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Effect of Drying Temperature on Warp and Downgrade of 2 by 4's From Small-Diameter Ponderosa Pine

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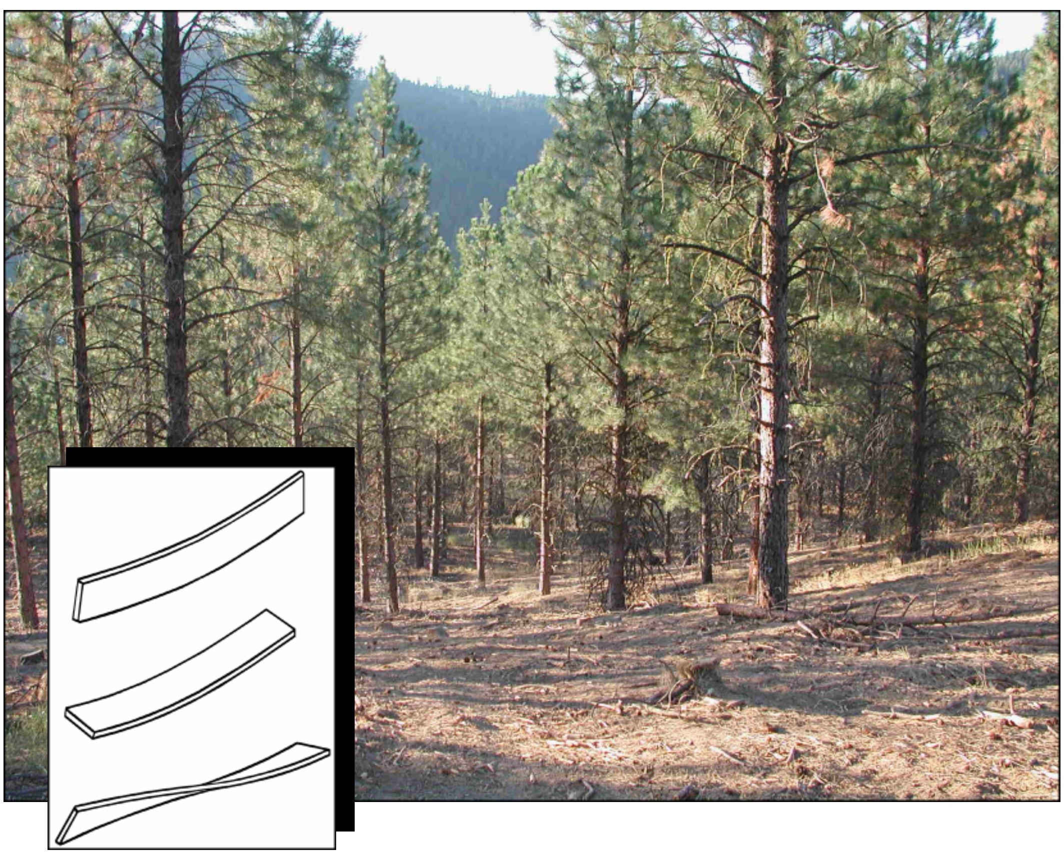

Abstract

Kiln drying at high temperature may reduce warp in dimension lumber sawn from small-diameter trees. In this study, we examined the effect on warp of high drying temperatures in conjunction with top loading immediately after drying and after storage in typical conditions that result in further moisture loss. Eight-foot-long 2- by 4-in. (2 by 4) boards sawn from open-grown, 30- to 35-year-old, 9-in.-diameter at breast height ponderosa pine trees were kiln dried at three temperatures, 160°F, 230°F, and 280°F. Crook, bow, and twist were measured and compared. Total grade loss from exceeding Structural Light Framing grade warp limits was also measured. Crook, bow, and twist measured after boards had equilibrated to 14% moisture content decreased by 12%, 29%, and 20%, respectively, with increase in kiln drying temperature from 160°F to 280°F. Total grade loss caused by all forms of warp was 24% lower in boards dried at 230°F than at 160°F and 39% lower in boards dried at 280°F than at 160°F. When boards were equilibrated to 4% to 5% moisture content, warp and grade loss from warp increased significantly.

