Effect of Drying Temperature and Relative Humidity on Contraction Stress in Wood

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As wood shrinks during the drying process, various stresses may develop and cause surface and internal checking. The aim of this study was to systematically investigate the effect of the drying temperature, relative humidity, and specimen thickness on the contraction stress in elm wood (*Ulmus pumila* L.) specimens during drying. The contraction stress was used as an indirect indicator of drying stresses. A measurement system was developed in-house and used to simultaneously and continuously obtain the required measurements during drying, which were then used to determine the moisture content, amount of shrinkage, and contraction stress of the wood specimens. In the process of drying, the contraction stress was initially negative with a decrease in the moisture content and an increase in the shrinkage. Then the contraction stress increased gradually and eventually stabilized upon reaching the maximum. The results also showed that as the temperature increased, the moisture content decreased, the shrinkage decreased, the maximum contraction stress decreased, and the contraction stress reached a maximum in a shorter amount of time.

Keywords: Contraction stress; Shrinkage; Moisture content; Checking

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INTRODUCTION

Shrinkage is one of the most important physical properties of wood because its magnitude directly affects the dimensional stability of lumber and wood products and it also contributes to the formation of surface and internal checks. When large laminated wood panels are subject to changing temperatures and relative humidity, the individual components in the panel will shrink or expand accordingly. However, their shrinkages or expansions are likely not to be homogenous because of wood property variation and anisotropy in shrinkage. This could result in the dimensional deformation of the whole panel and may also result in the formation of checking. Accurate and easy measurements of dimensional changes that occur in wood during drying are of great importance for improving our understanding in drying research and also for improving the efficiency and quality control in commercial production (Quan and Pang 2012; Lin and Wang 2013).

A large number of studies have shown that when tensile stresses, which are developed on the surface and inner layers of the wood during drying, exceed the tangential tensile strength of the wood, checks will form on the surface and inside the wood (McMillen 1955; Diao and He 1994; Guo 1995; Wang and Youngs 1996; Chen *et al.* 1997). The impact of drying in tangential direction can induce crack development in wood (Moutou Pitti *et al.* 2013). These studies found that shrinkage occurred even when the moisture content of the specimens was very high at the early stage of drying, although the shrinkage was very small (Barkas 1938; Gao and Teng 1998).

In a study of the effect of the temperature on the shrinkage of plantation larch, it was found that the tangential and radial shrinkage tended to decrease with increasing drying temperature (Gong *et al*. 1997). The state of the moisture content of the wood directly determines the amount of shrinkage during drying. The final contraction stress is primarily determined by the final moisture content.

Shrinkage is an important indicator of final contraction stress during drying, and their relationship is expected to vary at different temperatures and levels of humidity. This study aimed to investigate the effect of temperature and humidity on the shrinkage and contraction stress of elm wood during drying. In this article contraction stress will be defined as the internal stress developed in wood during the drying process, as the wood loses moisture and its dimensions change. Contraction stress is different from the commonly understood drying stress, which is the internal stress developed as a result of uneven shrinkages between the inner and outer layers of the wood throughout its thickness.

A measurement system that was previously developed in-house was used in this study, and we are currently applying for a national patent for this system. It is composed of various sensors, and was placed inside a laboratory-drying chamber where the temperature and relative humidity can be adjusted as required. During the drying experiments, the weight sensor, the displacement sensor, and the mechanical sensor (a kind of "s shape" tension sensor) simultaneously and continuously measured the changes in the weight, dimensions, and the contraction force of the specimens, respectively. These measured values were then used to calculate the moisture content and the contraction stress. The accuracy and stability of this system are neither affected by the type of wood materials, nor by the moisture content of the test materials at the time of the measurements (Wang 2005).

In this paper, the shrinkage data and its discussion specifically refer to, and are confined to the linear dimensional shortening of a wood specimen that was measured by the displacement sensor in a designated direction, either radial or tangential, in an individual experiment.

EXPERIMENTAL

Materials

Clear elm wood (*Ulmus pumila* L.) was used as the experimental material for this study. It had moderate hardness and strength. The initial moisture content of the wood material ranged from 80% to 90%. A total of 54 specimens were prepared, as shown in Table 1. They were cut into four different sizes: 30 x 50 x 30, 30 x 30 x 50, 30 x 25 x 30, and 30 x 30 x 25 (longitudinal x tangential x radial, all measured in mm).

Nine experiments were then conducted, as described in Table 1. The number and types of specimens for each experiment are also given in Table 1. To minimize the specimen variation within a set, the specimens within each set were obtained from items as similar as possible in the wood market, Hohhot, China. After being cut down, the specimens were packed in sealed bags and stored in a freezer at -20° C.

