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In situ observations of fracture mechanisms for radial cracks in wood

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This paper presents the findings of work carried out to describe the micromechanisms of radial crack growth in wood. *TR* and *TL* cracks are both radial cracks but *TR* grows radially and *TL* longitudinally. *TR* cracks are known to show higher fracture toughness than *TL* cracks. The *TR* fracture surfaces also indicate a more tortuous crack path. Since the reason for this is unclear, details of the *TR* crack growth mechanisms in green *Pinus sylvestris* L were studied. This was done by *in-situ* optical microscopy as the crack was cutting through alternating layers of soft earlywood and stiff latewood. At the scale of individual cells, the crack tip advanced by separating cell walls at the middle lamella in a splitting or peeling mode. At the scale of growth rings, stick-slip type of crack growth was observed and new crack planes were often formed. The stress distribution in a material with alternating stiff and soft layers is causing this. This stress distribution also contributes to the tendency for inclined cracks to deviate in the radial direction. For interpretation of fracture mechanisms, the importance of scale interaction and the combined influences of microstructure and stress state are emphasized. *© 2000 Kluwer Academic Publishers*

1. Introduction

Although the mechanical behavior of wood has been studied for very long, recent developments in experimental as well as theoretical methodologies may be used to improve our understanding. Conceptually, perhaps the most important insight we need is the fact that wood is an anisotropic polymer composite material. Gibson and Ashby recently provided a concise introduction to the structure and mechanical properties of wood, viewed as a cellular material [1]. The softwood structure, as we are concerned with here, is relatively simple as compared with hardwoods. The basic unit is longitudinally oriented cells arranged in arrays. The cells are tubular and often termed tracheids.

As the tree grows, a growth ring is added to the stem annually. The stiffness properties vary across this growth ring since the density varies. Early in the growth season, the tree forms an earlywood layer of low density. Later in the season, the higher density latewood layer is formed. The diameter of lumen, the cell cavity, is larger for the earlywood layers and the cell walls are thinner. The thicker latewood tracheids provide the major contribution to stem stiffness. The lower density earlywood tracheids contain larger diameter lumen cavities where water and mineral transport is facilitated.

In order to quantitatively characterize the fracture properties of wood at the macroscopic scale, fracture mechanics may be applied [2, 3]. Experimental studies have focused on effects from parameters such as density and moisture content on the fracture toughness of the wood material [3–8]. In these and other studies, the strong effects of cell orientation on fracture toughness has been established. The principal axes are usually defined as the radial, tangential and longitudinal direction, denoted R, T and L, see Fig. 1. Eight systems of crack growth planes may then be identified [9]. Each system is associated with a pair of letters where the first denotes the direction normal to the crack surface and the second describes the direction of crack growth. In the present study, we focus on *TR* crack growth where the crack grows in the radial direction and the tangential direction is normal to the crack surface.

One area in which crack growth processes are of industrial importance is in the cutting of wood products. Knife cutting is a cutting principle of interest since no saw dust is produced. In addition, there is some potential to create very smooth crack surfaces which are well suited for secondary bonding or painting operations. In this context, low fracture toughness is desirable since the energy consumption would then be minimized. However, *TR* cracks tend to result in rough fracture surfaces [10]. In order to understand the reasons for this on a more fundamental level, we need improved understanding of the crack growth mechanisms.

Crack growth mechanisms can be interpreted based on force-displacement curves from fracture mechanics tests and from the appearance of fracture surfaces. A more direct interpretation becomes possible if the crack is viewed by microscopic methods as it is growing, so called *in-situ* crack growth observations. For longitudinal tensile failure, this approach has been used in a scanning electron microscope [11, 12]. This mode of failure has also been interpreted based on the fracture surface of the cell wall [13, 14]. Obviously, the failure

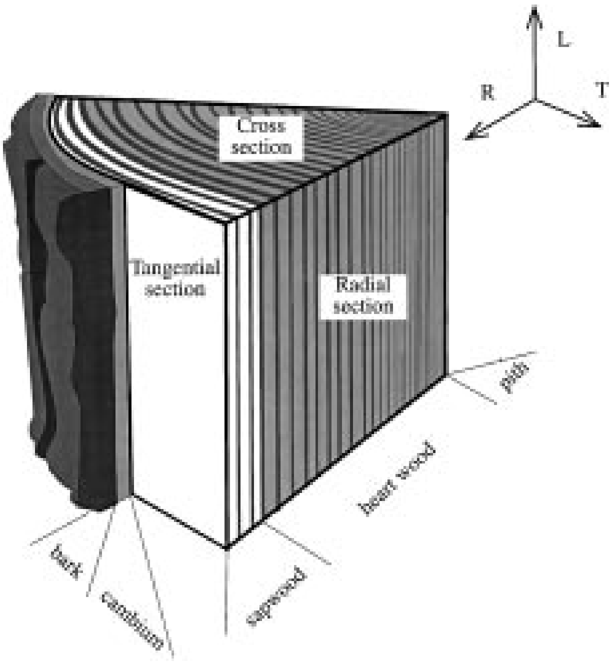

Figure 1 Axis of anisotropy, *R*, *T* and *L* for the radial, tangential and longitudinal direction respectively.