Keywords: kiln drying, ponderosa pine, small-diameter timber, drying degrade

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Contents

SI conversion factors

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
pound (lb) mass	0.454	kilogram (kg)
pound per square foot (lb/ft^2)	4.88	kilogram per square meter (kg/m^2)
temperature (°F)	$[T_F–32]/1.8$	temperature (°C)

Effect of Drying Temperature on Warp and Downgrade of 2 by 4's From Small-Diameter Ponderosa Pine

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Introduction

In some instances, ponderosa pine (*Pinus ponderosa*) nominal 2- by 4-in. (2 by 4) lumber has been shown to experience less grade loss from warp when dried at 230°F compared to 160°F (Simpson and Green 2001). When boards were measured immediately after kiln drying, drying temperature did not show any consistent effect on crook, bow, and twist. However, after equilibrating to approximately 12% moisture content, boards that had been dried at 230°F showed significantly less grade loss from warp than did boards dried at 160°F. The average percentage of boards meeting No. 3 warp limits in the Structural Light Framing grading system (WWPA 1998) was 59.7% for boards kiln dried at 160°F and 79.0% for boards dried at 230°F. Another way of analyzing the results after planing is to consider the total amount of grade loss; that is, the difference between the actual after-planing grade and the grade if no warp were present. This method of analysis recognizes when a board drops more than one grade because of warp. The average total grade loss from warp in boards kiln dried at 230°F was half the grade loss in boards dried at 160°F. The results also showed that heavy top loading (200 lb/ft^2) was effective in reducing warp. These results present encouraging evidence that high drying temperatures might significantly reduce grade loss from warp. The purpose of the study reported here was to explore this issue in more depth.

Background

The results of a previous study (Simpson and Green 2001) showed that high temperature kiln drying may have potential in reducing warp in ponderosa pine lumber sawn from small-diameter trees—especially warp that occurs during moisture equalization—possibly by providing stress relief during moisture equalization after kiln drying. Koch (1971) found that 2 by 4's sawn from small-diameter Southern Pine logs and veneer cores experienced less warp when dried at 240°F than when dried at temperatures of no more than 180°F, both 48 h after kiln drying and after equilibrating for 20 days. Price and Koch (1980) found that drying temperature (180°F as opposed to 270°F) had no appreciable effect on warp in Southern Pine nominal 2- by 6-in. (2 by 6) lumber immediately after kiln drying. After equalization, however, lumber dried at the higher drying temperature had an average 30.6% reduction in warp.

Other studies have explored the effect of drying temperature on warp but do not specify the time between removal of lumber from the kiln and measurement of warp. In a study by Arganbright and others (1978), studs sawn from small-diameter ponderosa pine trees (diameter unspecified) and dried by a high temperature schedule that varied from 210°F to 230°F had more warp than did studs dried by a schedule that varied from 135°F to 170°F. However, the studs were dried to lower moisture content at the higher temperatures, which may have been why they developed more warp. Maeglin and Boone (1983) found that 2 by 4's from small-diameter (8- to 12-in. diameter at breast height (dbh)) ponderosa pine trees dried at high temperature (240°F) developed 12.9% less crook, 9.6% less bow, and 25.0% less twist than did lumber dried at temperatures not exceeding 180°F, although only the reduction in twist was statistically significant. Taylor (1993) found no difference in the amount of warp in Southern Pine 2 by 6 boards dried at 245°F and boards dried at 305°F. Wu and Smith (1998) compared warp in loblolly pine (*Pinus taeda*, L.) 2 by 6's kiln dried by a schedule that ramped from 170°F to 200°F in 52 h to boards dried by a schedule that ramped from 180°F to 230°F for 12 h and was then held at 230°F for 18 h. At the higher drying temperatures, crook, bow, and twist were reduced by 18.6%, 6.0%, and 4.7%, respectively. Only the crook reduction of 18.6% was statistically significant. Milota (2000) compared warp in Hem–Fir (predominately western hemlock, *Tsuga heterophylla*, but with some true fir, *Abies* spp.) 2 by 4's dried at four temperatures (180°F, 240°F, 255°F, and 270°F). Although the differences were not statistically significant, the boards dried at 180°F had more crook, bow, and twist than did boards dried at any of the higher temperatures.

Several studies have explored the effect of equilibration to low equilibrium moisture content (EMC) after drying, which simulates end-use conditions in the arid interior western states. Markstrom and others (1984) showed the effect of post-kiln drying (at 165°F to 200°F) and moisture equalization on grade in studs sawn from 9- to 14-in.-diameter ponderosa pine trees. The studs were kiln dried to between 15% and 19% moisture content and then stored in conditions that reduced moisture content initially to 9% and then to 6% (typical in the interior western United States). The authors noted a marked reduction in the percentage of boards that met STUD grade as moisture content decreased to 9% and 6% in storage. Fahey and others (1986) also noted this effect in 2 by 4's and 2 by 6's sawn from ≤12-in.-diameter ponderosa pine trees.

This background literature provides some level of optimism that high temperature drying may reduce warp in dimension lumber sawn from small-diameter ponderosa pine trees. The previous study on ponderosa pine warp (Simpson and Green 2001) was designed to investigate the effect of several variables on warp and was not specifically designed to study the effect of equalization during storage. The purpose of the study reported here was to focus more closely on the effect of high drying temperatures, in conjunction with top loading, on warp both immediately after drying and after storage in typical conditions that result in further moisture loss.

