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Characterization of load-induced cracks in balsa wood

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The nature of load-induced cracks in balsa wood was studied by *in situ* testing of compact tension specimens within the specimen chamber of a scanning electron microscope. The cracks propagated in a generally straight path parallel to the grain, but they could not be described as parallel-sided cracks as assumed in fracture mechanics modelling. Frequently, wood cells were seen to bridge the crack walls, suggesting that the cracks cannot be considered as traction-free. The propagation of the cracks was associated with splitting within the cell walls, and fracture perpendicular to the cell walls could sometimes be seen.

1. Introduction

The mechanical properties of wood have been investigated intensively. Of particular interest are the relationships between these properties and the microstructure of wood, which is quite complex and anisotropic. Our understanding of these relationships can be enhanced by studies of the changes which take place on the microscopic level while the material is loaded to failure.

Many studies (e.g. [1–7]) have dealt with the microstructural changes taking place during loading in compression and tension. These have been based on scanning electron microscopy (SEM) observations. In most studies, the specimens were loaded outside the SEM chamber, but in one case [3], *in situ* compressive testing was carried out using a special loading rig that could be placed in the SEM chamber. The results of these tests have resolved some failure mechanisms, which are associated with effects such as slippage of microfibrils, buckling of cell walls and intracellular fracture within the different parts of the cell walls.

The object of the present work was to study microscopically the nature of a propagating crack induced in a compact tension specimen, in order to resolve some of the failure process taking place during crack extension. The experimental work was based on *in situ* testing of compact tension specimens loaded within the SEM specimen chamber. It is believed that tests using this technique can clarify some of those aspects of the cracking mechanisms which might be overlooked in the more conventional test method, in which the specimen is loaded outside the microscope and is then unloaded, sawn and treated for SEM observation.

2. Experimental details

Compact tension specimens, each with a sawn notch, were prepared and loaded within the specimen chamber of an SEM using a special testing rig which was developed for this purpose (Fig. 1a). Loading was carried out by moving a wedge with the aid of a motor-driven screw whose rate could be controlled externally. 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 notch. The specimens were cut so that their grain orientation was parallel to the sawn notch, as shown in Fig. 1b.

The specimens were prepared from air-dried balsa wood which was sawn to the appropriate size. The upper layer of the specimen was peeled off with the aid of a sharp razor blade, so that the microstructural features could be clearly observed in the SEM. The specimens were then vacuum-dried for 48 h and sputter coated with a 30 nm layer of gold–palladium. The testing was carried out in an SEM equipped with an environmental cell and a Robinson backscattered electron detector which permits reasonably good resolution even when the pressure in the cell is about 0.5 torr. The pressure in the environmental cell was controlled at 0.2 torr. The specimens were observed carefully before loading, and no shrinkage cracks could be seen.

A typical load against time curve is shown in Fig. 2. The crack was first seen to propagate when the peak load was reached. The crack propagated essentially instantaneously for about 10 mm and then became stable. The movement of the wedge was halted at this time, and detailed observations of the crack path and its tip were carried out (first stage of loading, Fig. 2). After the desired micrographs were obtained at this initial stage of loading, the loading was resumed,

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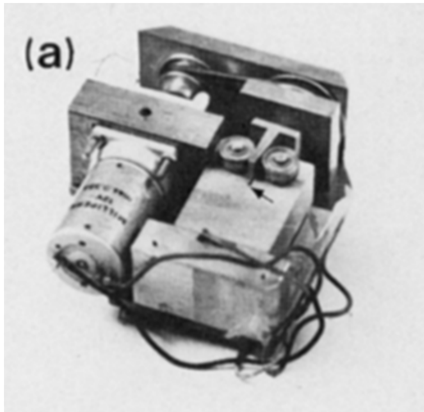


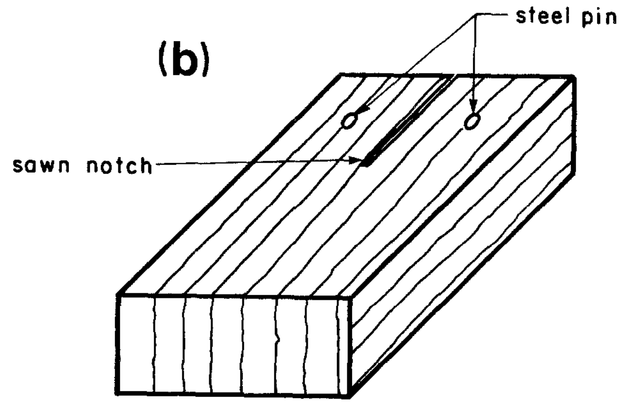


Figure 1 (a) The loading rig with a compact tension specimen. The arrow marks the tip of the notch. (b) Schematic sketch of the compact tension specimen, showing the grain orientation.

resulting in widening and progressive extension of the crack. This was stopped after arbitrary extensions of the wedge, and second, third and fourth rounds of observations were carried out. These stages of loading are marked in Fig. 2 as I, II, III and IV respectively. Special attention was given to the crack tip when it stabilized at each stage, and to the same zone after the crack was induced to propagate beyond it on subsequent loading.

