ZONES OF GELATINOUS FIBERS IN *POPULUS BALSAMIFERA* L.[1]

David C. Ritter[2]
Scientist

Robert E. Kroll
Research Associate

and

Roland O. Gertjejansen
Professor

Department of Forest Products
College of Natural Resources
University of Minnesota
St. Paul, MN 55108

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ABSTRACT

Although balsam poplar (*Populus balsamifera* L.) is a logical supplement to the aspen (*Populus tremuloides* Michx.) resource for the manufacture of oriented strandboard (OSB), it has not been utilized extensively because of reported machining problems. The machining difficulties usually have been attributed to fibers with thick gelatinous layers in their cell walls. This study employed scanning electron microscopy (SEM) to observe the cell-wall structure of balsam poplar grown in Minnesota. In a previous study, balsam poplar samples were identified as difficult to waferize on the basis of wood fibers plugging the waferizing knives. The balsam poplar samples that were difficult to waferize often contained areas that appeared as "white rings" to the naked eye. Observation with the scanning electron microscope revealed that the "white rings" in the wood were zones that contained very high concentrations of gelatinous fibers. In these fibers, the cell wall typically consisted of a gelatinous layer that occupied 30 to 90% of the cell wall. In most cases, the initiation and termination of zones with high concentrations of gelatinous fibers took place within one annual growth increment or slightly more. Additional observation of trees within the sample showed that the "white rings" and the accompanying high concentrations of gelatinous layers were usually restricted to one side of the tree. This observation has led us to believe that the "white ring" areas and the corresponding zones of gelatinous fibers were the result of tension wood formation in the balsam poplar trees and not a part of normal wood formation.

Keywords: Balsam poplar, gelatinous layer, G-layer, gelatinous fiber, machining, oriented strandboard, scanning electron microscopy, tension wood, waferizing.

INTRODUCTION

In the Lake States and Canada, aspen (*Populus tremuloides* Michx.) is the preferred raw material for oriented strandboard (OSB) and waferboard (WB). However previous studies (Jakes 1980; Jakes and Smith 1980; Leuschner 1972) have warned that the apparent surplus of aspen will not last indefinitely. Now the Minnesota Department of Natural Resources (1988) has predicted that there will be a shortage in Minnesota by the year 2000. In the past five years significant expansions in the OSB and paper industries have increased the demand for Minnesota's aspen resource. In light of the impending aspen shortfall, research at

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[2] Present address: Masonite Corporation, P.O. Box 808, St. Charles, IL 60174.

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the University of Minnesota Department of Forest Products has focused on the increased utilization of underutilized hardwood species such as balsam poplar (*Populus balsamifera* L.) and paper birch (*Betula papyrifera* Marsh.) for structural composite panels.

Balsam poplar is a logical supplement to aspen OSB or WB. It has a relatively low specific gravity (0.31) and is an abundant species in the aspen forest type. Unfortunately, balsam poplar and several other members of the genus *Populus* reportedly are difficult to machine. Shen (1980) indicated that waferizing[3] balsam poplar produced large quantities of fines and wafers with fuzzy surfaces, which he attributed to excessive numbers of gelatinous fibers in the balsam poplar. Panning and Gertjejansen (1985) found that balsam poplar was difficult to waferize because it resulted in excessive knife plugging. The presence of high concentrations of gelatinous fibers apparently has contributed to rough and fuzzy surfaces of lumber sawn from eastern cottonwood (Clark 1958; Kaeiser and Boyce 1965). Although the above studies attributed the inability to adequately machine balsam poplar to the presence of gelatinous fibers, the actual presence of gelatinous fibers in balsam poplar and the effect that they might have on the production of high quality strands and wafers have not been reported. In addition, reports from OSB plants indicate that the waferizing problem may be related to physical factors other than the presence of gelatinous fibers (Firman 1989).

