

ENHANCEMENT POSSIBILITIES FOR SURFACE FINISHED WOOD PROPERTIES WITH HYDROTHERMAL DEPOSITION OF TITANIA PARTICLES

Pavel PORI

University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology
Chemcolor Sevnica d.o.o.
Dolnje Brezovo 35, 8290 Sevnica, Slovenia
E-mail: pavli.pori@chemcolor.si

Marko PETRIČ

University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology
Jamnikarjeva 101, 1000 Ljubljana, Slovenia
Tel: 00386 1 3203620, E-mail: marko.petric@bf.uni-lj.si

Abstract:

The novel low temperature hydrothermal process of TiO₂ particles deposition on wood was developed. The crystal structure of the hydrothermally made rutile particles, their morphology their distribution in wood and their interactions with lignocellulose were already reported (Pori et al. 2016). However, some other results of investigations of the novel wood surface systems, consisting of hydrothermally deposited TiO₂ nanoparticles and the layers of transparent colourless coatings were presented on various conferences or have even not been published yet. Therefore, this paper brings an assembled review of our results, in order to demonstrate the possibilities for enhancement of surface properties of wood in outdoor exposure with hydrothermally deposited TiO₂ particles.

It was established that the process of hydrothermal deposition of titania nanoparticles has both positive as well as negative effects when outdoor applications of Norway spruce wood are considered. The results of artificial accelerated ageing of surface systems on the basis of titania particles and natural oils or some surface coatings were quite promising. In the case of oil and alkyd based surface systems, application of the titania deposits on wood and of the TiO₂ nanoparticles in the coatings resulted in considerably low colour changes after artificial accelerated ageing. On the other hand, data on effects of titania deposits on wood on its wettability are quite ambiguous and should be clarified by further investigations.

Key words: spruce; outdoor uses; hydrothermally deposited TiO₂ particles; hydrophobicity; bending strength; artificial accelerated ageing.

INTRODUCTION

Due to its mechanical properties and aesthetic appeal, wood has a high application potential for its use in constructions, as an insulation material and for production of furniture (Hayoz *et al.* 2003). Unfortunately and particularly when outdoor applications of wood are regarded, some drawbacks of this sustainable material have to be considered. Because of its hydroxylated nature, wood shows poor dimensional and optical stability. In outdoor applications, the combination of UV light (Todaro *et al.* 2015) with moisture (Rassam *et al.* 2012) and temperature (Esteves *et al.* 2013), can lead to destruction of the lignocellulosic network, changes of wood's natural colour and to wood degradation (Deka *et al.* 2008). The most common approach to prevent wood from negative impacts of weathering is surface treatment of wooden elements with surface finishes. Most usually, the expected functions of a finish are both protective and aesthetic. Aesthetically, there is a growing trend among homeowners to maintain the natural look of the wood's original colour. But, the best protection from ultraviolet radiation is achieved by pigmented products, which cover the wood's natural grain and texture (Daniel *et al.* 2004).

Colour of wood, when treated with a pigmented paint, becomes darker and the texture may lose its clearness by becoming hazed. A possible solution is incorporation of various nanoparticles into a coating (Sow *et al.* 2011, Fufa *et al.* 2012). Nanoparticles are small enough to provide excellent scattering and absorption of UV light, while coatings remain transparent with natural appearance of the wood (Bulian and Graystone 2009). To achieve better compatibility between nanoparticles and polymer matrix in a coating, their modification is needed. For instance, to improve dispersability of TiO₂ rutile nanoparticles in acrylic water based coating, two step surface modification of TiO₂ nanoparticles with Al₂O₃ and polyhedral oligomeric silsesquioxanes was investigated by Godnjavec *et al.* (2012). Another approach of application of nanoparticles is their deposition on surfaces to be protected. Rassam *et al.* (2012) reported the successful deposition of nano TiO₂ particles on wood, to improve the wood stability against ultraviolet (UV) light and moisture degradation. The final step was exposure of wood samples to 120°C - 150°C, which are very high temperatures for wood.

