Performance of water-borne coating systems on thermally modified wood

Michael Altgen[1], Jukka Ala-Viikari[2], Antti Hukka[2], Timo Tetri[2] and Holger Militz[1]

[1]Wood Biology and Wood Products, Burckhardt-Institute, Georg August University of Göttingen, Büsgenweg 4, 37077 Göttingen, Germany [email: maltgen@gwdg.de]

[2] International ThermoWood Association, Unioninkatu 14, Helsinki, Finland

Keywords: Adhesion strength, coating performance, penetration, thermally modified wood

ABSTRACT

Despite its improved dimensional stability and durability of thermally modified wood, a surface treatment with paints can be required for certain exterior applications. However, when applying water-borne coating systems to thermally modified wood, the altered surface characteristics of thermally modified wood potentially have an influence on the performance. Within this study, Scots pine and Norway spruce were thermally modified according to the ThermoWood® and acidity and wettability were evaluated. The same material was then coated with two different water-borne coating systems and both, the penetration depth and the adhesion strength, were assessed. The results show that while the penetration of the coating systems was not affected by the modification process, the adhesion strength of one of the applied coating systems decreased considerably on thermally modified wood, irrespective of the wood species, the treatment intensity or the surface preparation technique. Changes in the contact angle of deionised water, which were only significant for the high treatment intensity, did not seem to be correlated with the loss in adhesion strength. However, an increase in the acidity, already occurring at low treatment intensities, were considered as a potential drawback for certain water-borne coating systems on thermally modified wood surfaces.

INTRODUCTION

The understanding of the adhesion of coating systems on thermally modified wood is essential for an optimisation of its performance in outdoor conditions. When exposed to outdoor conditions, thermal modification does not protect the wood from discoloration, thus the original brown colour turns grey if no coating is applied (Jämsä *et al.* 2000; Huang *et al.* 2012). Furthermore, the crack formation of thermally modified wood in exterior conditions without coating is not improved compared to unmodified wood (Jämsä *et al.* 2000). Consequently, a surface treatment of thermally modified wood with oils or paints is often required.

For unmodified wood, traditionally used solvent-borne alkyd paints are increasingly replaced by water-borne coating systems, due to the need to avoid emissions of air polluting volatile organic compounds (de Meijer *et al.* 1998). Induced by chemical changes during the modification process, the improved dimensional stability of thermally modified wood should improve the service life of such coatings (Podgorski and Roux 1999). However, the chemical changes also result in an alteration of the surface characteristics, which potentially affect the adhesion of water-borne coating systems on thermally modified wood. Several studies show that the wood becomes more hydrophobic (Pétrissans *et al.* 2003, Hakkou *et al.* 2005, Kocaefe *et al.* 2008, Metsä-Kortelainen and Viitanen 2011) and more acidic (Sundqvist *et al.* 2006, Hofmann *et al.* 2013) after thermal modification.

This study follows the hypothesis that altered surface characteristics of thermally modified wood can affect the performance of water-borne coating systems that are intended for the application on unmodified wood surfaces. For this reason, wettability and acidity of thermally modified Scots pine and Norway spruce that were treated according to the ThermoWood® process were evaluated. On the same material, two commercially available water-borne coating systems were applied. One system is typically used for unmodified joinery material, while the other one is typically applied for unmodified cladding material. The performance of these coating systems on thermally modified wood surfaces was assessed by measuring the adhesion strength using the pull-off and the cross-cut test as well as by investigating the penetration depth using light microscopy. In addition to the effect of the thermal modification, the impact of the storage duration and different surface preparation techniques was evaluated.

EXPERIMENTAL

Material

Pre-dried boards of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) with a length of 2 m and dimensions typically used for cladding or joinery were thermally modified using the ThermoWood® process. Two different treatment intensities were applied for each product class, using the peak temperature and duration given in Table 1.

Table 1: Board dimensions and treatment intensities applied in the ThermoWood® process.