properties of the cell walls are essential for this failure mode. During crack growth in the *LT* and *LR* systems, cracks need to grow through the tracheids and cell wall failure is required. As a consequence, the fracture toughnesses are about an order of magnitude higher in these fracture systems as compared with the other systems. In fact, for crack growth experiments cracks even tend to deviate from the *LT* or *LR* system towards a cell wall peeling mode in a different direction [15].

In other systems than *LT* or *LR*, crack growth is in directions parallel to the tracheids. In the *TL* and *RL* systems, crack growth is primarily by cell wall peeling. The cell walls are then left intact since cell wall peeling takes place in, or close to, the middle lamella so that the lumens are not exposed [15, 16]. One may note that in spite of identical crack surface normals for *TR* and *TL* cracks, their respective fracture toughnesses differ. In Douglas fir, the fracture toughness is typically 30–50% higher in the *TR* system [17, 18]. For pine and spruce even larger differences have been reported [19, 20]. In order to explain these differences between *TR* and *TL* cracks, we need to determine the crack growth mechanisms in greater detail.

Even prior to the present study, *TR* cracks were reported to show stepwise growth [15] and the fracture surfaces were reported as rough [10]. The reason for this is not clear. The objective of the present study is therefore to describe the mechanisms for crack growth in the *TR* system. Mechanisms will be reported on both the scale of individual cells as well as on the previously often neglected scale of growth rings. Hopefully, this will help to explain the higher fracture toughness for *TR* as compared with *TL* crack growth. In particular, the influence of microstructure will be considered.

During our first attempts to grow *TR* cracks in dry wood, meaningful *in-situ* observations were hardly possible. The reason was that the extent of crack jumps and shift in planes of crack growth was so significant that it was impossible to keep track of the position of the crack tip. For this reason, the effect of drying on wood fracture was examined. Based on classical laminate plate theory, an analysis of the hygroscopic stresses in the cell wall was conducted [21]. It was demonstrated that the laminated structure of the cell wall may lead to substantial in-plane lamella drying stresses as moisture is leaving the cell wall. In an experimental study [14], fracture surfaces of green wood were then compared with fracture surfaces of wood subjected to one cycle of drying followed by resoaking of the wood sample. Small isolated earlywood and latewood samples were studied. As they were subjected to longitudinal tensile loading, the moisture content was the same in both groups of samples. The only difference was that the resoaked group had been subjected to one cycle of drying. As a consequence, the resoaked group showed a more brittle type of fracture surface appearance, indicating that drying of the wood may induce damage also on the scale of individual cell walls. Based on the reviewed results, we decided to study wood samples in the green state in the present study. The reason is that we would like to avoid any damage induced from drying of the wood. This may cause defects which can influence the crack growth process so that the path of crack growth becomes more irregular.

2. Experimental procedure

Square sections of $20 \times 20 \times 30$ mm were sampled from green sapwood of *Pinus sylvestris* L (the longest dimension is in the longitudinal direction). On the upper *RT* surface, a sledge microtome was used to cut a surface which would reveal the microstructure of the sample. A sharp, fine saw was then used to cut a 6 mm thick sample with a microtomed surface. The sample geometry is presented in Fig. 2. In order to enhance the photographic contrast between the wood substance in the cell wall and the lumen of moist green wood, a slurry of talcum powder and water was rubbed into the surface. The slurry filled the lumen. The surface of the sample was then wiped with a piece of soft paper. The sample was notched using a fresh razor blade so that a sharp crack was created. The specimen was then mounted for testing in a tensile testing machine (Minimat by Polymer Labs) placed under an optical microscope. The load was introduced through pins inserted in holes drilled in the sample, see Fig. 2. The specimen was loaded in

