An approach to classify thermally modified hardwoods by color

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Abstract

This study deals with an approach to classify thermally modified wood. In recent years, this material has gained a strong foothold in interior and exterior use. To guarantee the fulfillment of customer requirements as well as specific aesthetic preferences, quality grades for thermally modified European Ash (*Fraxinus Excelsior*) and European Beech (*Fagus Sylvatica*) wood have to be defined. Only consistency in the expected properties can guarantee the long-term success of thermally modified hardwoods on the market. This study shows, while the modified wood can be classified by color, the moisture adsorption of the wood depends significantly on the type of treatment. Moreover, it was concluded that the color information can also be used to define various grades of thermally modified hardwoods according to the bending strength. Guidelines to determine the aesthetic and technical quality of thermally modified wood have to be established, which this study underlines. These findings will be useful to develop international and national standards for thermally modified hardwoods for various applications.

In the last few years, thermally modified wood production has increased to more than 45,000 m^3 in Europe (Ewert and Scheiding 2005). Much of the thermally treated hardwood has been used in wood flooring; however, an increasing amount of such wood is used for building facades in Austria. In these applications customer attention has focused on the new aesthetic possibilities that arise mainly from the color differences due to the thermal treatment (see **Fig. 1**). A further aspect relates to the technical properties of treated wood. To meet the requirements of decision makers (e.g., architects and end-users), it is important to develop validated national and international standards for modified wood. A possible grading method is to divide the grading system into two features, based on quality classifications. One distinguishing feature is represented by the technical properties (e.g., antiswelling efficiency) of the modified wood. The other feature is the aesthetic quality (e.g., color) of thermally treated wood. The minimal technical requirements of the wood properties can be defined for different application areas (e.g., interior and exterior use). For example, an improvement in fungal resistance is important in exterior applications, and sometimes the dark wood color is the crucial factor in a buying decision. According to Hanger et al. (2002a), the swelling and shrinking behavior as well as the fungal resistance (Hanger et al. 2002b) is improved by thermal treatment. Based on these considerations, wood color can be used to classify thermally treated wood with regard to aesthetic quality.

The following were defined as research tasks for this study:

1. Is it possible to define different categories of thermally treated hardwoods based on the easy-to-measure feature color?
2. Is a clear grading of a wood sample possible?
3. Is it appropriate to use the wood color for online process control in the thermal treatment chamber?

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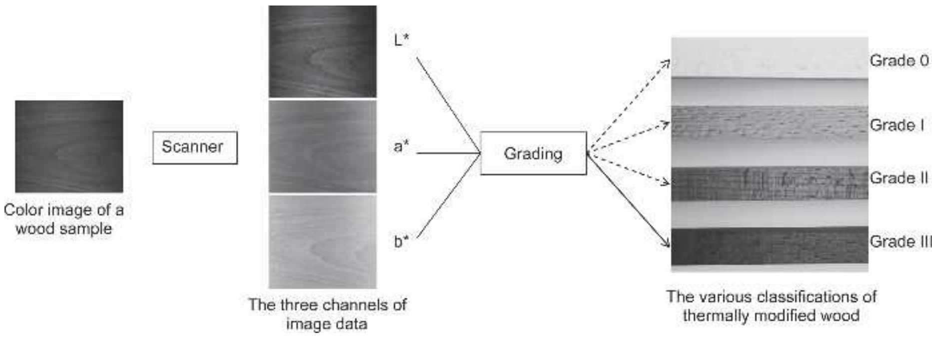

Figure 1. — Sketch of a method for grading thermally treated wood. The wood scanning system allows for the collection of three channels of image data: (L) black and white, (a*) red and green, (b*) yellow and blue. A cluster analysis method is performed separately for thermally modified wood in the grading (Grade 0, I, II, III).*