Product class	Wood species	Board dimensions [mm²]	Peak temperature and duration	
			Low intensity	High intensity
Joinery	Scots pine	50x125	180 °C/3h	212 °C/3h
	Norway spruce	50x150		
Cladding	Scots pine	25x125	180 °C/2h	212 °C/3h
	Norway spruce	25x150		

Acidity

Material originating from ten boards per variety was milled and mixed in a cutting mill using a mesh size of 2 mm. A cold water extraction with 25 g dry mass wood and 300 ml deionised water was performed for 24 h on a flatbed horizontal shaker. The extracts were filtrated and washed four times with 175 ml of deionised water. Afterwards, the filtrate and washings were diluted to 1000 ml in total. 200 ml of each extract was used to measure the initial pH and buffering capacity. 1 ml of 0.025 M NaOH was added every 120 seconds until reaching a pH of 7. The amount of NaOH required to reach the neutralisation point was determined and used as a measure for the acidity of the wood extracts (mmol NaOH/l extract). Each variety was measured in duplicate.

Wettability

Samples (15x40x100 mm³) with planed surfaces were prepared from conditioned boards of pine and spruce that were unmodified as well as thermally modified at low and high treatment intensity. The contact angles were measured within 24 hours after the sample preparation using the sessile drop technique with deionised water as a probe liquid. A Krüss G10 measurement system was used in connection with the corresponding Krüss DSA 1 software. After applying a volume of 10 µl to the surface, the contact angle of each droplet was recorded with 25 frames per second and a total of 250 frames. Additional measurements were conducted one and two weeks after the sample preparation. A minimum of 20 measurements per variety were conducted.

Coating application

Samples with dimensions of 20x40x300 mm^3 and an annual ring orientation of approximately 45° were prepared from different boards and conditioned at 20 °C and 65 % RH. Three different surface preparation techniques were applied shortly before the coating application by: (1) planning, (2) sanding with 100 grit sanded paper or (3) roughening with 40 grit sanded paper. The coating systems were applied by spray using a nozzle tip of 1.8 mm and a pressure between 2 and 3 bar. The solid content and the spreading amount of the applied coating systems are given in Table 2. For both water-borne coating systems the same water-borne priming oil was applied in one layer. Afterwards, two layers of coating A) or coating B) were applied to the joinery or cladding material, respectively. Both coatings were thinned with water within the limits of the instructions given by the manufacturer.

Table 2: Solid content and spreading amounts of the applied coating systems (commercial products from a coating manufacturer).

	Product class	Solid content (w/w) [%]	Spreading amounts per layer (unthinned)	
			Wet / one layer [g/m^2]	Theoretical dry film thickness [µm]
Priming oil		11	80	10
Coating A	Joinery	53	155	50
Coating B	Cladding	47	135	30

Coating penetration

From each coated sample, small cross sections were cut and the transverse surfaces were smoothened using a microtome. The cross sections were either evaluated directly using a reflected light microscope (Zeiss Axioplan 2), or stained with 1% safranin and analysed using a fluorescence light microscope (Nikon Eclipse E600) and a UV-2A filter.

Adhesion strength

The adhesion strength was assessed using the pull-off test on the basis of EN ISO 24624: 2003 as well as the cross-cut test on the basis of EN ISO 2409: 1994. For the pull-off test, three dollies with a diameter of 20 mm were bonded to the coating. The coating surrounding each dolly was removed 24 hours after the adhesion of the dollies. Using the PosiTest pull-off adhesion tester, the dollies were detached from the surface in a direction perpendicular to the substrate and the required force was recorded. Additionally, the amount of wood fracture was determined based on the surface area of the wood fractures detached to the tested dolly. A minimum of six dollies per variety were measured. For the cross cut test, a right angle lattice was cut into the coating with a sharp blade and a distance of 2 mm between the cuts. The cuts were done at 45° to the direction of the grain. A transparent pressure sensitive tape is attached to the lattice while ensuring good contact to the coating. The tape is then pulled off steadily in an angle of approximately 60°. The cross-cut area is examined and classified from 0 (very good adhesion) to 5 (poor adhesion) based on the amount of flaked coating.

