Industrial Validation of the Relationship between Color Parameters in Thermally Modified Spruce and Pine

Petteri Torniainen,* Diego Elustondo, and Ola Dagbro

Thermal modification causes the darkening of wood throughout its cross-section because of chemical changes in the wood. After treatment, naturally light wood species look darker or even tropical, depending predominantly on the treatment temperature and processing time. This study investigates the suitability of using color measurement to determine treatment intensity at the industrial scale. The color was determined using the *L**, *a**, and *b** color space, also referred to as CIELab, and the relationship between lightness (*L**) and the color parameters (*a**) and (*b**) was investigated for thermal modification treatments at 190 and 212 °C. The wood species studied were pine (*Pinus sylvestris* L.) and spruce (*Picea abies* L.). The results showed that yellowness (+*b**) and redness (+*a**) had a significant prediction ability for class treatments at 190 and 212 °C, respectively. After treatment, there were no noticeable differences in color between the species, but sapwood was darker than heartwood in both untreated and thermally modified wood. The thickness of the boards had a proportionally darkening effect on the color values.

Keywords: Thermal modification; Color measurement; CIELab; Quality control; Scots pine; Norway spruce

*Contact information: Luleå University of Technology, Division of Wood Science and Engineering, SE-931 87 Skellefteå, Sweden; *Corresponding author: petteri.torniainen@ltu.se*

INTRODUCTION

The thermal modification of wood implies the use of heat to improve the tolerance of wood to different environmental conditions (Viitaniemi and Jämsa 1996). In Europe, industrial methods for the thermal modification of wood have been developed in Finland (Viitaniemi 1997), the Netherlands (Boonstra and Groeneveld 1998; Militz and Tjeerdsma 2000), France (Dirol and Guyonnet 1993; Weiland and Guyonnet 1997; Vernois 2000), Germany (Sailer *et al.* 2000; Rapp and Sailer 2000), and Denmark (Ohnesorge *et al.* 2009). In general, thermal modification weakens some of the mechanical properties of the wood but increases its dimensional stability and biological durability without the need to add any chemicals or biocides into the wood (Rapp 2001).

Thermal modification also darkens the color of wood. The formation of the darker color is related to the degradation processes that take place during thermal modification. Studies have shown the importance of radicals to the formation of color (Sivonen *et al.* 2002). High correlations between color and the degradation of hemicellulose and lignin have also been found (Esteves *et al.* 2008). Furthermore, González-Penâ and Hale (2009) found correlations with both types of softwood hemicelluloses, namely, glucomannan and xylan. Both temperature and treatment time have an effect on the wood color (Schneider 1973). It has also been reported that color formation is affected by the presence of air during the thermal modification of pine and eucalypt wood (Esteves *et al.* 2008), and by humidity during the thermal modification of spruce at 200 °C (Bekhta and Niemz 2003). There are also natural color differences between wood of the same species (Boonstra *et al.* 2006).

Thermally modified wood at industrial-scale volumes was introduced to the European market in the late 1990s, and the market share of this product has been growing ever since (Anonymous 2014). Over time, appropriate standards and test methods for industrial-scale quality control were needed (Brischke *et al.* 2007). Early studies have shown that color measurement can be used for quality control. For example, Sullivan (1966) gave an overview of wood color measurement and investigated various influencing factors. Other studies have shown a relationship between color measurements and the different properties of thermally modified wood. In particular, Brischke *et al.* (2007) found that there is a linear correlation between the measured color data and the thermal modification intensity for spruce (*Picea abies* L.), pine (*Pinus sylvestris* L.), and beech (*Fagus sylvatica* L.).

Based on this knowledge, the objective of the present study was to develop an industrial-quality control procedure based on non-destructive color measurements. Thermal modification in industry is certified by measuring the temperature and time of the process, which in turn affects the color of the wood. Quality control in this context refers to the measurement of wood color as an indirect measure of treatment intensity. Brischke *et al.* (2007) stated that measuring wood that was ground by milling resulted in fewer color variations than measuring the surfaces of solid wood; thus measurements of ground wood are recommendable for obtaining results with a higher statistical significance. The method proposed in this study, on the other hand, was designed to be performed on the external surfaces of the wood; thus six locations were measured from each board to compensate for the natural color variations.

