The Study on Cell Collapse and Recovery of *Eucalyptus urophylla* during Drying

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To explore the collapse of eucalyptus wood cells during the drying process, continuous and intermittent drying were carried out on *Eucalyptus urophylla*. The shrinkage throughout the intermittent drying process was less than that of continuous drying. According to observations of cells made using scanning electron microscopy (SEM), there was a large difference in the degree of cell collapse between continuous and intermittent drying. Severe cell collapse was observed after freeze-drying at high moisture content, even after an intermittent drying process. It is clear that collapse recovery *via* intermittent drying was more extensive than in continuous drying. In particular, ray parenchyma and axial parenchyma recovered from collapse more than did wood fibers.

Keywords: Collapse; Intermittent drying; Recovery of collapse; SEM examination; Eucalyptus

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INTRODUCTION

Eucalyptus is a well-known, fast-growing species planted in large quantities in southern China. Currently, most eucalyptus plantations are managed primarily for pulpwood production. Plantation-grown eucalyptus often has limited use as timber. The drying of eucalyptus is difficult because of phenomena known as collapse and honeycomb. Thus, determining the drying properties of and appropriate drying procedures for eucalyptus is important (Northway 2005).

Collapse is one of the most severe, negative behaviors of eucalyptus wood. It results in degradation during drying (Terazawa and Hayashi 1972). Liquid tension is just one cause of collapse (Hayashi and Terazawa 1977a; Kauman 1964a; 1964b; Tiemann 1941). Liquid tension within cells is very strong, so it is difficult to prevent cell collapse once it begins, though some collapsed cells can be recovered with a reduction of liquid tension. This occurs when the moisture content reaches the fiber saturation point (FSP) (Hayashi and Terazawa 1977b). How to best recover collapsed cells is a key factor in developing better drying technology. With this in mind, sequential drying was used to dry the eucalyptus wood used in this study. Chafe (1995a, b) found that intermittent drying can help to reduce surface and inner checks, but he did not conclude whether or not it decreased total shrinkage and collapse. Hattori *et al.* (1979) observed cell collapse and recovery using freeze-dried samples, but they did not conduct research regarding the drying schedule. In recent years, intermittent drying procedures have been developed by Wu *et al.* (2005a,b,c) and Yang *et al.* (2010), but there are concerns about the development of a microstructure during cell collapse. A morphological study at the cellular level has been needed to understand the effect of intermittent drying on cell collapse and to develop new drying technology. The main purpose of this study was to explore the morphological characteristics of collapsed cells during different drying processes and to elucidate the effect of intermittent drying on the microstructure of collapse-prone *Eucalyptus urophylla*. Observations of cell collapse were carried out using scanning electron microscopy (SEM).

EXPERIMENTAL

Materials

Eucalyptus urophylla, a plantation-grown eucalyptus species commonly planted in China, was selected for this experiment. Its initial moisture content (IMC) ranged from 43.2 to 55.4%, and its bulk density ranged from 0.58 to 0.63 g/cm^3.

Forty 30 × 30 × 100-mm (radial × tangential × longitudinal) specimens, divided into two groups, were used in this experiment to generate shrinkage curves and for SEM examination. Group 1 was continuously dried at different temperatures (Runs 1 and 2), while Group 2 was intermittently dried for different durations of slow-drying (Runs 3, 4, and 5). Specimens were end-matched in each run. As shown in Fig. 1, thin sections were sawn from both ends of each drying sample to estimate the initial moisture content. Next, 3-mm thick sections were sawn to measure the initial cross-sectional area by image analysis (GT-8700 EPSON Colorio Transparent Scanner). Finally, eight 100-mm long samples were used for each run.