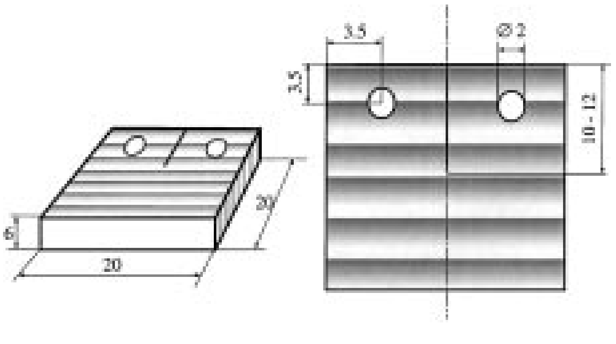

Figure 2 Compact tension specimen geometry (dimensions in mm).

displacement control. As the crack started to propagate, the load was not increased any further. The process of crack growth was observed and recorded through the microscope as the load was applied to the specimen in small steps and hence the growth rate small. Images were recorded through a video camera connected to a computer. Images were stored at the incremental load steps. The stepwise increase in crack opening displacement was continued until the specimen failed completely by separation. Images were aquired by the use of the NIH Image program, a shareware program from the National Institute of Health. In order to decrease the level of noise from the video signal in the images, the micrographs were aquired as the average of 32 images obtained at the same displacement. The equipment used to capture the images was a Macintosh Power PC 7600 equipped with a video card. The images had standard video resolution (PAL) with 256 grey levels.

3. Results and discussion

Let us consider a typical path for a *TR*-crack, a crack which grows radially with the tangential direction normal to the resulting crack surface, see Fig. 3. The fracture path is irregular and the crack plane is occasionally displaced in the tangential direction. Sometimes the crack plane is displaced just a few cell diameters, other times the extent of displacement in the tangential direction is in the order of the width of one earlywood layer.

In the following, focus is on the mechanism of crack growth for a *TR*-crack. This is at two different levels, the first at the scale of individual cells and the second at the scale of growth rings. In particular we would like to emphasize the importance of the often neglected growth ring scale.

3.1. Local crack growth at the tip

As we study *TR* crack growth in the microscope, we first consider a crack coming out of a latewood layer. As it grows in the earlywood, it progresses by cell wall peeling in, or close to, the middle lamella which connects two neighboring tracheids. The tip of the growing crack remains in the middle lamella and splits the cell rows with one set of cell rows to one side of the fracture surface and another set of cell rows to the other fracture surface, see Fig. 4. Hence the tracheids are separated without exposing the lumen at the crack surface. Also in the latewood layer, the *TR*-crack grows in the middle lamella, see Fig. 5. The lack of cell wall tearing or other mechanisms for energy absorption suggests low crack growth resistance for this type of local crack growth.

An important role of cellulose in the cell wall is to provide strength and stiffness. In the middle lamella, the cellulose content is low. Also the orientation of the cellulose fibrils is in the cell wall plane which in the case of cell wall peeling is unfavorable from the toughness point of view. The middle lamella is likely to be comparably weak in this mode of crack growth. The crack

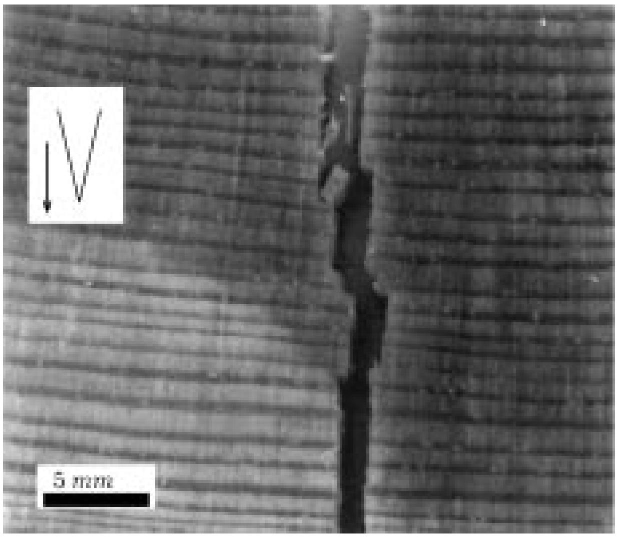

Figure 3 Crack path for *TR* fracture.

