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Crack propagation in notched wood specimens with different grain orientations

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Summary. The cracking patterns of load induced cracks were studied by in-situ testing of compact tension specimens within the specimen chamber of a scanning electron microscrope. The cracks propagated in a generally straight path parallel to the grain, regardless of the orientation of the notch. On a microscopic scale, the crack could not be described as an ideal parallel-walled crack as assumed in fracture mechanics models. Many irregularities such as tortuosities, branching, discontinuities and bridging between the crack walls could be seen. Observations were carried out at the tip of the stable crack and at the same zone after the crack was induced to propagate beyond it. The processes taking place in this zone are discussed. The implication of these observations on the applicability of linear elastic fracture mechanics to wood are also discussed.

Introduction

The concepts of fracture mechanics were first applied to wood by Atack et al. (1961); since then, there has been an increasing interest in using fracture mechanics to characterize the failure of wood under load. In particular, a number of researchers have suggested that linear elastic fracture mechancis (LEFM) can be used for this purpose. Porter (1964) proposed that wood fracture obeys a Griffith-Irwin relationship, with weak regions in the wood acting as intrinsic flaws. Much subsequent work (e.g. Leicester 1974; Schniewind, Pozniak 1971; Schniewind, Lyon 1973; Schniewind, Centeno 1973; Johnson 1973; Mindess, Nadeau, Barrett 1975; Mindess 1977) was devoted to determining fracture mechanics parameters for a variety of woods, and for different grain orientations. More recently, Triboulet, Jodin and Pluvinage (1984), employing finite element calculations, have shown that at least some of the assumptions underlying the use of LEFM for wood, namely the assumptions of plane strain, and of orthotropic and linear elastic behaviour, may be considered to be valid.

However, less attention has been given to the microstructural details of the physical processes that take place during crack propagation in wood. The scanning

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electron microscope (SEM) observations that have been reported in this area (e.g. Debaise 1972; Debaise, Porter, Pentoney 1966; Coté, Hanna 1983; Kučera, Bariska 1982) have generally involved first the fracture of the specimens, followed by sawing the specimens to the required size, drying and coating them, and finally inserting them into the SEM. These sample preparation techniques, in particular the strong drying required, may obscure some of the morphological details of the fracture surface. The object of the present work was to study the nature of load-induced cracks in wood specimens by in-situ testing of compact tension specimens of Douglas-fir, loaded directly within the specimen chamber of an SEM.

Experimental

Compact tension specimens with a sawn notch were prepared and loaded within the specimen chamber of an SEM by a special testing rig which was developed for this purpose, shown in Fig. 1 a. Loading was carried out by moving a 6° wedge with the aid of a motor driven screw, whose rate could be controlled externally. The specimens were loaded symmetrically on both sides. The pins, which extend all the way through the specimen, had diameters of about 3 mm. A small load cell placed against the other end of the specimen was connected externally to a recorder, and the load induced in the specimen during the different stages of loading could be continuously recorded.

The specimen dimensions were 24 mm × 32 mm × 10 mm, with a 13 mm deep sawn notch. They were sawn from air dried Douglas fir at three different grain orientations, with the grain at 0°, 45°, and 90° to the sawn notch, as shown schematically in Figure 1 b. The sawn specimens were vacuum dried for 48 hours and sputter coated with a 300 Å layer of Gold-Palladium. The testing was carried out in an SEM equipped with an environmental cell and a Robinson backscattered electron detector. The pressure in the environmental cell was controlled at 0.2 Torr. The specimens were observed carefully before loading; no drying shrinkage cracks could be seen.

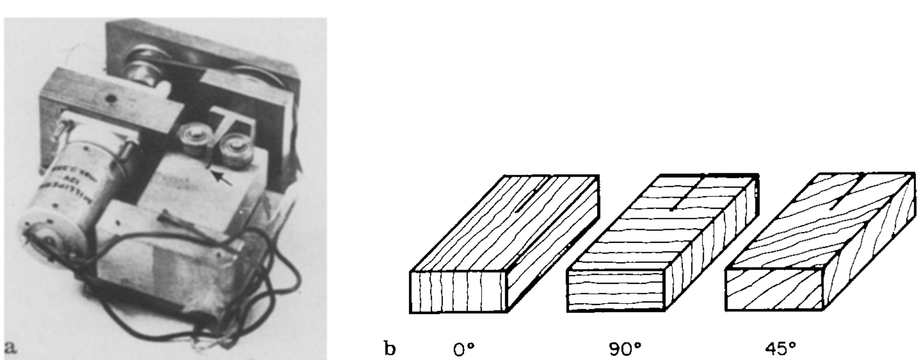

Fig. 1. a The loading rig with a compact tension specimen. The arrow marks the tip of the notch. **b** Schematic representation of the grain orientation with respect to the sawn notch