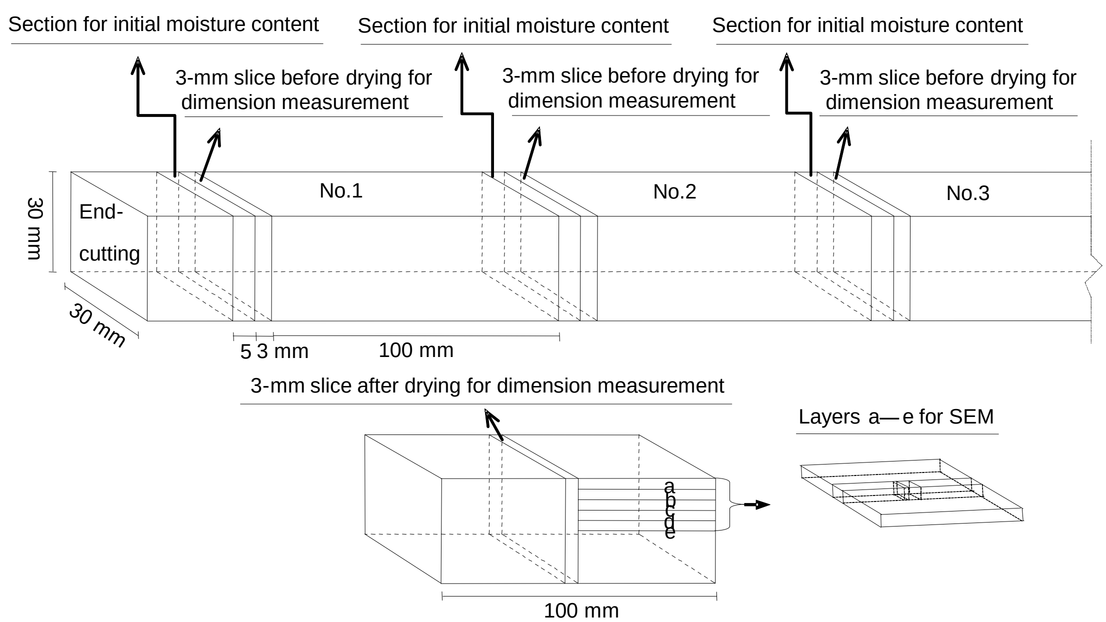

Fig. 1. Illustration of preparation of samples and slices from each group

Drying Conditions

Continuous drying was used on the samples of Group 1 at temperature (*T*) and relative humidity (*RH*) combinations of 45 ºC-62% and 60 ºC-66%, as shown in Table 1. Intermittent drying consisted of a fast-drying period of 60 ºC-66% and a slow-drying period of 45 ºC-62% within each run was used on the Group 2 samples, as shown in

Table 1, which was repeated until each specimen reached an equilibrium moisture content (EMC) of 10%. To investigate the effect of slow-drying period length on cell collapse and recovery, slow-drying was conducted on Group 2 for 1, 2, and 4 h, as shown in Table 1.

Table 1. Continuous and Intermittent Drying Schedules for Group 1 and Group 2

Code	Specimens	Items	Continuous drying		Intermittent drying					
			Run1	Run2	Run 3		Run 4		Run 5	
					Fast drying period	Slow drying period	Fast drying period	Slow drying period	Fast drying period	Slow drying period
Group1	16	T(°C)	45	60						
		RH(%)	62	66						
		EMC(%)	10	10						
		Total Time(days)	11	5						
Group2	24	T(°C)			60	45	60	45	60	45
		RH(%)			66	92	66	92	66	92
		Interval Time(h)			1	1	1	2	1	4
		EMC(%)			10	20	10	20	10	20
		Total Time(days)			7		9		12	

Shrinkage Curve

In this study, shrinkage was defined by the equation,

$$S_i = (A_{orig}-A_i)/A_{orig} *100\% \tag{1}$$

where S_i is the shrinkage value at moisture content i, A_{orig} is the initial cross-sectional area of the 3-mm slice, and A_i is the cross-sectional area of the corresponding specimen at moisture content i. The area was calculated automatically using Image J software.

Preparation of Micro Section and SEM Examination

To understand cell collapse and recovery, both the cut surface and a thin slice (which are mirror surfaces) were examined by SEM (JSM-5610LV, JEOL, Japan). The mirror surface can be examined to determine the initial state of collapse using the following method.

Eight samples were dried simultaneously. One after another sample was removed from the drying chamber when its moisture content had been decreased by 10%, and then the 3-mm slices were sawn to measure the cross-sectional area at different moisture contents using image analysis software (Fig. 1). Residual parts of the same sample were divided into five layers and freeze-dried to examine the state of collapse by SEM.