Table 1. Description of Experimental Conditions and Specimens

Experiment #	Number of specimens for each experiment	Number of repeats	Experimental conditions (temperature, humidity, measurement direction, and specimen thickness)
1	3	2	50 °C, 30%, tangential, 25 mm (30 x 25 x 30)
2	3	2	50 °C, 40%, radial, 50 mm (30 x 30 x 50)
3	3	2	50 °C, 50%, tangential, 50 mm (30 x 50 x 30)
4	3	2	70 °C, 30%, radial, 50 mm (30 x 30 x 50)
5	3	2	70°C, 40%, tangential, 25 mm (30 x 25 x 30)
6	3	2	70 °C, 50%, tangential, 50 mm (30 x 50 x 30)
7	3	2	90 °C, 30%, tangential, 50 mm (30 x 50 x 30)
8	3	2	90 °C, 40%, tangential, 50 mm (30 x 50 x 30)
9	3	2	90 °C, 50 %, radial, 25mm (30 x 30 x 25)

Experimental Design

An orthogonal experimental design was used to identify factors that have significant effects, while still requiring a reduced number of experimental conditions (Cheng 2005). An orthogonal experiment of the type L_9 (3^4) was adopted. The four selected factors and the three levels were: *T* as the temperature of the drying chamber (50, 70, and 90 °C, respectively), *H* as the relative humidity of the drying chamber (30%, 40%, and 50%, respectively), *D* as the direction of the wood structure (tangential or radial), and *Th* as the specimen thickness (25 or 50 mm). Table 2 shows the factors and levels of the orthogonal experiment with six specimens for each experiment.

Table 2. Factors and Levels for the Experiment

Level/Factors	Temperature (°C)	Relative Humidity (%)	Direction of Wood grain	Thickness (mm)
1	50	30	tangential	25
2	70	40	radial	50
3	90	50		

Experimental Method

Prior to each experiment, a set of three specimens (Table 1) was removed from the refrigerator and allowed to thaw at room temperature for 3 h. Then, the specimen for contraction force measurement was end-sealed and glued to a specimen holder with a contact area of approximately 706 mm^2. The three specimens were then kept in sealed bags at room temperature for 24 h, during which the bonding strength for the glued specimen by methyl acrylate reached maximum. At the beginning of the experiments, the initial weight of the specimen for moisture content changes was measured. Then, the three specimens were loaded onto the respective sensors, as shown in Fig. 1, and the drying started at the prescribed temperature and humidity. After the test, the specimens were quickly removed from the drying chamber, immediately weighed, then oven-dried in an air dry oven, and weighed again. The moisture content was calculated using the following equation,

$$MC(\%) = \frac{m - m_0}{m_0} \times 100\% \quad (1)$$

where MC is the moisture content, m is the original weight, and m_0 is the oven-dried weight. The contraction stress was calculated using the following equation,

$$S = \frac{F}{A} \quad (2)$$

where S is the contraction stress in MPa, F is the contraction force in N, and A is the original cross-sectional area of the specimen in mm^2.

The data obtained were calculated by Excel, for intuitive analysis, using the Excel formula and functions, and then drawing a trend. Analysis of variance was calculated by Excel formula functions and built-in functions, using the F-value.

Experimental Instruments

Figure 1 is the principle diagram of the measurement system that was developed in-house and used for this study. The temperature range of the drying chamber is 0 to 180 °C, with a temperature variation of less than 1 °C; the relative humidity range is 20% to 98%, with humidity fluctuation ≤ ± 0.5% and a humidity variation of less than 1% to 3%. The mechanical force sensor measures up to 500 N with a combined error of 0.02%; its working temperature is -20 to 70 °C, and the working relative humidity is ≤ 80%. The weight sensor measures up to 200 g with an accuracy of 0.05%; its working temperature is -10 to 60 °C, and the working relative humidity is ≤ 80%.

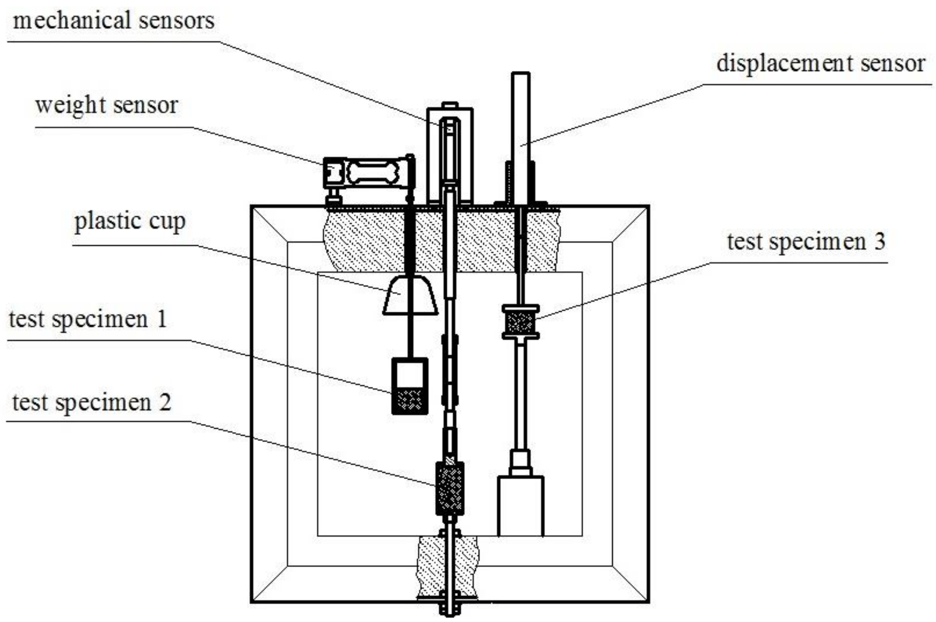

Fig. 1. The principle diagram of the measurement system

The displacement sensor measures up to 5 mm with an accuracy of ± 0.05%; its working temperature is 5 to 55 °C, and the working relative humidity is ≤ 85%. As the sensors were placed outside, on the top of the drying chamber, shown in Fig. 1, their functionality was not affected by the temperature and humidity of the chamber.