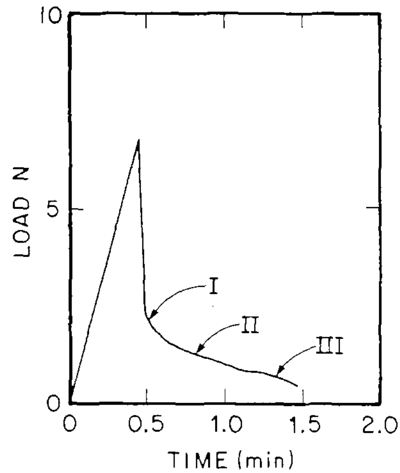

Fig. 2. A typical load – time curve

In the specimens with the grain perpendicular to the notch, the load crack propagated instantaneously to the edges of the specimen. When the grain was parallel to the notch or at 45° to it, stable crack growth could be obtained. A typical load vs. time curve is shown in Fig. 2. The crack was first observed at the peak load, and it extended almost instantaneously for a distance of about 10 mm. At this stage, loading was halted and observations were carried out (first stage of loading – Fig. 2). Loading was then resumed, and the crack propagated further, beyond its previous tip. Loading was again discontinued, and observations were carried out at the second and third stages of loading (Fig. 2). In these cases special attention was given to the zone of the crack tip when it stabilized, and to the same zone after the crack was induced to propagate beyond it.

Observations

The load cracks induced in the various specimens tended to run in a generally straight path, parallel to the fibers. Along the cracks, some irregularities could be observed, and the cracks could not be described as being simple, parallel-sided cracks. The nature of these irregularities was the same, regardless of the orientation of the grain with respect to the notch.

Specimens with the grain perpendicular to the notch

A crack induced in a specimen with fibers perpendicular to the notch is presented in Fig. 3. The point marked "O" represents the origin of the crack, at the upper left hand corner of the sawn notch which is shown at higher magnification in Fig. 4a. The crack propagated at 90° to the direction of the sawn notch, all the way to the edge of the specimen. The propagating crack took off immediately to the left, and it can be seen that the crack walls were not perpendicular to the specimen's surface. The inclined wall surface exposed is seen at higher magnification in Fig. 4b,

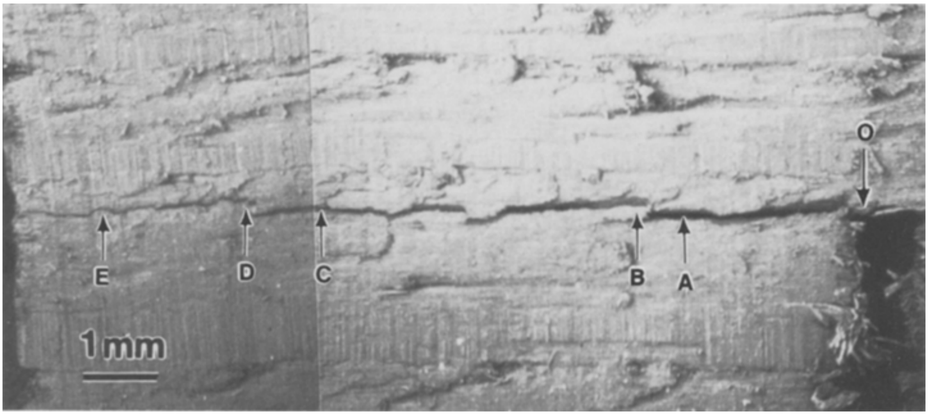

Fig. 3. Crack induced in the first stage of loading in a specimen with the grain perpendicular to the notch. The point marked "O" represents the origin of the crack, at the upper left hand corner of the sawn notch shown at higher magnification in Fig. 4a