As shown in Fig. 2, thin slices (less than 0.1 mm thick) were cut from small samples taken from the centers of layers a, c, and e (Fig. 1). The slices were then put into hot water for 20 min for collapse recovery. Next, they were turned over, dried, and fixed to a holder with double-sided tape. Finally, both samples were coated with gold and examined using SEM.

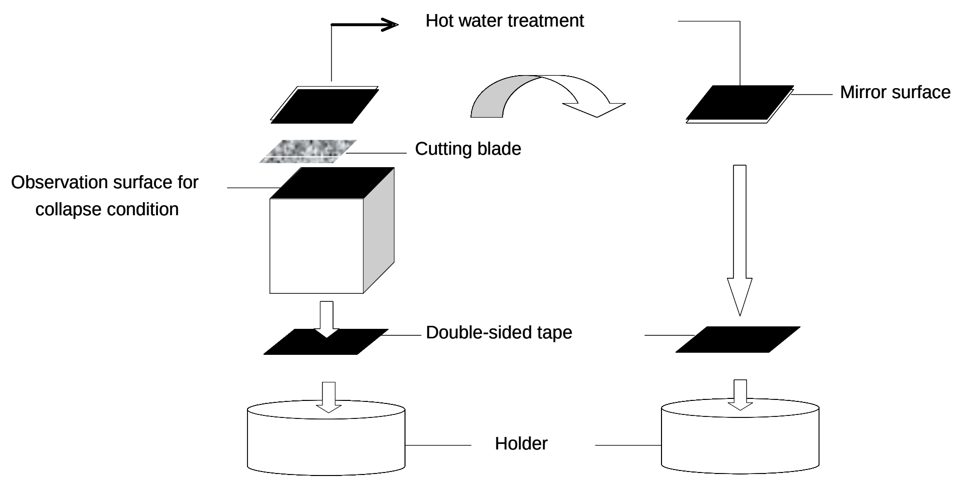

Fig. 2. Illustration of SEM sample production

RESULTS AND DISCUSSION

Shrinkage Curves of Different Drying Processes

In a previous paper (Yang 2010), it was concluded that intermittent drying decreased total shrinkage as compared to continuous drying. It is believed that the mechanism of this decrease is the recovery of collapsed cells by elastic lag after reduction of liquid tension. To investigate cell shrinkage during the drying process, shrinkage curves for each of the five runs were created; they are presented in Fig. 3. Eight end-matched samples were used in each run, and one after another was removed from the drying chamber when its moisture content had been decreased by 10%. Image analysis software was used to measure total shrinkage to avoid a quasi-intermittent drying process due to interruptions to measure sample weight and dimensions.

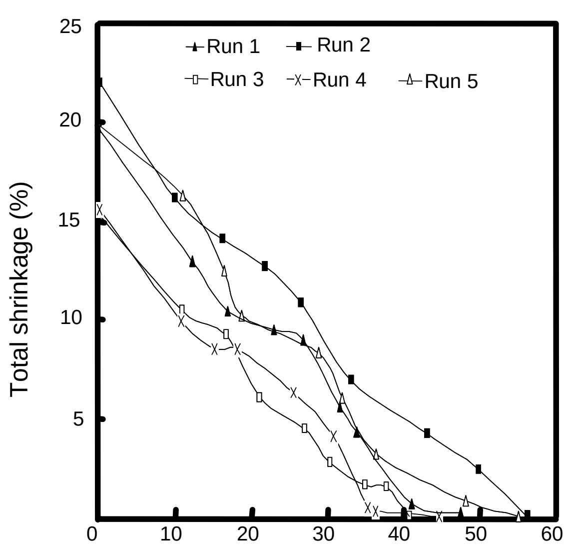

Fig. 3. The effects of continuous and intermittent drying on total shrinkage. Run 1 represents continuous drying at 45 ºC and Run 2 represents continuous drying at 60 ºC; Runs 3, 4, and 5 represent intermittent drying with a slow-drying period of 1, 2, and 4 h, respectively.

