

Determining the Moisture Gradient Profile of Wood Using the X-Ray Technique

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Abstract

Moisture gradients in wood are known to affect the internal stresses that could cause dimensional changes and defects. Severe deformation of finished products has the potential to damage a manufacturer's reputation and significantly increase the cost of manufacturing. An innovative approach to nondestructively examine the moisture gradients of different wood species using vertical density profiles from a commercial X-ray-based density profiler was described and illustrated. The results indicate that the estimated moisture gradients by the X-ray technique matched well with the actual moisture gradients. It is expected that the new method will provide accurate and prompt information about moisture transfer/movement that will help optimize manufacturing processes.

Introduction

Wood is a hygroscopic material and moisture gradients in wood are known to affect internal stresses that cause dimensional changes and defects. Severe deformation of finished products has the potential to damage a manufacturer's reputation and significantly increase the cost of manufacturing. There are many methods available in the literature that estimate the moisture gradient in wood. Some use a mechanical method which physically removes layers of wood to measure the moisture content, i.e., bandsaw slicing (McMillen 1955), drill bit (Feng and Suchsland 1993), and microtone knife (Wand and Youngs 1996). These techniques are not entirely accurate due to the kerf and moisture losses caused by heat generated during high speed cutting. The electrical resis-

tance of wood was found to be highly correlated with its moisture content (Myer and Rees 1926, James 1963). This technique was improved by adding electrical capacitance and phase (Dennis and BeaU 1977, Steele and Cooper 2006). But, the relationship between moisture content in wood and its electrical properties were not fully understood. The radiofrequency techniques are dependent on the experimental data to create an empirical relationship for each species.

Loos (1961, 1965) used radiation techniques to determine moisture content and density of wood and other materials. Hattori and Kanagawa (1985) estimated moisture in wood with a medical x-ray computer tomograph (CT) scanner. When a narrow beam of monoenergetic photons with an incident intensity I_0 , penetrating wood with transmitted distance t and density, emerges with intensity I given by the exponential attenuation law:

$$I = I_0 e^{-\mu \rho t} \quad [1]$$

where:

μ = mass attenuation coefficient of wood
with density of ρ .

The mass attenuation coefficient is a basic quantity used in calculations of the penetration and the energy deposition by photons. By comparing the incident intensity I_0 and the transmitted intensity I , the exponential attenuation law (Eq. [1]) will determine the wood density with known mass attenuation coefficient and the penetration thickness. The relationship between mass attenuation coefficient and moisture is used to determine moisture content (MC). Since the radiation covers a large portion of the specimen, the method is used to estimate the average MC throughout a given volume of wood is related to the size of the radiation plume.

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A procedure to determine water absorption distribution in particleboard, medium density fiberboard, and oriented strandboard was investigated by Xu et al. (1996). The procedure was based on the direct measurement of the vertical density distribution from a gamma-ray densitometer before and after water soak, and the vertical density distribution after the water-soaked specimens had been reconditioned to their pre-soak weights. They then used these data sets to separate "wood mass" and "water" from the different vertical density distributions. Thus, Xu et al. estimated the water absorption inside the sample. In order to separate the water from wood mass, the method assumed that the wood within a divided volume before soaking was the same (location and mass) of the wood after soaking. The problem, however, is that after water soaking, each layer inside the sample expanded evenly. It is possible to divide the sample into layers so that the each pair of corresponding layers before and after water soaking have the same wood weights, but it is impossible to precisely locate those layers after soaking so that they are identical to those before soaking. There has not been any work in the literature that looks at using X-ray technology to determine the moisture gradient through wood.

The moisture gradient in wood is an important wood physical parameters that needs to be accurately determined and has numerous implications for optimizing wood drying for high-quality stress-free wood material. Drying stresses during wood drying are generated across moisture gradients. Excessive moisture gradients cause excessive stresses can then cause external and internal cracks or honeycombing in wood. The primary objective of this paper was to investigate a radiation technique that could be used to accurately determine MC gradients in wood.