RESULTS AND DISCUSSION

The optimal structure design can be obtained by using intuitive analysis of orthogonal experiment (Cheng 2005) considering the Dry Contraction Stress (*DCS*), Shrinkage (*S*), and Moisture Content (*MC*), as shown in Table 3. Through a comparison of the factors with extreme differences, the relative importance of each factor can be determined for each drying shrinkage indicator. Through a comprehensive analysis of significant differences, the significant factor affecting the dry contraction stress (*DCS*) is temperature; the significant factors affecting shrinkage (*S*) are the specimen thickness and the direction of shrinkage; and the significant factors influencing the moisture content (*MC*) are temperature and humidity.

Table 3. Experimental Results and Intuitive Analysis

Sample number		Factors				Average values		
		T (°C)	*H* (%)	*D*	*Th* (mm)	*DCS* (MPa)	*S* (mm)	*MC* (%)
1		50	30	tangential	25	0.31	0.48	7.08
2		50	40	radial	50	0.38	1.96	8.13
3		50	50	tangential	50	0.30	1.58	9.39
4		70	30	radial	50	0.20	3.11	5.9
5		70	40	tangential	25	0.16	0.62	7.32
6		70	50	tangential	50	0.30	1.69	8.36
7		90	30	tangential	50	0.24	1.53	5.30
8		90	40	tangential	50	0.14	1.07	6.25
9		90	50	radial	25	0.13	0.92	7.56
DCS	k_1	0.33	0.25	0.241	0.2			
	k_2	0.22	0.23	0.236	0.26			
	k_3	0.17	0.24					
	Extreme difference	0.16	0.02	0.005	0.06			
	Significance	*						
S	k_1	1.34	1.71	6.97	0.67			
	k_2	1.81	1.22	5.99	1.82			
	k_3	1.17	1.40					
	Extreme difference	0.18	0.34	0.84	1.15			
	Significance			*	*			
MC	k_1	8.2	6.09	7.28	7.32			
	k_2	7.19	7.23	7.20	7.22			
	k_3	6.37	8.44					
	Extreme difference	1.83	2.34	0.09	0.1			
	Significance	*	*					
***** This factor is significant								

Intuitive Analysis of Data

The purpose of this study was to explore the influence of drying temperature and humidity on the contraction stress, shrinkage, and the moisture content of wood specimens during wood drying. Thus, the contraction stress, shrinkage, and moisture content were the key indicators in the analysis. The intuitive data results are shown in Figs. 2 through 10, for which the arrows in figures indicate that shrinkage reached the maximum values.

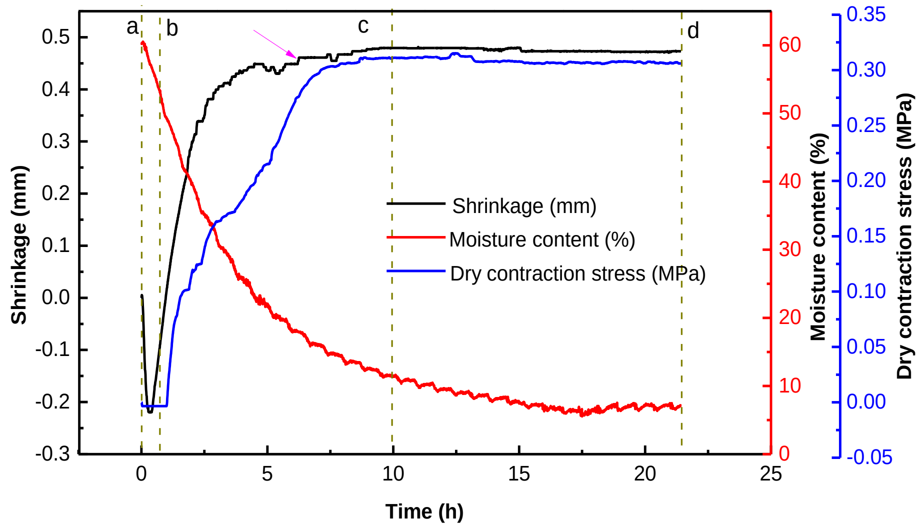

Fig. 2. Shrinkage indicators of elm wood at 50 °C and 30% relative humidity (specimen No. 1)