We developed a low temperature approach for the deposition of rutile TiO₂ particles on a Norway spruce wood surface by hydrolysis of TiCl₄ in aqueous solutions acidified with HCl, and crystallization at 75°C or 90°C (1h) (Pori *et al.* 2016). In the mentioned paper, the focus was on studies of the crystal structure of the hydrothermally made rutile particles, their morphology, and their distribution in wood. It was shown that TiO₂-wood coordinative bonds of titanium ions with hemicellulose and lignin were established. TiO₂ deposited on wood treated with sodium dodecyl sulphate (SDS) became hydrophobic, contrasting the properties of untreated wood with a deposited TiO₂ particle coating, which remained hydrophilic (Pori *et al.* 2016).

OBJECTIVE

The mentioned paper of Pori and co-authors (Pori *et al.* 2016) reported the most important results of PhD dissertation of Pori (2016). Some other results from his doctoral dissertation were also already published, predominantly on various national and international conferences and some other results have not been published yet. So, the main aim of this paper, bringing the review of our own results, is to report sensibly assembled results from previous years, in order to demonstrate the possibilities for enhancement of surface properties of wood in outdoor exposure with hydrothermally deposited TiO₂ particles.

MATERIAL, METHOD, EQUIPMENT

For all tests, spruce wood (*Picea abies* (L.) Karst.) was used. The size of the samples was dependent on the test, as described in subsequent paragraphs.

Hydrophobic properties and water-vapour transmission

For the purpose of determination of equilibrium moisture content (EMC) and water vapour transmission of the specimens with titania deposits, the samples of the following size were prepared: 70mm (radial) × 70mm (axial) × 25mm (tangential). Half of samples was modified with hydrothermal synthesis of TiO₂ on their surfaces, as described in details in our previous papers (Pori *et al.* 2012, Pori *et al.* 2016). After conditioning of the surface modified and non-modified samples, they were treated with the polyacrylic coating (in the following text named as “acrylic”, Lesoton Aqua, produced by Chemcolor Sevnica, d.o.o., Slovenia) or with the organofunctionalised fluorinated silane surface system (“silane”, Silles by Chemcolor). The acrylic paint was applied in two layers (2x100g/m²) and the application rate of the silane surface system coating was 180g/m². The tests were performed also with the titania modified samples without coatings and with the control specimens.

Contact angles of water were determined by the sessile drop method, and the water vapour transmission and diffusion coefficient were determined by the standard method ISO 7783-1, by the Payne cup. More experimental details can be found in the paper of Pori and co-authors (2012).

Mechanical properties

Bending strength was determined with Zwick Z100 (6 specimens per one series), in accordance with the standard method (Pori 2016).

Resistance of various surface systems against accelerated artificial ageing

As a substrate, spruce wood samples without and with deposits of TiO₂ particles were used. The plates of the dimensions of 150mm (L) × 50mm (R) × 5mm (T) were applied. In some cases the substrate's surfaces were pre-treated with sodium dodecyl sulphate, and deposition of TiO₂ particles (of the rutile or of the anatase crystalline form) was carried out from mixtures of aqueous solutions of TiCl₄ and HCl, where the concentration of HCl varied between 0 mol/L to 1 mol/L (Petrič *et al.* 2014). The following finishes were applied: a natural oil based finish, and coatings of a polyacrylate (OIL), polyalkyd (ALKYD) and a polyurethane (PU) types. Into the coatings, pre-treated (coated) nanoparticles of TiO₂ were dispersed, or the coatings without nanoparticles were applied. TiO₂ (mTiR) to be dispersed in the coatings was purchased from Cinkarna Celje d.d., Celje, Slovenia. As a surface modifier for the nanoparticles, the polyhedral oligomeric silsesquioxane trisilanol (POSS) was used. The process of surface coating of the nanoparticles is described in (Petrič *et al.* 2014). Into the coatings, the pre-treated (surface modified) TiO₂ nanoparticles were dispersed with the Ultra Turrax Ika T 25 for 15min at 8000min⁻¹ – 10000min⁻¹.