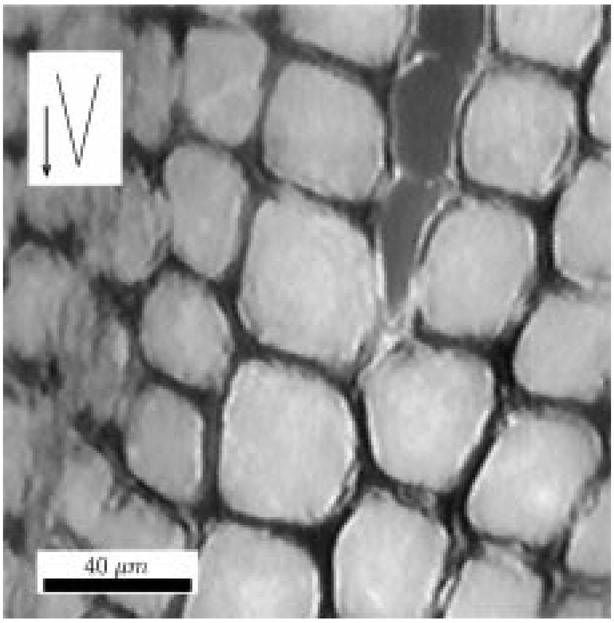

Figure 4 Crack tip in middle lamella of earlywood. Tracheids are intact in this mode of crack growth, often termed cell splitting or peeling.

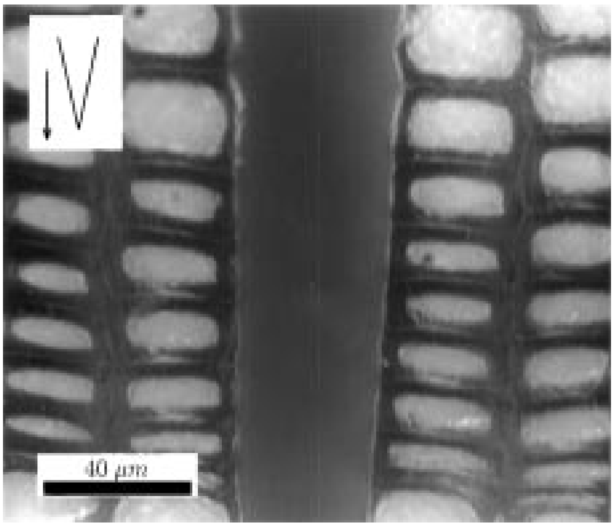

Figure 5 Part of crack in latewood. The crack path is in the middle lamella in a cell peeling mode of failure.

stays in the middle lamella without deviating into cell cavities and, therefore, the crack maintains a sharp tip during growth. This results in low energy requirements for extension of the crack. In the radial direction, the tracheids are well-aligned in rows and the crack in the middle lamella typically has an almost straight path through a single earlywood or latewood layer. Despite the regular arrangement of tracheids, the crack plane tends to jump at the scale of growth rings, as observed in Fig. 4. The local mechanism of crack growth at the scale of individual cells does not explain this irregular crack path. On the contrary, a smooth fracture surface is expected from the tracheid separation growth mechanism at the level of individual cells.

3.2. Crack arrest

Consider a *TR*-crack with its tip in the earlywood layer and subjected to a constant displacement rate. As the slowly growing crack approaches the latewood layer, its growth rate decreases and the crack comes to a halt. Despite further increase in load, the crack typically stays at this position. The latewood layer ahead then often fails abruptly. The crack thus formed in the latewood may or may not be a direct extension of the previously arrested crack. The latewood crack often grows in an unstable manner into the earlywood layer where it is again arrested. Additional increase of the crack opening displacement repeats this process. Stable growth within the earlywood layer is followed by decreasing crack growth rate and arrest of the crack as the next latewood layer is approached. Hence the crack comes to grow stepwise where the length of the steps is comparable with the width of the growth ring. This stepwise growth is somewhat related to the stick-slip type of crack growth in isotropic polymers [22]. As a plastic zone is formed ahead of the crack tip, arrest takes place. Further loading leads to slow growth through the plastic zone followed by rapid unstable growth as the crack tip reaches the “virgin” region which has not been plastically deformed. Documentation of stepwise crack growth in the radial direction of wood can be found in the literature. Ashby *et al*. [15] studied crack growth in ash and observed stepwise crack growth where arrest occured in the compliant clusters of sap channels. The porous rings in ash, which is a hardwood, may be compared with the compliant earlywood layers in softwood. Observations in the present study are in agreement with those of Schniewind and Pozniak [17]. Although no reason was suggested, they also observed crack arrest in the earlywood layers in their fracture toughness measurements on Douglas fir.

3.3. Stress state around the crack

Previous discussions on the reasons for crack path changes and arrest phenomena have primarily considered toughness differences in earlywood and latewood as well as in different crack growth directions [15]. Also the aforementioned arrest mechanism by crack tip blunting in sapwood channels has been discussed. We feel that in addition to this we need also to consider effects from the vast difference in stiffness between earlywood and latewood. The high density latewood has a tangential stiffness which is about 20 times higher than that of the earlywood. This strongly influences the stress state at a *TR* crack tip. One consequence is that during crack extension, the released elastic energy from surrounding material will differ greatly depending on the position of the crack tip.