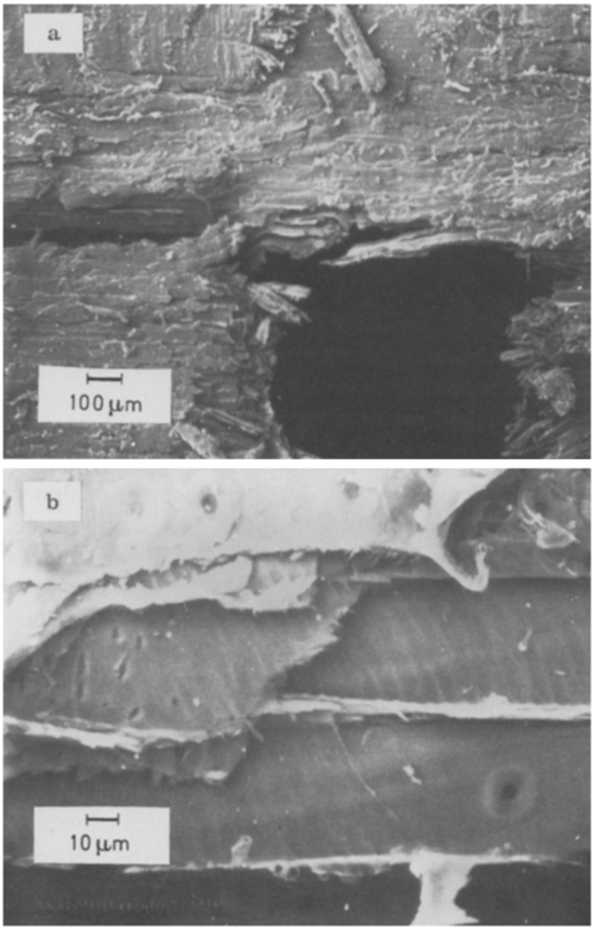

Fig. 4. **a** Higher magnification of the crack at the tip of the notch in Fig. 3. **b** Region in which the wall is inclined, on the upper side of the crack wall shown in **a**

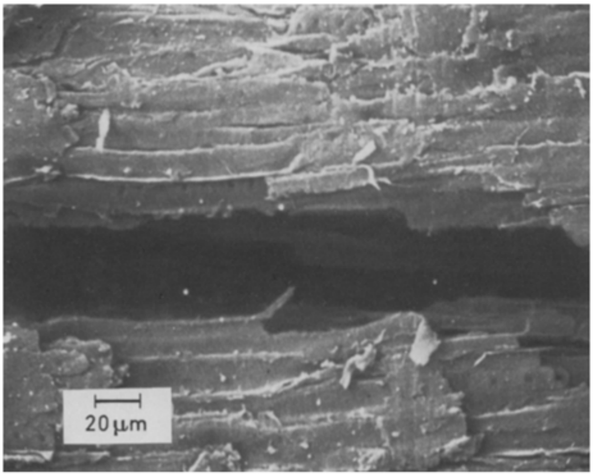

Fig. 5. Higher magnification of zone A in Fig. 3, showing a crack segment with walls perpendicular to the surface