3. Observations

The load-induced crack always propagated in a generally straight path parallel to the grain. However, along the crack and at its tip, many irregularities could be observed. In the present section, a detailed description of the crack patterns in three of the specimens tested will be given. The irregularities along the crack path in these specimens were typical, and occurred also in other specimens not documented in this paper. It should be noted that, in an SEM study such as this, one is inevitably confined to an examination of only the *surface* of the specimens. Thus, there is always the possibility that the features observed are confined to the top few layers of cells; they may be unrepresentative of the body of the material.

Further, in the course of preparing the specimens for observation in the SEM, which involved both peeling off their upper surfaces with a razor blade and subsequent vacuum drying, some damage to the specimens must have occurred (such damage to the structure is shown for instance in Fig. 8b below). Therefore, the possible occurrence of artefacts must be considered. However, while some disturbance of the specimen surfaces was often noted in the SEM, cracks as such did not appear before loading; they became visible only after loading of the specimens, and are thus considered here to be a part of the failure process rather than artefacts due to sample preparation.

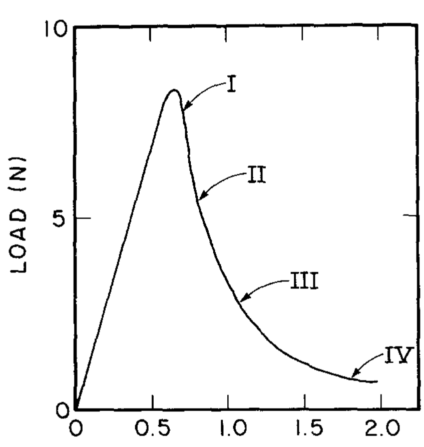


Figure 2 A typical load–time curve, showing the four different stages of loading (I, II, III, IV) at which observations were carried out.

3.1. Specimen A

The crack after the first stage of loading is shown in Fig. 3. It is about 0.5 mm wide at its origin (where it leaves the sawn notch) and narrows down as it

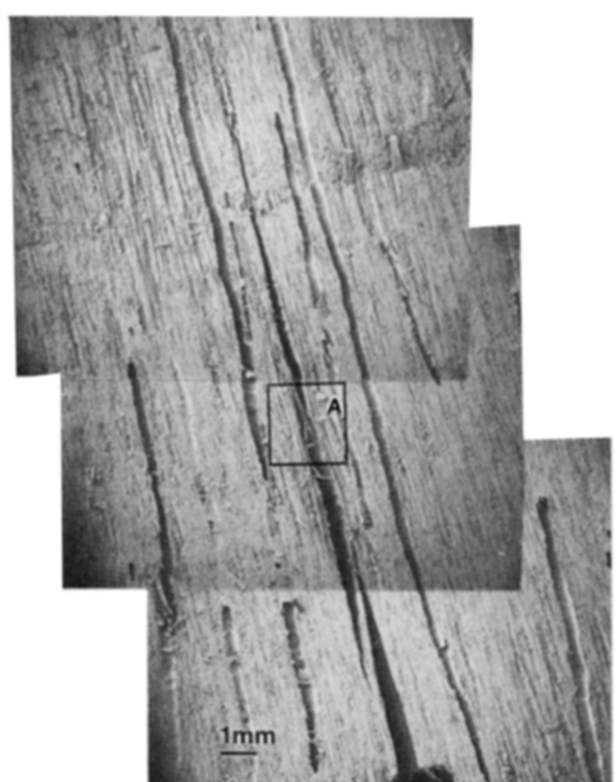
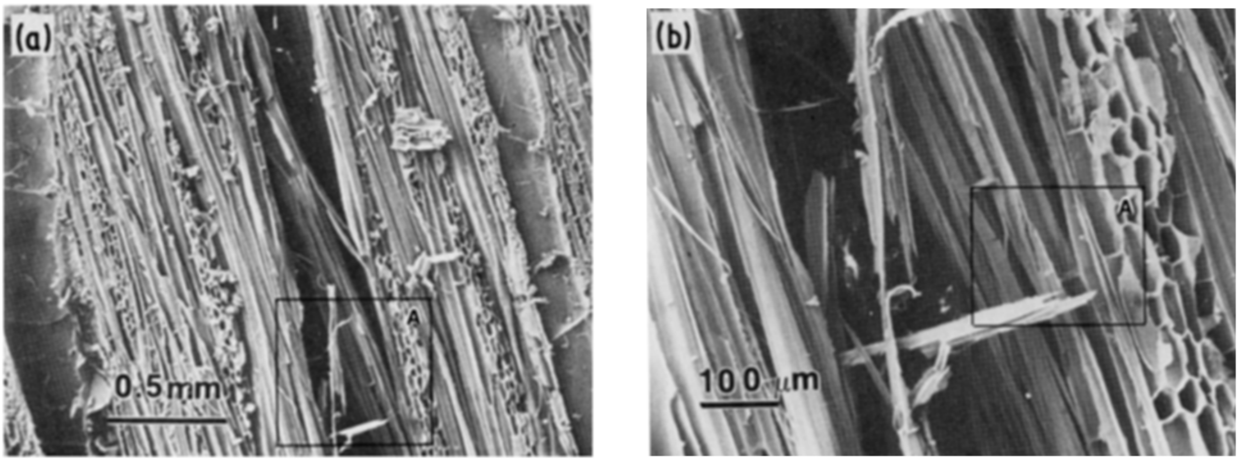