The present observations have inspired a recent experimental analysis of the state of strain at a *TR* crack [23]. The presence of alternating earlywood and latewood layers strongly influenced the state of strain at the crack tip. The tangential strains extended significantly in the tangential direction but were heavily constrained in the radial direction. This constraint was due to the presence of a stiff latewood layer ahead of the crack tip. This case of a *TR* crack in a material consisting of alternating strips with stiffnesses corresponding to the present case, was also theoretically analyzed by FEM [24].

As the crack tip was positioned in the earlywood layer, increasing load was found by FEM to be carried primarily by the stiff latewood ahead of the crack tip. These results are presented in Fig. 6 where the extension of the highly loaded region in the latewood is significant. The length of the highly loaded latewood region is at least of the same order of magnitude as the width of the growth ring.

As the crack tip approaches the latewood layer, the tensile stress in the latewood will increase. This will be

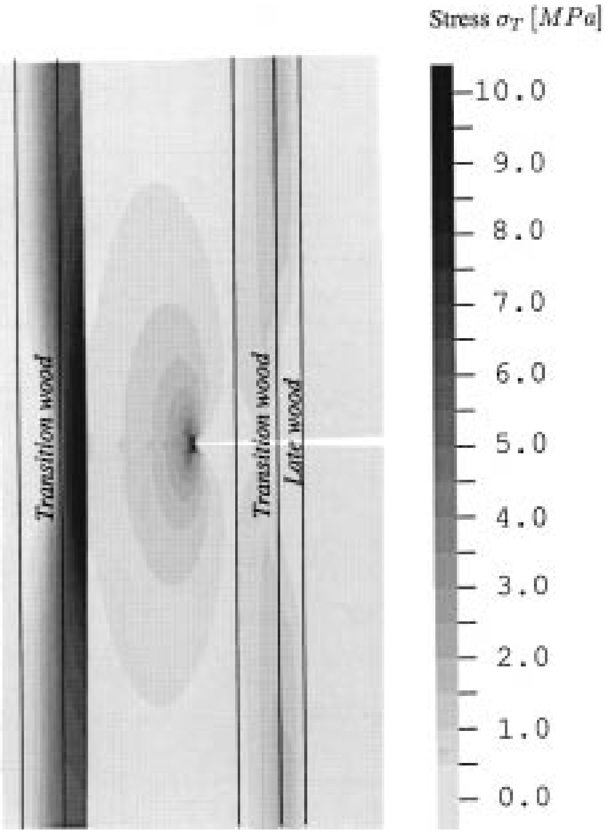

Figure 6 FEM-predictions of the distribution of tangential stress, σ_T, for a growth ring width w of 1.6 mm [24]. Only the relative differences in levels of stress are of interest. The term transition wood corresponds to an interphase region of gradually changing stiffness. The crack tip is positioned in the earlywood region.

accompanied by decreased stress intensity at the crack tip. For this reason, the global load needs to be further increased in order to propagate the crack. Note that this is a stress state effect only and does not require higher local crack growth resistance of the latewood layer as compared with the earlywood. In fact, since we observed that both earlywood and latewood cracks tend to extend by cell wall peeling in the middle lamella, we do not expect dramatic changes in crack growth resistance. However, the apparent global fracture toughness of the combined material system will vary with crack tip position because of the stress state effect. This was analyzed by calculation of the J-integral for different crack tip positions [24]. Assuming constant local fracture toughness, the results were in agreement with the present observations of crack arrest in the earlywood layers. One can therefore explain the phenomenon of crack arrest in the soft earlywood as a consequence of the alternation of stiff and soft layers bonded together. This in fact agrees with the fracture toughness results in ref [25]. They found increasing global fracture toughness values as the crack tip position approached the latewood layers.

3.4. Formation of new crack planes

The latewood layer ahead of the crack carries significant stress when the crack is arrested in the earlywood. Since our tests are conducted at constant global displacement rate, the stress in the latewood layer is increasing. Eventually, the latewood layer will fail in tension, also the latewood fails at the middle lamella, see Fig. 5. This failure event may occur as a result of crack tip extension but there is also another possibility. Since the highly stressed region ahead of the crack tip extends considerably in the tangential direction, fracture of the latewood may also occur well away from the original plane of fracture. This is because fracture may be caused by weak sites in the highly stressed latewood. Fig. 7 illustrates failure in the latewood layer ahead of an arrested crack and formation a secondary crack.