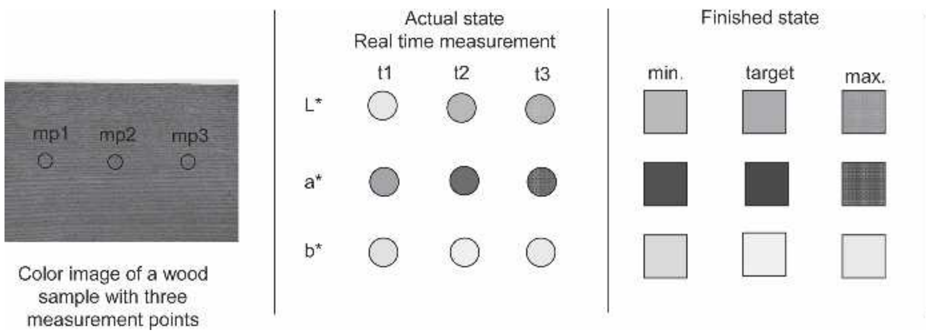

Figure 2. — Sketch of a method for the process control in real time. The wood scanning system (for example wood color measurement in points (mp1, mp2 and mp3)) allows for the collection of three channels of image data (L, a* and b*) in relation to three symbolic periods of time (t1, t2 and t3). The image data in real time are compared to the target wood color.*

In **Figure 1** there is a sketch of a grading system for wood grading after thermal treatment. After scanning the wood boards, the wood color could be divided into three color parameters (L*, a* and b*). The three color parameters provided information concerning the wood color, which varied for each parameter. This information about the wood color can be used to define ranges of color values for the grading classes after the heat treatment.

Also this method can be applied for an evaluation system during the heat process, see **Figure 2**. The wood color is measured in real time during the process. A desired wood color can be attained by stopping the process when the appropriate tone is visible.

Today various modification types are used by manufacturers of thermally modified wood in Europe (Ewert and Scheiding 2005). The principle behind the various modification types is that the cell-wall components are changed by high temperatures. The heat is transferred to the wood using either oil or steam.

Several wood properties are changed. As a result of heat treatment, the antiswelling efficiency is increased (Hanger et al. 2002a). Investigations on natural durability indicate an improvement in heat-treated wood (Hanger et al. 2002b). Furthermore, the mechanical properties (e.g., bending strength) of heat-treated wood were investigated (Rusche 1973, Giebeler 1983, Hanger et al. 2002a, Bekhta and Niemz 2003). The reason for some changes can be found in the chemical structure of modified wood. Numerous investigations deal with these changes, for example Fengel (1966a, 1966b, 1967), Kollman and Fengel (1965), Fengel and Przyklenk (1970), and Tjeerdsma and Militz (2005).

A further effect of heat treatment is the change in wood color. Early studies show that color measurement can be used for wood. For example, Sullivan (1966a, 1966b) gives an overview of wood color measurement and investigates various influencing factors (e.g., surface smoothness). Beckwith (1979) concentrates on hardwood color measurement for various surfaces (radial, tangential, transverse).

In addition, Schneider (1973) described that both the temperature and the processing time have an effect on the wood color. Moreover, Wiberg (1996), Charrier et al. (2002), and Sundqvist (2002) evaluated the color change during wood processing. The wood color in combination with other measurement categories formed the basis for further investigations. The interaction between the bending strength and the change in wood color after the modification process was investigated by Bektha and Niemz (2003). Bourgois et al. (1991) explain the correlations between the wood color and the chemical composition during the heat treatment process.

This investigation deals with an approach relating to the use of wood color for grading thermally treated wood. It could be important to develop guidelines for quality assurance to save time and money in industrial utilization.

Experimental

European ash (*Fraxinus Excelsior*) and European beech (*Fagus Sylvatica*) wood samples were used for the investigation. The equilibrium MC (EMC) and the bending strength were determined in order to evaluate the technical quality of the thermal influence on the wood. The color was measured to obtain the basic information for the classification.

Materials and methods

Two half-timber boards (see **Fig. 3**) were selected from various ash and beech trees. To identify changes in technical properties, one board was left untreated and became the reference. The other board was heat treated in an industrial wood processing chamber. **Table 1** shows the number of boards used. Two different heat treatments were used for the ash samples. Three different heat treatments were used for wood modification for the beech samples. The difference between each heat treatment was the processing temperature, which was divided into three intensities (low, medium, and strong) of the thermal modification process.