The finishes were applied to wood specimens manually, by brushing, and therefore the film thickness could not be controlled precisely. The coated samples were left to dry at ambient conditions for one day and on the next day, the second layer of a finish was applied, and on the third day, we applied the third layer (only in the case of the oil based finish). In all cases, approximately total of 200g/m² of the finish was applied.

Artificial accelerated ageing was carried out by exposure of the specimens in the Atlas SUNTEST® XXL Light Exposure and Weathering Testing Instrument, with three air-cooled 2100W xenon lamps in a controlled chamber temperature, with an ultrasonic humidification system for humidity control and a

specimen spray system. For the artificial accelerated weathering, the pre-programmed standard test in accordance with the EN ISO 11341 1A:2005 standard was applied. The influence of ageing was followed by colour and gloss measurements and by determination of contact angles of water.

Colour was measured in accordance with the standard ISO 7724-2 (1984) with the spectrophotometer SP62, X-Rite GmbH - OPTRONIK™, and gloss with the X-Rite AcuGloss TRI according to SIST EN ISO 2813 (60°). Finally, the sessile drop technique was used to determine the apparent contact angles of water on the specimens. This method is based on the observation of the profile of the drop deposited on the surface of the solid. The contact angle of water on each surface system was determined 1 second after deposition of a drop.

RESULTS AND DISCUSSION

Hydrophobic properties and water-vapour transmission of surface treated and non-treated wood, modified with TiO₂ deposits

To prolong durability of wood used outdoors, surface coatings for protection of wood against uptake of water vapour are normally applied. They should increase hydrophobicity of surfaces in order to protect wood against liquid water - rain. Our various experiments with deposition of titania particles of wood gave quite ambiguous results in terms of hydrophobic / hydrophilic influence of TiO₂ particles on wood surfaces. As described by Pori *et al.* (2016), wood with TiO₂ deposits remained hydrophilic, but when prior to TiO₂ deposition, wood was treated with sodium dodecyl sulphate, hydrophobic properties were obtained. Hydrophilic behaviour of titania treated wood (59.4°) was observed also by Pori *et al.* (2012) – see Fig.1, “modified wood – non-treated”. It seems that concentration of HCl in the reagent solution for deposition of titania plays an important role with this respect. In the cases of 1 mol/L HCl and without HCl, contact angles on wood with titania deposits increased, and the contact angles of water were significantly decreased when concentrations of HCl had values of 0.01, 0.1 and 0.5 mol/L (Pori *et al.* 2014). On the contrary, Križan (2017) performed deposition of titania particles from the solution without HCl, but observed hydrophilic nature of wood with TiO₂ deposits. So, additional research is needed to clarify ambiguous data on hydrophilic / hydrophobic character of titania treated wood surfaces and to find the way, how to control the wettability effect of titania deposits. On the other hand, it is quite clear that titania deposits in combination with surface treatment of wood with surface finishes have a positive effect on hydrophobicity of a finish. For instance, it was shown Pori *et al.* (2012) that the most hydrophobic surfaces of finished spruce wood were that of the silane finish treated ones, with the water contact angle of more than 133°. In average, the contact angles of water on the acrylic coated surfaces were 65.4°. Relatively hydrophobic was also wood itself (90.7°). When we compare contact angles on surface coated non-modified wood with those on the coatings on the TiO₂ modified wood surfaces, we see that modification of wood has a positive influence (Fig. 1). The contact angles were in both cases slightly increased (acrylic 6.5°, silane 2.1°). Similarly, Križan (2017) noticed that that the initial contact angles of water were increased from around 80° on wood, oiled with a commercial natural oil based finished for about 10°, when wood with titania deposits was finished with the same oil finish formulation.

