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ANISOTROPIC FRACTURE OF A HOT-STRETCHED ACRYLIC THERMOPLASTIC

Keith Williams*

INTRODUCTION

Biaxially hot-stretched acrylic plastics were developed for use as aircraft glazing material to overcome the crazing and fracture problems encountered during the early 1950's in cast acrylic transparencies. The stretched plastics offered increased resistance to crazing and crack propagation [1]. The almost exclusive use of these plastics for both the canopies of military aircraft and the cabin windows of airliners has virtually eliminated castastrophic failures. There is, however, one problem encountered in airliner cabin windows which demands the continued attention of airline service engineers [2]. After a period in service cracks initiated at the edge of the window propagate in the plane of the window, Figure 1. Not only are these defects unsightly but the cracked window has reduced bending stiffness and must be replaced. This type of failure resembles the delamination of a laminated windscreen but in fact takes place along the stretch plane of a monolithic material.

This investigation is intended to elucidate the various modes of crack propagation in the stretched material, and, particularly, environmental effects on the growth of in plane cracks. The work presented in this paper covers the initial stages of the investigation.

MATERIAL SPECIFICATION

Materials intended for use in aircraft transparencies must comply with U. S. military specifications MIL-P-8184, for cast materials and MIL-P-25690, for hot stretched material. These specifications give limits of performance covering mechanical and optical properties and their environmental degradation rather than specific compositions and manufacturing procedures.

One of the major mechanical requirements of MIL-P-25690 is a minimum fracture toughness of 2.5 MPa $m^{1/2}$ for specimens of the type and orientation shown in Figure 2. This toughness is greater than that, of cast acrylics, 1.6 MPa $m^{1/2}$. Though this fracture toughness test fulfills a useful quality control function it cannot be used in a predictive manner as the cracks encountered in service are not of this orientation.

The materials used in this investigation were from two sources; 3 mm sheet supplied to MIL-P-25690 for the manufacture of laminated aircraft windscreens and 9 mm sheet taken from airliner windows removed after some time in service.

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* Faculty of Technology, Open University, Milton Keynes, England, U.K.

VARIATION OF FRACTURE BEHAVIOUR WITH CRACK ORIENTATION

There are three simple crack orientations, Figure 3:

1. Orientation 1, through thickness crack, as specified in MIL-P-25690, with the crack plane perpendicular to the stretch plane and crack front also perpendicular to the stretch plane, Figure 3a.

2. Orientation 2, the crack plane perpendicular to the stretch plane and the crack front parallel to the stretch plane, Figure 3b.

3. Orientation 3, the crack plane parallel to the stretch plane, Figure 3c.

Tests have been carried out on single edge-notched specimens in each of these orientations. Specimens of orientation 3 were prepared by bonding the sheet of stretched material between two strips of Perspex, Figure 4. The specimens were then ground smooth and notched; the notch was first cut with a jeweller's saw and sharpened with a scalpel blade.

The stress intensity at the onset of fast fracture for each of the three orientations is listed in Table 1. The difference in K values is reflected in the different fracture behaviour shown by each orientation.

Orientation 1

A typical fracture produced from this orientation can be divided into two zones; an initial deeply ridged region of slow crack growth, which gives way to a less ridged fast fracture which covers the majority of the surface. In each region the ridges lie parallel to the direction of crack growth. This overall appearance has been previously reported [3]. Scanning electron micrographs of these regions show that the ridges in the slow growth region are separated by deep fissures, Figure 5, whereas those in the fast fracture region are simply surface steps, Figure 6. The planar areas between the steps show fine river markings and surface tears. Whilst these features are clearly visible on specimens tested at a crosshead displacement of 1 mm per min an increase in crosshead speed to 100 mm per min produces a surface devoid of ridges but with a specular appearance rather than the smooth glassy appearance of a cast acrylic.

Orientation 2

The first observation that must be made is that the fracture does not lie perpendicular to the tensile axis but at an angle of 50° - 60° to it. The fracture surface has a terraced appearance, Figure 7, with the lines of terracing parallel to the crack front. The vertical steps of the terracing lie along the tensile axis, hence the vertical faces lie parallel to the stretch plane of the material.

Close examination of the fracture at the tip of the starting crack reveals quite extensive cracking parallel to the tensile axis, Figure 8. Observation during testing shows that this cracking occurs prior to fast fracture, Figure 9.

Orientation 3

This orientation produces fractures which are similar in appearance to those found in cast acrylics and other glassy polymers, Figure 10, having smooth glassy surfaces, river markings and what are probably Wallner lines. Scanning electron microscopy revealed no unusual features.

