics
PMMA	polymethylmethacrylate
SIF	stress intensity factor

studies dealing with the crack paths and the crack growth stability by consideration of T-stress effects are presented in Ref. [19]. Lazzarin et al. proposed the Average Strain Energy Density (ASED) criterion to consider the effect of T-stress on the fatigue behavior of welded joints [20]. Ayatollahi et al. recently proposed a criterion based on the generalized minimum strain energy density (GSED) which allows taking into account the influence of the T-stress on the mixed mode I/II fracture strength of brittle and quasi-brittle materials [6].

In the present manuscript, the crack growth paths and the fracture loads for PMMA specimens of different shapes are investigated experimentally under pure mode I loading. The experimental results are then estimated theoretically using the GSED criterion. It is shown that the specimen geometry can strongly influence the mode-I fracture strength and the crack trajectory. The geometry dependency of the experimental results under pure mode-I loading is justified by considering the T-stress effects in the conventional minimum strain energy density (SED) criterion.

2. Experiments

PMMA (polymethylmethacrylate or Perspex) has been recognized by numerous researchers as a favorite material for conducting fracture experiments. The brittle type of fracture at room temperature, the convenience of machining and introducing a sharp crack and the optical transparency (which allows direct observation of fracture path) are among the advantages of PMMA in brittle fracture experiments.