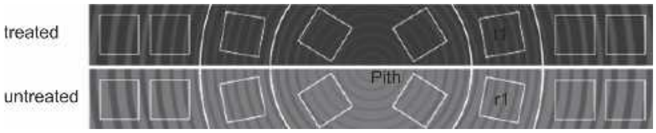

Figure 3. — Sketch of the board cross section with the possible adjustment of the samples. The sample r1 is the reference of the heat treated sample t1.

Table 1. — Number of boards and samples used and their heat treatment condition.

	Treatment intensities			
	Untreated	Low	Medium	Strong
Wood species	Number of boards used			
Ash	19	10	9	—
Beech	23	7	7	9
	Number of samples used			
Ash	212	118	94	—
Beech	249	78	61	110

Figure 3 shows the implementation of samples on the cross section of the board. The samples were cut so that they provided a radial face for analysis. The samples for the color measurement and bending strength test were cut into dimensions of 20 by 20 by 360 mm in radial, tangential and longitudinal directions. For the determination of the MC, the samples with dimensions of 20 by 20 by 10 mm (radial, tangential and longitudinal) were applied. All samples were stored in a climate chamber at a relative humidity of 65 percent and a temperature of 20 °C before testing.

The total number of samples tested is shown in **Table 1**. The varying sample numbers resulted from the various board numbers, see **Table 1**.

Color measurement

The wood color was measured with the Mercury 2000 spectrophotometer (Datacolor) and the selected diameter for the measurement was 11 mm. Measurements were made using a standard illuminant D_{65} and a 10° standard observer. The wood color was determined according to the Commission International de l'Eclairage (CIE) L*a*b* color space (abbreviation CIELAB), which is characterized by three parameters L*, a* and b* (Wyszecki and Stiles 2000). Detailed information about the CIELAB color space is given by Wyszecki and Stiles (2000).

Five points per sample were measured on radial surfaces.

Bending test

For the determination of the bending strength, the samples were stored in the ambient climate (temperature 20 °C and relative humidity 65%). All samples were tested in three-point bending test according to a standard (DIN 52186 1978).

Determination of the equilibrium MC

To determine the equilibrium MC of wood, all samples were exposed to the ambient climate (temperature 20 °C and relative humidity 65%) except for weight differences lower than 0.1 percent. The specimens were measured for the first time and then all samples were oven dried (103 ±2 °C) to obtain the dry mass. This procedure was performed according to a standard (DIN 52183 1977).

Table 2. — Equilibrium MC in ash and beech samples.

	MC	
	-----------(%)-----------	
Heat treatments	Mean	SD
	Ash	
Untreated	10.6	0.4
Low intensity	5.6	0.3
Medium intensity	4.3	0.3
	Beech	
Untreated	10.6	0.4
Low intensity	5.6	0.2
Medium intensity	4.6	0.3
Strong intensity	3.6	0.3

Data analysis

In this study, the mean color of a sample is used for analysis. The SPSS® 10.0.7 software package was used for the statistical analysis.

Descriptive analysis

Descriptive statistical methods were employed to provide an overview of the results. Ash and beech specimens were separated for this part of the investigation. Detailed analysis was carried out separately for each color parameter. The results are shown in box plots, which provide an overview of the data distribution.

Clustering

The cluster analysis was performed separately for ash and beech samples. To answer the Task 1 to 3, the clustering method used is the single linkage method, where at the beginning of clustering, every sample is treated as one specific group and the samples which are closest together are grouped in a cluster. Detailed information about the cluster analysis is given by Hartung and Elpelt (1999). The three parameters of the CIEL*a*b*–space were employed for the cluster analysis. The number of clusters that should be attained by the clustering method corresponds to the number of types of treatment for the samples. It could be seen that if all samples in one cluster were from the same heat treatment process, then the color would be useful to define the treatment grades. Three clusters (untreated, treatment intensities low and medium) were formed for ash and four for beech (untreated, treatment intensities low, medium and strong).

Results

A comparison of the results for treated and untreated samples was attained in compliance with the research design regulations. The sample numbers differ between the treatment intensities. Because of the large number of tested samples, these differences do not affect the analysis. The extensive number of samples allowed plausible results for each type of treatment. The results are shown separately for ash and beech samples and for L*, a* and b* values.

The influence of heat treatment on the equilibrium MC of wood

The untreated samples and the samples treated with various intensities could be separated by using the equilibrium MC (EMC), see **Table 2**.