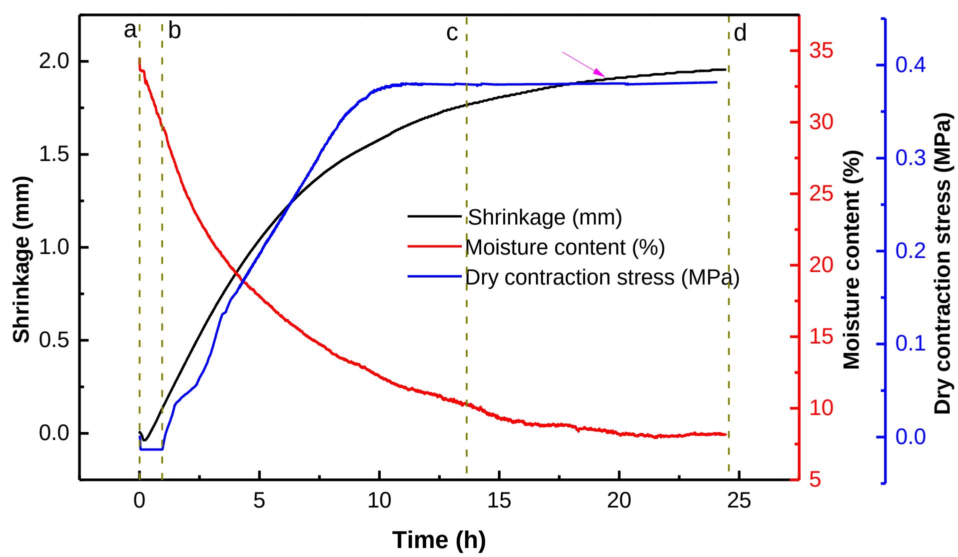

Fig. 3. Shrinkage indicators of elm wood at 50 °C and 40% relative humidity (specimen No. 2)

The shrinkage process can be approximately divided into three stages. The a-b stage was the thermal expansion stage, with the contraction stress reducing, the shrinkage also reducing, and the moisture content remaining more or less unchanged. The b-c stage was the shrinking stage, with the contraction stress rising, the shrinkage also rising, but the moisture content decreasing. The c-d stage was the final stage, during which the contraction stress, shrinkage, and moisture content showed very small changes after having reached the maximum or minimum values. There were exceptions however. In Fig. 6 there was an extra d-e stage, with the contraction stress decreasing whilst the shrinkage remained more or less unchanged. Figures 8 and 9 show that at a high temperature, the contraction stress decreased sharply during the c-d stage, before it settled in the final stage. Figure 10 shows that during the d-e stage, the shrinkage was rising whilst the contraction stress did not change noticeably.

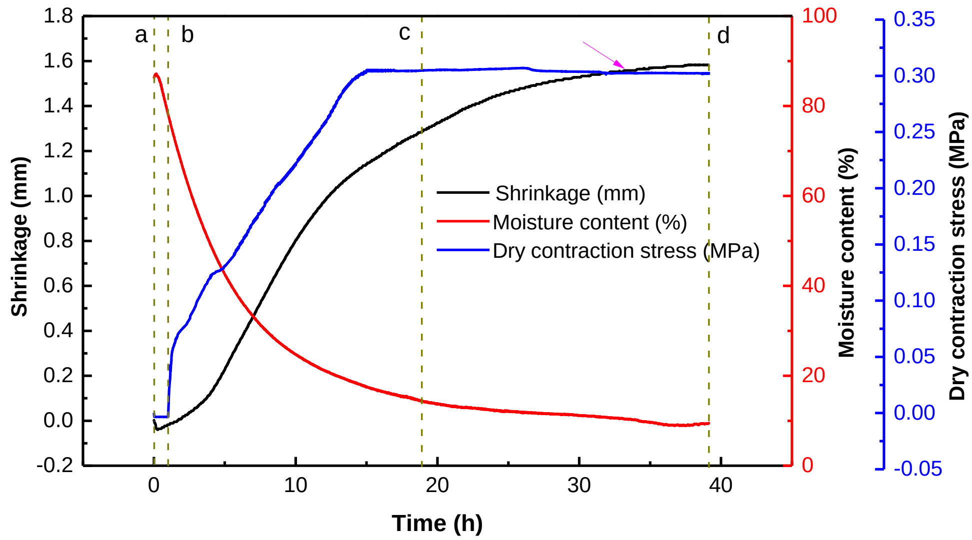

Fig. 4. Shrinkage indicators of elm wood at 50 °C and 50% relative humidity (specimen No. 3)

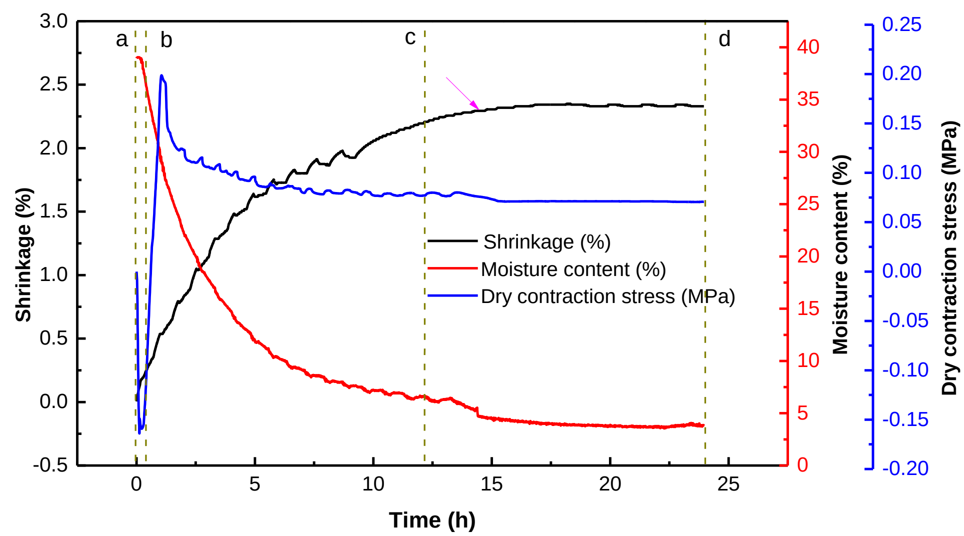

Fig. 5. Shrinkage indicators of elm wood at 70 °C and 30% relative humidity (specimen No. 4)