Procedure

The 8-ft-long 2 by 4's were sawn from small-diameter (about 9 in. dbh) open-grown ponderosa pine trees from a thinning treatment on a 30- to 35-year-old stand in Idaho. The logs were sawn near the harvesting area, and the lumber shipped to the Forest Products Laboratory in Madison, Wisconsin. The lumber was wrapped in plastic to prevent drying during shipment, and then held, still wrapped, in cold storage until it was kiln dried.

When the lumber was received, it was graded green as Structural Light Framing (WWPA 1998). Measurements were made of dynamic modulus of elasticity (MOE) by transverse vibration for each board in the rough, green condition. These data were used to assign each board to one of eight experimental groups on the basis of MOE within each grade. Then within a grade, the boards were ordered by MOE. The first eight boards in the ranking were randomly assigned to one of the eight groups. Then, the next eight boards were randomly assigned. This process was repeated until all boards were assigned to a group.

The study design was six experimental groups of 152 boards each (kiln loads of 12 boards wide by 13 courses high). The plan was for three kiln schedules with two replicate kiln runs per schedule. The two extra experimental groups were planned for test runs to ensure the kiln was operating correctly and to establish some background data for determining some drying times for the six experimental kiln runs. The kiln schedules were at three temperature levels (160°F, 230°F, and 280°F) and are shown in Table 1. Top loading of 200 lb/ft^2 was included. Target final moisture content was 12% to 15%, which was estimated with a pin-type conductance moisture meter at intervals near the end of drying. After kiln drying, top loads were left in place during a 24-h cooling period.

Table 1—Kiln drying schedules for ponderosa pine 2 by 4's

Kiln schedule	Time (h)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)
Conventional	0 to 24	160	140
	24 to 36	165	140
	36 to end	170	140
High temperature #1	0 to end	230	180
High temperature #2	0 to end	280	180

Soon after drying and cooling, the 2 by 4 boards were measured for crook, bow, and twist using a wedge gauge and flat reference table. These warp measurements were made within 1 to 2 days after the weights were removed from the stacks. Each board was metered in two places along its length for an estimate of moisture content. The boards were then planed. After planing, the boards were stickered and equilibrated in an environment of 75°F and 70% relative humidity, which is about 13% EMC. After equilibration, crook, bow, and twist were remeasured and the boards metered for moisture content. The boards were then equilibrated in an environment of approximately 60°F to 70°F and 20% to 30% relative humidity, which is about 4% to 5% EMC and simulates typical conditions in the interior west. Crook, bow, and twist were again measured after equilibration.

Analysis

The data for the crook, bow, and twist measurements were analyzed using two-way analysis of variance with kiln run and drying temperature as the two factors tested for their effect. The analysis was conducted soon after kiln drying and also after the equalization period (Glanz 1992). When results of the analysis of variance showed a significant effect, the Tukey test for individual group comparisons was used (Glanz 1992).

The results were also analyzed in terms of the number of boards that failed to meet the maximum warp allowed in 8-ft-long 2 by 4 lumber in the Structural Light Framing grades (WWPA 1998). The general approach was to determine if each 2 by 4 maintained the green grade after drying (on the basis of meeting the warp limit of the grade). These

Table 2—Warp limits for 8-ft-long 2 by 4's under Structural Light Framing grading rules (WWPA 1998)

Grade	Warp (in.)		
	Crook	Bow	Twist
Select Structural	• 0.250	• 0.50	• 0.375
No. 1	• 0.250	• 0.50	• 0.375
No. 2	• 0.375	• 0.75	• 0.500
No. 3	• 0.500	• 1.00	• 0.750

warp limits are shown in Table 2. The green grade distribution in all groups was 2% Select Structural, 40% No. 1, 48% No. 2, and 10% No. 3. It is possible for a Select Structural 2 by 4 to drop up to four grade levels: from Select Structural to No. 1, 2, or 3, or below No. 3. Similarly, a No. 1 board can drop three grade levels and a No. 2 board one or two grade levels; a No. 3 board can drop only one grade level.

Results

One test run from the two extra experimental groups was conducted at 280°F. We had no experience with the required drying time at 280°F, and there are no guidelines in the literature. We conducted three kiln runs at 280°F and obtained a range of final moisture contents. One run was overdried, another underdried, and the third within the target final range of 12% to 15% moisture content. Because the results offered some possible insight into the effectiveness of high temperature drying in controlling grade loss from warp, we decided to include all three 280°F runs in the statistical analysis even though this unbalanced the experimental design. Inclusion of the third group for only one drying temperature precluded analysis of interactions, but the interactions between drying temperature and replicate were of little useful interest.