As the load increases, crack growth may continue from the tip of the secondary crack. This creates a new crack plane which is often observed as the crack passes through a latewood layer, see Fig. 3. We conclude that the large stiffness variation in the growth ring causes high stress in the latewood. This gives a mechanism for formation of new crack planes at weak latewood sites. Although previous studies have noted the tortuous crack path for *TR* cracks, we have not found any satisfactory explanation in previous work.

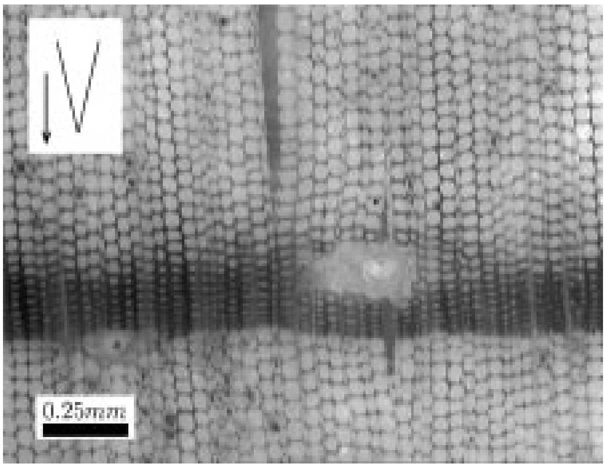

Figure 7 Primary *TR* crack arrested in front of latewood layer. A secondary crack is present in the latewood, its plane somewhat displaced with respect to the primary crack.

As the primary and secondary cracks are linked, the bridging material is torn so that the lumen is exposed at the fracture surface. In Fig. 8, this tearing process of the bridging earlywood close to the latewood is presented. We suggest that this process is responsible for the reported lumen exposure close to the latewood layer, previously attributed to differences in cell diameter between earlywood and latewood [26].

Interestingly, in latewood layers which fractured without crack plane deviation, we frequently find secondary cracks next to the main plane of fracture. Such an inactive crack is presented in Fig. 9. These inactive cracks are formed in the latewood and do not become part of the primary crack. Hence, failure of the latewood layer and the associated formation of a secondary crack may also occur without a change in crack plane for the

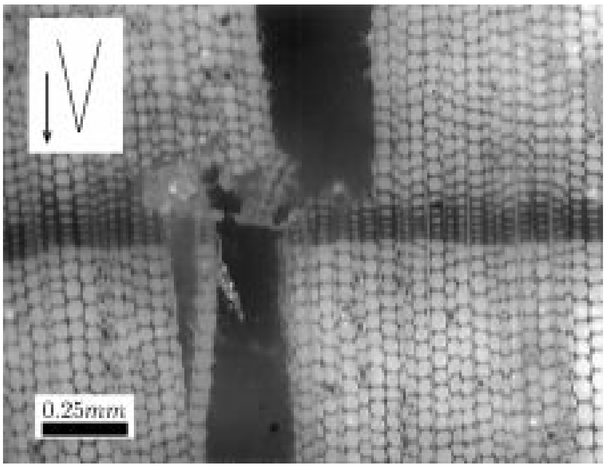

Figure 8 Illustration of the tearing process as primary crack is linked with secondary crack initiated in a different crack plane. Bridging material is torn so that lumen is exposed on the fracture surface.

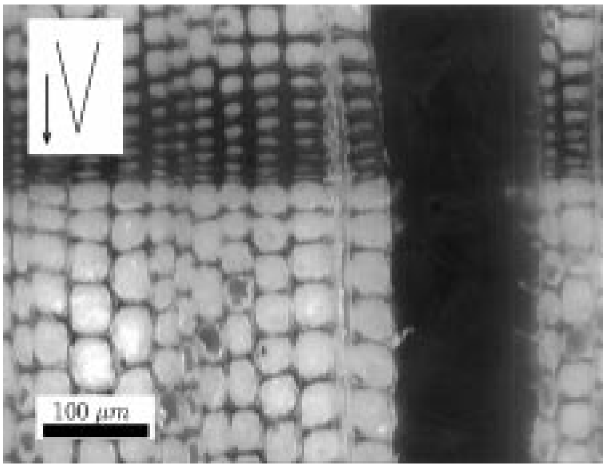

Figure 9 Inactive secondary crack present to the left of the primary crack.

primary crack. Closer examination of the surface of the latewood behind the crack front indicates further inactive secondary cracks well away from the plane of the primary crack. Since new surface area is created, the formation of secondary cracks is expected to contribute positively to the apparent toughness of the material.

Regarding the nature of the latewood layer defects, it is tempting to suggest that they may often be rays since they are known as planes of weakness [9]. In this context, one needs to keep in mind that our observations are made at the surface of a three-dimensional object. Rays have a finite extension in the longitudinal direction but cracks initiating at rays may extend longitudinally and reach the observable surface of our specimen. However, in the present study we have no direct observations confirming this speculation.