In Figs. 2 through 10 it can be seen that the shrinkage and moisture content reached the final stage almost at the same time. In Figs. 2 through 4, the trend was nearly the same, except that the initial contraction stress was negative, and it was caused by a thermal expansion (Liu *et al.* 2015). Figures 6 through 10 show that the thermal expansion of wood occurred in every experiment, and the peak of the contraction stress varied: as the temperature increased, the contraction stress took less time to reach the peak. The contraction stress progressed into the final stage when the shrinkage and moisture content also reached their respective final stages. At higher temperatures, the formation of internal checks will lead to a sharp fall of the contraction stress.

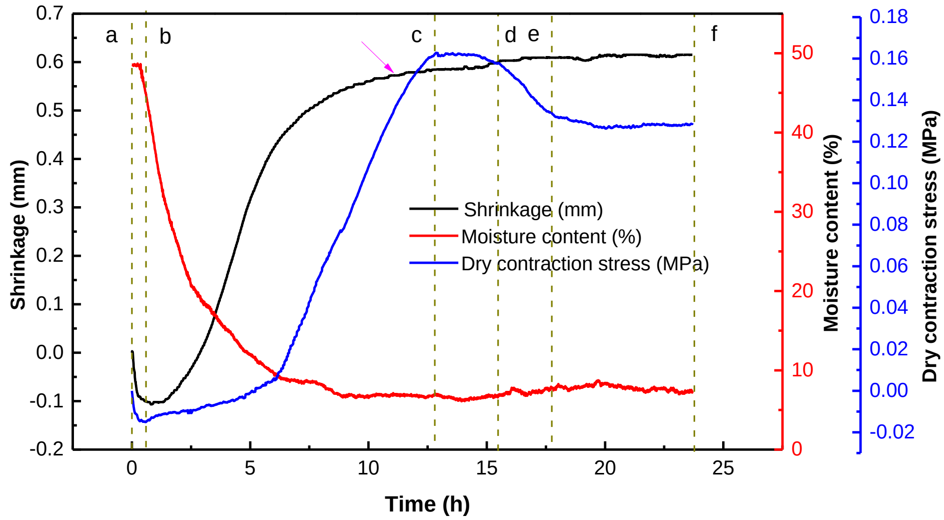

Fig. 6. Shrinkage indicators of elm wood at 70 °C and 40% relative humidity (specimen No. 5)

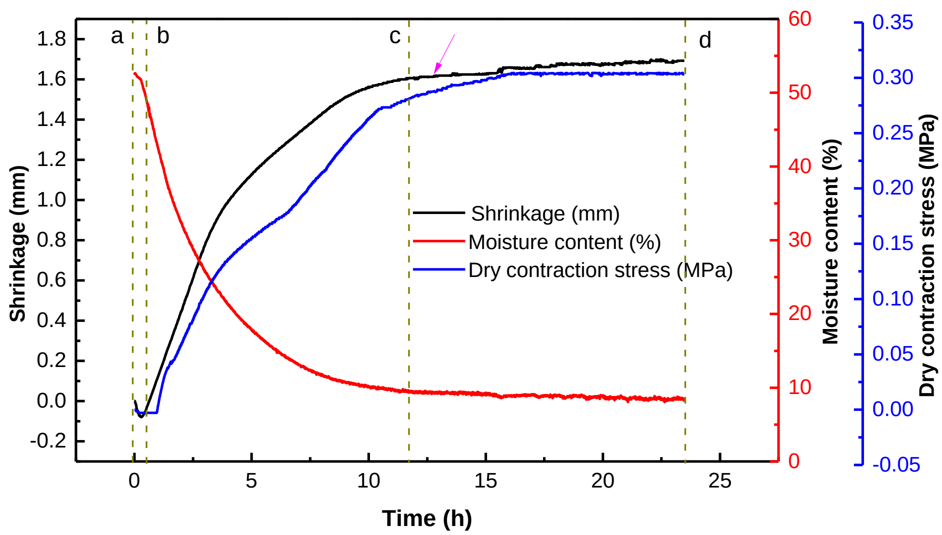

Fig. 7. Shrinkage indicators of elm wood at 70 °C and 50% relative humidity (specimen No. 6)