Drying Time

Kiln drying time was reduced from about 84 h by the conventional temperature (160°F) schedule to 36 h at 230°F and 15 h at 280°F (Fig. 1). Although surface checking and honeycomb are not degrading factors in softwood dimension lumber, it is noteworthy that no honeycomb was observed on the ends of boards, and only a few boards showed any surface checking.

Warp Soon After Drying

Warp measured within 1 to 2 days after drying is shown in Table 3. Results of the analysis of variance and Tukey test are shown in Tables 4 and 5. Both kiln run and drying temperature significantly affected all three types of warp. However, there does not appear to be any pattern in the effects. One possible reason for differences observed as a result of both factors (kiln run and drying temperature) is the effect of variation in final moisture content. It was not possible to end each kiln run at exactly the same final moisture content, and a distribution of final moisture contents occurred regardless of the average final moisture content. We would expect overdried 2 by 4's to show more warp than would underdried 2 by 4's. For example, in Table 3, replicate B at 280°F, which was overdried to 6.8% moisture content, had an average bow of 0.785 in. Replicate C, which was underdried to 23.4% moisture content, had only 0.262 in. of bow. This underscores the necessity of equilibrating all boards to a common moisture content for evaluating the effects of drying temperature on warp.

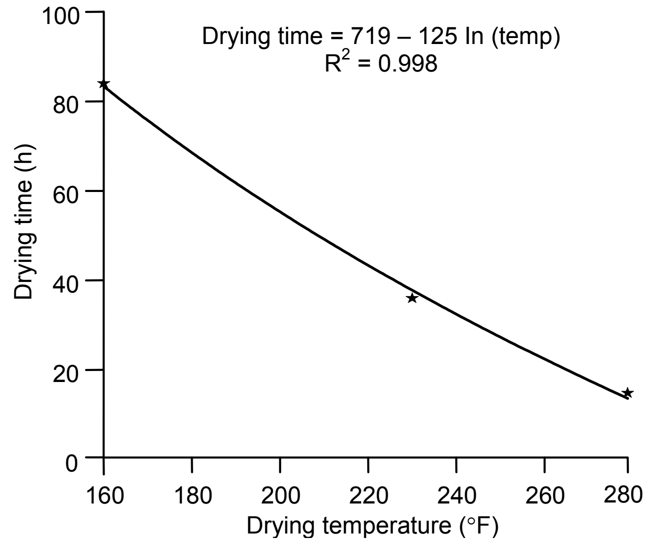

Figure 1. Amount of time required to dry ponderosa pine 2 by 4's to 12%–15% moisture content as a function of drying temperature.

Table 3—Warp in 8-ft-long ponderosa pine 2 by 4's soon after kiln drying

Temp	Replicate	Warp (in.)			MC[a] (%)
		Crook	Bow	Twist	
160°F	A	0.211	0.407	0.201	14.7
	B	0.199	0.525	0.269	11.6
	Average	0.205	0.466	0.235	13.2
230°F	A	0.213	0.509	0.190	14.2
	B	0.179	0.391	0.144	17.2
	Average	0.196	0.450	0.167	15.7
280°F	A	0.201	0.505	0.235	12.4
	B	0.267	0.785	0.228	6.8
	C	0.155	0.262	0.120	23.4
	Average	0.208	0.517	0.194	14.2

[a]MC is moisture content.

Table 4—Two-way analysis of variance for effects of drying temperature on warp measured 1 to 2 days after kiln drying

Warp	Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*	*p* [a]
Crook	Kiln run	2	0.6411	0.3205	**10.73**	**<0.0001***
	Temp	2	0.2427	0.1213	**4.06**	**0.0175***
	Residual	1059	31.63	0.0299		
	Total	1063	32.30	0.0304		
Bow	Kiln run	2	16.467	8.233	**71.80**	**<0.0001***
	Temp	2	6.843	3.422	**29.84**	**<0.0001***
	Residual	1059	121.431	0.1147		
	Total	1063	138.777	0.1306		
Twist	Kiln run	2	1.248	0.624	**18.69**	**<0.0001***
	Temp	2	0.893	0.446	**13.67**	**<0.0001***
	Residual	1059	35.357	0.0334		
	Total	1063	37.325	0.351		

[a] Asterisk indicates statistical significance.