DISCUSSION

The stretched plastic shows a distinct anisotropy in its fracture behaviour with orientations 1 and 2 being markedly tougher than orientation 3. The toughness of similar case acrylics, 1.6 MPa $m^{1/2}$ lies between that of the tough orientations and the brittle orientation. It is well established that the tensile strength of stretched plastics perpendicular to the stretch directions is considerably less than the strength along these directions [4]. One possible explanation for this difference in strength could be the presence of weak interfaces between strong structural blocks of material, i.e., that a biaxially stretched plastic can be considered as a lamellar composite. It has been shown [5] that the mode of crack propagation in such composites is dependent on the relative strengths of the lamellae and the interfaces.

This supposition is supported by both the stress intensities required for crack growth and the morphology of the fracture surfaces. Cracks in orientation 3 grew at the lowest stress intensity and produced smooth, largely featureless, fracture surfaces. Viewed in isolation such surfaces could be taken as being typical of virtually any brittle amorphous polymer with the extent of river lines, Wallner lines and featureless regions dependent on the crack velocity [6, 7, 8]. However when viewed alongside the features produced in orientations 1 and 2 they have a greater significance. The major morphological feature of these orientations is the presence of linear markings on the fracture surface. In orientation 1 these correspond with the direction of crack growth [3], and so could be regarded as particularly prominent river lines, but Figure 6 shows them to be distinct steps; the vertical face of the step lying in the stretch plane of the material. In orientation 2 the linear markings, Figure 7, lie perpendicular to the direction of crack growth, once again the vertical faces of the steps lie parallel to the stretch plane of the material. It is proposed that these two features are produced by crack branching along the planes of easy crack growth followed in orientation 3.

In orientation 1, adopting the normal convention for the stress field at a crack tip, the stretch plane is subjected to the tensile stress σ_{zz}. From Figure 5, it appears that a large number of stretch plane cracks are formed and some of these grow during slow crack growth forming deep fissures. Following the transition to fast fracture deep fissures are no longer formed. One consequence of the formation of stretch plane cracks is that a much larger surface area is associated with crack growth than in an isotropic truly amorphous material. Also a difference in surface energy between cracks of this orientation and orientation 3 has been previously reported [9] and is a likely contributing factor to its higher toughness.

Crack orientation 2 complies fairly closely with the Cook-Gordon model [5], the weak interfaces being subject to σ_{xx}. Failure of the interface ahead of a growing crack results in either crack arrest or an increase in the energy required for crack growth. In this material it appears that initially crack arrest occurs, as is shown by the slow growth of a stretch plane crack symmetrically from the starter crack. Continued loading results in fast fracture from the end of one arm of this. This fracture takes place in a stepped fashion with the crack alternately following the stretch plane and the plane of the starter crack, producing the characteristic terraced appearance.

Further evidence of the importance of stretch plane cracks in this material is provided by the observation that crazes terminate by branching into the stretch plane.

One of the most interesting features of these observations is the role played by the slow growth of stretch plane cracks. Subcritical crack growth in amorphous polymers has been extensively studied [9, 10], and can be accounted for by both environmental and relaxation effects. Subcritical crack growth of stretch plane cracks is currently being investigated by the author using the double torsion specimen geometry [11, 12]. It is interesting to note that cracks corresponding to orientation 3 propagate in a stable manner with no change in geometry whereas those corresponding to orientation 1 propagate in an unstable manner and are arrested by deviation into the stretch plane. In view of airline experience with this material it is thought that the effect of liquids such as water might be particularly important. In cast acrylics the introduction of water can arrest a growing crack by inducing extensive crazing at the crack tip. Its effect on a material with such marked anisotropy might well be very different.

The propensity for stretch plane cracking has both positive and negative effects on the performance of stretched acrylic aircraft windows. The crack and craze diverting mechanisms reduce the risk of in-flight and impact failures but introduce the new problem of slow stretch plane growth.

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Table 1

	K_I at onset of fast fracture MPa $.m^{\frac{1}{2}}$
Orientation 1.	4.47 ± .20
Orientation 2.	3.10 ± .37
Orientation 3.	0.66 ± .17

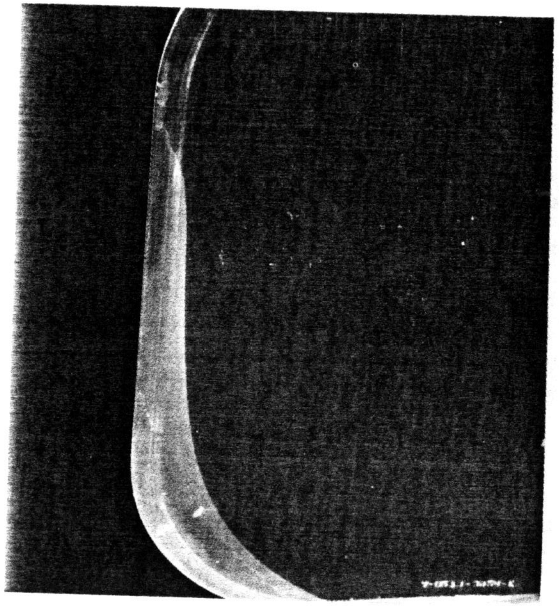


Figure 1 In Plane Cracking in an Airliner Cabin Window. Window Size Approximately 385 mm x 285 mm