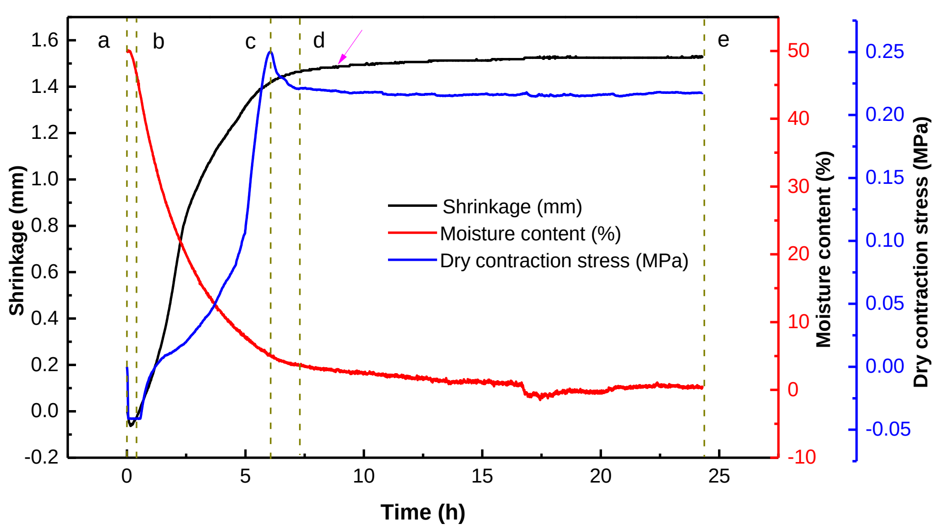

Fig. 8. Shrinkage indicators of elm wood at 90 °C and 30% relative humidity (specimen No. 7)

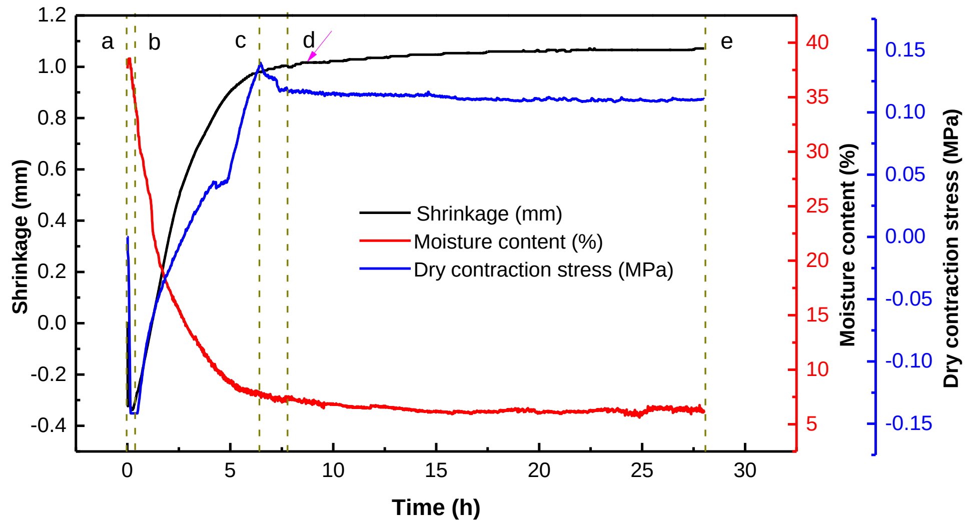

Fig. 9. Shrinkage indicators of elm wood at 90 °C and 40% relative humidity (specimen No. 8)

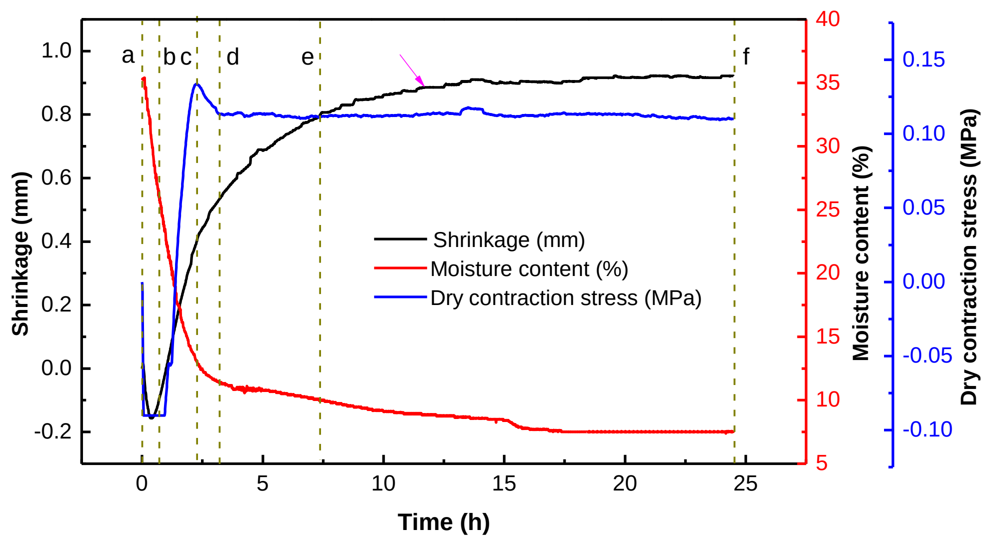

Fig. 10. Shrinkage indicators of elm wood at 90 °C and 50% relative humidity (specimen No. 9)

It can be interpreted that the shrinking of the wood helped to prevent the onset of the shrinkage stress during the drying process, as drying stress is developed before the wood shrinks in the beginning of the drying (Hu and Gao 2008). We observed that shrinkage and contraction stress could develop in the specimens above the fiber saturation point.