Figure 3 shows a comparison of the shrinkage curves of continuous and intermittent drying. Intermittent drying had a noticeably greater influence on total shrinkage than did continuous drying. This result is in agreement with the conclusion in a previous paper (Yang 2010). This figure also shows the effect of the length of the slow-drying period of intermittent drying on the total shrinkage. Total shrinkage increased as the slow-drying period length increased to 4 h. An excessively long slow-drying period during intermittent drying produced the same effect as continuous drying under the same temperature. This agrees with the results of a study by Kanagawa and Hattori (1978); only an increase in relative humidity during the slow-drying period of intermittent drying resulted in greater total shrinkage at the same drying temperature as in continuous drying. An excessive slow-drying period not only increases the total drying time but also increases total shrinkage.

SEM Examination of Collapsed Cells Following the Final Drying Stage

Figures 4a, 4b, 4c, and 4d show SEM micrographs of collapsed cells following continuous drying, the magnified part of the collapsed sample, and the mirror surfaces of the two previously mentioned micrographs, respectively. The samples photographed were perfectly recovered. Collapse occurred in all types of cells, including wood fibers, rays, and axial parenchyma. Little or no collapse occurred in other parts of the wood. Collapse is only minor in Fig. 4 (1) but is severe in Fig. 4 (2). As such, it is clear that collapse occurs selectively, based on the local properties of the wood. The amount of residual collapse is defined as the difference between the initial collapse and the recovery observed on the mirror surface. The residual collapse value of the cross section shown in Fig. 4 was 10.2%. There was a difference of 6.1% between this value and the amount of residual collapse shown in Fig. 3 (16.3%).

Figures 5a, 5b, 5c, and 5d show cell condition following intermittent drying, a magnified region containing collapsed cells, and the mirror surfaces of the two images previously mentioned, respectively. The samples photographed were perfectly recovered. Figure 5 shows that wood fibers are slightly collapsed but that rays and axial parenchyma appear round. It was inferred from these SEM photos that intermittent drying helped wood rays and parenchyma to more thoroughly recover to their green moisture content, but that intermittent drying had little effect on the recovery of wood fibers. The residual collapse value was 7.6% in the samples shown in Fig. 5, which is less than that of continuous drying. There was a difference of 2.9% between this value and the amount of residual collapse shown in Fig. 3 (10.5%). Intermittent drying decreased total shrinkage and collapse as compared to continuous drying, not only according to quantitative calculations, but also according to qualitative analysis. Even though it is very difficult to accurately calculate degree of collapse from SEM photos (because collapse does not occur uniformly), SEM is an effective way to qualitatively analyze collapsed cells. Further, the level of collapse was different even for the intermittent drying procedures illustrated in Figs. 5 (1) and (2).

Effect of Moisture Content on Collapse Intensity

To confirm the structural characteristics of collapse in the different layers of one sample during the drying process, two samples of approximately 30% average MC were removed from a continuous drying (Run 2) and an intermittent drying (Run 3). Three slices (layers a, c, and e, as shown in Fig. 1) along the radial direction, in the cross section, were obtained. Figures 6 and 7 show collapse in the middle of different layers of different moisture contents from samples from both the continuous and intermittent drying processes.