Figure 3 The crack induced in the first stage of loading of Specimen A.



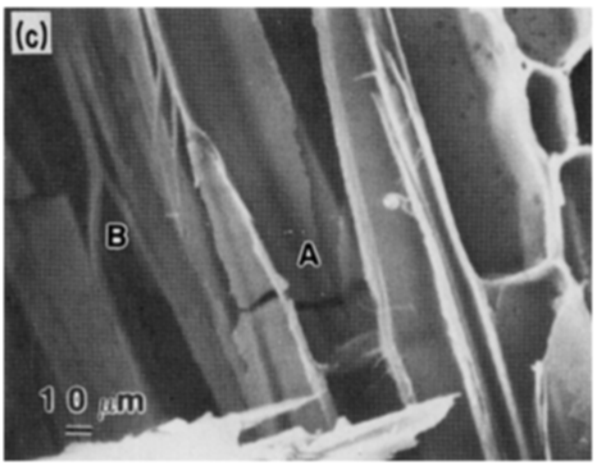


Figure 4 (a, b) Higher magnifications of Zone A in Fig. 3. (c) Still higher magnification of Zone A, showing crack of cell wall (A) and splitting within cell wall (B).

approaches its tip, about 15 mm ahead of tne sawn notch. It may be seen that the crack is not continuous; it is bridged at two locations along its path. The root of such a bridge is shown at higher magnification in Fig. 4. In this zone, the crack seems to be associated with splitting within the planes of the cells walls (Figs. 4a and b). Higher magnifications indicate additional types of damage, associated with rupture of the cell perpendicular to its axis (Zone A in Fig. 4c). The intrawall splitting is shown in greater detail in Zone B in Fig. 4c. Higher magnification of the region around the tip of the stablized crack shows separation within the cell walls around the apparent crack tip (arrow in Fig. 5a). Additional damage can be observed ahead of the crack tip, which also shows up as splitting of the cell wall (Fig. 5b).

It should be noted that at the relatively low magnifications used in this study, it often appears that the