Temperature, moisture content, stress level, tree species, and material variation have an effect on creep (Yu *et al*. 2007). Creep experiments are usually conducted in a controlled temperature and humidity chamber (Moutee 2006; Hering and Niemz 2012). To investigate the creep behavior of wood, a constant temperature and relative humidity must be maintained to keep MC constant during the test (Jin *et al*. 2016). Figure 9 shows that when the shrinkage was increasing, the contraction stress remained more or less unchanged. In Fig. 5, after 15 h of drying, the contraction stress started to decrease, whereas the shrinkage remained more or less unchanged.

Table 4. Experimental Results and Intuitive Analysis

Specimen number and drying condition	Maximum DCS (MPa)	Time (h)	*S* (mm)	*MC* (%)
1 (50 °C, 30%)	0.31	8.7	0.47	13
2 (70 °C, 40%)	0.38	10.1	1.59	12.1
3 (90 °C, 50%)	0.30	14.5	1.12	18.06
4 (50 °C, 30%)	0.20	1.1	0.35	29
5 (70 °C, 40%)	0.16	12.6	0.58	6.79
6 (90 °C, 50%)	0.30	15.45	1.63	7.42
7 (50 °C, 30%)	0.24	5.9	1.41	5.30
8 (70 °C, 40%)	0.14	6.5	0.98	5.75
9 (90 °C, 50%)	0.13	2.45	0.44	8.26

Table 4 shows that for specimen No. 2, the maximum contraction stress was 0.38 MPa, the shrinkage was 1.59 mm, and the moisture content was 12.1% when the drying time was 10.1 h. It can also be seen from Table 3 that as the temperature increased, the maximum contraction stress decreased and reached a maximum in a shorter amount of time, while as the shrinkage decreased, so did the moisture content.

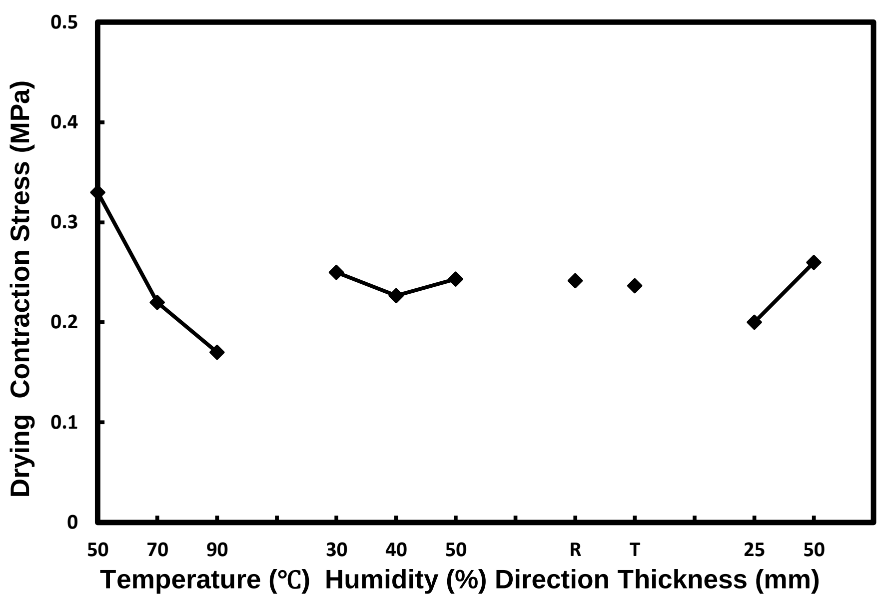

Fig. 11. Drying contraction stress trend chart

From Fig.11 and Table 5, it can be seen that the significant factor affecting drying contraction stress was temperature; as the temperature increased, the maximum contraction stress decreased. High-temperature drying causes a minute shortening of the distances between the filaments of cellulose microfibrils, a reduction of the number of free hydroxyls on the cellulose molecules in the amorphous regions, and the formation of new hydrogen bonding between cellulose molecules. These changes result in a reduction of the moisture absorption of the wood.

