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Micromechanics of the growth of a craze fibril in glassy polymers

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Abstract

The primary objective of this work is to model the growth and eventual failure of a craze fibril in a glassy polymer, starting from a primitive fibril. Experimental investigations have shown that properties like the entanglement density of a polymer play a pivotal role in determining whether macroscopic failure of a polymer occurs through crazing or shear yielding. Failure is seen to be related to the formation of a soft 'active zone' at the craze-bulk interface, through disentanglement. The present work aims at explaining some of the experimental findings about fibril growth and failure in glassy polymers on the basis of a continuum model of a craze with a constitutive model that accounts for yield, network hardening and disentanglement. The results show that this approach is capable of providing explanations for experimentally observed facts such as the propensity to crazing in polymers with low entanglement density and the linearity between the stretch in a fibril and the maximum stretch of a molecular strand in the fibril.

Keywords: Amorphous polymers; Crazing; Disentanglement

1. Introduction

A predominant fracture mechanism in polymeric materials is crazing. Crazes are planar crack-like defects, where the two faces of the craze are bridged by thin fibrils. Upon application of stress, crazes widen, leading to stretching of the bridging fibrils until eventual failure. The fibrils render the craze some stress-bearing capabilities until their breakdown leads to the formation of a crack. An understanding of the craze widening and failure processes is, therefore, important to gain insight into the mechanics of fracture in these materials.

It is instructive at this stage to look at successive idealisations of the craze structure as depicted by Estevez et al. [12]. Fig. 1(a) is a schematic of a craze as an interconnected structure of voids and polymer fibrils. Though the load-carrying capacity of the craze stems mainly from the 'primary' fibrils oriented normal to the craze plane, it is now known that the cross-tie fibrils also bear some amount of load (see, Ref. [9]). For our purpose, however, the cross-tie fibrils are ignored and the craze is idealised as being bridged by a number of cylindrical fibrils, Fig. 1(b). These fibrils again are of two types: primitive fibrils close to the craze tip and much thinner, mature fibrils spanning the rest of the craze. A further abstraction of the craze structure involves 'lumping' the three-dimensional physical picture of Fig. 1(b) into a so-called 'cohesive zone' (or cohesive surface) governed by a constitutive law between the craze opening Δ_n and the normal traction σ_n acting on its faces. This idea, as shown in Fig. 1(c), was used by Estevez et al. [12] in the form of a cohesive zone model for crazing under Mode I, plane strain conditions. The success of such a model depends solely on the ability of the assumed traction-separation law to mimic the actual physical response of a craze to the same normal tractions.

Much of our current understanding of this physical response is born out of detailed experimental investigations into craze growth and failure done by Kramer and co-workers (e.g. Refs. [10,15]). Particularly striking among their findings is the fact that the volume fraction v_f of the mature fibrils remains constant over the length of the craze (i.e. in the x_1-direction in Fig. 1) at all cross-sections along the fibrils (i.e. for all values of x_2), except at the midriff ($x_2 \simeq 0$), where the stretch in the fibril is found to be significantly larger. It follows therefore that, under the