Table 5—Tukey's pairwise multiple comparison for effects of drying temperature on warp measured 1 to 2 days after kiln drying

Warp	Comparison	*p*
Crook	230°F vs 280°F	**0.0176***
	160°F vs 280°F	0.0936
	160°F vs 230°F	0.8419
Bow	230°F vs 280°F	**<0.0001***
	160°F vs 280°F	**<0.0001***
	160°F vs 230°F	0.8718
Twist	230°F vs 280°F	**<0.0001***
	160°F vs 280°F	0.9615
	160°F vs 230°F	**0.0002***

Warp After Equilibration

In the three kiln runs at 280°F, one run was overdried to 6.8% moisture content, one underdried to only 23.4%, and one dried to the target 12% to 15% range. These results are illustrated in Figure 2, where the amounts of crook, bow, and twist both before and after equilibration to 14% EMC are plotted against moisture content measured soon after drying. Figure 2 shows that the higher the out-of-kiln moisture content, the lower the amount of warp, as measured before equilibration. Although unplanned this observation was fully expected because when warp was measured, the 2 by 4's with higher out-of-kiln moisture content had not dried as much as the boards with lower out-of-kiln moisture content and thus would be expected to have less warp. The unexpected observation was that after equilibration to 14% moisture content, a decrease in out-of-kiln moisture content was associated with a decrease in warp. For example, crook (measured at 14% moisture content) averaged 0.272 in. when out-of-kiln moisture content was 23.4% (replicate C), but only 0.115 in. when out-of-kiln moisture content was 6.8% (replicate B) (Table 6). The 2 by 4's that were dried to 6.8% moisture content were exposed to the high temperature at low moisture contents but the boards dried to only 23.4% were not exposed to high temperature at low moisture contents, and this difference could be the cause for the different response. This observation suggests the possibility that overdrying at 280°F is more effective at reducing warp after equilibration than is underdrying at 280°F.

Warp after the 2 by 4's had equalized at 75°F and 70% relative humidity is shown in Table 6 and Figure 3. Crook, bow, and twist all decreased with an increase in drying temperature. As drying temperature was increased from 160°F to 280°F, crook, bow, and twist were reduced 12%, 29%, and 20%, respectively. The statistical summary is shown in Tables 7 and 8. The overall effect of drying temperature on all three forms of warp is statistically significant, and in most individual comparisons, the higher drying temperature resulted in significantly less warp. Kiln run replicate was also a significant factor in the amount of crook, bow, and twist. This observation was unexpected and its cause is unknown. Warp after equilibration to 4%–5% moisture content is shown in Table 9. The amount of warp increased from the amount measured at 14% EMC.