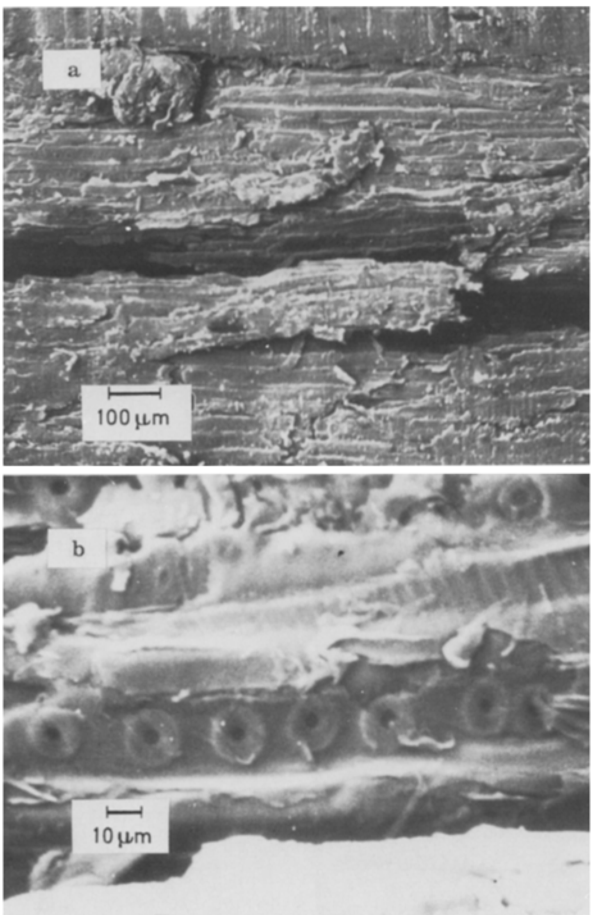

Fig. 6. a Higher magnification of zone B in Fig. 3, showing branching. **b** Higher magnification of the upper side of the crack in **a,** showing the inclined plane

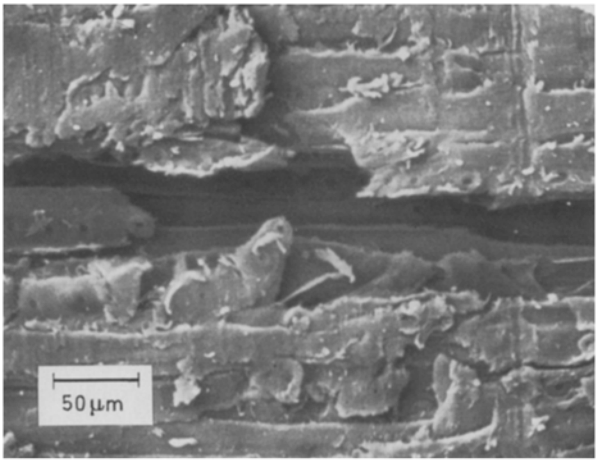

Fig. 7. Higher magnification of zone C in Fig. 3, showing tortuosity

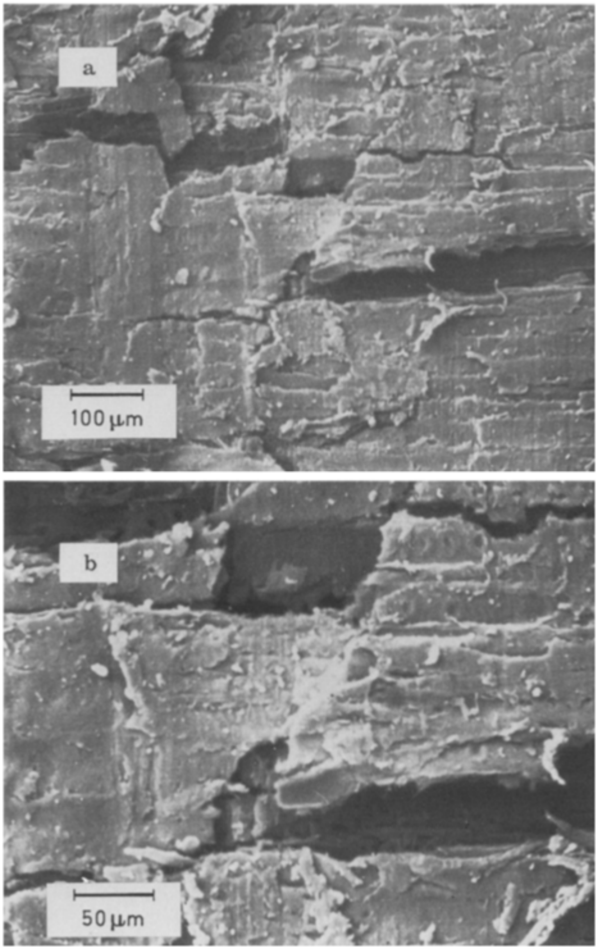

Fig. 8 a and **b.** Higher magnifications of zone D in Fig. 3, showing discontinuity and microcracking