Research (Kroll et al. 1990, 1992) was undertaken to characterize the anatomy and to quantify the presence of gelatinous fibers in Minnesota-grown balsam poplar as well as to ascertain the effect of gelatinous fibers on waferizing characteristics. During the course of that study, only a small number of specimens within the balsam poplar sample were difficult to waferize (Kroll et al. 1990). That small number of balsam poplar specimens, however, immediately plugged the waferizer in a manner similar to that described previously (Panning and Gertjejansen 1985; Gertjejansen and Panning 1985). In addition, these same specimens also contained zones that were difficult or impossible to thick-section adequately (18 μm) with the sliding microtome (Kroll et al. 1992).

Many of the areas that were extremely difficult to waferize and thick-section also appeared as grayish "white rings" to the naked eye. In most cases, these "white rings" were not continuous in an annual growth increment or increments around the entire diameter of the tree cross section. Rather, they appeared as a whitish area of xylem encompassing approximately 180° of one or more growth increments in the stem cross section. Perem (1964) stated that the tension wood of certain hardwood species might appear as light-colored areas relative to normal wood on the cross section. This visual phenomenon apparently is the result of significantly lower lignin content in tension wood bands and the subsequent lower photodegradation of the wood. In the study of balsam popular anatomy (Kroll et al. 1992), portions of 10 trees were examined by light microscopy after having been stained with Chlorazole Black E. This microscopy revealed the gelatinous layers when present but did not permit identification of the gelatinous layers with respect to the primary, secondary, and tertiary wall attachment. Therefore, the present study was initiated to ascertain, by observation of electron micrographs, the extent to which the "white ring" zones in balsam poplar, as well as bordering areas, were composed of gelatinous fibers and to determine if the poor machining properties of balsam poplar could be attributed to those zones of wood that consisted of fibers with thick gelatinous layers. In addition, it might provide insight into the origin of these areas by determining their points of initiation and termination.

CHARACTERISTICS OF TENSION WOOD AND GELATINOUS FIBERS

Numerous studies have been devoted to the description of the gelatinous cell-wall layer (G-

[3] In this paper, the term "waferizing" is used to describe the process whereby wafers or strands are cut on a disk or drum flaker.

layer) (Dadswell and Wardrop 1955; Côté and Day 1962). Because of the thoroughness with which this subject has been reviewed, the authors have provided only a brief review on this and related material.

Fiber tracheids and libriform fibers[4] possessing gelatinous layers (commonly referred to as gelatinous fibers) are found most frequently in the tension wood of hardwoods. Tension wood usually is located on the upper side of leaning trees or stems (Isebrands and Bensend 1972), as well as in hardwoods exhibiting rapid growth (Berlyn 1961; White and Robards 1965). In addition, gelatinous fibers often are found in the normal wood of *Quercus* and *Populus,* and a number of other genera (Kaeiser 1955). Occasionally, tension wood may lack the abnormally high numbers of gelatinous fibers usually observed in this type of wood (Onaka 1949; Barefoot 1963). In these species, abnormally low lignin content may be the principal evidence for the presence of tension wood (Côté and Day 1965). Barefoot (1963) reported on the presence of "incipient" tension wood. He classified hardwood fibers as lignified (normal), partially lignified (intermediate), unlignified (abnormal), and gelatinous (abnormal). Those fibers lacking or with reduced quantities of lignin without the presence of gelatinous layers were considered "incipient" tension wood.

Dadswell and Wardrop (1955) reported three types of cell-wall configurations in which the G-layer was present. The G-layer may be present in addition to the S1, S2, and S3 layers, or it may exist with only the S1 layer or with both the S1 and the S2 layers. There did not appear to be an established relationship between the type of cell-wall configuration and species. In addition, more than one type of cell-wall configuration may occur in a single species.

The G-layer appears to be loosely attached to the adjacent cell-wall layer. When viewed in cross section, the G-layer often conforms to the shape of adjacent cell-wall layers, while in other cases the G-layer appears crumpled and not connected with the other parts of the cell wall (Panshin and DeZeeuw 1980).

The G-layer is composed of highly crystalline cellulose and in most cases has a much lower lignin content relative to normal wood. Depending on the thickness of the G-layer, the cellulose content of tension wood is much higher than that of normal wood, while the lignin content is considerably lower than that of normal wood (Timell 1969). Electron microscopy of longitudinal sections through tension wood has shown that the cellulose microfibril arrangement in the G-layer is nearly parallel to the longitudinal axis of the cell (Côté and Day 1965).