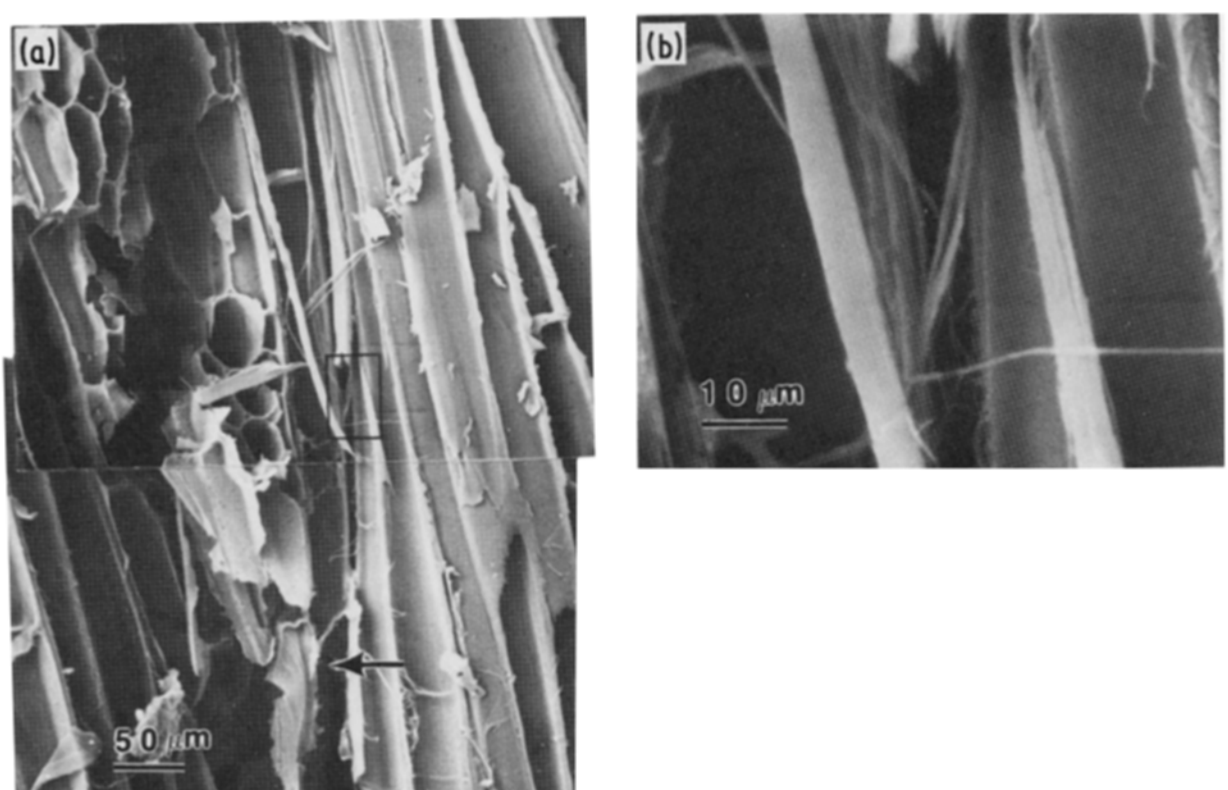


Figure 5 (a) The zone of the crack tip shown in Fig. 3. (b) Higher magnification of a zone in front of the crack tip in (a), showing splitting of a cell wall.

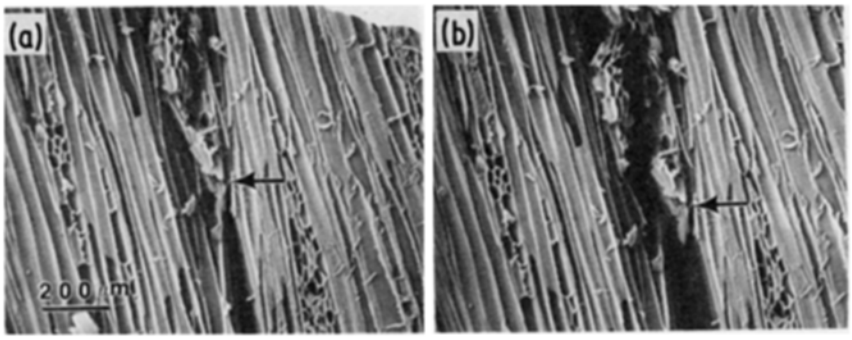


Figure 6 (a) The zone of the crack tip in Fig. 3 at the first stage of loading; and (b) the same zone at the second stage of loading, after the crack was induced to propagate beyond it.

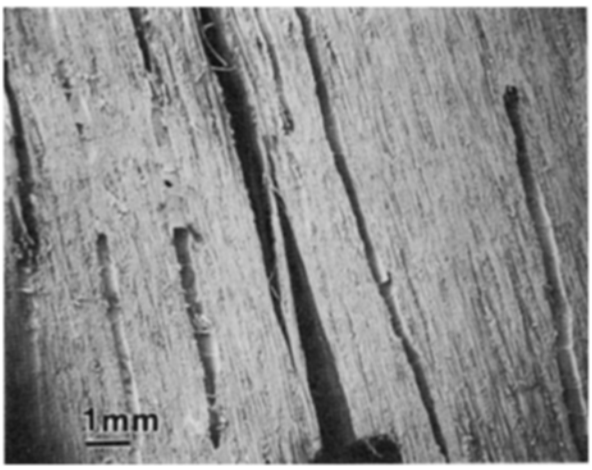


Figure 7 The zone of the crack near the notch at the second stage of loading, showing bridging.

splitting occurs between adjacent cells. However, as has been shown by Mark [6], failure is most likely to occur within the plane of the cell wall between the S_1 and S_2 layers; Dinwoodie [5] has suggested that failure may also occur within the S_1 layer. This may be seen at higher magnifications; however, for most of the micrographs presented here the resolution is not high enough to show these details.