Method

All radiation measurement techniques require a source of radiation and a radiation detector. A typical source detector configuration for measuring density profile across a flat-sawn board thickness is shown in **Figure 1**. Usually, the radiation beam is passed through a slit to provide a collimated beam that penetrates the sample.

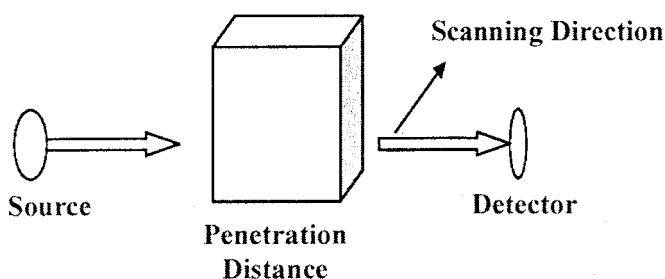


Figure 1.—Configuration to obtain radiation measurement of the density profile.

The dimension of the sample is 50.8 by 50.8 by 20.3 mm. The radiation penetrates the sample through either its longitudinal or tangential directions. The radiation system then incrementally scans the sample at multiple sites through its thickness direction (usually the radial direction). Using this data, a vertical density profile (VDP) is obtained. **Figure 2** shows typical oven-dried density ρ_0 profile and ρ_m profile for the same sample at MC m . Comparing the two profiles, Equations [2] and [3] can be used to determine the moisture gradient along the thickness direction.

$$\text{when } m \geq 30\%: \quad m = \frac{\rho_m - \rho_0}{\rho_0} \times 100 \quad [2]$$

$$\text{when } m < 30\%: \quad [3]$$

$$m = \frac{\rho_m - \rho_0}{\rho_0} \times 100 \times \frac{1}{\left(1 - \frac{10\rho_m S_0}{3\rho_0(1 - S_0)}\right)}$$

where:

S_0 = the total volumetric shrinkage from the green condition to oven-dry condition.

It is noticed that the sample thickness changes when the MC of the sample is different. Thus, it is necessary to precisely map the two profiles to ensure ρ_0 and ρ_m matching. Equations [4] and [5] can be used to compensate the thickness shrinkage according to its moisture profile.

$$S_m = S_0 \left(\frac{30 - m}{30} \right) \quad [4]$$

and

$$V_m = V_{green}(1 - S_m) \quad [5]$$

where:

S_m = volumetric shrinkage from the green condition to MC m ($<30\%$),

V_m = volume at the MC m , and

V_{green} = volume measured at the green condition.

The oven-dried exponential attenuation cannot be measured until the sample is oven-dried. Alternatively, the oven-dried density ρ_0 can be estimated earlier by perform-

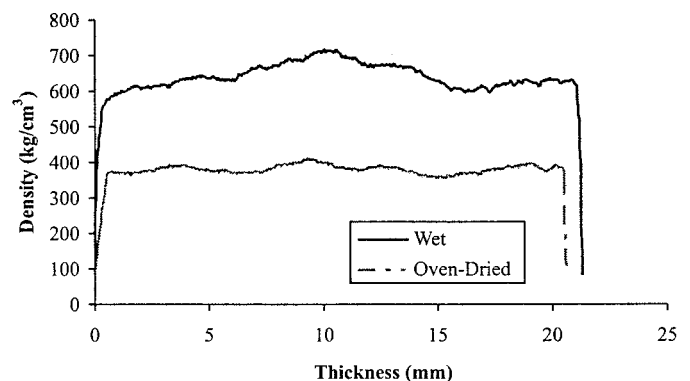


Figure 2.—Vertical density profiles of a sample when wet and oven-dried.

ing the radiation test on its edge-matched of side-matched samples.