RESULTS AND DISCUSSION

Acidity and wettability

The acidity increases for thermally modified wood due to the formation of organic acids, *i.e.* acetic and formic acid (see Table 3). Since the cleavage of acetyl-groups of hemicelluloses and the consequent formation of acetic acid already occurs at low treatment intensities, a high acidity is evident for a treatment at 180°C and 2 hours.

Table 3: Average contact angle of deionised water recorded after 5 seconds [°] with respective standard deviations in parentheses as well as average acidity [mmol NaOH/l extract].

Wood species	Variety	Contact angle after 5 sec. [°]	Acidity [mmol NaOH/l]
Norway spruce	Unmodified	37.28 (6.53)	0.310
	180 °C/2h	40.56 (3.68)	1.168
	212 °C/3h	53.21 (6.27)	0.945
Scots pine	Unmodified sapwood	47.39 (12.05)	1.227
	Unmodified heartwood		1.039
	180 °C/2h	52.65 (10.39)	1.790
	212 °C/3h	79.67 (3.37)	1.080

Remarkably, a thermal modification at higher temperatures (212 °C/3h) leads to a lower acidity than a treatment at low intensity (180 °C/2h). This might be caused by a further release of organic acids as volatile organic compounds out of the kiln at higher temperature, resulting in the incorporation of the acids in the waste water (Hofmann *et al*. 2013). Furthermore, organic acids might react with the cell wall compounds, *e.g*. by esterification and thus become non-extractable (Tjeerdsma and Militz 2005). Using the sessile-drop technique, an increase in the contact angle of deionised water could be found after the thermal modification process (see Table 3), which is in line with earlier investigations (Pétrissans *et al*. 2003; Metsä-Kortelainen and Viitanen 2011). However, the increase compared to unmodified wood is only significant for high treatment intensities ($p < 0.05$). Compared to spruce with a contact angle of 53° for a treatment at 212 °C/3h, the increase in the contact angle during thermal modification is far more severe for pine, which reaches a contact angle of approx. 80°. In addition to the impact of the thermal modification, the effect of the storage of the samples after the surface preparation was evaluated (see Figure 1). Coinciding with Nussbaum (1999), the contact angle of deionised water increases with the storage duration, thus indicating a surface inactivation. This increase over time is more pronounced for unmodified wood, leading to fewer differences in the contact angle between unmodified and thermally modified wood after 15 days of storage.

Coating penetration

The penetration of both water-borne coating systems into the wood substrate is limited to the flow through open connections, which is in line with the observations of de Meijer *et al.* (1998). As can be seen in Figure 2, there is no evidence of a penetration from cell to cell via the interconnecting pits or through the ray tissue. The coatings can therefore only be found at the very outer layer of the surface. Also, there is no difference in the penetration between unmodified and thermally modified wood. After planning, the surface is very smooth with only little destruction of outer tracheids within the earlywood, while sanding and roughening of the wood lead to more destruction to the outer tracheids, therefore to a higher surface area for coatings. Although a high surface area might be beneficial in terms of adhesion by secondary forces, a destruction of tracheids might also lead to a mechanical weak layer.