In Fig. 6 the zone of the crack tip at the first stage of loading is compared with the same zone at the second stage of loading, after the crack was induced to propagate beyond the original crack tip. In the first stage it seemed as if the crack tip was oriented slightly to the right of an array of ray cells which were located slightly to the front and left of the crack tip (Figs. 5a and 6a). However, on additional loading the crack propagated slightly to the left, through the ray cells, and not through the previous crack tip (arrow in Fig. 6b), which became inactive and remained to the right of the main crack path (Fig. 6b). Even at this stage of loading the bridging near the notch tip remained effective (Fig. 7), as the crack widened from about 0.3 to 0.6 mm.

3.2. Specimen B

The crack after the first stage of loading is shown in Fig. 8. Near its tip, it seemed to run parallel to a "vessel" (Fig. 8b). In this case too, the crack was discontinuous with two zones of bridging. On additional loading the crack continued to propagate parallel to the vessel (Fig. 9a) but its tip may be seen to have deviated into the vessel (Fig. 9b). At the third stage of loading the crack crossed to the other side of the vessel and continued to propagate on this side, and parallel to it, for about 4 mm (Fig. 10).

3.3. Specimen C

At the first stage of loading the crack had propagated into a vessel where it seemed to terminate (Figs. 11a and b). Discontinuity and bridging along the crack path could be seen. The discontinuity seemed to be associated with splitting within the cell walls between adjacent cells, but at higher magnification fracture of cell walls could also be observed (Fig. 11c). On additional loading the crack extended further to cross the vessel (Fig. 12a). The extended crack was also discontinuous. Higher magnification of the crack tip (Fig. 12b) showed some damage in the form of thinner, discontinuous microcracks ahead of the crack tip.

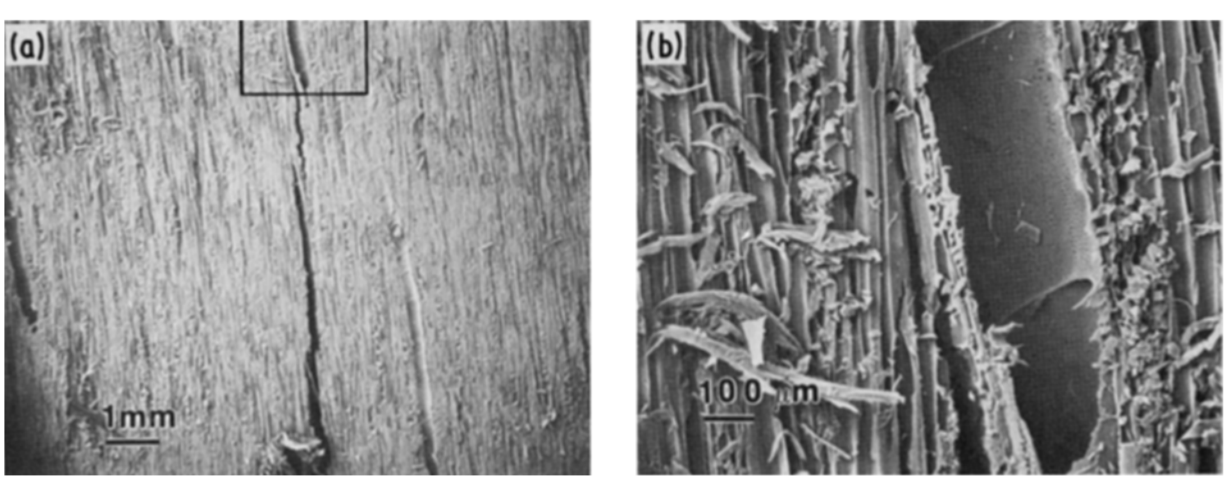


Figure 8 (a) The crack induced at the first stage of loading of Specimen B, and (b) higher magnification of the crack tip.