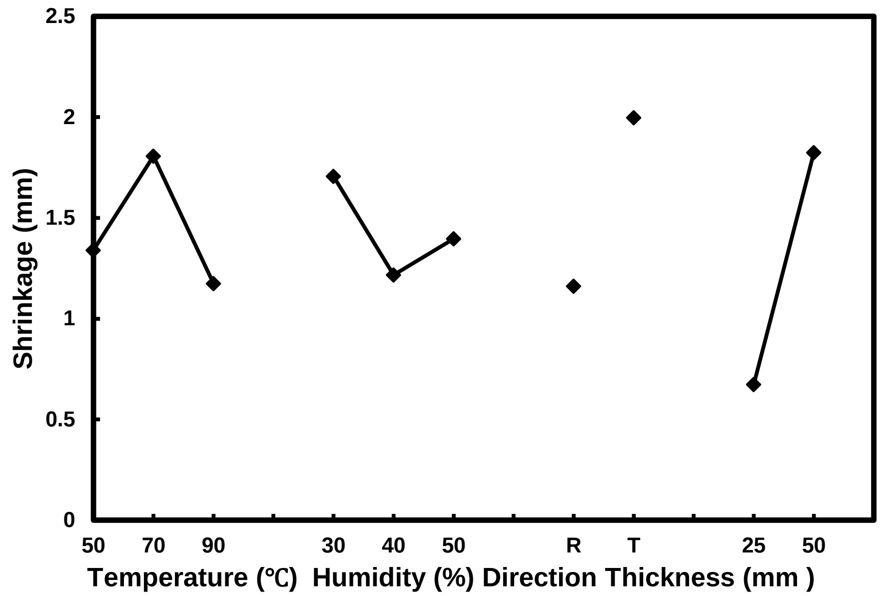

Fig. 12. Shrinkage trend chart

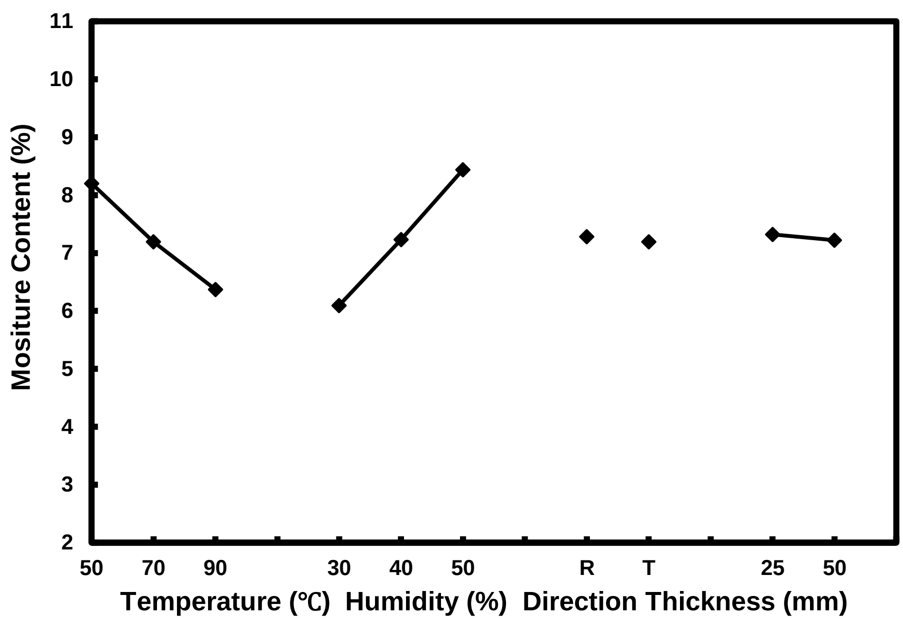

Fig. 13. Moisture content trend chart

Table 5. Drying Contraction Stress Analysis of Variance

Source of variance	SS	df	MS	F	Significance
Temperature	0.0402	2	0.0201	6.979167	*
Humidity	0.000867	2	0.000433		
Thickness	0.00045	1	0.00045		
Direction	0.0072	1	0.0072		
Deviation	0.013483	2	0.006742		
Summation	0.0618	8			

Figure 12 and Table 6 show that the significant factors affecting shrinkage are the direction of the shrinkage, in which tangential shrinkage is larger than radial shrinkage, and the specimen thickness. In the range from 50 to 90 °C, as the temperature increases, so does the shrinkage; however, these changes are not significant.

Figure 13 and Table 7 show that the significant factors influencing the moisture content are temperature and humidity, as commonly known and expected.

Table 6. Shrinkage Analysis of Variance

Source of variance	SS	df	MS	F	Significance
Temperature	0.646667	2	0.323333		
Humidity	0.3686	2	0.1843		
Thickness	1.39445	1	0.5832	29.02585	*
Direction	2.645	1	1.39445	55.05637	*
Deviation	0.096083	2	1.078942		
Summation	5.1508	8			

Table 7. Moisture Content Analysis of Variance

Source of variance	SS	df	MS	F	Significance
Temperature	5.040156	2	2.520078	162.9946	*
Humidity	8.238822	2	4.119411	266.4369	*
Thickness	0.002689	1	0.015022		
Direction	0.00005	1	0.00005		
Deviation	0.059106	2	0.023386		
Summation	13.34082	8			

CONCLUSIONS

1. When the shrinkage and moisture content reached stable values, the change in the drying contraction stress also became very small. At higher temperatures, the formation of internal checks would lead to a sharp fall of the contraction stress.
2. In the beginning of the drying process, the contraction stress was negative, which resulted from a thermal expansion of the wood. As the moisture content kept decreasing and the shrinkage kept increasing, the contraction stress gradually increased and eventually reached stable values.
3. In the experiments, the maximum contraction stress observed was 0.38 MPa at a drying time of 10.1 h, with a corresponding shrinkage of 1.59 mm, and a moisture content of 12.1%. It can also be shown that as the temperature increased, the maximum contraction stress decreased, the contraction stress reached a maximum in a shorter amount of time, the shrinkage decreased, and the moisture content decreased.
4. The significant factor affecting the contraction stress is temperature. The significant factors affecting the shrinkage are the direction of the shrinkage and the specimen size. The significant factors influencing the moisture content are temperature and humidity, as commonly known and expected.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the International Science and Technology Cooperation Program of China (2013DFA32000) and Inner Mongolia Agricultural University.

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Article submitted: March 19, 2016; Peer review completed: May 28, 2016; Revised version received and accepted: June 11, 2016; Published: June 27, 2016.
DOI: 10.15376/biores.11.3.6625-6638