EXPERIMENTAL PROCEDURE

The samples selected for this SEM study of balsam poplar were part of a larger study that has described the anatomy of Minnesota-grown balsam poplar (Kroll et al. 1992). The samples utilized in this study were from four trees and were selected: 1) on the basis of visual appearance (presence or absence of "white rings"); 2) from samples located directly opposite from "white ring" samples in the tree cross-section; 3) on the basis of machining characteristics as determined in a previous study (Kroll et al. 1990); and 4) randomly from the larger, 10 tree sample size utilized in the previous anatomy study (Kroll et al. 1992). Trees from which SEM samples were obtained, sample location within the tree, presence or absence of a "white ring," machining characteristics, and average cell-wall thickness are shown in Table 1. The geographic location, selection process, and cutting procedure of the balsam poplar trees utilized in this study were described previously by Kroll et al. (1992). There were 10 trees whose ages ranged from 28 years to 56 years and whose diameter ranged from 152 mm to 250 mm (6 in. to 10 in.).

SEM specimens were cut from green balsam poplar wood and stored in either distilled water or 95% ethanol. Each SEM specimen was approximately 7 mm wide radially and tan-

[4] For the sake of simplicity and clarity, fiber tracheids and libriform fibers will be referred to in the future as "fibers."

TABLE 1. *Cell wall characteristics of balsam poplar SEM specimens.*

Sample	"White ring" present?[1]	Machining difficulty[2]	G-layer concentration[3]	Total cell wall thickness (μm)[4]	G-layer thickness (μm)	% G-layer
1a[5]	no	yes	none	2.13		
1b	no	yes	scattered	1.79		
1c	no	no	scattered	1.60		
1d	no	no	none	2.52		
2a	no	no	heavy	4.00	3.08	77
2b	yes	yes	heavy	2.25	1.85	82
			none	1.65		
2c	no	no	none	2.46		
2d	no	no	none	1.88		
			scattered	1.90	1.44	76
4a	no	yes	scattered	2.91		
4b	no	yes	scattered	1.98		
4c	no	no	scattered	3.09		
4d	no	no	scattered	1.97		
6a	no	no	none	2.53		
6b	no	no	none	2.26		
6c	yes	yes	heavy	2.63	2.06	78
			moderate	4.11	0.78	19
6d	yes	yes	moderate	2.78	0.72	26
			moderate	2.29	0.90	39

[1] Based on visual observation in previous study (Kroll et al. 1992).
[2] From Kroll et al. (1990).
[3] Subjective observation based on presence or lack of G-layer.
[4] Samples were measured twice if cell-wall characteristics were distinctly different within the same specimen.
[5] Number represents tree number in original sample, while the letter represents location within stem cross section; a represents middle of north facing sapwood, b for middle of north facing heartwood, c for middle of south facing heartwood, and d for middle of south facing sapwood.

gentially and 10 mm in the longitudinal direction. Each specimen cross section included at least two portions of separate annual growth increments and often three. Several specimens comprised as many as thirteen annual growth increments in the 7-mm radial width.

While still in the green condition, the cross section of each specimen was shaved smoothly with a never-used single edge razor blade and air-dried to induce drying stresses in the cell-wall layers. The SEM specimens were mounted with carbon paste on SEM examination stubs and were vacuum-coated with a thin carbon film.

The cross sections of the specimens were examined across several growth increments with a Phillips CM-30 scanning electron microscope. Micrographs typical of the cross sections were taken at several different levels of magnification, usually starting with the latewood of a specific growth increment, followed by successively later formed growth increments. In most cases, micrographs of each specimen included the latewood-earlywood boundary of two adjacent growth increments, the middle of the earlywood, and the middle of the latewood in the same increment of one growth season. This procedure was repeated for the next youngest growth increment and adjacent boundaries. An additional latewood-earlywood boundary was included if the cross section of the specimen comprised more than two portions of growth increments. In all, at least two latewood-earlywood boundaries were included in the inspection of each sample.