For *TL* cracks, the crack surface orientation is identical to the crack surface for *TR* cracks. The stress state experienced by a growing *TL* crack is significantly different though. A point at the crack tip extends in either earlywood or latewood. For this reason, the presented *TR* mechanism for changes in crack plane is not in operation. This is likely to be an important reason why *TL* cracks generally show lower fracture toughness and less tortuous crack paths.

3.5. Deviation of inclined cracks

When a crack is introduced at an angle with respect to the radial direction, it has a tendency to deviate towards pure radial growth [26]. A typical fracture path is presented in Fig. 10. During our *in-situ* observations, we observed the growing inclined crack as it approached the latewood layer. The angle of inclination is maintained as the first latewood layer is reached. Due to the cutting process during which the crack was created, the crack is sometimes positioned in the lumen. Crack extension is by a mixture of peeling in the middle lamella and tear of the cell wall itself. Of those two mechanisms, the cell wall peeling mode dominates.

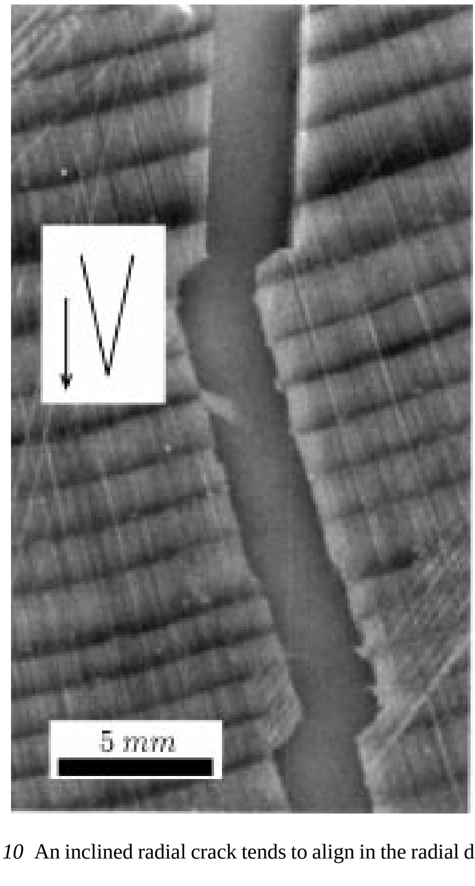

Figure 10 An inclined radial crack tends to align in the radial direction.

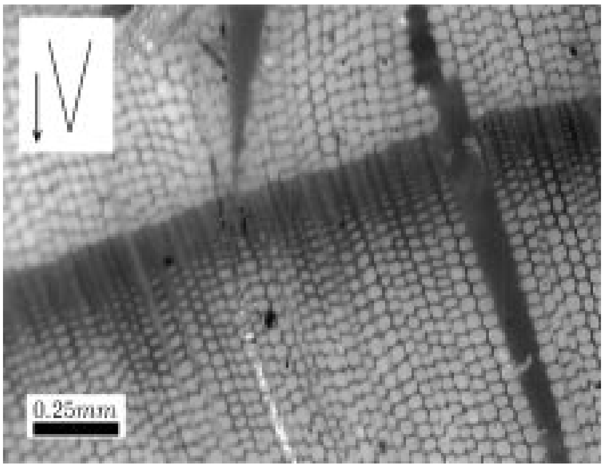

Figure 11 An inclined crack (left) is arrested at the latewood layer. The latewood fails at a weak location and a secondary crack is created, orientated in the radial direction.

When the crack approaches the latewood, its growth rate decreases and it is eventually arrested. Further increase in the crack opening displacement leads to failure of the latewood layer. A secondary crack is formed, orientated in the radial direction, see Fig. 11. The secondary crack then continues to grow whereas the primary, inclined crack is arrested. The new crack direction is in the radial direction and extension is by cell peeling in the middle lamella only.

The phenomenon of preferred deviation towards radial growth for inclined cracks has been observed in other studies [15, 26]. In [26], the explanation was the presence of ray cells acting as weak planes. Ashby *et al*. used the lower crack growth resistance for the cell peeling mode in their explanation [15]. In the related FEM analysis discussed previously [24] an additional explanation was found. Inclined cracks were introduced in the model. As this was done, the tangential distance in the latewood with high tensile stress was found to be relatively independent of moderate variations in inclination angle. Because of the weak middle lamella, latewood failure is bound to occur by cell splitting. In other words, the alternating stiff and soft layers in the material leads to a stress distribution which contributes to the observed mechanism. However, the low energy requirements for cell peeling obviously contributes to the phenomenon.

