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Loading rate effects in the mode II fracture of carbon fibre poly-ether-ether-ketone composites

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Traditionally, many high performance composite structures, such as those used in the aerospace sector, have been based on carbon fibres in an epoxy matrix. Although such systems exhibit extremely high strength and stiffness properties, they are prone to delaminate extensively when subjected to localized impact loading [1–4]. This somewhat poor impact resistance of epoxy-based composites has been improved considerably following the introduction of toughened systems containing either an elastomeric or thermoplastic dispersed phase [5, 6]. One other possibility to improve the impact resistance of such materials is to use a tough thermoplastic as the matrix material. A typical example is poly-ether-ether-ketone (PEEK). Extensive testing [7–11] has shown that the mode I and mode II interlaminar fracture toughnesses of carbon fibre PEEK are up to an order of magnitude greater than that of traditional thermosetting-based composites. All of this work was conducted at very low loading rates, typically several millimetres per minute. Very little work, however, has been undertaken at deformation rates approaching those encountered during impact loading. Smiley [12] conducted a series of high rate mode I double cantilever beam (DCB) tests on PEEK-based and epoxy-based carbon fibre composites. His results indicated that the mode I fracture toughness of these materials dropped dramatically at high rates of loading. Aliyu and Daniel [13] observed an increase in the mode I strain energy release rate for a brittle carbon fibre reinforced epoxy composite. More recent tests [14] on a toughened carbon fibre epoxy showed a reduction in toughness with increasing crack velocity. Béguelin *et al.* [15] conducted DCB tests on AS4/PEEK and observed a slight reduction in G_{Ic} at high rates of loading. Few workers have attempted to characterize the mode II fracture toughness characteristics of composite materials at high rates of strain. This is little surprising since Masters [16] showed that G_{IIc} is a fundamental parameter in determining the impact resistance of a composite laminate. His work showed that the mode II fracture toughness determined at quasi-static rates of loading could be related directly to the compression after impact properties of the composite. Chapman *et al.* [17] showed that the mode II fracture toughness of carbon fibre composites based on an epoxy resin and PEEK dropped dramatically even at intermediate rates. This is clearly alarming and suggests that the excellent fracture characteristics exhibited by tough thermoplastic-based systems may be lost even at moderately high rates of strain.

The work presented here examines the rate-dependence of the mode II fracture toughness of AS4 carbon fibre reinforced PEEK. Unidirectional samples having a nominal thickness of 3 mm were compression moulded according to the manufacturer's recommendations. End notch flexure (ENF) specimens having a width of 15 mm were cut from the panels using a diamond slitting wheel. Testing at rates of 0.1, 1.0, 10 and 1000 mm min^{-1} was conducted on a screw-driven Instron 1122 testing machine. Since the response time of the load cell was not considered to be sufficient for the tests at 100 and 1000 mm min^{-1}, a piezo-electric load cell connected to a UPM60 high speed data logger was used. Impact testing was conducted on an instrumented drop-weight tower. Here, load was measured using the aforementioned load cell and data logger, and displacement using an optical extensometer system consisting of an optical fibre positioned on the carriage and a transducer located directly behind it. A thin piece of rubber was placed at the impact location to reduce ringing effects in the load cell. Unless otherwise indicated, the specimens were shear pre-cracked by mode II loading. Frictional effects between the upper and lower crack surfaces were minimized by placing a 100 μm thick piece of Teflon film close to the crack tip. This was found to be extremely important since failing to do so resulted in measured values of G_{IIc} some 33% higher than in cases where the Teflon was included. The specimens were supported on 6 mm cylinders placed 100 mm apart. The overall specimen length was taken as 120 mm in order to avoid dynamic effects associated with the overhanging regions at high rates of loading.

The mode II strain energy release rate was calculated according to the beam theory compliance method [18], where:

$$G_{IIc} = \frac{9P^2a^2}{16B^2Eh^3}$$

where h is the specimen half thickness, B the specimen width, a the initial crack length and P the applied force (in this case the maximum force). The elastic modulus, E, was measured on an unnotched specimen at the appropriate strain rate.

The flexural tests on the unnotched samples indicated that the elastic modulus of the AS4/PEEK was constant at approximately 130 GPa over the entire range of rates examined. The applicability of the high rate mode II test technique was then verified by determining the elastic modulus of the ENF samples from the specimen compliance C, where:

$$E = \frac{2L^3 + 3a^3}{8CBh^3}$$

The variation of the calculated flexural modulus with loading rate for the same specimen is shown in Fig. 1. It is clear that, as expected, E does not vary with rate. In this case the values of E are slightly lower than those determined on the unnotched samples. The fact that the data are self-consistent suggests that the high rate test set-up is reliable and that spurious dynamic effects were not present. This conclusion was further supported by the fact that the load–displacement curves were very similar at all rates of loading.