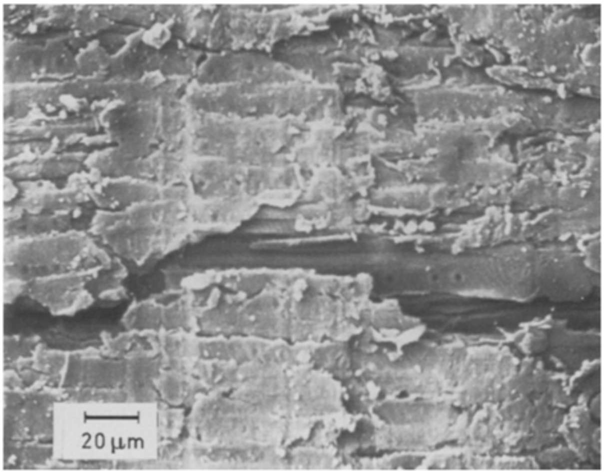

Fig. 9. Higher magnification of zone E in Fig. 3, showing tortuosity

revealing a single ray cell. The inclined nature of the crack surface is probably the result of the orientation of the growth ring. Since the path of least resistance usually lies in the L–T plane, if it is inclined to the surface, so will be the crack.

In some zones along the crack path (Fig. 5; zone A in Fig. 3) the crack walls were perpendicular, as is expected in "ideal" crack separation.

Some of the irregularities along the crack path in Fig. 3 are marked B to E, and are shown at higher magnifications in Figs. 6–9. They can be classified as tortuosities (Figs. 7, 9), branching (Fig. 6), and discontinuities (Fig. 8). In all of these instances, the crack wall was inclined, and was not perpendicular to the surface. Observations at higher magnifications of these inclined planes revealed rows of ray cells which are best seen in Fig. 6 b. In some cases, a few microcracks could be observed around the irregularities in the crack path, as seen in Fig. 8 b.

Specimens with fibers at 45° to the notch

A typical crack path observed after the first stage of loading is shown in Fig. 10. Tortuosities and discontinuities can clearly be seen even at this low magnification. They were similar in nature to those described above. The zone of the crack tip at the first stage of loading is shown at higher magnifications in Figs. 11 a and c, in which the arrows mark the apparent crack tip. The crack in this zone is discontinuous. The same zone is shown in Figs. 11 b and d at the second stage of loading after the crack was induced to propagate further. The arrow points to the apparent crack tip at the first stage of loading. The extension of the crack did not take place through the previous crack tip; instead, the crack took off at point A behind the crack tip, resulting in formation of a branch (or an inactivated crack segment) between point A and the previous crack tip.

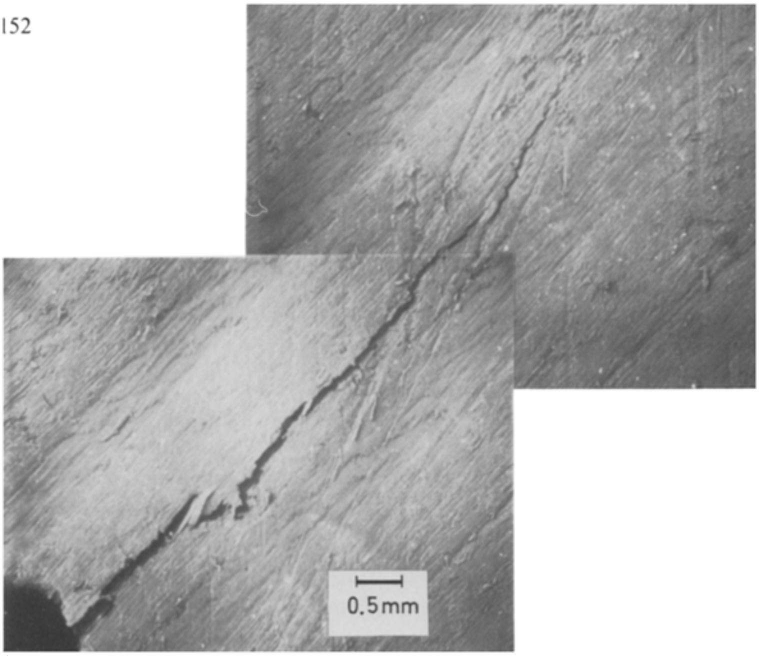

Fig. 10. Crack induced in the first stage of loading in a specimen with the grain at 45° to the notch