The EMC differs between the untreated (10.6%) and the low-intensity treated samples for ash wood (5.6%). The low-intensity treated beech samples showed a reduction in EMC from 10.6 percent to 5.6 percent. Medium-intensity heat treatment showed an EMC of 4.3 percent for ash wood and 4.6 percent for beech wood. Strong-intensity treated beech wood exhibited the lowest EMC of 3.6 percent.

This result shows that after an intensive thermal treatment of wood, the EMC is decreased with reference to the untreated wood. A similar result was reached by Burmester (1975), Giebeler (1983) and Hanger et al. (2002a). Low water absorption of the heat-treated wood, which is generally an explanation of the dimensional stability, was not observed in this study. Burmester (1975) described that the decrease in polyose (hemicellulose) during thermal treatment was the reason for the increase in dimensional stability. The results show that the treatment level could be set to produce a product that would have a desired EMC for a specified in-use ambient climate (temperature and relative humidity).

The influence of heat treatment on the wood color

On visual inspection, it was clear that the wood became darker. To give an impression of the data distribution, the effect of the heat treatment on L*, a* and b* is shown in **Figure 4**. The L* value decreased significantly during each heat treatment process. The change in the a* and b* chromatic coordinates follow another pattern. The heat treatments of low and medium intensities led to a rise in the a* value. The a* value of beech wood remained unchanged using heat treatment of strong intensity. The b* value increased slightly due to low heat treatment. However, even when high temperatures were applied, the b* value decreased. The difference in the b* values for all treated samples was significant. Bourgois et al. (1991) mentions the same behavior of the three color parameters on thermal treated wood.