Cell-wall thicknesses of selected specimens were measured directly from the electron micrographs. From these measurements, the percentage of G-layer present in the cell wall was determined, as well as a comparison of cell-wall thickness between specimens.

RESULTS AND OBSERVATIONS

"White ring" samples

SEM examination of selected "white ring" samples revealed that abrupt changes in cell-wall layering occurred from one growth increment to the next. In all cases, the samples visually identified as "white ring" samples contained zones of fibers that had thick, gelatinous layers in the cell wall. In many cases, the gelatinous layers in the fiber wall were distorted as a result of the cutting and tearing action during specimen preparation. In general, the "white ring" areas were characterized by fibers with cell walls that consisted of an S1 layer adjacent to a relatively thick G-layer. In the "white ring" specimens, cell-wall thickness averaged 2.92 μm, with the G-layer occupying 20 to 80% of the total cell-wall thickness.

Sample 2b (Figs. 1 and 2, Table 1 footnote 1) was representative of the samples that contained "white ring" material. Micrographs of 2b showed an abrupt transition from a growth increment with fibers lacking thick-walled gelatinous layers to the next formed increment

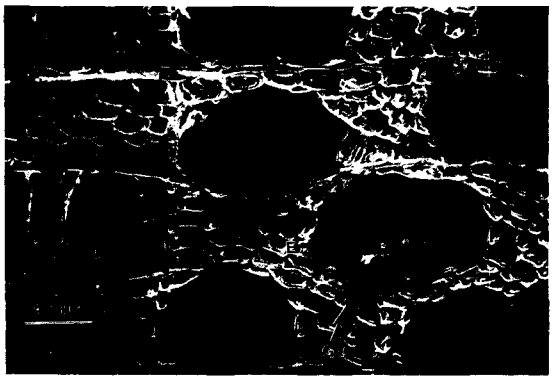

FIG. 1. Specimen 2b with normal latewood (L) fibers on the left and earlywood (E) fibers on the right, which contain very distinct gelatinous layers (G) (×320).

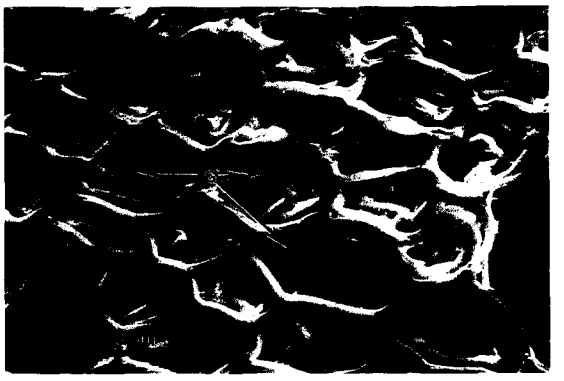

FIG. 3. Specimen 2b with thick-walled gelatinous fibers (G) from the center of the same growth increment shown on the right side of Fig. 2 (×1,250).

in which the fibers had relatively thick gelatinous layers. The abrupt transition to a zone of highly gelatinous fibers (Figs. 1 and 2) coincided with the "white ring" zone previously seen with the naked eye and corresponded to the same area in the sample that had machined poorly.

With the exception of small amounts of residue that were the result of surface preparation, the fibers in the left side of Fig. 1 were free of distortion and had few signs of separation between the cell-wall layers. In Fig. 2, the same specimen with a higher magnification, the fibers on the right side (those of the next formed increment) had very thick gelatinous layers relative to the entire cell wall. The first formed fibers of this growth increment displayed a distinct gelatinous layer in which the G-layer was separated from the S1 layer of the cell wall and was distorted in the direction in which the razor blade cut the surface during sample preparation (Fig. 3). Although the cell walls in this area of sample 2b averaged only 2.25 μm in thickness, the G-layer made up 82% of the total cell wall, with the remainder consisting of an S1 layer. The last rows of latewood fibers in the next latewood-earlywood boundary consisted of fibers with and without G-layers (Fig. 4). The zone of fibers with thick gelatinous layers terminated very early in the subsequent growth ring. The earlywood shown on the right

FIG. 2. Specimen 2b with normal latewood (L) fibers on the left and earlywood (E) fibers on the right, which contain very distinct gelatinous (G) layers (×640).