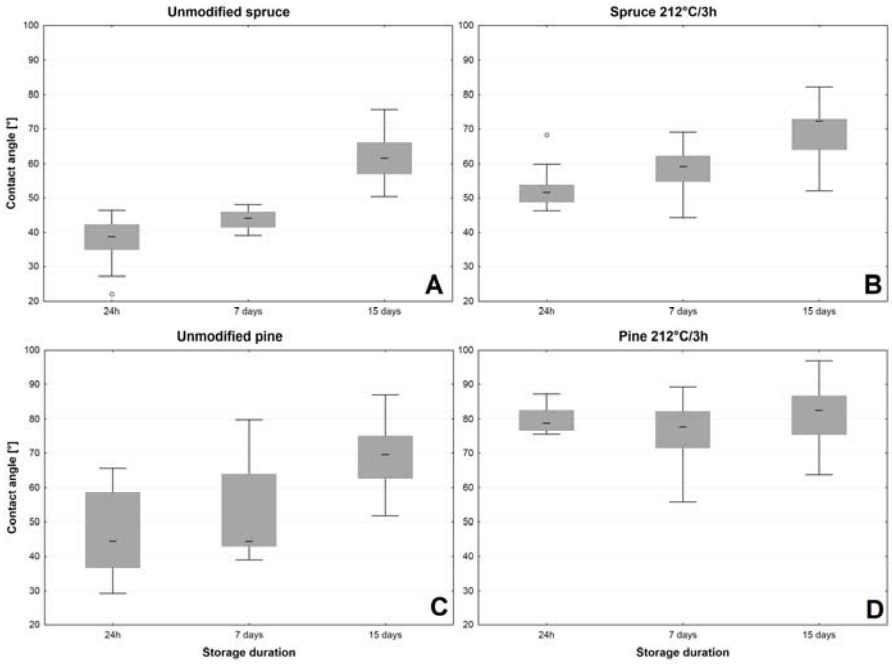

Figure 1: Box plot for contact angle measurements recorded after 5 seconds [°] for a storage duration of 24 hours, 7 days and 15 days for A) unmodified spruce, B) spruce treated at 212 °C/3h, C) unmodified pine and D) pine treated at 212 °C/3h.

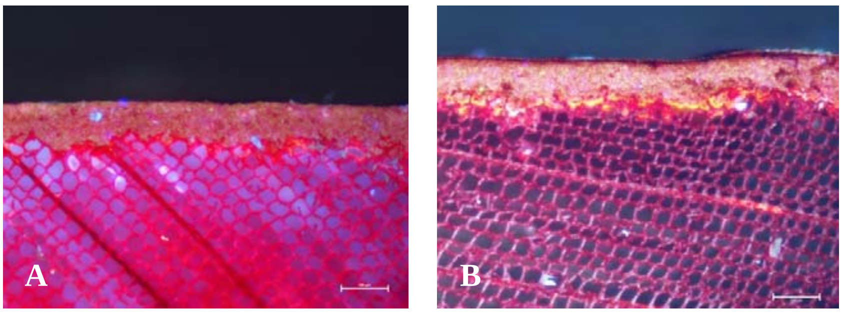

Figure 2: Fluorescence microscopic images of safranin-stained cross cuts of pine samples with a sanded surface and coated with coating B). (A) Unmodified pine (B) Thermally modified pine.

Adhesion strength

Depending on the coating systems that are applied, the adhesion strength differs considerable. For coating A) that is used for the joinery material, the average adhesion strength of the pull-off test is approximately 3 N/mm², as can be seen in Figure 3. With 2.5 and 2.8 N/mm², a thermal modification at low or high treatment intensity features slightly lower adhesion strength in case of spruce. However, this slight decrease in the adhesion strength of thermally modified spruce for coating A) can be explained by high amounts of wood fracture during the pull-off test. In contrast, the difference in adhesion strength between unmodified and thermally modified pine and spruce is far more pronounced for coating B). While unmodified pine and spruce feature an average adhesion strength above 3 N/mm² (pine 3.6, spruce 3.3 N/mm²), an adhesion strength of only approx. 2 N/mm² is evident for thermally modified wood, irrespective of the treatment intensity or the wood species. Although most likely contributing to the strong loss in adhesion strength, the high amount of wood fracture is not considered as the sole reason, as it does not differ considerably from the wood fracture measured for the joinery material. Furthermore, the amount of wood fracture increases considerably with the treatment intensity, but the adhesion strength of coating B) does not differ for thermally modified varieties.

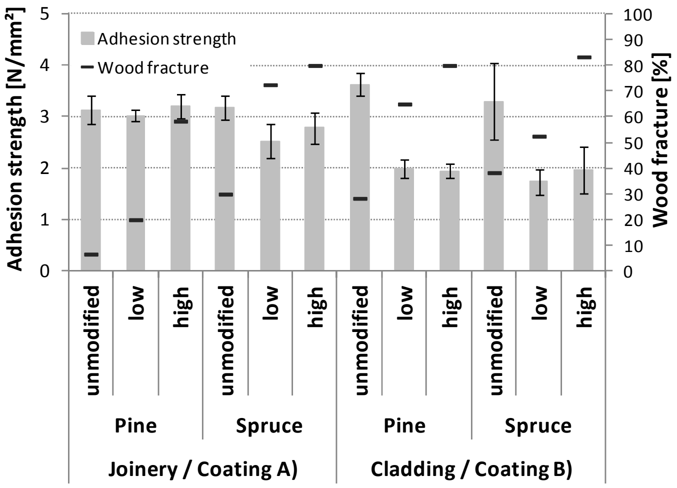

Figure 3: Average adhesion strength [N/mm²] with corresponding standard deviation as well as the respective amount of wood fracture [%] during the pull-off test for pine and spruce modified at different treatment intensities and coated with two different coating systems.