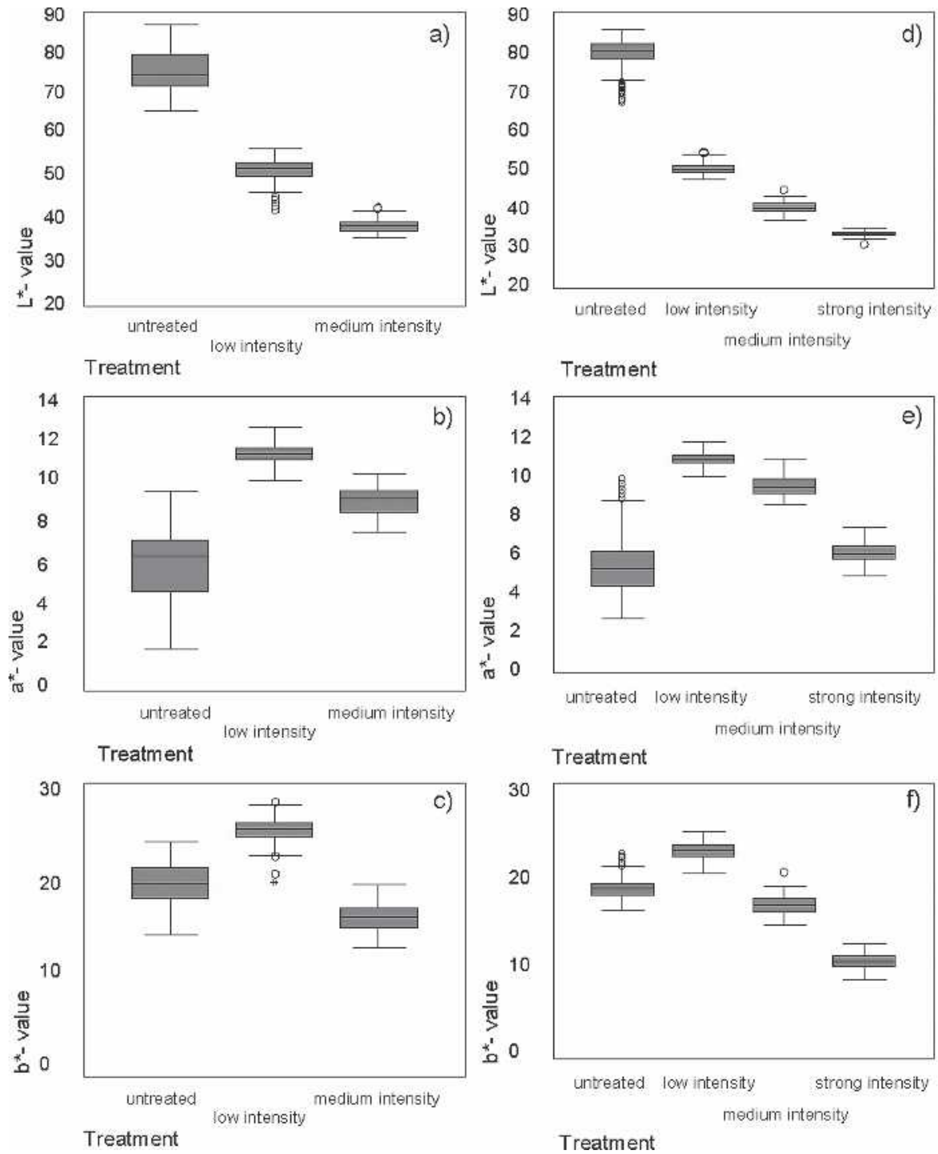

Figure 4. — Influence of heat treatment on L, a* and b* for (a-c) ash and (d-f) beech samples. Outliers are marked with (o) and extreme values are denoted with (*).*

Figure 4 shows the wood color could be influenced by the heat-treatment process. Each heat-treatment process was given a unique wood color. With regard to all three color parameters L*, a* and b*, the color change increased when higher temperatures in the modification process were set. Also Bektha and Niemz (2003) mention the strong influence of the heat treatment on changing the wood color of Norway spruce. Moreover, earlier investigations describe that the wood color was indicated for information about the chemical transformation during heat treatment, see Bourgois et al. (1991).

Cluster analysis

The results of the cluster analysis for ash samples are given in **Table 3**. The group of untreated samples is combined in cluster 1a. The comparative results between the heat treatments and the cluster analysis show differences. The samples treated with low intensity are divided into cluster 2a and cluster 3a. Two samples are misclassified, see **Table 3**. By accurate analysis of the two samples, it could be assumed that the reason for the incorrect classification were the L*- and b*-values, see **Figure 5**. The cluster centers show the average of the L*-, a*, and b*-values. In cluster 3a, the cluster center was calculated with all 96 samples.

The results of the cluster analysis on the beech samples show that all clusters (1b, 2b, 3b and 4b) conformed to the heat treatments. **Table 3** shows that there were no false classifications.

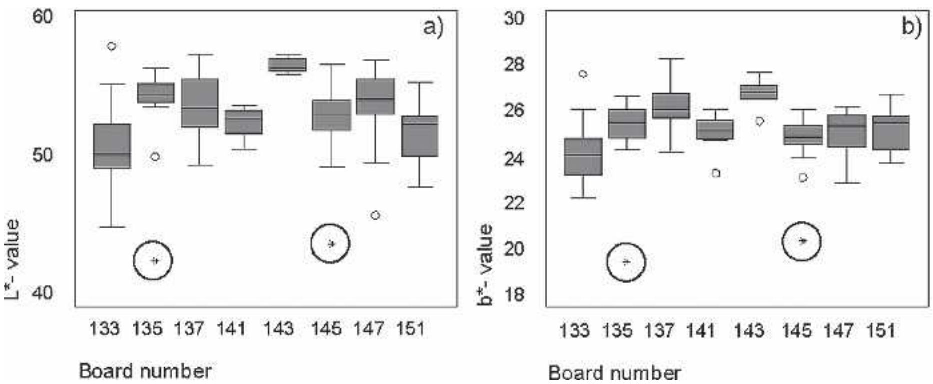

Figure 5. — Influence of heat treatment (low intensity) on L and b* for the ash sample. The two misclassified samples are indicated by circles. Outliers are marked with (o) and extreme values are denoted with (*).*

Table 3. — Distribution of the cluster and the cluster center for the ash and beech sample.