It is important to clarify that most of the results reported in this manuscript are not novel from the scientific standpoint. For example, de Cademartori *et al.* (2014) recently summarized possible causes for color changes in thermal modification and compared results between L^*C^*h and $L^*a^*b^*$ color scales. However, thermal modification is a highly empirical science, and industrial implementation involves uncontrolled variables that are not present in laboratory conditions. This study is also intended to confirm that color of thermally modified wood is also measurable and predictable in industry within ranges of error that are acceptable for a commercial application.

EXPERIMENTAL

Materials

This study was performed using the ThermoWood® process, which is a registered trademark owned by the International ThermoWood® Association (Anonymous 2008). Two treatment classes were defined in 2002, namely, Thermo-S treated at 190 °C and Thermo-D treated at 212 °C. The letters S and D indicate “stability” and “durability,” respectively, based on the recommended applications according to EN 335 (2013): Use classes 1 and 2 for Thermo-S and use classes 1, 2, and 3 for Thermo-D.

The color data for this study were acquired at the MetsäGroup Kaskinen production plant in Finland between 2011 and 2013. The wood species used in this study were Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) harvested in Finland. The boards were dried in conventional kilns before thermal modification to average moisture contents between 15% and 18%, and they were subsequently thermally modified in two identical 100 m^3 treatment chambers.

Wood color was measured with a Minolta Chroma Meter CR310 (Konica Minolta Sensing Inc., Japan). The Minolta Chroma Meter measures color in a three-dimensional space described by lightness (L), chroma/saturation (C), and hue angle degree (h). The data were subsequently converted into the L^*, a^*, b^* color space by performing $L^* = L$, $a^* = C \cos(h)$, and $b^* = C \sin(h)$. The L^*, a^*, b^* color space (also referred to as CIELab) is one of the most popular color spaces and is widely used in virtually all fields (Minolta 1996). In this color space, L^* indicates lightness, and a^* and b^* are the chromaticity coordinates. In simple words, the color changes from green to red as a^* increases from $-a^*$ to $+a^*$, and the color changes from blue to yellow as b^* increases from $-b^*$ to $+b^*$.

Methods

The results of this study were compared with the current European technical specifications for thermally modified wood described in the first available standardization document CEN/TC 175 (Scheiding *et al.* 2007). The current requirements for the Thermo-S and Thermo-D color are reported in Table 1, which are applicable to both spruce and pine:

Table 1. Current Color Guidelines for Thermally Modified Spruce and Pine

Class	L^*	$+a^*$	$+b^*$
Thermo-S	58–68	8–10	-
Thermo-D	45–55	-	19–24

The thermal modification process was carried out in a high-temperature chamber using superheated steam without adding any additional chemicals into the wood. The manufacturing process used high temperatures and superheated steam. The process was carried out in a one-stage system starting with pre-dried timber and finishing with the final product. Within that stage, the process consisted of the following consecutive phases: Phase 1—Warming-up the wood and kiln (90 to 100 °C); Phase 2—High temperature kiln drying (100 to 130 °C) and mild thermal modification (130 to 190 °C); Phase 3—Intensive thermal modification for 2 to 3 h at a temperature dependent on the treatment class (Thermo-S = 190 °C ± 3 °C; Thermo-D = 212 °C ± 3 °C); Phase 4—Cooling down to approximately 80 to 90 °C and reconditioning to a final moisture content between 4 and 7%; and Phase 5—Final cooling down.

The thermal modification process can be controlled by either the temperature of the wood or the chamber environment (Dagbro *et al.* 2010). In the case of this study, the treatment schedules were "time-based" and the air temperature was measured at several points inside the chamber. Wood temperature was not measured during the process. Table 2 reports the total number of measured batches sorted by species and treatments (Thermo-D and Thermo-S), where 5 full-sized boards were randomly sampled and measured from each batch:

Table 2. Number of Measured Batches Sorted by Species and Treatments

	Thermo-S	Thermo-D	Total
Spruce	33	21	54
Pine	-	61	61
Total	33	82	115

Table 3 reports the total number of measured batches sorted by board dimensions, where treatment classes were distinguished by reporting the Thermo-S batches between brackets. The thickness ranged between 22 and 50 mm for both species, while the width ranged between 150 and 225 mm for spruce and 77 and 150 mm for pine. In order to decrease the process variables, all the treatments were performed using the same thermal modification unit. For each class, the same duration and temperature were used during the intensive thermal modification stage of the process. The intensive thermal modification time in all charges was 180 min. After treatment, the process history concerning temperature and time was reviewed to confirm that the batches met the process requirements.