The variation of G_{IIc} with loading rate is shown in Fig. 2. At the very lowest rate the average strain energy release rate was aproximately $1600\,J\,m^{-2}$. Increasing the loading rate resulted in a small but steady increase in G_{IIc} until a plateau value of approximately $2000\,J\,m^{-2}$ was reached at 100 mm min^{-1}. These results are particularly interesting since they are contrary to what one might intuitively expect. A scanning electron microscopy (SEM) study of the fracture surface of specimens tested at the lowest rate highlighted large amounts of plastic deformation in the matrix. Nevertheless, a large number of the fibres were bare. This is apparent in the micrograph of the crack initiation region shown in Fig. 3a. A close examination of the fracture surface shows that a large number of fibres have little or no matrix on them. At higher rates significantly greater quantities of matrix were in evidence on the fracture surface, as shown in Fig. 3b. An examination of the regions where the crack propagated dynamically, i.e. at very high velocities, indicated that the crack propagated entirely within the thermoplastic matrix, there being no fibres in evidence. It appears, therefore, that the locus of crack propagation changes with increasing loading rate. The reasons for this are not clear at present. It is possible that the strength of the fibre–matrix interface is itself rate-dependent, being stronger at higher rates of loading. Tensile tests on 90° samples did indeed highlight a distinct rate-dependent behaviour. In the ENF specimen, however, the interface was subjected to a mode II form of loading. Unfortunately, there is very little information available in the literature concerning strain rate effects under this form of loading. Clearly, further work is required in order to resolve this matter. The evidence obtained from the SEM micrographs suggests, however, that the full potential of the tough thermoplastic matrix is not realized at very low rates of loading.

The influence of starter defect on the mode II strain energy release rate is shown in Fig. 4. For clarity, only the average values are shown. Here, the values of G_{IIc} obtained by undertaking the mode II test directly from the 25 μm thick aluminium starter