Material

Four solid oak wood samples with nominal dimension of 50.8 by 50.8 by 20.3 mm (L by T by R directions) were equilibrated at 22°C and 65 percent relative humidity (RH) and tested to verify the technique previously discussed. The equilibrated samples were then edge-sealed with a sealer and oven-dried for 24 hours using a temperature of 105°C. Their oven-dried density profiles were measured using QMS¹ x-ray density profiler. Then the samples were placed in water with one L by T face submerged and about half of each sample block immersed in the water to purposely induce moisture gradients in the radial direction of the samples (Fig. 3). The samples were then taken out at different time intervals for VDP measurements.

Results

Figure 4 shows density profiles at different intervals for a typical oak sample with induced moisture penetra-

¹ QMS is a trademarked product. Any reference in this paper is not an endorsement but provided for the benefit of the reader.



Figure 3.—Samples immersed in the water with one side down and sealed sides.

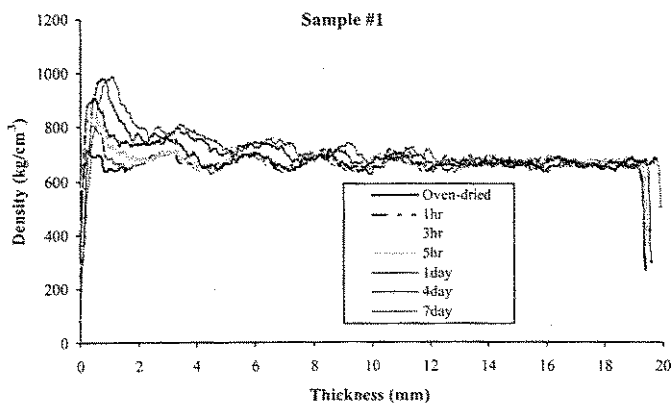


Figure 4.—Density profiles as a function of time immersed in water.

tion from one side. After 7 days, all of the samples were sliced in their radial direction with a microtome knife (Fig. 5). Each sliced layer (about 1 mm thick) was carefully marked and oven-dried to determine the individual MC of each microtomed lamina according to method described in the *Wood Handbook* (USDA 1999). This data was then plotted across its radial direction to estimate the actual moisture gradient. There were about 12 to 14 layers sliced starting from the surface that was immersed in water.

Figure 6 shows the measured moisture gradient and the estimated moisture gradients for sample 1. The measured moisture gradient was determined using the microtome oven-dry method after 7 days of immersion in water. The estimated moisture gradients were determined using the VDP information obtained using the x-ray profiler at 0.05-mm intervals and could be used to estimate the moisture gradients through the thickness. It is apparent from Figure 6 that the estimated gradients seem bumpy and overly sensitive. The reason is that the sample thickness changes as wood absorbs moisture (below the saturation point) and it is impossible to exactly match ρ_0 and ρ_m when the thickness changes. Although Equations [4] and [5] were used to compensate the thickness shrinkage according to its moisture profile, the ρ_m

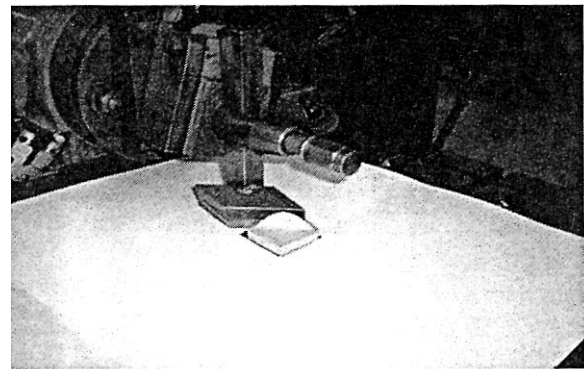


Figure 5.—Slicing a thin wood layer with a microtome knife.

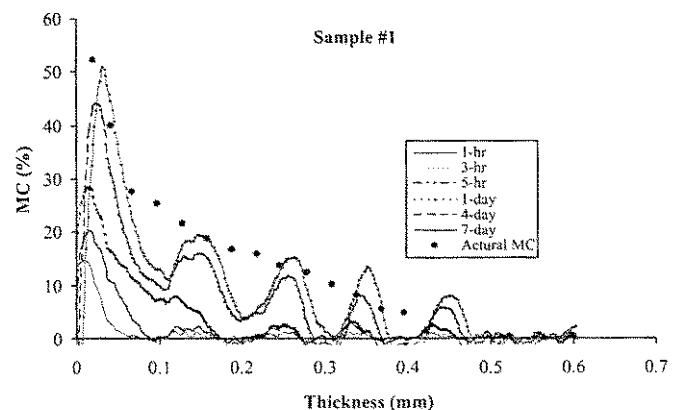


Figure 6.—Estimated MC gradients at different immersion time.