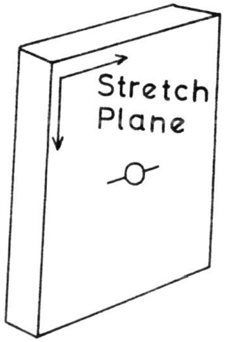
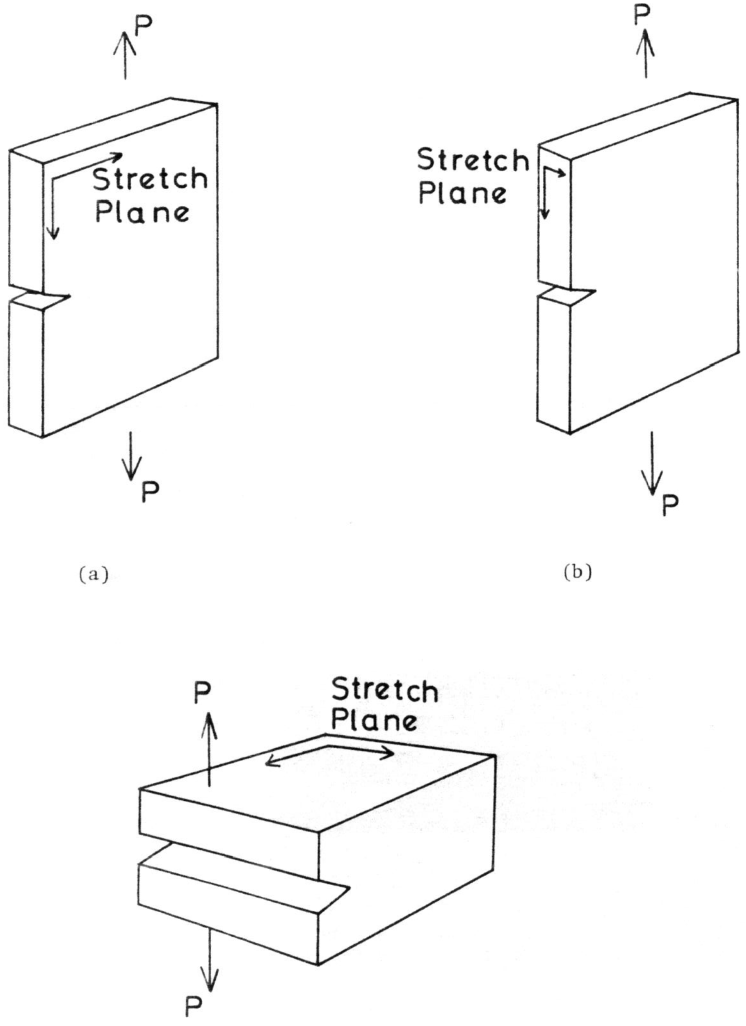


Figure 2 The Specimen Geometry Specified for the Fracture Toughness Test in MIL-P-25690



(a)

(b)

(c)

Figure 3 Crack Orientation with respect to the Stretch Plane

(a) Orientation 1
(b) Orientation 2
(c) Orientation 3

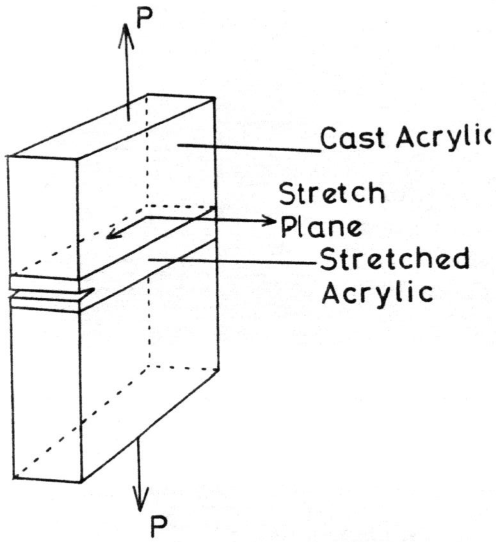


Figure 4 Configuration of Test Specimens Used for Tests in Orientation 3

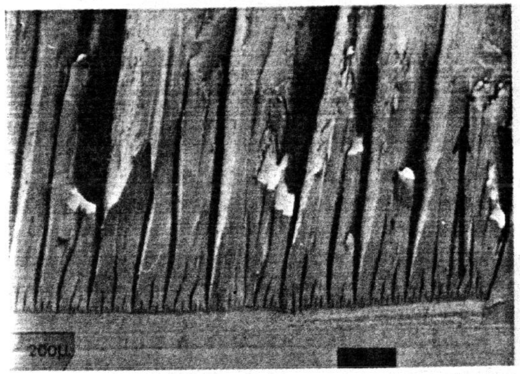


Figure 5 Orientation 1. Scanning Electron Micrograph of the Region of Slow Crack Growth Immediately Adjacent to the Starting Crack. The Arrow Indicates the Crack Growth Direction