Table 3. Number of Thermo-D (D) and Thermo-S (S) Batches Sorted by Board Dimensions

Thickness (mm)	Width (mm)							
	77	100	125	132	150	175	200	225
22					8D + 6S	3D + 2S	7D + 7S	7D + 7S
25		1D	12D		15D		6D + 3S	6D + 4S
32		3D	10D		14D			2D + 2S
38		1D	3D					1D + 1S
40	4D			3D		1		
41				1D				
50		3D			4D + 1S			

The color was measured from boards planed between 2 and 3 mm and with surfaces without any visual defects or remarkable discrepancies from normal wood. In the x-log sawing pattern (the most common sawing pattern used in Scandinavia), there are usually color differences between top and bottom surfaces of the same board. For simplicity, the board surface closer to the log pith (bottom) is referred as heartwood surface, and the board surface further from the log pith (top) is referred as sapwood surface (Fig. 2).

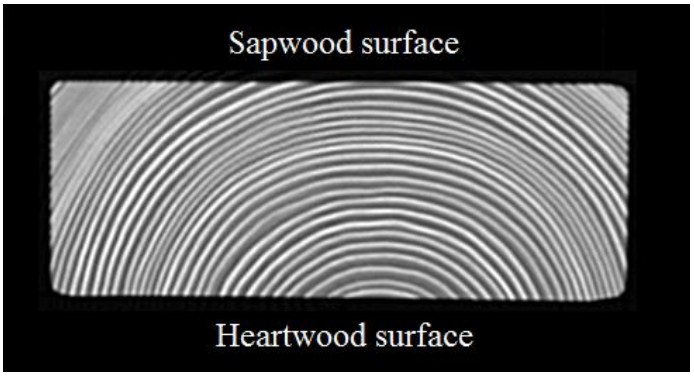

Fig. 1. Cross section of board showing the definitions of sapwood and heartwood surfaces

The sapwood and heartwood surfaces were measured in the middle and the ends of the boards. This means that there were 6 measuring locations for each board. The diameter of the colorimeter measuring area was approximately 50 mm; thus three adjacent measurements were averaged at each selected location to account for the entire width of the boards. Figure 2 shows that each reported color value was the average of three adjacent measurements covering the entire width of the board surfaces.

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001
L  50.46 a+10.24 b+22.65
002
L  50.90 a +9.82 b+21.11
003
L  50.66 a +9.36 b+21.79
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Fig. 2. Procedure for measuring color at one board location

Color was measured on planed surfaces, since otherwise differences from the wood under the surfaces increase (Pfriem *et al.* 2010). Non-planed surfaces may contain different types of process impurities, such as resin, tar, stick marks, and cooling water stains. The color of non-planed surfaces is therefore different for external reasons, and it does not necessarily represent the color achieved by the process. The alternative option of measuring color from sawdust or board cross sections gives naturally less variation, but it requires destructive sampling.

RESULTS AND DISCUSSION

Figures 3, 4, and 5 show the distributions of *L**, *a**, and *b** color parameters, respectively, measured for the three classes/species analyzed. The figures show that there was a clear difference between the treatment classes Thermo-D and Thermo-S, and the majority of the color parameters were well within the ranges reported in Table 1. Figures 3 and 5 also show that there are not large differences between spruce and pine in the measured ranges of color variation. For industrial application, therefore, it is possible to accept the same color range of variation (minimum and maximum *L** and *b** values) for both spruce and pine.

Figures 6, 7, and 8 compare the distribution of *L** measured in the sapwood and heartwood surfaces for the three treatments. These figures show that there was a slight difference between the sapwood and heartwood surfaces. In all treatments, the *L** values of the sapwood surface were slightly lower (darker) than those of the heartwood surface. This can be explained as a consequence of the sawing pattern. In typical Scandinavian x-log sawing pattern the annual rings exposed on the sapwood surface are more parallel to the external surface than the annual rings exposed on the heartwood surface (Fig. 2). This in turn tends to create a darker latewood band in the center of the sapwood surface.