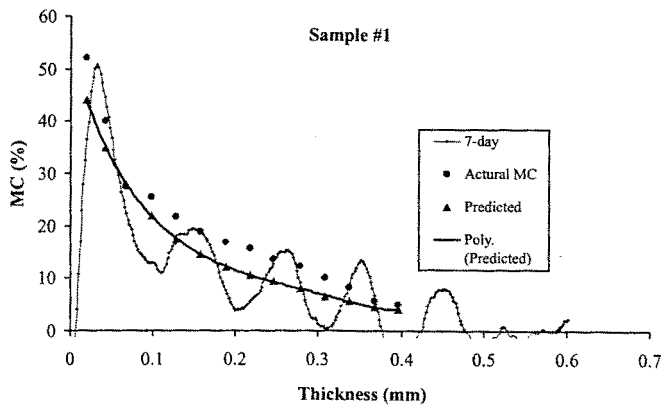


Figure 7.—Comparison between the estimated and measured MC gradients.

profile could be slightly offset from the Poprofile. In addition, the dimension changes (i.e., warp, twist, and cup) during moisture absorption and density differences between early and latewood could also make an uneven moisture gradient.

Comparison between the estimated gradient and the actual measured gradient after 7 days of immersion in water indicated that the two gradients matched well. After the estimated MC gradient was smoothed using a polynomial regression method, the estimated MC gradient more accurately match the measured gradient. **Figure 7** shows the smoothing MC gradient, and **Figure 8** presents high correlation between the two MC gradients. This procedure was used to analyze the data for the other samples. An average R^1 after smoothing is 0.97. The high correlation indicates that the radiation method discussed in this paper provided an accurate *and rapid* (there was no discussion on how fast it was compared to the other methods) estimation of MC gradient.

The new method could provide a very useful tool for understanding the internal moisture movement and moisture-related stress development. Prompt information about the internal MC gradient could help to dynamically control the wood drying processes. The information on the inside moisture distribution could also assist in understanding the warping performance of wood composites and allow engineers to find solutions to minimize product dimensional instability.

Summary and Conclusion

A new methodology for using the x-ray method to determine the moisture gradient of wood has been described. The method employed a collimated x-ray beam from a radiation source. The beam scans the material through its thickness direction and comparison between the transmitted and the incident radiation beam will provide the material density profile. The moisture gradient can be estimated based on the dimensional compensation and previously determined or estimated dried den-

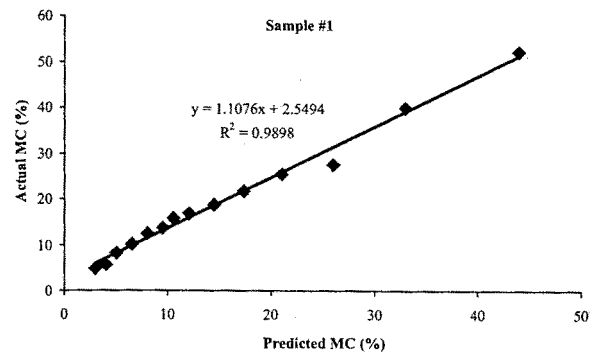


Figure 8.—Linear regression between the estimated and measured MC gradients.

sity profile. Four oak solid wood samples were tested and the results indicated that the moisture gradient was highly correlated to the actual measured moisture gradient. The new method shows a potential tool to monitor the internal moisture movement in lumber drying process. The X-Ray method could provide "online" information about the moisture movement that could be useful to dynamically control the kiln-drying process.

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