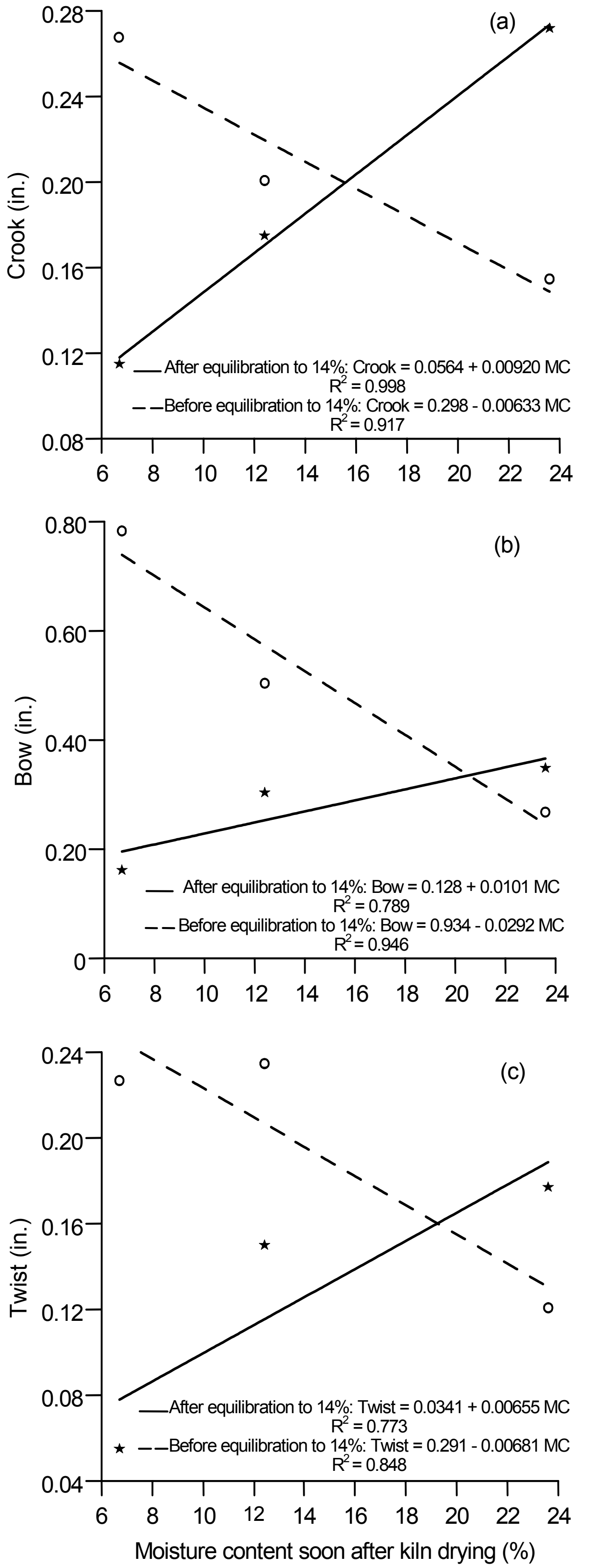

Figure 2—Relationship of moisture content measured within 1 to 2 days after kiln drying to amount of warp: (a) crook, (b) bow, (c) twist.

Table 6—Warp in planed 8-ft-long ponderosa pine 2 by 4's after kiln drying and equilibrating at 70°F and 70% relative humidity

		Warp (in.)			
Temp	Replicate	Crook	Bow	Twist	MC (%)
160°F	A	0.255	0.379	0.162	15.0
	B	0.170	0.390	0.156	12.6
	Average	0.213	0.385	0.159	13.9
230°F	A	0.191	0.337	0.140	13.5
	B	0.199	0.358	0.127	15.0
	Average	0.195	0.348	0.134	14.3
280°F	A	0.175	0.304	0.150	13.4
	B	0.115	0.162	0.055	12.6
	C	0.272	0.349	0.177	14.5
	Average	0.187	0.272	0.127	13.5

Figure 4 shows the effect of drying temperature on the number of grades lost (on a per 100 boards basis for ease of comparison) from the green grade because of exceeding the warp limits of Structural Light Framing because of crook, bow, twist, or any combination of these. The results of the two-way analysis of variance and Tukey's multiple comparison are shown in Tables 10 and 11. Not all the results are statistically significant, but they suggest that higher drying temperatures reduce grade loss from warp in 2 by 4's that have been allowed to equilibrate to about 14% and 4% moisture content. After boards were equilibrated to 14% moisture content, the loss in grade resulting from warp was 24% lower for 2 by 4's dried at 230°F than at 160°F and 39% lower for lumber dried at 280°F than at 160°F. Higher drying temperature also reduced grade loss after equilibration to 4% EMC, but the overall grade loss was very large compared to that after equilibration to 14% EMC. Very few 2 by 4's escaped downgrading after equilibrating to 4% EMC.

Table 12 offers some insight into the question of whether or not any particular form or warp—crook, bow, or twist—was responsible for a larger share of the total grade loss. Twist was an insignificant source of grade loss—less than two grades were lost per 100 boards, regardless of drying temperature. Crook was responsible for more total grade loss than was bow—grade loss per 100 boards ranged from 27.6 grades at 160°F drying temperature to 22.1 grades at 280°F. Total grade loss per 100 boards for bow ranged from 22.0 grades at 160°F to 9.2 grades at 280°F. The data in Table 12 suggest that reduction in bow at the higher drying temperatures is the most important factor in reducing total grade loss, with grade loss per 100 boards dropping from 22.0 grades at 160°F to 10.5 and 9.2 grades at 230°F and 280°F, respectively, which represent reductions in total grade loss of 52.3% and 58.2%, respectively. The comparable reductions in total grade loss from crook were 14.1% and 19.9%.