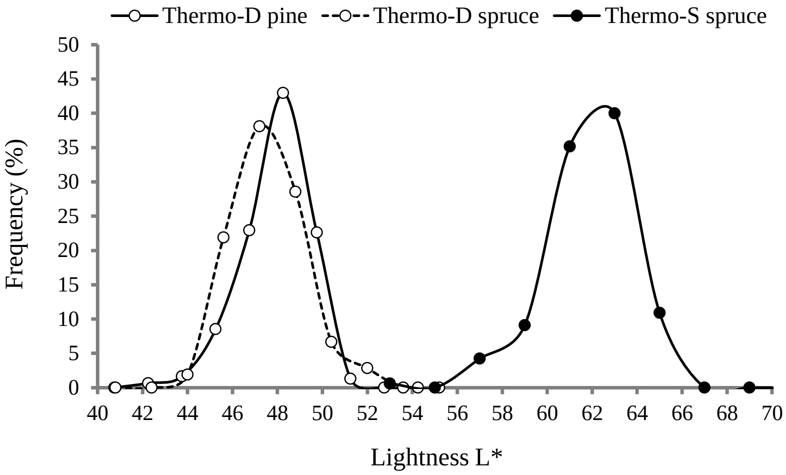

Fig. 3. Distribution of *L** values compared among class/species treatments

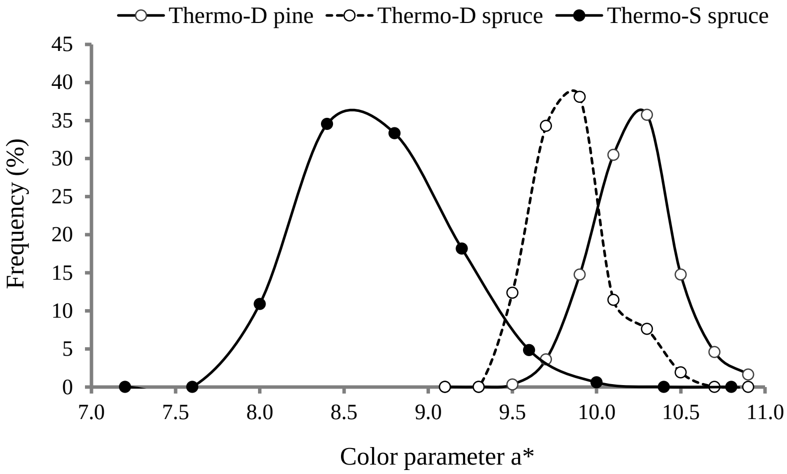

Fig. 4. Distribution of *a** values compared among class/species treatments

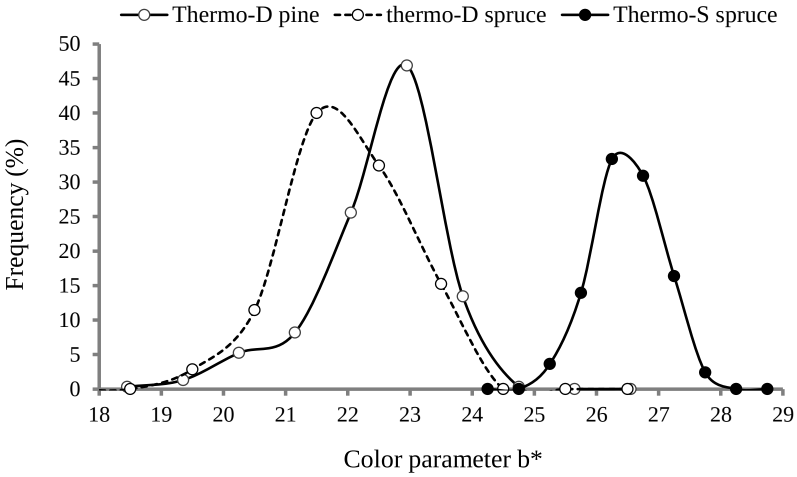

Fig. 5. Distribution of *b** values compared among class/species treatments

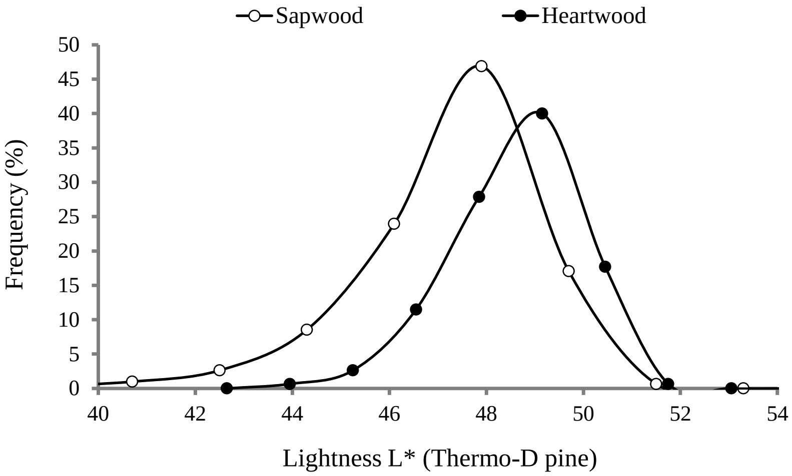

Fig. 6. Distribution of *L** values for sapwood and heartwood in Thermo-D pine

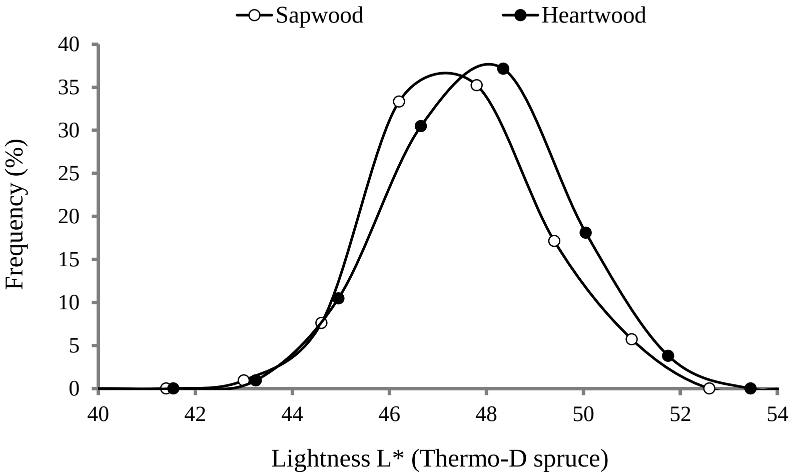

Fig. 7. Distribution of *L** values for sapwood and heartwood in Thermo-D spruce