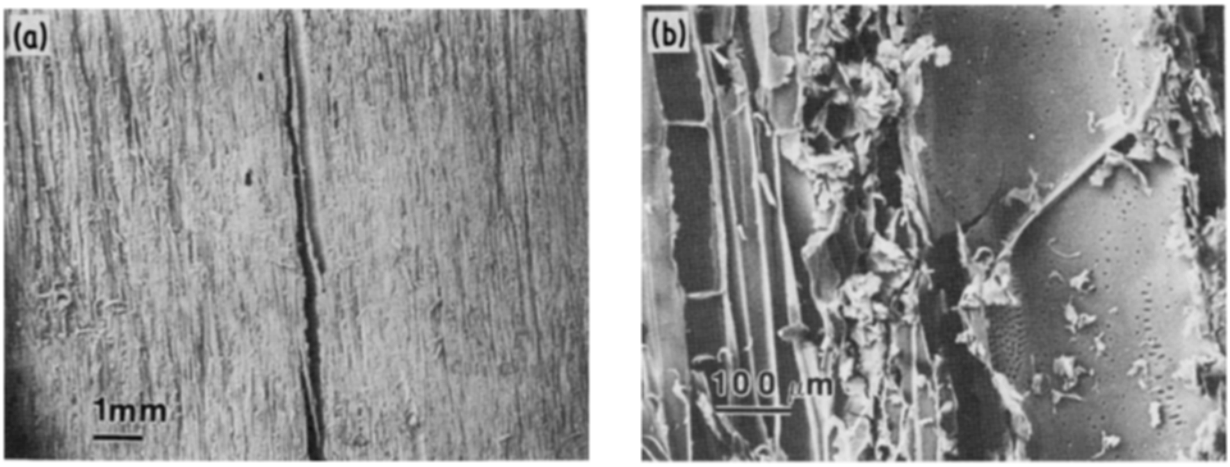


Figure 9 (a) The crack induced at the second stage of loading of Specimen B, and (b) higher magnification of its tip.

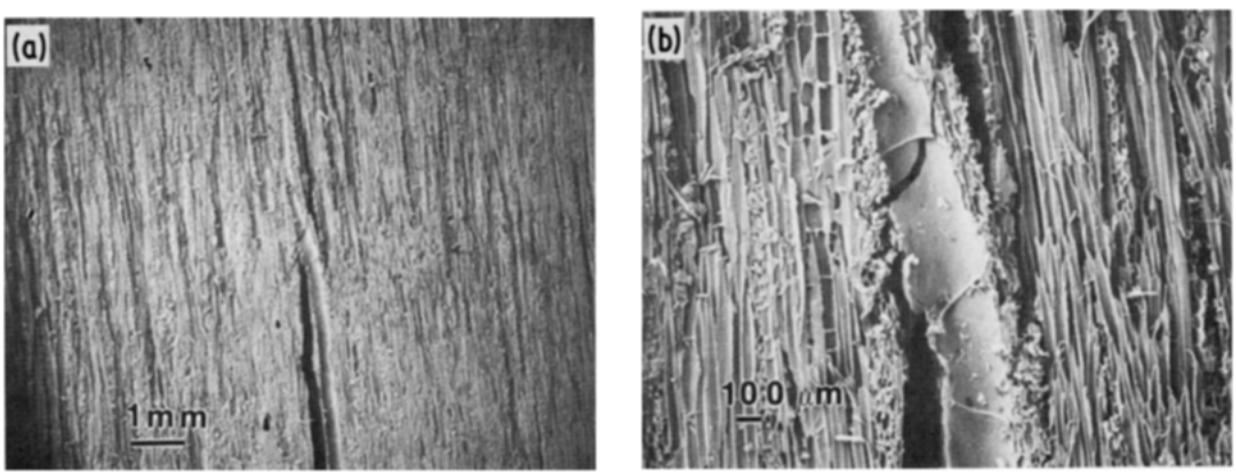


Figure 10 (a) The upper part of the crack induced at the third stage of loading of Specimen B, and (b) higher magnification of the zone in which the crack tip was located at the previous stage of loading (shown in Fig. 9b).

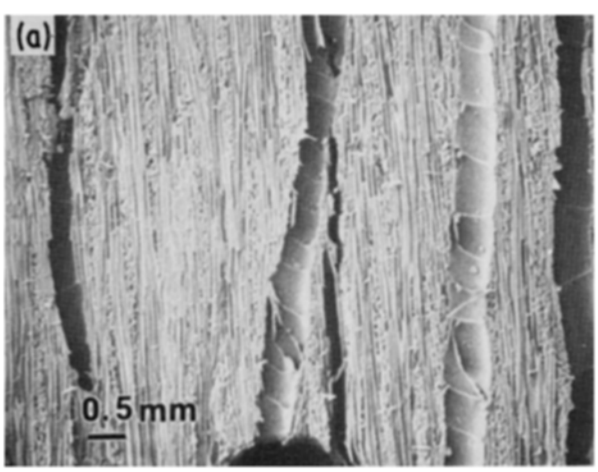
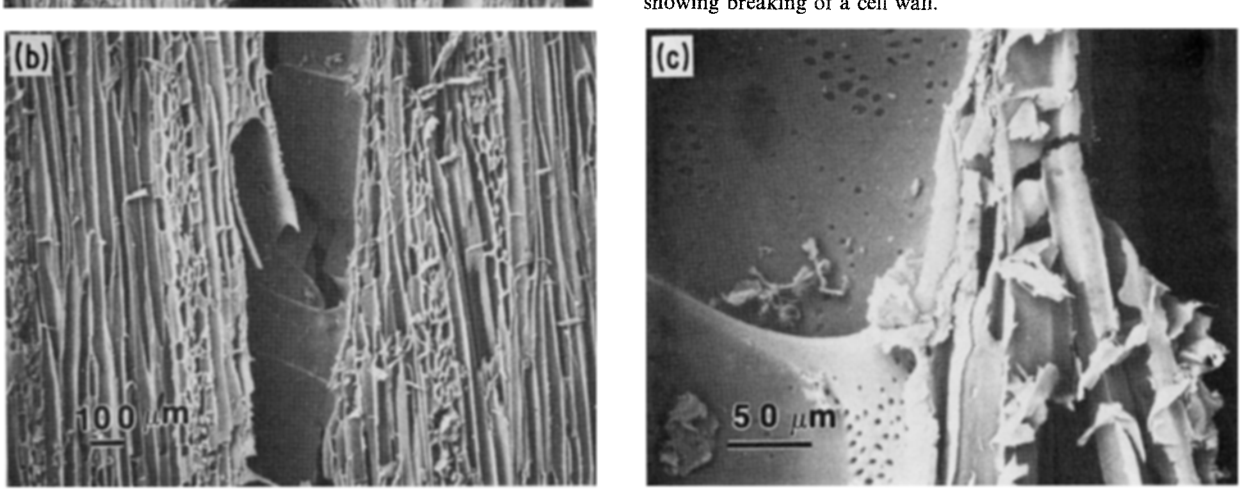