	Heat treated intensities				Cluster center		
	Untreated	Low	Medium	Strong	L*	a*	b*
				Ash			
Cluster 1a	208	0	0	—	75.8	5.9	19.7
Cluster 2a	0	116	0	—	52.7	11.2	25.1
Cluster 3a	0	2	94	—	39.3	9.0	16.3
				Beech			
Cluster 1b	249	0	0	0	79.5	5.4	18.5
Cluster 2b	0	78	0	0	50.6	10.8	22.6
Cluster 3b	0	0	61	0	40.6	9.4	16.7
Cluster 4b	0	0	0	110	34.0	6.1	10.6

Table 4. — Bending strength of the clusters.

	Bending strength ----------(N/mm^2)----------	
Classification	Mean	SD
	Ash	
Cluster 1a	119.0	16.6
Cluster 2a	111.5	21.4
Cluster 3a	83.9	27.7
	Beech	
Cluster 1b	121.7	11.8
Cluster 2b	114.4	17.6
Cluster 3b	103.0	29.7
Cluster 4b	84.5	21.7

The cluster center could be used for the identification of the process control, therefore the process is deemed finished if the CIEL*a*b*-values are met. The single linkage method is a useful cluster method for the separation of the wood samples treated.

Only two samples in cluster 3a were misclassified using this clustering method. **Figure 5** shows the L* and b* values on all ash wood samples of the low intensity heat treatment. The values were separated for every board used. The most relevant samples were from boards number 135 and 145. The two misclassified samples were identified by a circle, and the values showed a deviation from the mean value. The a* value did not show any significant differences.

On visual inspection of the modified samples, a discoloration in the two samples was found. The wood color of these samples was darker than the other board samples. In addition, the two reference samples did not show any extraordinary variation in the wood color. Thus, it could be accepted that the discoloration of the two samples was an exception.

Bending strength of the cluster

The bending strength values of ash and beech samples differed during the heat-treatment process, see **Table 4**. The bending strength decreased when the treatment temperature was raised. Also Hanger et al. (2002a) mentioned this behavior of the thermally modified wood.

Table 4 shows that each cluster differs according to the mean bending strength. As the SD seemed to be rather high, a one-way analysis of variance (ANOVA) was applied. For the ash samples, three independent groups (clusters) with 424 observations were obtained. The beech samples were divided into four groups (clusters) with 498 measurements. For the ash samples observed, the analysis showed that the mean squared deviation between the groups was 41,859.7 and the mean squared deviation within the groups was 433.3. For the bending strength of the beech samples the analysis indicated that the mean squared deviation between the groups was 36,622.6 and the mean squared deviation within the groups was 329.4. The analysis showed that there is a significant difference between the bending strength of the clusters, and as a consequence the null hypothesis could be dismissed. Therefore, the color information can also be used to define various grades of thermally modified hardwood according to the bending strength.

Discussion

The results show that it is possible to define classes of thermally modified wood. The heterogeneity of the color within the defined groups is small compared to the variance in the color of all samples. The cluster analysis showed that it was possible to categorize 424 ash wood samples of which only two were classified incorrectly.

Based on the cluster analysis, the mean color (cluster centers) for every color category was calculated. These colors could be used to define the target color of the treatment process.

The analysis of the wood color with the CIEL*a*b*-system shows that the three parameters (L*, a* and b*) are adequate for a clear classification into different heat treatments. For ash and beech samples the wood color became darker (decreasing L* value). A further conclusion derived from the results was the behavior of wood color using different heat treatments. A lower process temperature affects a rise in the chromatic coordinates (a* and b*). The values of chromatic coordinates decrease under higher temperature. It is shown that the effect of the heat treatment on wood properties is significant. The equilibrium MC of wood decreases with increasing treatment temperature. In addition it could be noted that bending strength decreases when treatment intensities are increased. Each defined cluster demonstrates a difference to the mean of the bending strength.

Conclusion

Concluding, the results of cluster analysis show that the clustering by color correlated with the heat treatment. The wood color is a suitable parameter for the classification of thermally modified ash and beech hardwood. The color information can also be used to define various classifications of heat-treated wood in compliance with the bending strength. These results are a useful basis to establish grading rules and guidelines for the quality assurance of thermally treated wood. Further studies will be carried out to find out if there is a significant correlation between color information and certain technical wood properties (e.g., compressive strength, tensile strength). This information could be used to develop thermal treatment to modify wood according to the specific needs of the customers, based on process control by color measurement.

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