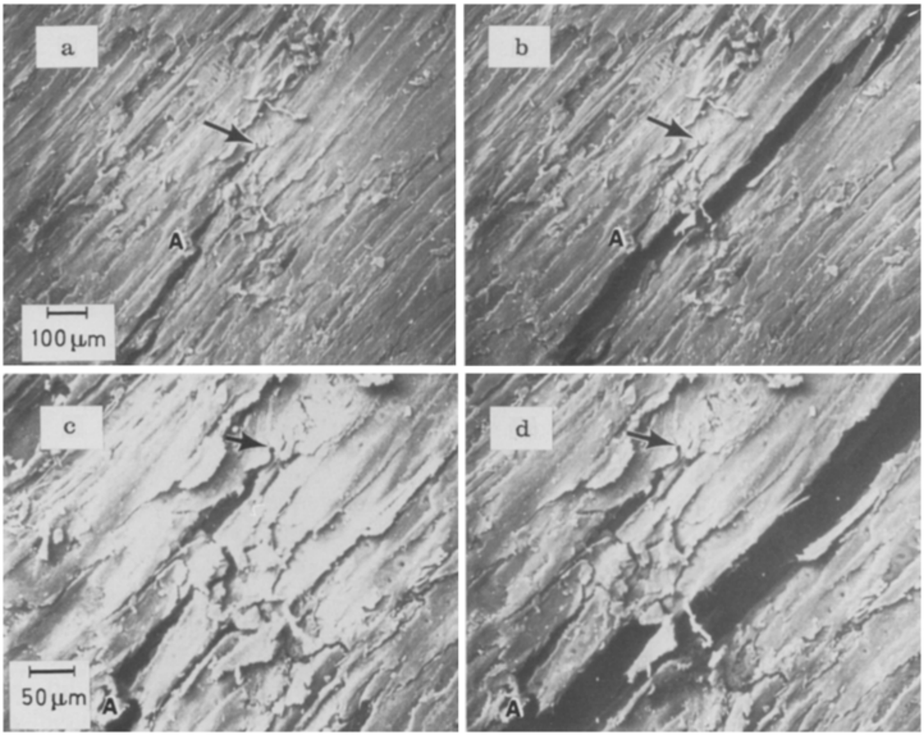

Fig. 11. a The zone of the crack tip in Fig. 11 at the first stage of loading; **b** and **d** the same zone at the second stage of loading after the crack was induced to propagate beyond it

Specimens with fibers parallel to the notch

A typical crack path observed after the first stage of loading is shown in Fig. 12. Tortuosities and branching can also be observed here, and they are similar to those described in the previous section.

Some typical processes taking place at the crack tip are presented in Figs. 13, 14 which show the region around the stabilized crack tip at the first stage of loading and the same zone at the second stage of loading, after the crack had extended beyond it. The branching and discontinuities produced in this zone when the crack was induced to propagate beyond it are clearly apparent in Figs. 13 b, 14 b. In some cases considerable multiple cracking was produced, as seen in Fig. 13 b, while in others the extent of microcracking was more limited (Fig. 14 b). In most of the specimens studied in this work, the extension of the crack beyond the stabilized crack tip zone was associated with formation of irregularities like the ones observed in Figs. 11, 13, 14.

Discussion and conclusions

As expected, the crack always propagated in a generally straight path, parallel to the direction of the grain, regardless of the orientation of the notch. On the

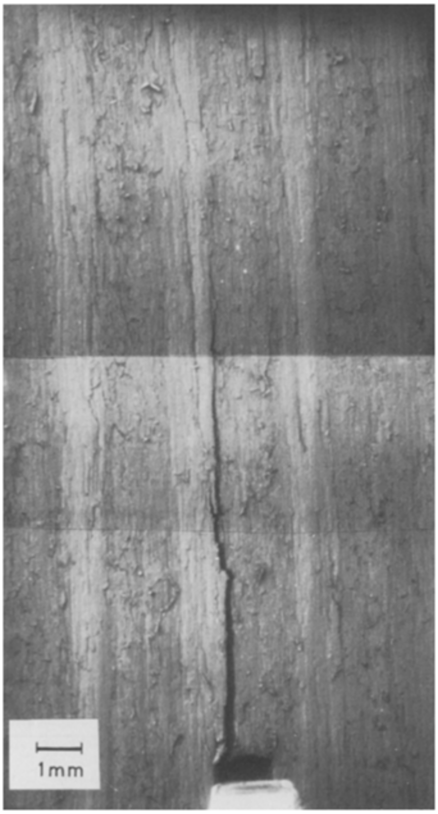

Fig. 12. Crack induced in the first stage of loading in a specimen with the grain parallel to the notch