Figure 11 (a) The crack induced in the first stage of loading of Specimen C. (b) Higher magnification of a zone near its tip where it propagates into a vessel. (c) Higher magnification of a zone in (a), showing breaking of a cell wall.



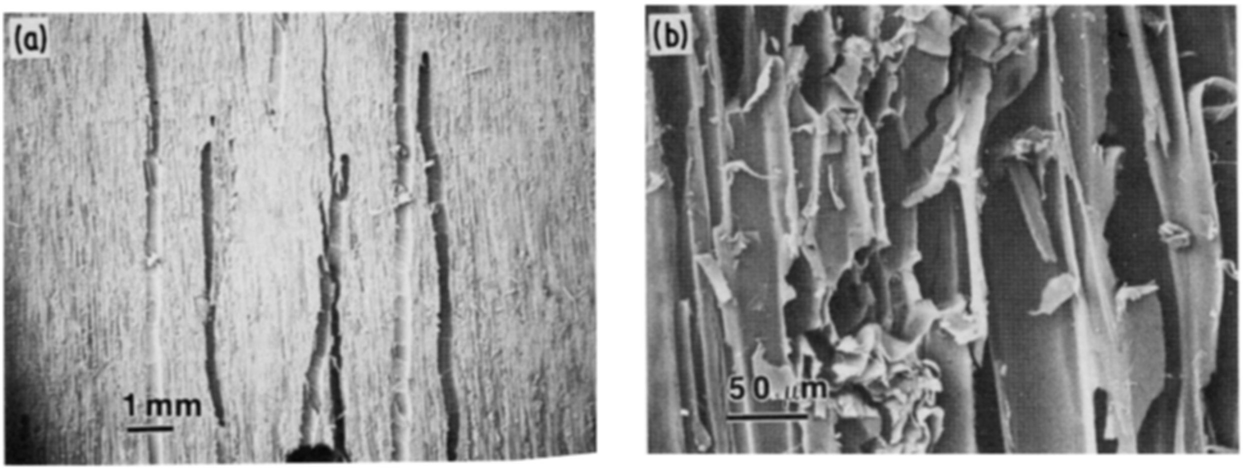


Figure 12 (a) The crack induced in the second stage of loading of Specimen C. (b) Higher magnification of the crack tip.