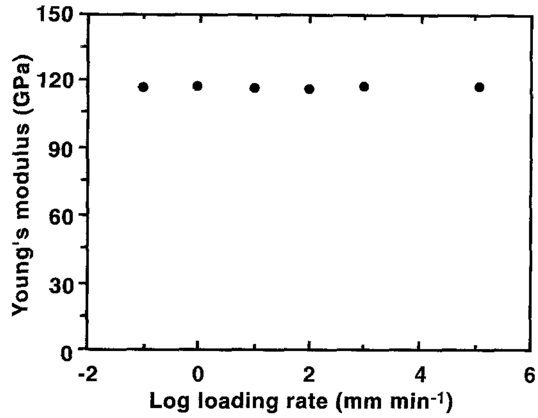

Figure 1 The influence of loading rate on the Young's modulus of AS4/PEEK

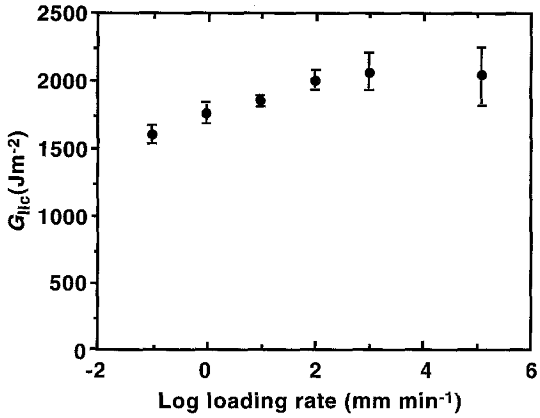

Figure 2 The influence of loading rate on the GIIc of AS4/PEEK

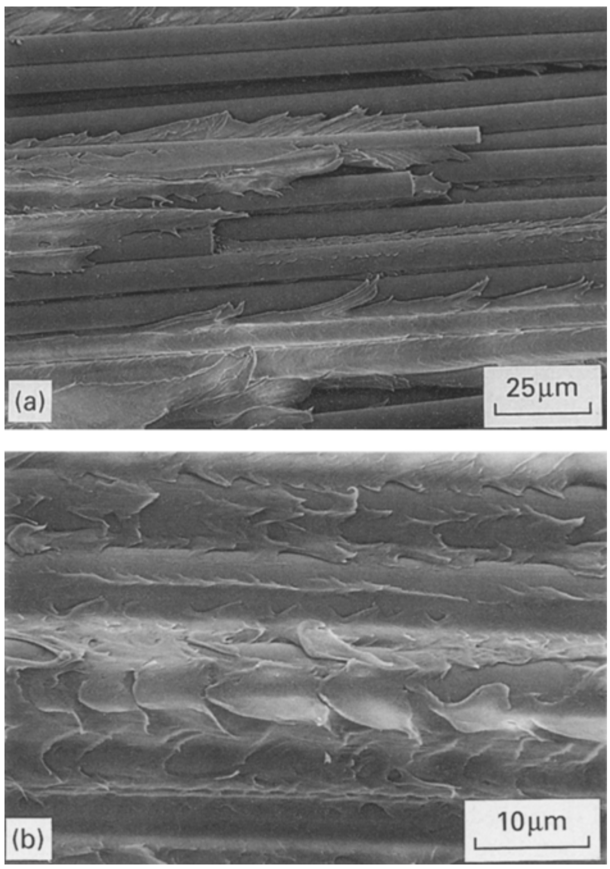

Figure 3 Scanning electron micrographs showing the mode II fracture surface of AS4/PEEK tested at (a) 0.1 mm/min (b) 100 mm/min.

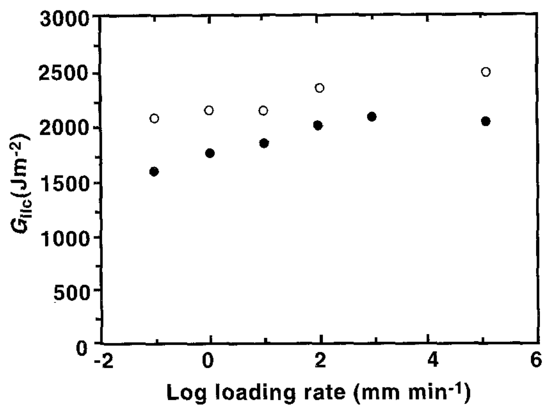

Figure 4 The influence of starter defect on the GIIc of AS4/PEEK. (○), from film; (●), shear pre-crack.

film were compared with those obtained from a mode II pre-crack. Clearly, the presence of the aluminium film has a considerable effect on the measured values of G_{IIc}. This has been observed elsewhere [19] and has been attributed to the presence of a resin-rich area directly in front of the defect. It is interesting to note that these samples also exhibited a slight rate-dependency.

Engineering structures based on composite materials are rarely unidirectional in nature but contain plies orientated at widely differing angles. Previous work [20, 21] has shown that the interlaminar fracture energy at such a ply interface may be significantly different to that associated with an interface between parallel plies. This difference in response is probably associated with fibre bridging, which frequently occurs in unidirectional composites. In this study a number of ENF tests were conducted on samples in which the two centremost plies were offset by four or five degrees. Although this offset angle is comparatively small, it is sufficient to effectively prevent fibre bridging occurring. Fig. 5 compares the rate-dependent fracture characteristics of the modified ENF specimens with the standard unidirectional samples. Once again, an initial increase in G_{IIc} with rate is apparent, followed by a plateau. It is particularly interesting to note that the modified ENF specimen exhibits an even greater rate-sensitive behaviour at the lower loading speeds. Indeed, the value of G_{IIc} at 0.1 mm min^{-1} was some 40% lower than the plateau value. Clearly, the presence of fibre bridging has quite a significant effect on the fracture properties of this material. The fact that the mode II fracture toughness of this material drops off very rapidly at low rates of loading represents a cause for concern. Long-term mode II tests are presently under way to see if this loss in properties is even greater at very long times.

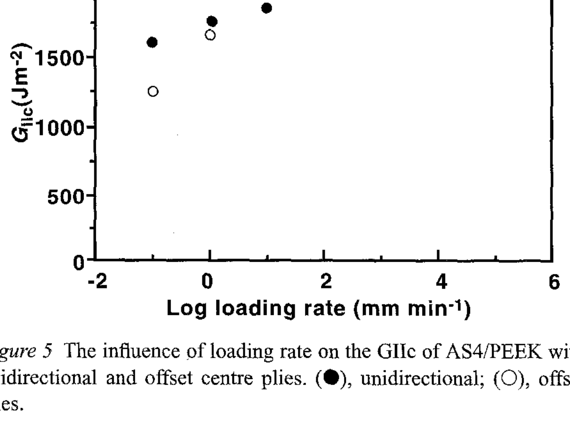

Figure 5 The influence of loading rate on the GIIc of AS4/PEEK with unidirectional and offset centre plies. (●), unidirectional; (○), offset plies.

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