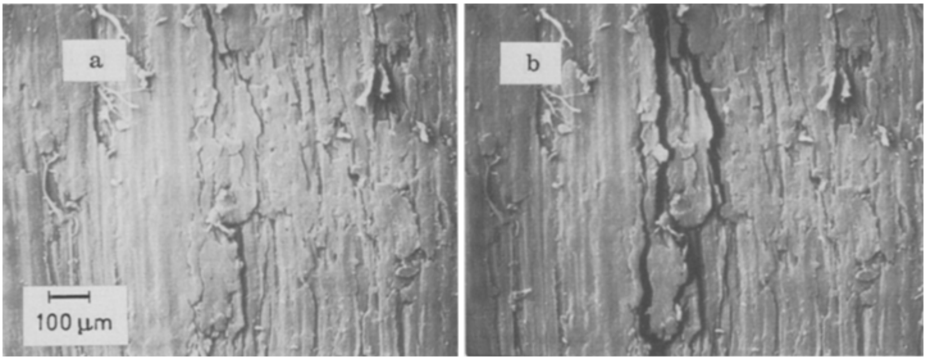

Fig. 13. **a** Zone of the crack tip at the first stage of loading, and **b** the same zone at the second stage of loading after the crack was induced to propagate beyond it, showing the formation of extensive microcracking

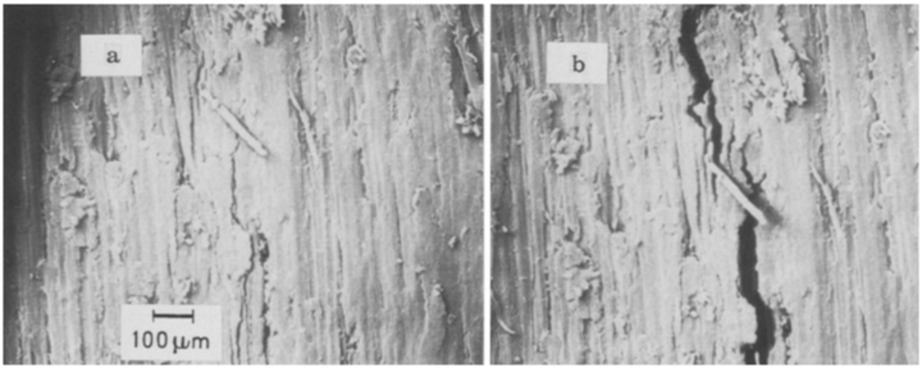

Fig. 14. **a** Zone of crack tip at the first stage of loading, and **b** the same zone at the second stage of loading, after the crack was induced to propagate beyond it, showing the formation of a discontinuity

microscopic level, however, the crack can not be described as an ideal straight, parallel-sided crack. Its path was characterized by various irregularities such as tortuosities, branching, bridging and discontinuities, and in some regions of the crack, its walls were inclined.

Some of the complexities of the cracking process could be resolved when observing the zone of the crack tip as the crack became stable, and after it was induced to propagate beyond it. It is evident that at this stage, irregularities in the crack path are generated, since the crack at its tip zone seldom propagated straight ahead. These irregularities showed up as a branch whose edge was the previous inactivated crack tip, microcracking and discontinuities. This behavior may imply that the stable crack tip is arrested at a zone of high toughness and in order to propagate further, the crack prefers the path of least resistance which bypasses this tough zone.

These characteristics of the crack morphology suggest that the cracking process can not be simply described as an extension of straight parallel wall crack, and therefore fracture mechanics and especially LEFM should be applied with some caution to this material. In particular, the various irregularities and discontinuities described above, and the microcracking, all involve energy-dissipative processes which should be considered when carrying out fracture mechanics calculations.

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