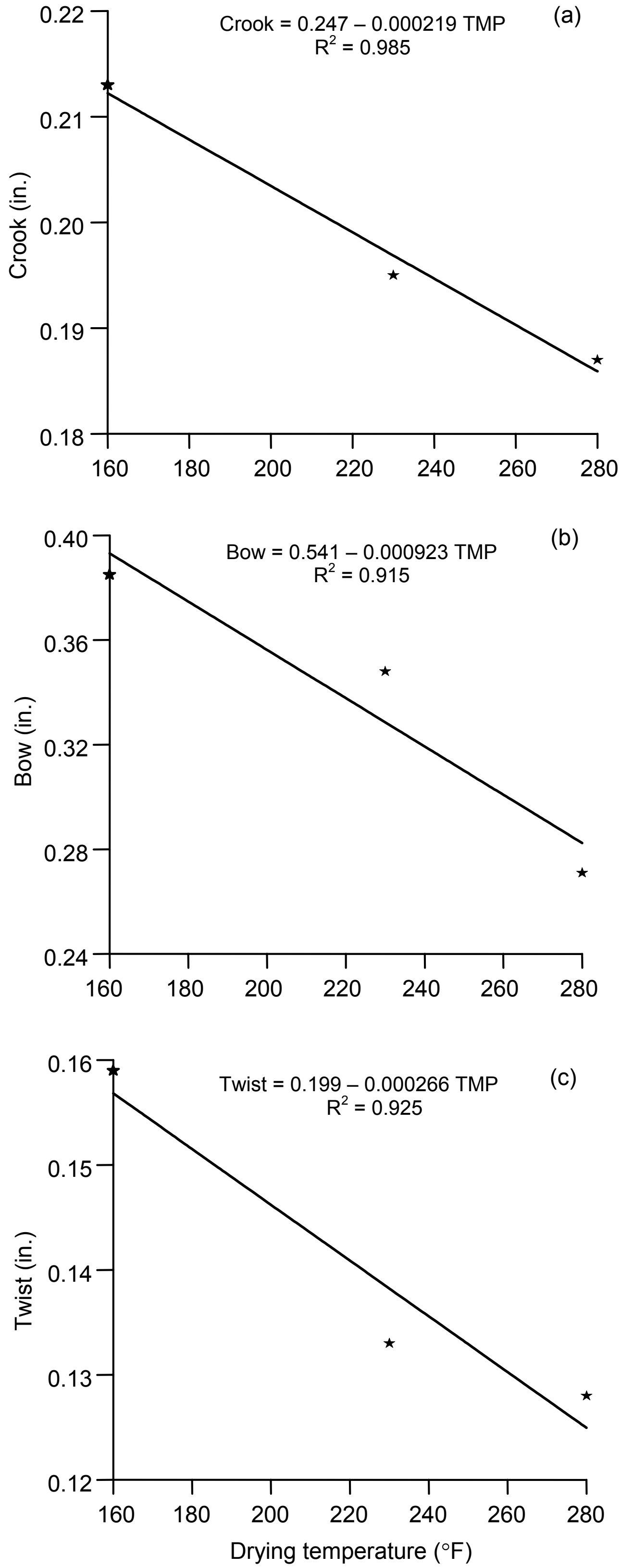

Figure 3. Relationship of warp to drying temperature: (a) crook, (b) bow, (c) twist.

Table 7—Two-way analysis of variance for effects of drying temperature on warp measured after equilibration to approximately 14% moisture content

Warp	Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*	*p*[a]
Crook	Kiln run	2	2.141	1.070	**25.30**	**<0.0001***
	Temp	2	0.756	0.378	**8.93**	**0.0001***
	Residual	1059	44.802	0.0423		
	Total	1063	47.059	0.0443		
Bow	Kiln run	2	1.656	0.828	**20.37**	**<0.0001***
	Temp	2	3.789	1.894	**46.61**	**<0.0001***
	Residual	1059	43.040	0.0406		
	Total	1063	47.225	0.0444		
Twist	Kiln run	2	0.903	0.451	**33.56**	**<0.0001***
	Temp	2	0.486	0.243	**18.05**	**<0.0001***
	Residual	1059	14.242	0.0135		
	Total	1063	15.336	0.0144		

[a]Asterisk indicates statistical significance.

Table 8—Tukey's pairwise multiple comparison for effects of drying temperature on warp measured after equilibration to approximately 14% moisture content

Warp	Comparison	*p*
Crook	230°F vs 280°F	**0.0069***
	160°F vs 280°F	**0.0002***
	160°F vs 230°F	0.6426
Bow	230°F vs 280°F	**<0.0001***
	160°F vs 280°F	**<0.0001***
	160°F vs 230°F	0.1223
Twist	230°F vs 280°F	**0.0031***
	160°F vs 280°F	**<0.0001***
	160°F vs 230°F	**0.0472***

Table 9—Warp in planed 8-ft-long ponderosa pine 2 by 4's after kiln drying and equilibrating at 70°F and 20%–30% relative humidity

		Warp (in.)		
Temperature	Replicate	Crook	Bow	Twist
160°F	A	0.692	1.332	0.452
	B	0.469	1.261	0.397
	Average	0.581	1.297	0.425
230°F	A	0.473	1.173	0.316
	B	0.439	0.933	0.261
	Average	0.456	1.053	0.289
280°F	A	0.390	0.983	0.298
	B	0.259	0.650	0.164
	C	0.729	1.143	0.519
	Average	0.459	0.925	0.327