By applying the cross-cut test, the same pattern in the adhesion strength can be observed, as shown in Figure 4. In particular, a clear loss in adhesion strength is evident for thermally modified pine and spruce if coating B) is applied. While unmodified pine and spruce is rated as class 0 (very good adhesion), thermally modified wood is mostly rated as class 5 (very poor adhesion), irrespective of the treatment intensity. In contrast, the differences in the adhesion strength between unmodified and thermally modified wood is much less pronounced for coating A).

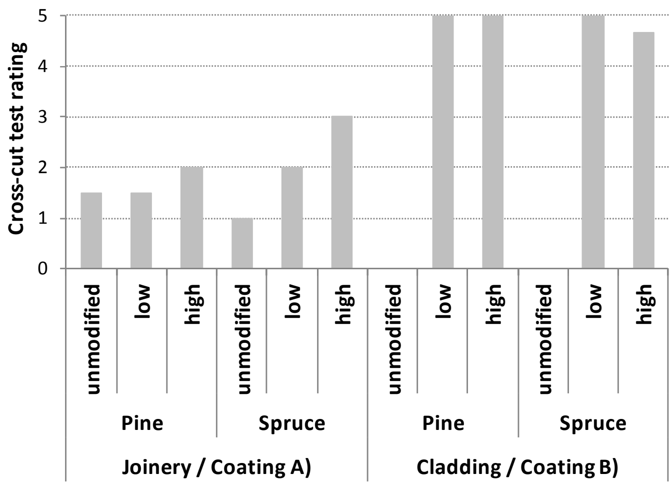

Figure 4: Average cross-cut test rating for pine and spruce modified at different treatment intensities and coated with two different coating systems.

As one potential explanation for the severe loss in adhesion strength for thermally modified wood, coating B) is potentially not compatible with the altered surface characteristics of thermally modified wood. However, the decrease in adhesion strength cannot be explained by the decrease in the contact angle of deionized water observed in this study. While the adhesion strength already decreases for low treatment intensities, high treatment intensities are required to significantly increase the contact angle of deionised water. Investigations by Petric *et al.* (2007) showed that while the contact angle of water increased on thermally modified wood surfaces, it decrease for different water-borne coating systems. Therefore, a higher hydrophobicity of thermally modified wood might not be a critical factor for the application of water-borne coating systems. In line with the losses in adhesion strength, the acidity already increases for low treatment intensities. Potentially, high amounts of organic acids might be a drawback for a good performance of coating B). Concerning the impact of the surface preparation technique, no significant difference in the adhesion strength can be observed whether the surface was planed, sanded or roughened prior to the coating application (see Figure 5). Compared to planed surfaces, sanded and roughened surfaces result in a higher amount of wood fracture based on the surface area. This corresponds to the microscopic evaluations showing more destruction of tracheid walls at the outer layer for sanded and roughened surfaces.

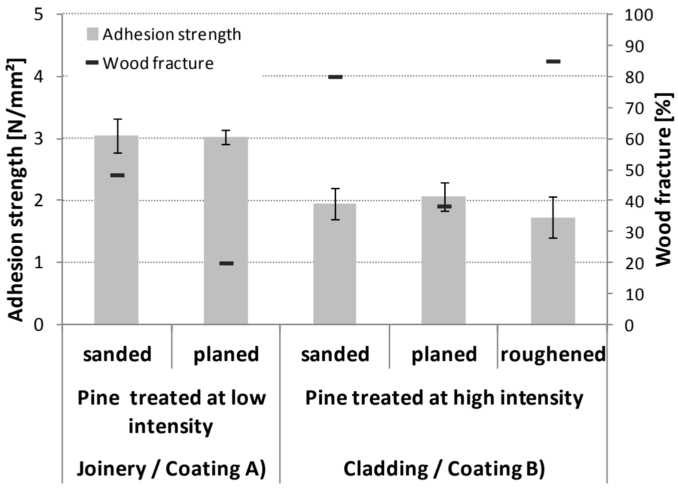

Figure 5: Average adhesion strength [N/mm²] with corresponding standard deviation as well as the respective amount of wood fracture [%] for thermally modified pine with different surface preparation techniques.