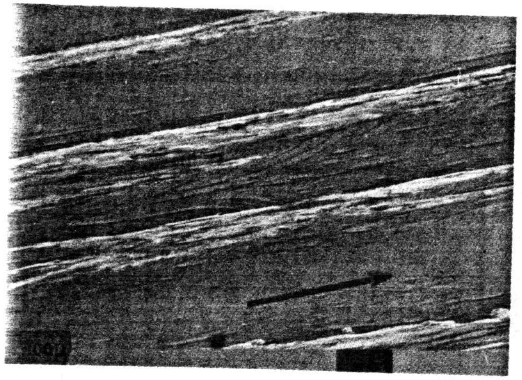


Figure 6 Orientation 1. Scanning Electron Micrograph of the Region of Rapid Crack Growth. Note the Steps in the Surface Lying Parallel to the Direction of Crack Growth (Arrow)

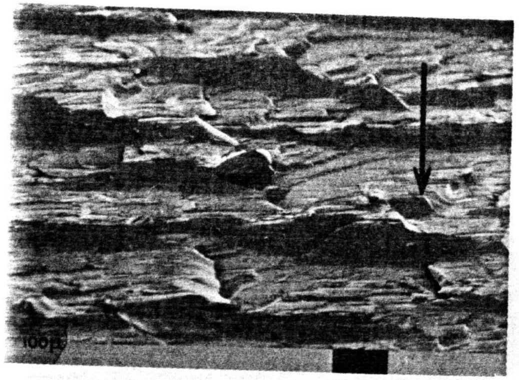


Figure 7 Orientation 2. Scanning Electron Micrograph of the Terraced Fracture Surface. The Terraces Lie Perpendicular to the Crack Growth Direction (Arrow)

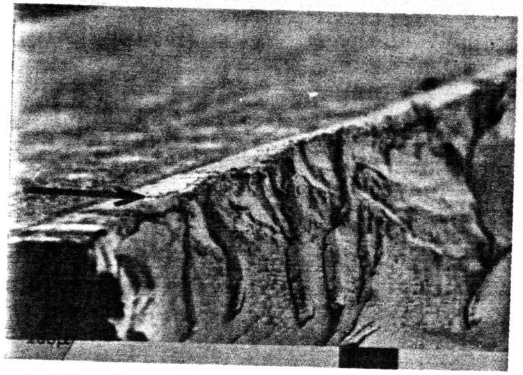


Figure 8 Orientation 2. Scanning Electron Micrograph of the Region Adjacent to the Starting Crack, there is Extensive Cracking Parallel to the Tensile Axis and Perpendicular to the Crack Growth Direction (Arrow)

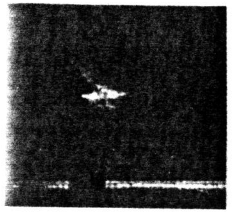


Figure 9 Orientation 2. Cracking Parallel to the Tensile Axis at the Crack Tip Prior to the Onset of Fast Fracture

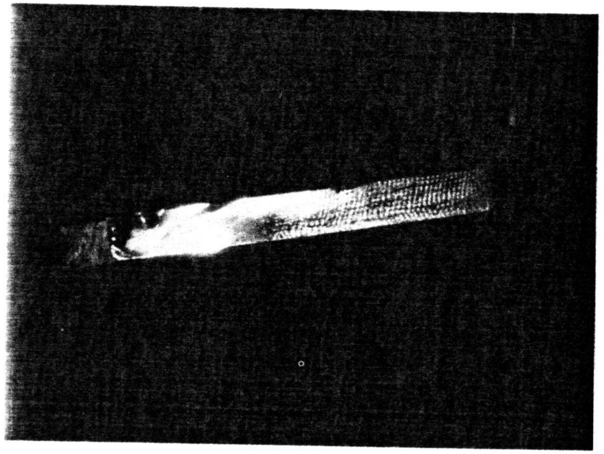


Figure 10 Orientation 3. Optical Micrograph of the Fracture Surface. Specimen Dimensions 20 mm x 3 mm