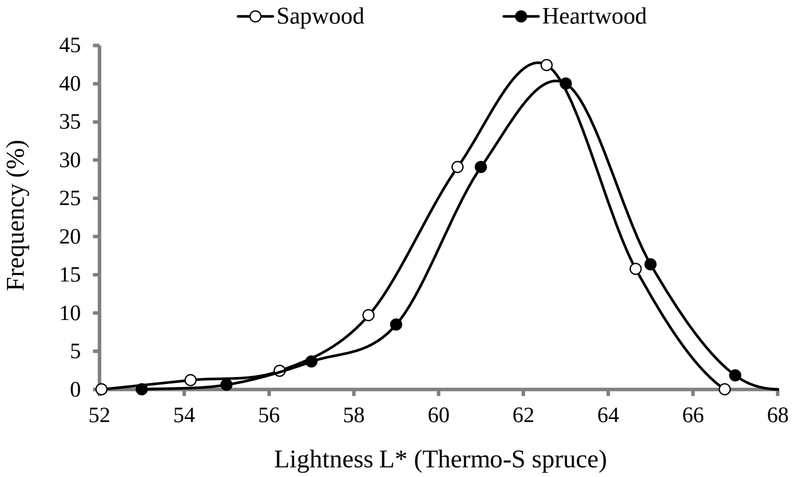

Fig. 8. Distribution of *L** values for sapwood and heartwood in Thermo-S spruce

If the color is determined by a single measurement in the middle of the board, then the difference between the surfaces would be even larger. From that point of view, it can be justified that the whole width is taken into consideration. It should also be decided which one of the surfaces is measured. Usually the surface that is exposed to the user in the final application is the one that should be measured.