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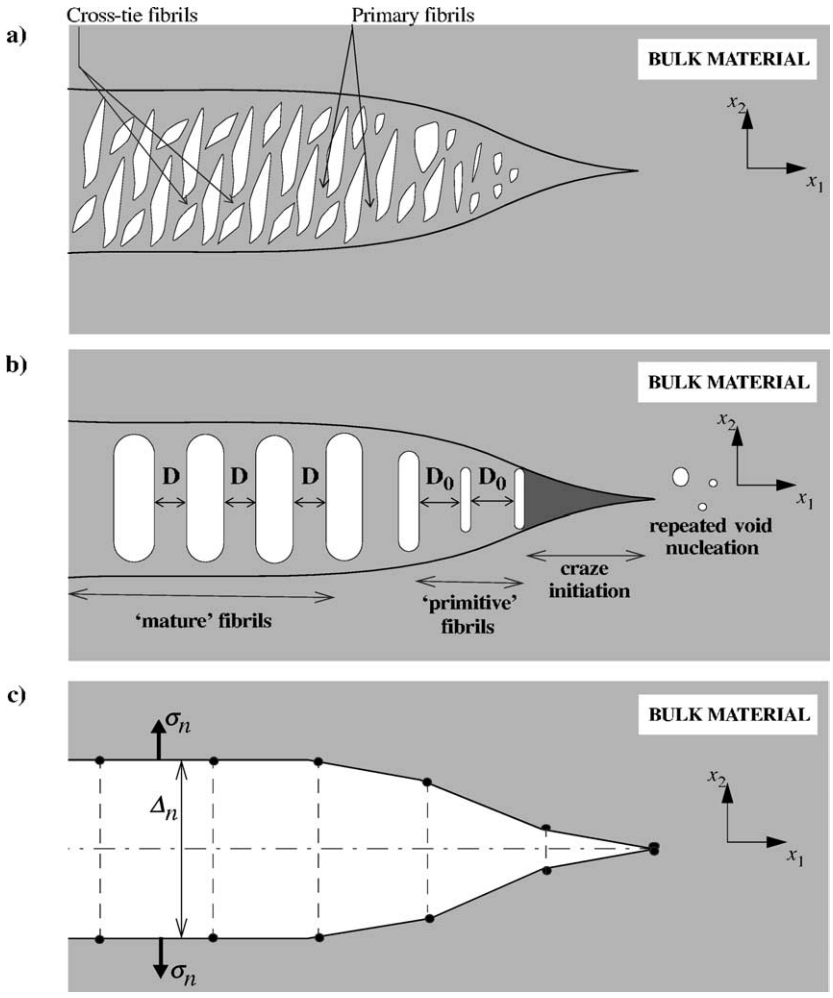

Fig. 1. Schematic representation of (a) a real craze, (b) the idealisation of a craze according to Kramer and Berger [15] and (c) as discrete cohesive surfaces.

assumption of incompressibility, the local stretch $\lambda = 1/v_f$ is also a constant. At any point on a fibril, along the x_2 direction, the fibril diameter can be expressed as $D = D_0\lambda^{-1/2}$ in terms of the diameter D_0 of a primitive fibril and hence, D is a constant as well. The value of λ has been inferred from optical measurements of v_f by Donald and Kramer [11] along a craze fibril (i.e. in the x_2-direction in Fig. 1) and was found to be almost the same all along the length, except at the midriff where it is generally significantly larger. The stretch λ, measured either at the midriff or elsewhere over the fibril length, is in turn found to be directly proportional to the maximum stretch λ_{max} of a molecular strand between entanglements. Moreover, since λ_{max} is an indicator of the entanglement density of the material, these findings suggest that increasing the entanglement density is a viable way of craze suppression. Indeed, it is found that materials with low entanglement density are more prone to crazing than ones with high entanglement density (see, Ref. [14]).

The quantity λ_{max} also appears in constitutive models for elastoviscoplasticity of glassy polymers, which according to Ref. [13] can be idealized as a network of entangled long molecules embedded in the flowing continuum. At large strains, the network stretches considerably, leading to a rather steep hardening regime. The hardening continues till a limit stretch is reached, beyond which the material 'locks' in the sense that it no longer deforms plastically. The material becomes almost rigid after locking and therefore it's stiffness is arbitrarily increased to five times that at zero strain. The mechanical response of the network is governed by two parameters: the density of molecular strands between entanglements, n, and the number of statistical segments N making up each strand. Their product, nN, represents the number of monomers in a unit volume of the material. The maximum stretch that a strand can undergo according to standard non-Gaussian description is then given by $\lambda_{max} = \sqrt{N}$. A continuum model of this type has been used by Tijssens and Van der Giessen [21] to study the widening of a craze, but it did not pick up the remarkable correlation between the fibril stretch and λ_{max} mentioned above.

The objective of this paper is to improve on this and build a more physically realistic continuum description of the widening and failure mechanisms of a craze fibril in a amorphous glassy polymer. With this model in place, we compute the overall response of a craze subject to an