Adiabatic decohesion in a thermoplastic craze thickening at constant or increasing rate

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Abstract

When a crack in a thermally non-diffusive material is impact loaded—or propagates at high speed—a cohesive process which resists slow crack extension may itself cause decohesion by adiabatic heating. By assuming that decohesion ultimately occurs by low-energy disentanglement within a melt layer of critical thickness, the fracture resistance of craze-forming crystalline polymers can be estimated quantitatively. Previous estimates used a simple, thermomechanically linear representation of craze fibril drawing. This paper presents a more physically realistic, numerical formulation, and demonstrates it for constant craze thickening rate (as imposed by an ideal full-notch tension test) and for linearly increasing thickening rate (as at the tip of an impact-loaded or rapidly propagating crack). For a linear material, the numerical formulation gives results which asymptotically approach those from analytical solutions, as craze density approaches zero. In more realistic model polymers, the enthalpy of fusion increasingly delays decohesion as impact speed increases, although the temperature distribution of an endotherm appears to have little effect. Increasing molecular weight, heuristically associated with decreasing craze density and increasing structural dimension, increases the predicted impact fracture resistance. In every case, fracture resistance passes through a minimum as impact speed increases. The conclusions encourage the use of impact fracture tests, and discourage the use of the full-notch tension test, to assess the dynamic fracture resistance of a craze-forming polymer.

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1. Introduction

Several non-reinforced crystalline thermoplastics, e.g. polyolefins, are exceptionally tough when loaded at moderate rates, but succumb to brittle fracture under impact—i.e. when loaded rapidly enough to exceed their static strength within about 1 s. This transition in behaviour is expressed as a rapid decline in fracture initiation resistance G_c as impact speed increases (Clutton and Channell, 1995; Channell and Clutton, 1996; Gensler et al., 2000; Rager, 2003; Yu et al., 2004) and in a rapid decline in dynamic fracture resistance G_D as crack speed increases to about 100–300 m/s (Wheel and Leevers, 1993a). There is usually a corresponding

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Nomenclature

β	thermomechanical efficiency
ΔH	enthalpy
ΔH_f	latent heat of fusion
$\dot{q}''$	planar thermomechanical heat source at active layer
$\eta, \dot{\eta}$	local thickness, opening rate of cohesive zone
Γ_v	dimensionless crack driving force
κ	bulk thermal diffusivity
λ_D, λ_F	natural draw ratio, fibril draw ratio
ρ^*	relative density of craze
ρ	mass density
σ_c	cohesive stress
Fo; Fo_{dc}	Fourier number; Fourier number at decohesion
ξ	distance from craze tip to crack tip
$a, \dot{a}$	crack length, velocity
B	specimen thickness
B_c	crack path width
c	crack-tip craze length
C, C^*	absolute, normalised load-point compliance of specimen
C_p	specific heat
E'	reduced tensile modulus
G	crack driving force
G_c	fracture initiation resistance
G_D	dynamic fracture (rapid crack propagation) resistance
h	craze fibril surface heat transfer coefficient
j	finite volume cell number
k	bulk thermal conductivity
L_0	initial finite volume cell size
M, M_{eff}	monodisperse, effective polydisperse molecular mass
N_F	number of craze fibrils per unit craze area
N_a	number of active Lauterwasser–Kramer craze surfaces
N_z	number of heat transfer directions ($1 \leqslant N_z \leqslant 2$)
q	heat exchange
s_c	critical structural dimension of material
T	temperature
T_0	initial bulk temperature
t_{dc}, t_{dc0}	decohesion time, decohesion time for zero-density craze
T_m	melting temperature
$v, \dot{v}$	load-point displacement, displacement rate
V_c	applied constant craze opening rate
W	crack path length of specimen geometry
z	coordinate normal to active surface

transition to a more brittle fracture surface. Here G_c and G_D represent, for each case, the local energy expenditure needed to overcome cohesion of the material across a unit-area plane.

These rate effects on fracture initiation and propagation are surely related, but the relationship can be established only when the underlying decohesion mechanisms are understood. Leevers (1995) proposed that in both cases the mechanism was the same: low-energy separation within a melt layer created by adiabatic heating.