CONCLUSIONS

Due to the alteration of surface characteristics, the thermal modification process results in a modified substrate for the application of water-borne coating systems. While the wetting is found to significantly decrease only for high treatment intensities, an increase in the acidity is already evident for low treatment intensities of the modification process. The penetration of water-borne coating systems, which is already very limited for unmodified wood, is not affected by the thermal modification process. In contrast, the adhesion strength of water-borne coatings strongly depends on the system that is used. While one coating system performs well, the other system features very low adhesion strength on thermally modified wood. Furthermore, the surface preparation techniques applied in this study do not have an impact on the adhesion strength. It is concluded that although thermally modified wood can be coated with water-borne coating systems that are intended for the application on unmodified wood surfaces, it should be verified that the coating systems can cope with the modified surface characteristics.

REFERENCES

de Meijer, M., Thurich, K. and Militz, H. (1998). Comparative study on penetration characteristics of modern wood coatings. *Wood Science and Technology*, **32**(5), 347-365.

Hakkou, M., Pétrissans, M., El Bakali, I., Gérardin, P. and Zoulalian, A. (2005). Wettability changes and mass loss during heat treatment of wood. *Holzforschung*, **59**(1), 35-37.

Hofmann, T., Wetzig, M., Rétfalvi, T., Sieverts, T., Bergemann, H. and Niemz, P. (2013). Heat-treatment with the vacuum-press dewatering method: Chemical properties of the manufactured wood and the condensation water. *European Journal of Wood and Wood Products*, **71**(1), 121-127.

Huang, X.A., Kocaefe, D., Kocaefe, Y., Boluk, Y. and Pichette, A. (2012). A spectrocolorimetric and chemical study on color modification of heat-treated wood during artificial weathering. *Applied Surface Science*, **258**(14), 5360-5369.

Jämsä, S., Ahola, P. and Viitaniemi, P. (2000). Long-term natural weathering of coated thermowood. *Pigment & Resin Technology*, **29**(2), 68-74.

Kocaefe, D., Poncsak, S., Doré, G. and Younsi, R. (2008). Effect of heat treatment on the wettability of white ash and soft maple by water. *European Journal of Wood and Wood Products*, **66**(5), 355-361.

Metsä-Kortelainen, S. and Viitanen, H. (2011). Wettability of sapwood and heartwood of thermally modified Norway spruce and Scots pine. *European Journal of Wood and Wood Products*, 1-5.

Nussbaum, R.M. (1999). Natural surface inactivation of Scots pine and Norway spruce evaluated by contact angle measurements. *Holz als Roh- und Werkstoff*, **57**(6), 419-424.

Petric, M. et al. (2007). Wettability of waterborne coatings on chemically and thermally modified pine wood. *Journal of Coatings Technology and Research*, **4**(2), 203-206.

Pétrissans, M., Gérardin, P., Bakali, I. and Serraj, M. (2003). Wettability of heat-treated wood. *Holzforschung*, **57**(3), 301-307.

Podgorski, L. and Roux, M. (1999). Wood modification to improve the durability of coatings. *Jocca-Surface Coatings International*, **82**(12), 590-596.

Sundqvist, B., Karlsson, O. and Westermark, U. (2006). Determination of formic-acid and acetic acid concentrations formed during hydrothermal treatment of birch wood and its relation to colour, strength and hardness. *Wood Science and Technology*, **40**(7), 549-561.

Tjeerdsma, B.F. and Militz, H. (2005). Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. *Holz als Roh- und Werkstoff*, **63**(2), 102-111.