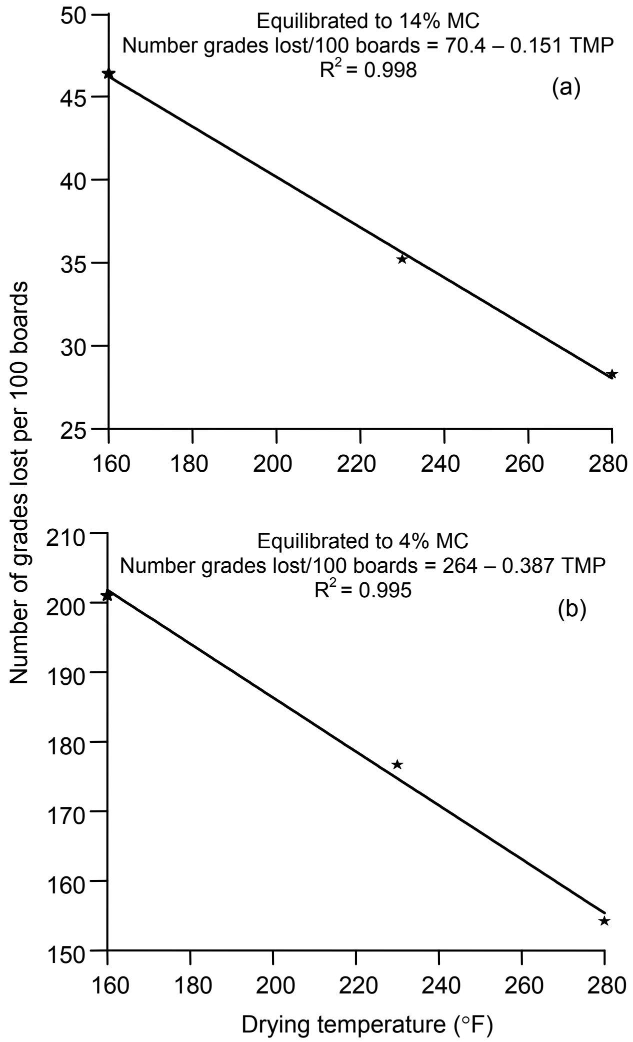

Figure 4—Effect of drying temperature on total number of grades lost per 100 boards for boards equilibrated to (a) 14% moisture content and (b) 4% moisture content.

Table 10—Two-way analysis of variance for effects of drying temperature on grade loss[a]

Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*	*p*
Kiln run	2	12.675	6.338	**11.68**	**<0.0001***
Temp	2	4.147	2.074	**3.82**	**0.0222***
Residual	1059	574.772	0.543		
Total	1063	593.420	0.558		

[a]Warp measured after equilibrating lumber to approximately 14% moisture content.

• **Table 11—Tukey's pairwise multiple comparison for effects of drying temperature on grade loss[a]**

Comparison	*p*
230°F vs 280°F	0.6870
160°F vs 280°F	**0.0192***
160°F vs 230°F	0.2368

• [a]Warp measured after equilibrating lumber to approximately 14% moisture content.

Table 12—Total grades lost in ponderosa pine 2 by 4's by form of warp and drying temperature

	• Grades lost/100 boards [a]		
Warp	• 160°F	• 230°F	• 280°F
Crook	• 27.6	• 23.7 (14.1)	• 22.1 (19.9)
Bow	• 22.0	• 10.5 (52.3)	• 9.2 (58.2)
Twist	• 1.6	• 6 (0)	• 0.9 (43.8)

[a] Numbers in parentheses are percentage of reduction in total grades lost compared to total grades lost at 160° drying temperature.

Conclusions and Recommendations

The results show that kiln drying time for ponderosa pine 2 by 4's can be reduced from about 84 h at 160°F to 36 h at 230°F and 15 h at 280°F. The results also offer evidence that the amount of crook, bow, and twist that develop in 2 by 4's sawn from open-grown 30- to 35-year-old ponderosa pine trees of about 9 inches in diameter progressively decreases with an increase in drying temperature from 160°F to 230°F to 280°F. The percentage of decrease from 160°F to 280°F drying temperature was 12%, 29%, and 20% for crook, bow, and twist, respectively. This observation applies to 2 by 4's that were allowed to equilibrate to about 14% moisture content. Warp measured immediately after drying, that is, before boards were equilibrated to 14%, did not show any consistent relationship to drying temperature.

The total loss in grade because of exceeding warp limits under the Structural Light Framing rules decreased with increase in drying temperature. The total number of grades lost because of any form of warp was 24% lower for 2 by 4's dried at 230°F than at 160°F and 39% lower for 2 by 4's dried at 280°F than at 160°F. Warp and grade loss from warp were excessively large after boards were equilibrated to 4% equilibrium moisture content.

The results of this study and our previous work indicate that high temperature kiln drying may be effective in reducing warp and grade loss from warp in dimension lumber sawn from small-diameter ponderosa pine. Suggested next steps in the verification of this approach could be pilot-scale studies in full-size commercial kilns. Another question to be addressed is the length of time after kiln drying that is necessary for warp reduction to develop and how this might affect the timing of grading and sales.

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