Color was also measured in untreated spruce and pine. The results showed that the ranges of measured *L** values were approximately the same for both spruce and pine. The color of untreated wood was also darker in the sapwood than in the heartwood surface. The average color parameters measured for treated and untreated wood are reported in Table 4.

Table 4. Color Parameters Measured in Treated and Untreated Wood

Parameter		Thermo-S		Thermo-D		Untreated	
		Average	SD	Average	SD	Average	SD
*L**	Pine	--	--	47.9	1.9	81.9	2.3
*L**	Spruce	61.9	2.3	47.6	1.8	81.3	2.7
+*a**	Pine	--	--	10.2	0.2	4.6	1.5
+*a**	Spruce	8.7	0.4	9.8	0.2	3.8	1.0
+*b**	Pine	--	--	22.5	1.0	19.6	1.7
+*b**	Spruce	26.5	0.5	21.9	0.9	18.0	1.5
*L**	Sapwood	61.5	2.2	47.3	1.9	81.4	2.5
*L**	Heartwood	62.2	2.2	48.4	1.6	82.1	2.5
*L**	Center	62.0	2.4	47.9	1.8	--	--
*L**	End	61.8	2.1	47.8	2.0	--	--

Table 4 shows that lightness (*L**) in spruce was reduced from 61.9 at a treatment temperature of 190 °C (Thermo-S) to 47.6 at 212 °C (Thermo-D). Table 4 also shows that the color of spruce became more red (+*a**) and less yellow (+*b**) with increased temperature, from 8.7 and 26.5 at 190 °C (Thermo-S) to 9.8 and 21.9 at 212 °C (Thermo-D), respectively. These data confirm that the treatment temperature was a main factor determining the color of the thermally modified wood. The thickness of the boards had also a slight darkening effect on the wood color. This can be observed in Figs. 9 and 10, where the lightness of Thermo-S and Thermo-D wood tended to be reduced proportionally to the product thickness. The explanation is that thicker boards were exposed longer times to temperatures capable to produce thermal modification. Thicker boards require longer heat-up times to reach the temperature defined by the thermal modification class, and during this heat-up time there is also some degree of thermal modification. This can be observed in Figs. 9 and 10, where the lightness of Thermo-S and Thermo-D wood tended to be reduced proportionally to the product thickness. From that point of view, a larger range of color values must be accepted in order to account for different thicknesses, but no distinction between wood species seems to be required.

The results also confirmed previous studies reporting linear relationships between color parameters in thermally modified wood (Brischke *et al.* 2007; Pfriem *et al.* 2010). This is clearly visible in Figs. 11 and 12, which show the linear relationships between *L** and *a** in Thermo-S spruce and between *L** and *b** in Thermo-D spruce and pine. The coefficients of regression were, respectively, $r^2 = 0.83$ and $r^2 = 0.73$, and the standard deviations of the residual error with respect to the linear relationships were 0.82 and 0.80 for Thermo-S and Thermo-D, respectively.