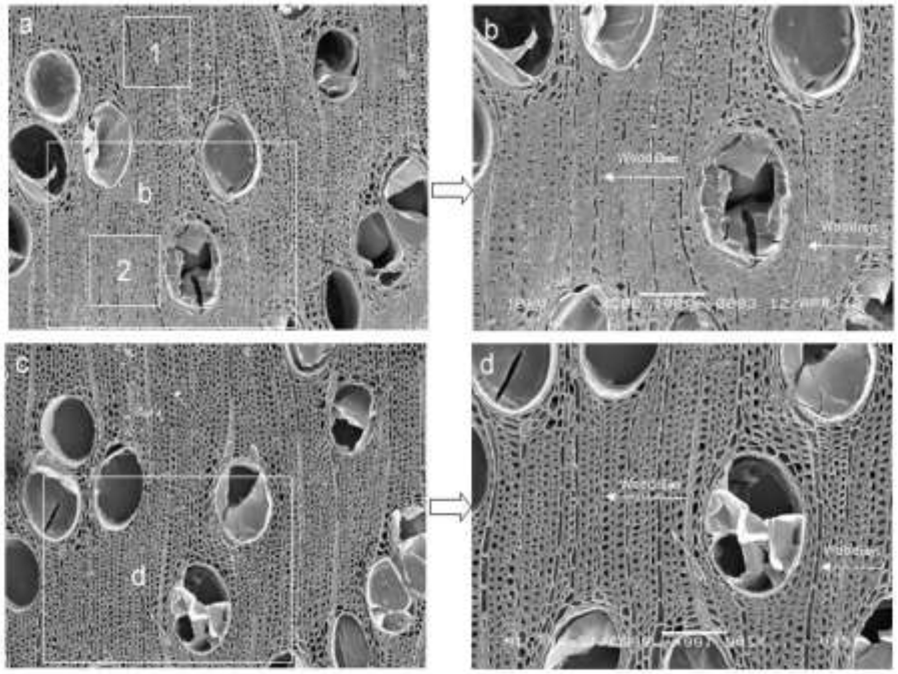

Fig. 4. The collapse and recovery of cells following continuous drying at temperature 60 ºC (Run 2, after which the moisture content was nearly 10%, the sample was taken from the middle of the c layer showed in the Fig. 1). a: collapsed cells; b: enlargement of the outlined area in photo (a); c: recovered cells on the mirror surface; d: enlargement of the outlined area in photo (c); 1: area with slight collapse; 2: area with severe collapse.

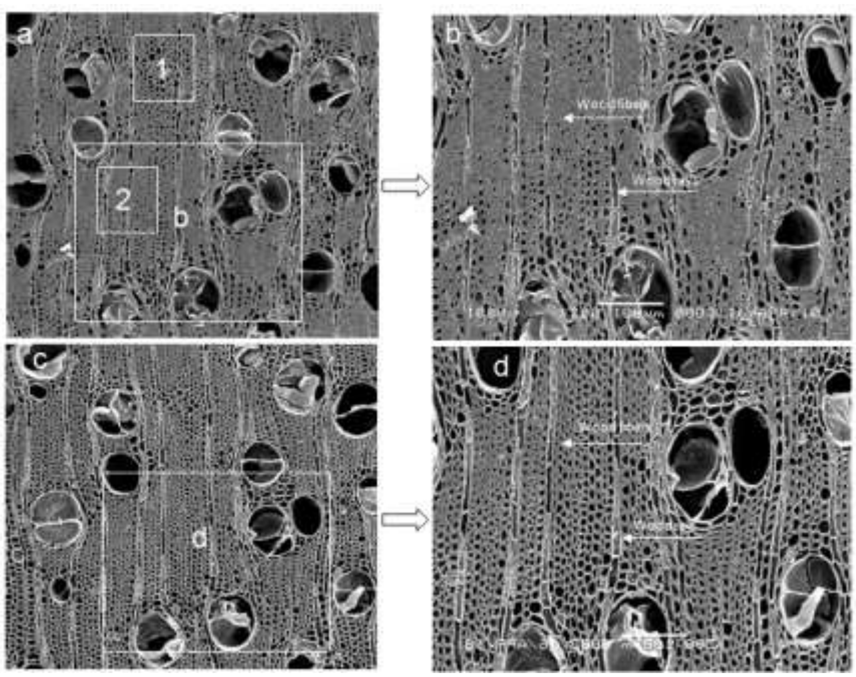

Fig. 5. Collapse and recovery following intermittent drying at temperatures 60/45 ºC (fast-drying/slow-drying) (Run 3, after which the moisture content was nearly 10%, the sample was taken from the middle of the c layer showed in the Fig. 1). The legend is the same as in Fig. 4.

In the center of the sample, the moisture content of layer e was approximately 40%. At this point, collapse recovery had not begun, so collapse was observed in almost all types of cells (except vessels), including wood fibers, rays, and parenchyma. Collapse also occurred in wood fibers and some wood rays and axial parenchyma. At this point, the moisture content was lower than the fiber saturation point, and with reduction in liquid tension, collapse had already been recovered.

Recovery occurred in some wood rays during continuous drying, whereas it occurred in all wood rays and axial parenchyma and some wood fibers during intermittent drying. Collapse rarely occurred in the layer nearest the surface. No collapse whatsoever was observed in layer a.