4. Conclusions

At the scale of individual cells, the *TR* crack tip advanced by separating cell walls at the middle lamella in a splitting or peeling mode. At the scale of growth rings, stick-slip type of crack growth was observed and new crack planes were often formed. The stress distribution in a material with alternating stiff and soft layers is causing this. An extended latewood region ahead of the crack tip is subjected to high stress. This induces secondary cracks ahead of the primary crack but in a different plane than the primary crack. Although *TL* cracks have identical crack surface orientation as *TR* cracks, the stress state experienced by a growing *TL* crack is significantly different. For this reason, the presented *TR* mechanism for changes in crack plane is not in operation. This is likely to be the reason why *TL* cracks generally show lower fracture toughness and less tortuous crack paths. The stress distribution at *TR* cracks also contributes to the tendency for inclined cracks to deviate in the radial direction. However, the low energy required for cell peeling crack growth in the middle lamella also contributes. The necessity of taking scale interaction between cell and growth ring mechanisms into account should be apparent from the present results. In particular, the scale of growth rings is often neglected, although the present results demonstrate that this scale strongly influences *TR* crack growth. In addition, the results illustrate the combined influences of microstructure and stress state on *TR* crack growth mechanisms.

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References

1. L. J. GIBSON and M. F. ASHBY, "Cellular Solids Structure and Properties" (Pergamon Press, Oxford, 1988).
2. A. P. SCHNIEWIND and D. E. LYON, *Wood Sci. Technol.* **7** (1973) 45.
3. B. YEH and A. P. SCHNIEWIND, *Wood Fiber Sci.* **23** (1992) 364.
4. M. M. GAPPOEV, *Ind. Lab.* **60** (1994) 680.
5. G. PROKOPSKI, *Int. J. Fract.* **79** (1996) R73.
6. A. P. SCHNIEWIND, T. OHGAMA, T. AOIKI and T. YAMADA, *Wood Sci.* **15** (1982) 101.
7. S. E. STANZL-TSCHEGG, E. K. TSCHEGG and A. TEISCHINGER, *Wood Fiber Sci.* **26** (1994) 476.
8. I. SMITH and Y. H. CHUI, *Wood Sci. Technol.* **28** (1994) 147.
9. J. BODIG and B. A. JAYNE, "Mechanics of Wood and Wood Composites" (Van Nostrand Reinhold Company Inc, New York, 1982).
10. T. ENGØ, K. J. MÅLLØY, A. HANSEN and S. ROUX, *Phys. Rev. Lett.* **73** (1994) 834.
11. J. BODNER, G. GRÜLL and M. G. SCHLAG, *Holzforschung* **50** (1996) 487.
12. J. BODNER, M. G. SCHLAG and G. GRÜLL, *ibid.* **51** (1997) 479.
13. L. A. DONALDSON, *ibid.* **51** (1997) 303.
14. G. KIFETEW, F. THUVANDER, L. BERGLUND and H. LINDBERG, *Wood Sci. Technol.* **32** (1998) 83.
15. M. F. F. ASHBY, K. E. EASTERLING, R. HARRYSSON and S. K. MAITI, *Proc. R. Soc. London A* **398** (1985) 261.
16. G. R. DEBAISE, A. W. PORTER and R. E. PENTONEY, *Mat. Res. Stand.* **6** (1966) 493.
17. A. P. SCHNIEWIND and R. A. POZNIAK, *Eng. Fract Mech.* **2** (1971) 223.
18. A. P. SCHNIEWIND and J. C. CENTENO, *Wood Fiber* **5** (1973) 152.
19. K. RIIPOLA and M. FONSELIUS, *Journal of Structural Engineering* **118** (1992) 1741.
20. M. FONSELIUS and K. RIIPOLA, *ibid.* **118** (1992) 1727.
21. F. THUVANDER, G. KIFETEW and L. A. BERGLUND, *Wood Sci. Technol*, accepted.
22. A. J. KINLOCH and R. J. YOUNG, "Fracture Behaviour of Polymers" (Applied Science Publishers Ltd, London, 1983).
23. F. THUVANDER, M. SJÖDAHL and L. A. BERGLUND, *J. Mater. Sci.*, accepted.
24. F. THUVANDER, L. O. JERNQVIST and J. GUNNARS, *J. Mater. Sci.*, submitted.
25. K. ANDO and M. OHTA, *Mokuzai Gakkaishi* **41** (1995) 640.
26. S. W. J. BOATRIGHT and G. G. GARRET, *J. Mater. Sci.* **18** (1983) 2181.

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and accepted 1 February 2000