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Anisotropic fracture properties and crack path prediction in glass and cellulose fiber reinforced composites

Paul O. Judt [a,*], Jan-Christoph Zarges [b], Andreas Ricoeur [a], Hans-Peter Heim [b]

[a] Institute of Mechanics, University of Kassel, 34125 Kassel, Germany
[b] Institute of Material Engineering, University of Kassel, 34125 Kassel, Germany

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ABSTRACT

Natural fiber reinforced composites exhibit beneficial features compared to conventional engineering material, e.g. a comparable strength and a reduced weight at the same time. To exploit these beneficial properties at technical structures, fracture mechanical concepts must be taken into account. The fracture behavior in composite materials is related to the interplay of crack growth in the matrix material and the reinforcements and the delamination of interfaces between the constituents. The spacial distribution and orientations of the reinforcements in general induces anisotropic elastic and fracture mechanical properties in composites. In this work, the directional crack resistance of polypropylene containing a defined amount of glass fibers or regenerated cellulose fibers is measured first. Next, various experiments at compact tension specimens with defined fiber orientations are carried out, in order to investigate the crack growth behavior. A crack deflection criterion based on the J-integral, accounting for the local anisotropy of the crack resistance, is introduced and implemented into a crack growth model. The crack tip loading quantities are calculated applying large integration contours, excluding all numerically inaccurate values at the crack tip. One major outcome of the model based investigation is a bifurcation of the solution for the crack path at pure mode-I loading, depending on the degree of anisotropy and fiber orientations. Crack growth simulations show good agreement with the experiments and are capable of predicting the basic features of deflection.

1. Introduction

In many modern engineering structures composite materials represent important ingredients. In the course of an economic and environment-friendly operation of modern vehicles, such as space- and aircrafts, vessels or automobiles, the consideration of lightweight structures is an important contribution to the reduction of fuel consumption and the optimization of transportation capabilities. The reason for the use of short, natural fiber reinforced composites with polypropylene (PP) as the matrix material in serial production, e.g. in the field of automotive parts, is a rising demand for renewable resources and the recyclability of technical components. Furthermore, such composites provide mechanical properties comparable to conventional engineering materials and thereby being of light weight.

* Corresponding author.
E-mail addresses: judt@uni-kassel.de (P.O. Judt), zarges@uni-kassel.de (J.-C. Zarges), ricoeur@uni-kassel.de (A. Ricoeur), heim@uni-kassel.de (H.-P. Heim).

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Nomenclature

a	crack length
A_G	elastic-plastic work
A_0	linear-elastic strain energy
b	specimen thickness
c_0, d_0	constants of the function approximation the flow front
C_{ijkl}	elasticity tensor
D	extruder screw diameter
G	energy release rate
L	extruder process length
J_{Ic}, J_c	critical J-integral, crack resistance
J_k	J-integral vector
n_j	normal vector of the integration contour
Q_{kj}	energy-momentum tensor
u	strain energy density
u_i	displacement vector
w	characteristic length of the CT-specimen
z_k	crack growth direction

Greek letters

α	global crack deflection angle
β	ratio of the coordinates J_2 and J_1
γ	angle describing the material orientation
Γ	integration contour
δ_{ij}	identity tensor
ϵ	material dependent coefficient
ε_{ij}	strain tensor
φ	angular coordinate
φ_c	crack deflection angle
η	geometry factor
χ	ratio of orthotropic fracture toughness or orthotropic crack resistance
σ_{ij}	stress tensor

Abbreviations

CT	compact tension
GF	glass fiber
LEFM	linear elastic fracture mechanics
NFC	natural fiber composite
MFD	melt flow direction
PD	predominant direction
PP	polypropylene
RCF	regenerated cellulose fiber
TD	transverse direction

Most natural fiber composites (NFC) used in the automobile industry, e.g. for interior parts, consist of natural plant fibers and a polyolefin matrix material, which can be processed at comparatively low temperatures and without thermal degradation of the fibers [1–6]. In addition to plant fibers, cellulosic fibers, such as man-made cellulose fibers, have been used as reinforcement in previous studies, providing an improved notched impact strength, which is about four times larger compared to conventional glass fiber reinforced composites containing the same fiber weight percentage [5–8]. Next to their lower density [9–11], cellulosic fibers have a three times larger elongation at rupture in comparison to glass fibers, resulting in a ductile and less spontaneous fracture behavior of the composites [5,7].

It is well known, that the elastic properties of composites are anisotropic, thus their elastic behavior depends on the loading direction with respect to the material orientation [12,13]. During the production of materials, processes such as rolling, drawing or extrusion, and in the specific case of composites especially the injection molding process, induce elastic anisotropic and directional fracture mechanical properties. The applied process parameters during the production play an important role regarding the resulting properties of composites, which were e.g. invested for carbon fiber reinforced composites [14], glass fiber/polyamide laminates [15] as well as glass and cellulose fiber reinforced polyamide composites [8].

The fracture behavior of composite materials is related to the effects of fiber breakage, a local delamination at the interfaces between matrix and fiber and to growing cracks in the matrix material. Therefore a complex system of interacting

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