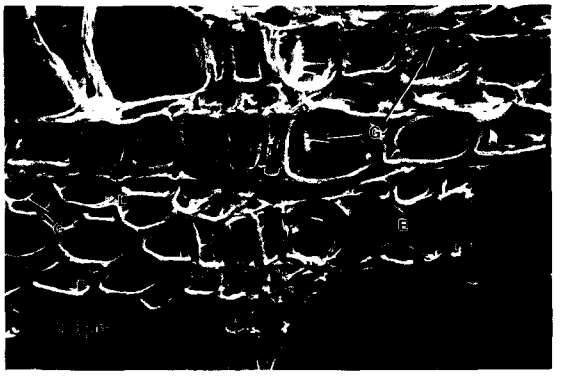

FIG. 4. The next formed latewood (L)-earlywood (E) boundary of 2b. Latewood on left has scattered gelatinous fibers (G), while earlywood on right also has a number of gelatinous fibers (×640).

FIG. 5. The latewood (L)-earlywood (E) boundary of 6c, which shows the normal fibers of the first formed increment followed by gelatinous fibers in the preceding increment (×320).

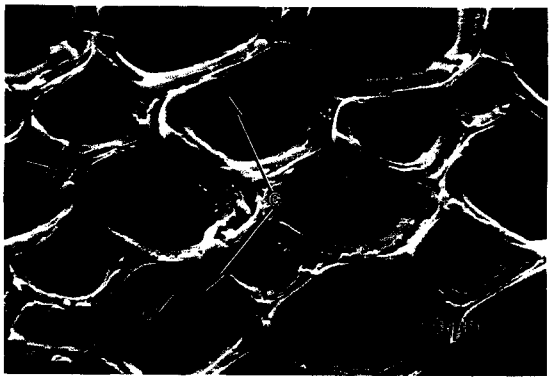

FIG. 7. Micrograph of 6c showing fibers that have relatively thin G-layers (G) adjacent to an S2 cell-wall layer. Note the checks (C) in the G-layer, which are parallel to the microfibril orientation (×1,250).

side of Fig. 4 had fibers with substantial concentrations of G-layers. Proceeding towards the latewood within the same growth increment, the gelatinous layers, when present, were sporadic and thin relative to those seen in the previous growth increment.

Examination of sample 6c revealed that it had many of the same characteristics as sample 2b. There was an abrupt transition from fibers with infrequent and thin G-layers (Fig. 5, left side) to an adjacent growth increment where fibers with relatively thick gelatinous layers were abundant (Fig. 5, right side). With respect to the G-layers observed in sample 2b (Figs. 2 and 3), the G-layers in 6c were less distorted by surface preparation (Fig. 6). The fibers observed in Fig. 6 had a thin S1 layer adjacent to a relatively thick G-layer. Total cell-wall thickness averaged 2.63 μm, with the G-layer occupying 78% of the cell-wall thickness. The presence of fibers with thick G-layers in sample 6c ended abruptly with the terminating cells of the growth increment. The subsequent growth increments did not have substantial quantities of fibers with gelatinous layers.

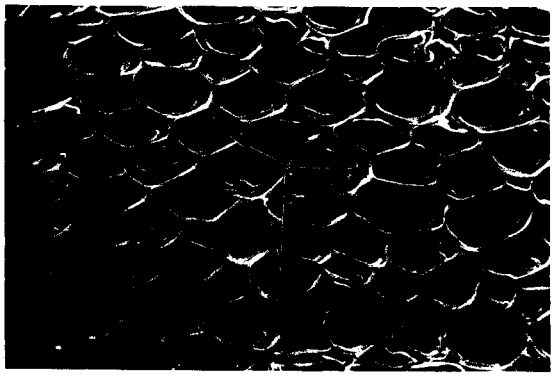

FIG. 6. Gelatinous fibers from the center of the growth increment shown on the right side of Fig. 5. Note the presence of distinct gelatinous layers (G) that have separated from the adjacent layers of the cell wall (×640).