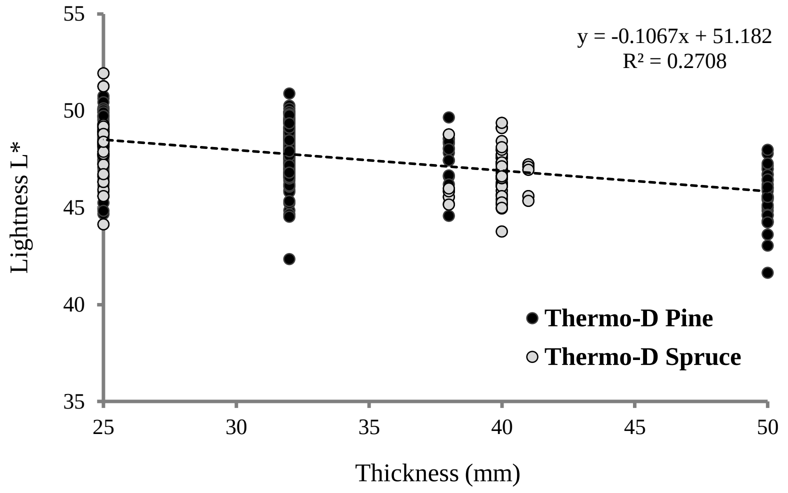

Fig. 9. Lightness (*L**) as a function of product thickness in Thermo-S wood

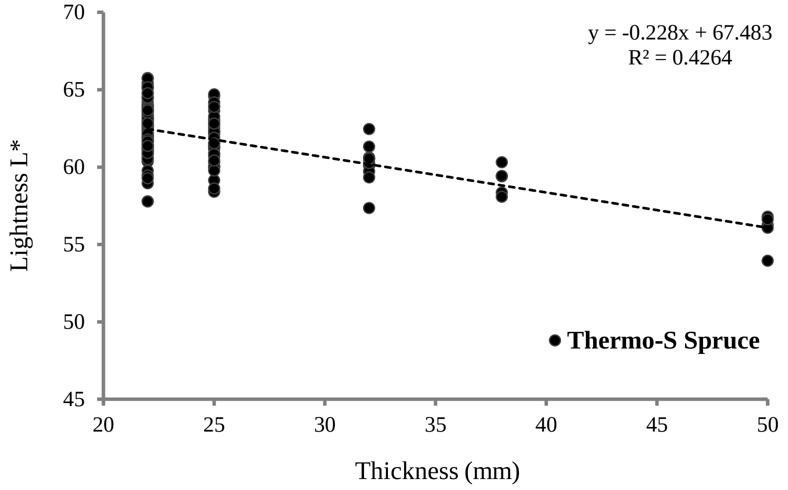

Fig. 10. Lightness (*L**) as a function of product thickness in Thermo-D wood

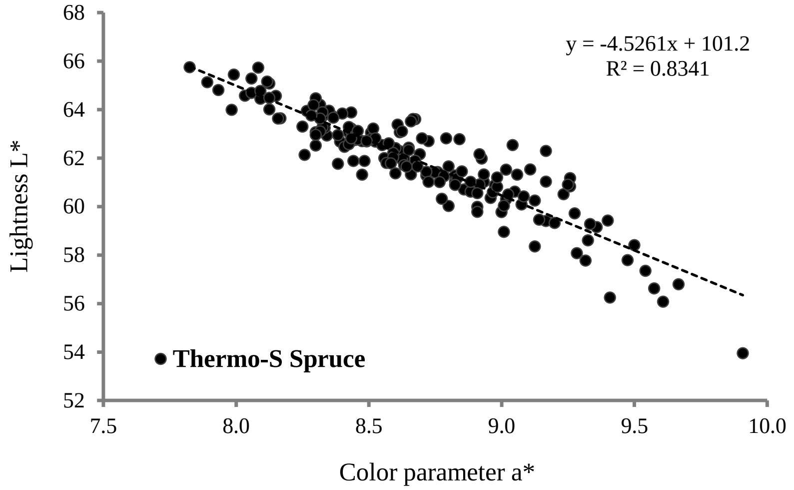

Fig. 11. Relationship between L* and a* values in Thermo-S spruce

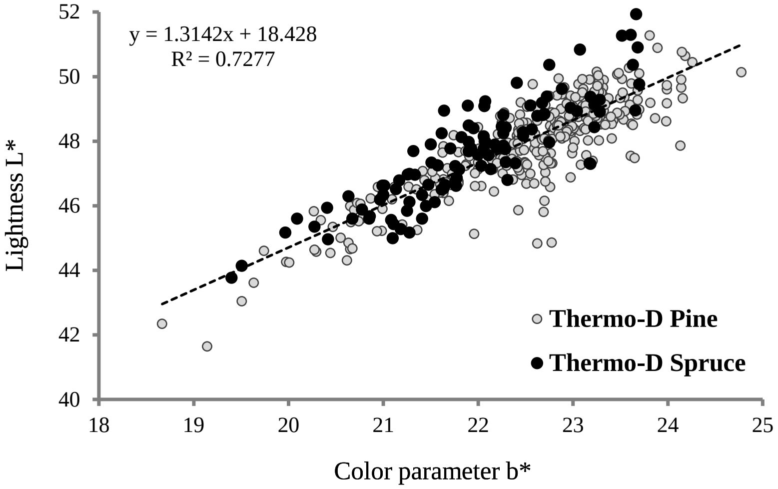

Fig. 12. Relationship between L* and b* values in Thermo-D spruce and pine

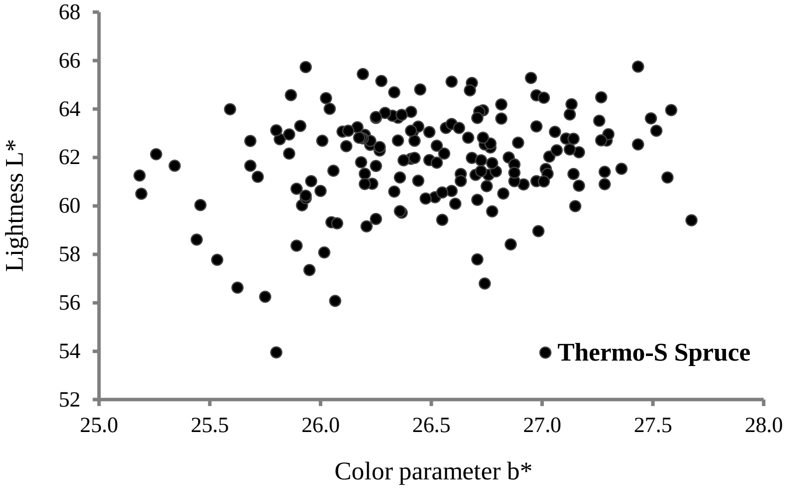

Fig. 13. Relationship between L* and b* values in Thermo-S spruce

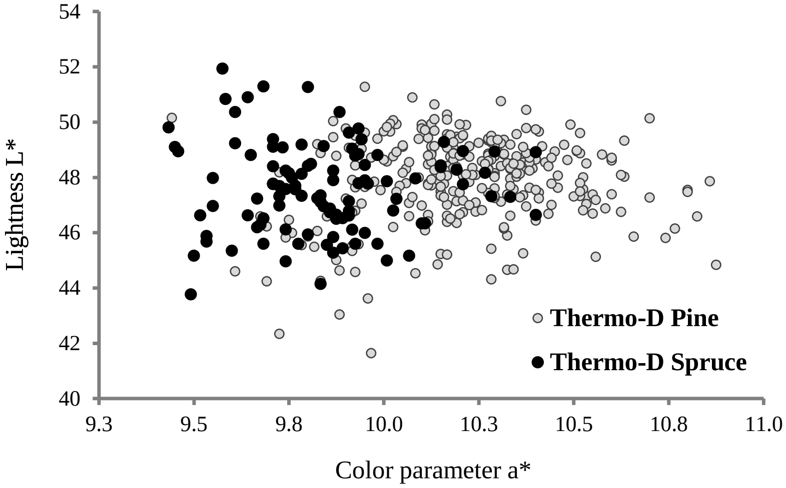

Fig. 14. Relationship between L* and a* values in Thermo-D spruce and pine

It can be said, therefore, that the dark surfaces in Thermo-S tended to be more reddish, while the light surfaces in Thermo-D tended to be more yellowish. Regarding the other complementary color parameters, Figs. 13 and 14 show no apparent relationship between L^* and b^* in Thermo-S spruce and between L^* and a^* in Thermo-D spruce and pine.

CONCLUSIONS

This paper reports results of industrial color measurements from 115 batches of thermally modified spruce and pine produced by a certified sawmill. The study did not show obvious discrepancies with previous laboratory studies, thus basically confirming that color change in thermally modified spruce and pine is measurable and predictable in an industrial production facility. In summary, the study confirmed that in an industrial scenario:

1. It is possible for quality control purposes to measure the color of thermally modified wood from the surfaces of planed boards instead of sawdust or board cross sections
2. There are clear linear relationships between L^* and a^* in spruce thermally modified at 190 °C, and between L^* and b^* in spruce and pine thermally modified at 212 °C
3. The large majority of the measured L^*, a^*, and b^* color values were within the ranges of values currently required for certified thermally modified wood

In addition, this study also showed other minor effects that were not previously observed in laboratory:

4. There was a color difference between the sapwood and heartwood surfaces, where the sapwood surfaces were slightly darker. This was explained by the differences in the angle of the annual rings with respect to the board surfaces
5. There is a slight influence of the board thickness in the color of thermally modified wood. This was because the process requires a heat-up time to reach the thermal modification temperature, and this was adjusted depending on the thickness

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