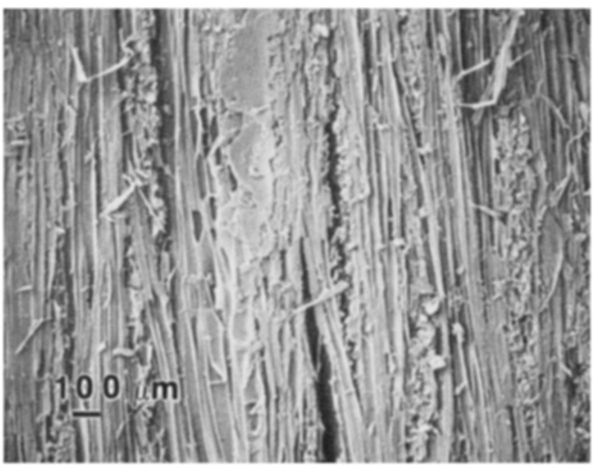


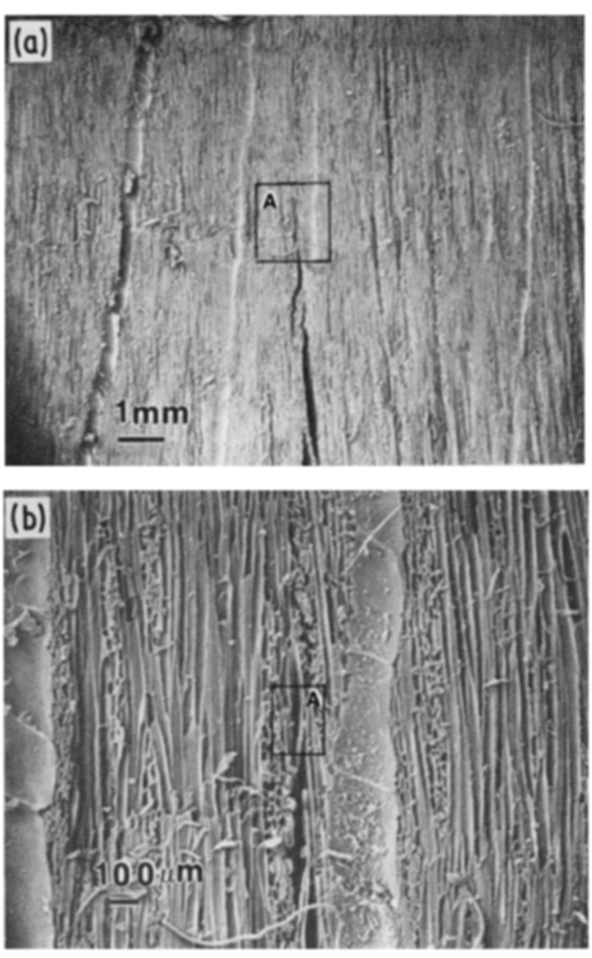
Figure 13 The crack tip in Specimen C at the third stage of loading.

The zone of crack tip at the third (Fig. 13) and fourth stages of loading (Fig. 14a) was also discontinuous and somewhat tortuous; it consisted of individual segments which were a few millimeters in length. Higher magnification showed that the uppermost segment was discontinuous and subdivided (Fig. 14b). This subdivision was associated with splitting along the boundaries between adjacent cells (Fig. 14c).

4. Discussion and conclusions

The crack path observed at low magnifications seemed to run in a straight line, as might be expected in the case of an "ideal" crack. However, in most of the specimens studied the crack could not be described as an ideal parallel-walled defect, because its two sides were frequently bridged, suggesting that the crack may be able to transmit stresses across its surfaces. Another typical characteristic was the fact that the crack tip could not be well defined; generally, some damage could be observed in front of the apparent crack tip. This damage could be very local in nature or it could show up as a series of disconnected, short microcracks.

On the microscopic level, the crack path was somewhat tortuous in nature. In many of the specimens studied, deviations could be observed around the



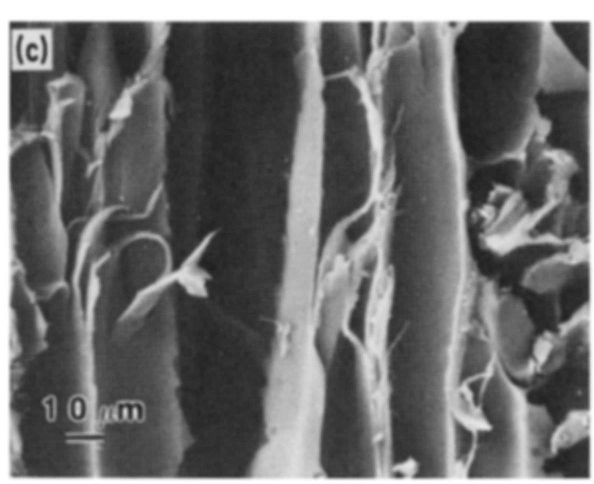


Figure 14 (a) The zone of the crack tip in Specimen C, at the fourth stage of loading. (b) Higher magnification of Zone A in (a). (c) Higher magnification of Zone A in (b).

stable crack tip when it was induced to propagate in a subsequent stage of loading. This behaviour suggests that the crack tip is arrested and stabilized at zones which are characterized by a higher capacity to absorb energy. As the crack tip is subsequently forced to propagate, it would choose a path that bypasses such zones. For instance, with regard to intrawall failure the crack may either continue to propagate within the plane of the cell between the S_1 and S_2 layers, or it may deviate into the depth of the S_2 layer following the helical arrangements of the microfibrils, as suggested in Figs. 5b and 9b.

Most of the crack propagation seems to be associated with splitting within the cell walls. However, there are also indications of additional processes which are associated with the breaking of cells.

The characteristics described here suggest that the cracking process in the wood is more complex than it may appear from macroscopic observations. Therefore, crack extension cannot be simply described as a process in which a parallel-sided crack propagates in a straight path.

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