In the growth increment formed prior to the increment described above, there were numerous fibers with thin gelatinous layers adjacent to thicker S2 layers (Fig. 7). These G-layers exhibited nearly vertical drying checks, which corresponded to the near vertical alignment of microfibrils in the gelatinous layers. The gelatinous layers observed in these cells usually were adjacent to a relatively thick S2 layer and a thin, obscure S1 layer. In this portion of the specimen, the G-layer occupied only 19% of the total cell-wall thickness, which averaged 4.11 μm.

Micrographs of sample 6d revealed that it was not similar to the previous two "white ring" samples. Whereas the previous "white ring" SEM samples consisted of two to three growth increments, 6d consisted of seven growth increments in their entirety and portions of two others. Of the nine growth incre-

FIG. 8. Fibers with thin G-layers (G) in specimen 6d. Note the orientation of the microfibrils as shown by the checks (C) and vertical ridges (R) in the G-layer (×1,250).

FIG. 9. Fibers with thicker and greatly distorted G-layers (G) in 6d (×1,250).

ments present in the sample, all but one had large areas containing fibers with gelatinous layers. As in the previous "white ring" samples, there was an abrupt transition from an annual growth increment with fibers containing infrequent and thin gelatinous layers to a growth increment with a high concentration of gelatinous fibers containing thicker and discontinuous gelatinous layers.

Inspection of gelatinous fibers in the "white ring" area of 6d (Fig. 8) revealed that there were two distinctly different types of gelatinous fibers present in the specimen. Fibers that contained an S1, S2, and a relatively thin G-layer were common (Fig. 8), as were fibers that consisted of an S1 layer and a relatively thick and often distorted G-layer (Fig. 9). In the former case, the cell wall averaged 2.78 μm in thickness with the G-layer comprising 26% of the cell-wall thickness. In the latter case, the G-layer averaged 2.29 μm in thickness and comprised 29% of the cell-wall thickness. In both cases, the G-layer was not as thick and occupied a lower percentage of the cell wall relative to the thickest G-layers present in samples 2b and 6c. Drying checks visible on the cell wall adjacent to the fiber lumena were nearly vertical with respect to the cell orientation, indicating the presence of a G-layer. In addition, vertical ridges of tissue, which indicated a nearly vertical microfibril arrangement and therefore the presence of a gelatinous layer, were visible in the lumena of the fibers (Fig. 8).

Normal wood samples

SEM examination of the normal wood samples (those not having a "white ring") revealed that many of them had a clean appearance relative to the "white ring" samples. Several samples that had been difficult to waferize did not have high concentrations of gelatinous fibers. One other sample had a high concentration of fibers with gelatinous layers without exhibiting visible evidence of the "white ring."

Samples 4a and 4b were examined with the SEM because they had proven difficult to waferize (plugged the waferizer knives) even though "white ring" material was not evident to the naked eye in either sample (Kroll et al. 1990). These samples contained only scattered fibers with thick gelatinous layers. The earlywood and latewood cell walls from these samples had little or no distortion from sample preparation, and the cell-wall layer nearest the lumen appeared to be attached to the adjacent cell-wall layers (Fig. 10). Cell-wall thickness averaged 2.91 and 1.98 μm for samples 4a and 4b, respectively.

Samples from 4c and 4d were examined with the SEM because they were located on the opposite side of the tree from 4a and 4b. Wood from these two samples was not identified as "white ring" material, nor had they previously been identified as difficult to waferize by Kroll

FIG. 10. Earlywood-latewood boundary of 4a showing fibers completely lacking a G-layer (×320).

et al. (1990). Micrographs from these samples revealed fibers with intact cell walls and only scattered fibers with gelatinous layers. The fibers in 4c and 4d had average cell-wall thicknesses of 3.09 and 1.97 μm, respectively. Both 4c and 4d contained ten or more annual growth increments in a 7-mm radial specimen.