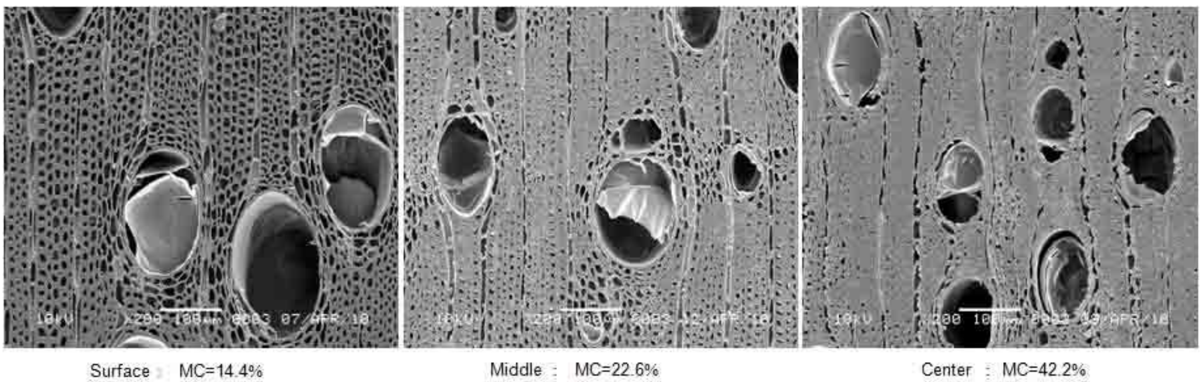

Fig. 6. Changes of degree of collapse in sample layers from center to surface of the same sample during the continuous drying (Run 2) of *Eucalyptus urophylla*

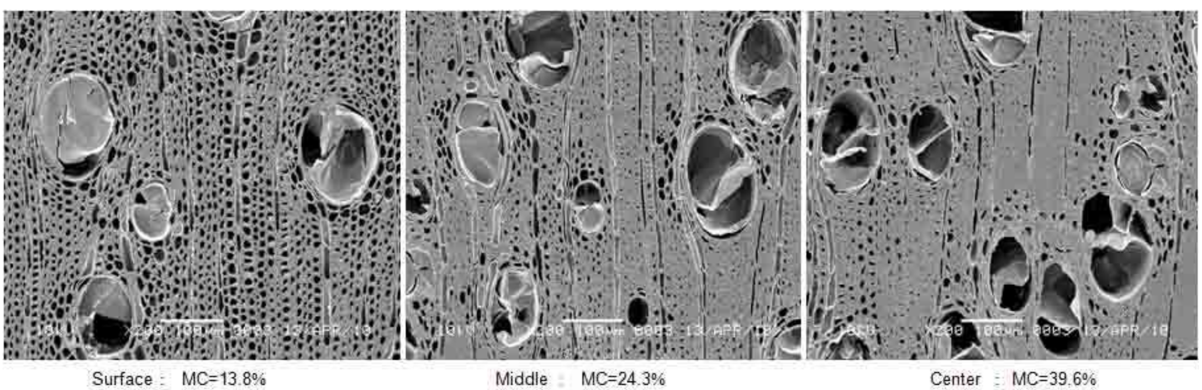

Fig. 7. Changes of degree of collapse in sample layers from center to surface of the same sample during the intermittent drying (Run 3) of *Eucalyptus urophylla*

Therefore, intermittent drying can recover collapsed wood rays and axial parenchyma than continuous drying, but does not help to recover collapses occurring as a result of green moisture content. In the case of wood with a moisture content gradient from the surface to the interior, collapse intensity will differ, and SEM can be used to examine the degree of collapse throughout the wood and to examine differences in the numerous layers of the same sample.

CONCLUSIONS

1. Intermittent drying initially decreased total shrinkage, but when exceeding 2 h of slow drying period, the result was similar to continuous drying at the same temperature.
2. SEM examination is valid for understanding the cell collapse process. It is very difficult to accurately calculate the degree of collapse because the intensity of collapse is not uniform.
3. SEM examination of the mirror surface and the collapsed surface of samples is a good way to observe collapse and recovery and to understand residual collapse.
4. Intermittent drying can help recover collapsed wood rays and axial parenchyma, but not collapsed wood fibers.
5. Severe collapse was observed after samples were freeze-dried at high moisture content following the intermittent drying process. It is clear that intermittent drying can help recover more collapsed cells than continuous drying, but it does not help prevent collapse from occurring due to green moisture content.

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