Samples 1a, 1b, 1c, and 1d exhibited characteristics similar to those described for 4a and 4b, with the one exception that 1a through 1d contained only four annual growth increments in a 7-mm radial specimen. Although Kroll et al. (1990) reported that samples 1a and 1b caused waferizing problems, these samples did not have the characteristic "white ring" as described earlier, and they did not have large concentrations of fibers with thick gelatinous layers.

Samples 6a and 6b also were examined with the SEM because their origin in the tree cross section was directly opposite where "white ring" samples were observed with the naked eye and with the SEM (Figs. 5–9). Samples 6a and 6b did not have large concentrations of fibers with gelatinous layers. Cell-wall thicknesses for 6a and 6b were 2.53 and 2.26 μm, respectively. Unlike many of the other samples that had only three or four growth increments per sample, these two samples had as many as fourteen growth increments per sample.

Sample 2a, a sapwood sample adjacent to the heartwood sample 2b, was not visually identified as "white ring" material as was 2b and was not identified as difficult to waferize. Observation with the SEM revealed that it had extensive accumulations of gelatinous fibers in two of the twelve growth increments present in the SEM specimen. The growth increments containing extensive G-layers were separated by two narrow increments that contained fibers lacking gelatinous layers. As in the other samples that had extensive zones of fibers with G-layers, the transition from normal wood with only scattered quantities of gelatinous fibers to an increment with large concentrations of G-layers was extremely abrupt. The transition from an increment containing fibers with a large concentration of G-layers to an increment with normal fibers was similarly abrupt. Those fibers with thick G-layers usually had much thinner S1 layers. The average cell-wall thickness of fibers containing extensive G-layers was 4.00 μm, with the G-layer comprising 77% of the total cell-wall thickness.

Samples from 2c and 2d were examined because they were from the portion of the stem diametrically opposed to 2a and 2b. Samples 2c and 2b, both heartwood, did not exhibit any area of fibers with high G-layer concentrations.

DISCUSSION

In all cases, the "white ring" areas identified with the naked eye coincided with zones in the wood that contained high concentrations of fibers with gelatinous layers. There was one instance (sample 2a) in which large concentrations of gelatinous fibers were identified in SEM specimens that were not recognized previously as "white ring" material.

In those SEM specimens that contained two to four growth increments, the transition between zones of fibers with extremely high G-layer concentrations and the so-called normal fibers was usually very abrupt. The transition from normal fibers to fibers with high G-layer concentrations and then back to normal fibers often took place at the boundary area of successive growth increments. Those samples that consisted of more than four

growth increments often contained two or more successive increments with zones of highly concentrated gelatinous fibers. In those cases, the transition from an increment with high concentrations of G-layers to one containing fibers with few gelatinous layers also was abrupt.

Visual observation, as well as SEM examination of the "white ring" samples, showed that the zones of fibers with high concentrations of gelatinous layers were restricted to one side of the tree. This has led us to believe that the presence of the "white ring" and the concomitant concentrations of fibers with substantial gelatinous layer formation within a growth increment were associated with the formation of tension wood. An abrupt initiation and transition from normal wood to wood with an extremely high concentration of gelatinous fibers are often associated with tension wood formation (Clarke 1936; Dadswell and Wardrop 1955). Tension wood in turn often is related to tree lean. Rapidly grown wood also has been shown to contain a high proportion of gelatinous fibers.

In several samples, the formation of zones with extremely large concentrations of gelatinous fibers lasted only one growing season as evidenced by the presence of only one annual growth increment with high concentrations of gelatinous fibers. However, several other samples from the same tree displayed prominent zones of gelatinous fibers that lasted over several growth increments. The presence of large zones of gelatinous fibers on only one side of the tree cross section lends credibility to the idea that the "white rings," and therefore the zones of highly gelatinous fibers, were the result of tension wood formation.

In the case of the "white ring" samples, which were difficult to waferize and microtome, SEM examination revealed that the fibers in the "white ring" areas generally did not cut cleanly with the razor blade. Instead, the thick G-layer had a tendency to pull in the cutting direction of the knife and in most cases they actually separated from the rest of the cell-wall layers. In the case of a disk waferizer, it is easy to envision that a knife passing through a zone of highly gelatinous fibers (a "white ring" area) would become plugged with the residue from the G-layers when it separated from the adjacent cell-wall layers.

On an industrial level, only a few zones of highly gelatinous fibers could result in major machining problems. If a log section containing a zone of highly gelatinous fibers was processed through a commercial waferizer, it conceivably could plug a large number of knives until the cell-wall material was removed manually or forced off the cutting edge by subsequent cutting action (Gertjejansen and Panning 1985).

Questions remain about why portions of the balsam poplar sample machined poorly when lacking high concentrations of gelatinous fibers and why several SEM samples with high concentrations of gelatinous fibers were not identified as "white ring" samples. From the studies of Kroll et al. (1990, 1992), as well as this SEM examination of selected balsam poplar samples, there were a number of samples within this study that machined poorly, but did not comprise a mass of gelatinous fibers. Thus other materials or factors also must contribute to the machining problem.

The presence of "incipient" tension wood may play a role in waferizing or machining (Barefoot 1963; Arganbright and Bensend 1968). Abnormally low lignin content in the cell wall would result in fibers possessing less individual rigidity. During waferizing or machining, the potential result would be torn or pulled fibers that would produce an irregularly cut surface.

Cyr and Laidler (1987) have suggested that the relatively high water-soluble hemicellulose content of balsam poplar may contribute to poor machining properties. They assumed that the lower molecular weight hemicelluloses would have a low phase transition temperature. The hemicelluloses might soften as a result of the heat generated during the waferizing or machining operation, which then would clog the cutting knives with the hemicellulosic material. Additional study is needed to ascertain

if the glass transition temperature of the balsam poplar hemicellulose is reached at the knives during waferizing. If balsam poplar has a hemicellulose content variable both in quantity and type, then this theory may aid in the explanation concerning the poor machining characteristics of balsam poplar.

It also has been reported in the literature that balsam poplar is characterized by an abundance of bacterial wetwood (Wallin 1953, 1954). This trait may result in zones of partially decayed wood, which may play a role in the poor machining characteristics of this species. In addition, the relatively high overall moisture content of balsam poplar and the temperature of the wood at the time of machining may play a role in the efficiency of the waferizing process (Firman 1989; Kroll et al. 1990).

These statements, *vide supra,* in themselves do not explain why only limited balsam poplar samples have proven difficult to waferize. It is likely that the presence of gelatinous fibers, the presence of "incipient" tension wood, the hemicellulose makeup and content, bacterial wetwood, and wood moisture content all may affect the machining characteristics of this species.

Why several zones of high concentrations of gelatinous fibers were not identified as "white ring" samples could be based in part on the inability to visually identify the areas. They may not be visible in all instances due to differences in moisture content, amount of total exposure to light in the ultra-violet range, color of the wood (sapwood versus heartwood), and the available light at the time of viewing.

CONCLUSIONS

Scanning electron microscopy of balsam poplar samples that had been identified previously as difficult to waferize, as well as having "white rings," revealed that these samples generally contained zones of fibers with thick, gelatinous layers in the cell wall. The zones of highly gelatinous fibers, with several exceptions, were initiated and terminated within the boundary of the previous year's growth and the succeeding year. The cell walls of the fibers within the highly gelatinous zones generally consisted of an S1 layer followed by a conspicuous G-layer. As a result of the cutting action, the G-layer was often separated from the rest of the cell. Because of the high degree of visual correlation between the "white ring" areas, which generally were very difficult to waferize, and the extensive accumulation of fibers with thick G-layers, the waferizing difficulty was attributed directly to the presence of gelatinous fibers in these samples.

For balsam poplar to be utilized extensively for non-veneered structural composites, additional research must focus on more clearly defining the causes of poor wafer/strand quality and develop waferizing schemes that will result in the efficient machining of this species. We will report in future papers on studies aimed at answering these and other questions concerning the nature of balsam poplar and its machining characteristics.

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