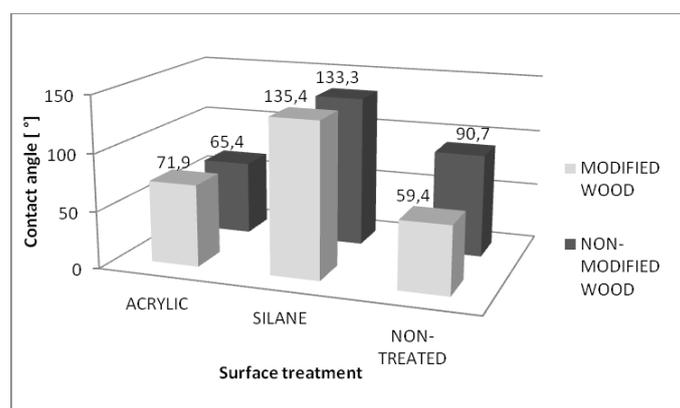


Fig. 1.

The contact angle of water on TiO₂ modified and non-modified spruce wood, either treated or nontreated with acrylic or silane based coatings.

Due to modification (deposition of TiO₂ and also degradation by HCl), wood had a slightly increased equilibrium moisture content (EMC) (14.66% - 13.77%) compared the EMC of non-modified wood (12.77% - 12.59%) (Table 1). In general, the modified samples (no matter of the final surface treatment) achieved higher EMC compared to the non-modified ones. The non-modified samples (Table 1) exhibited differences in EMC due to orientation (UP or DOWN) of the treated surface in the cup only at acrylic coatings. The

samples with the upside DOWN orientation of the treated surface had a higher average EMC. However, the specimens with TiO₂ deposits showed much higher EMC than non-modified ones (Table 1). Based on the analysis of the results from Table 1, we can assume that the bottleneck for internal mass transfer resistance of water is the surface system.

Water vapour diffusion coefficient and WVT (Water vapour transmission) through the systems had a similar character and they were mostly related to the surface system of the sample. The samples with acrylic films had the lowest WVT and diffusion coefficient without any significant difference between TiO₂ modified and non-modified samples (Table 2). On the other hand, silane penetrated into wood cells, what was preliminary detected by optical microscope. Hydrophobicity was ensured due to chemical composition of silane and maybe also due to the nanostructure of the surface, but the net is open for the vapour transmission, just like in non-treated wood. However, the modified silane treated and non-treated samples had even larger WVT and diffusion coefficient values than the non-modified wood.

The fact that the synthesized TiO₂ exhibited hydrophilic influence on the surface is not favourable in terms of outdoor applications. Also, the same can be concluded for TiO₂ modified surface finished and non-finished wood - it unfortunately exhibited higher water vapour transmission and diffusion of the system.

Table 1

Equilibrium moisture content of samples, conditioned at air humidity of 65% (u_E 65%) and at high relative air humidity; the samples were during the cup test with the treated surface facing up (u_E UP) or down (u_E DOWN)

	Modified* wood + acrylic coat	Modified wood + silane coat	Modified wood	Non-modified wood + acrylic coat	Non-modified wood + silane coat	Contro l
u_E 65% [%]	14.66	13.79	13.77	12.59	12.77	12.69
u_E UP [%]	21.60	30.19	29.27	16.88	22.92	22.77
u_E DOWN [%]	43.69	27.45	26.55	27.09	22.93	23.05

* modified means wood with titania deposits

Table 2

WVT and diffusion coefficient of modified and non-modified surface treated and nontreated samples, depending on orientation of the sample in the Payne cup

	Modified* wood + acrylic coat	Modified wood + silane coat	Modified wood	Non- modified wood + acrylic coat	Non- modified wood + silane coat	Control
WVT_{UP} [g ² 24h]	1190	3545	3147	1188	2086	2257
WVT_{DOWN} [g ² 24h]	1019	2740	2692	1166	2191	2374
D_{UP} [m ³ /m s]	8.50×10^{-13}	2.75×10^{-12}	2.25×10^{-12}	8.19×10^{-13}	1.43×10^{-12}	1.63×10^{-12}
D_{DOWN} [m ³ /m s]	7.64×10^{-13}	2.17×10^{-12}	1.92×10^{-12}	8.27×10^{-13}	1.52×10^{-12}	1.73×10^{-12}

* modified means wood with titania deposits

Bending strength and modulus of elasticity of wood with titania deposits

Although the bending strength and modulus of elasticity are not surface properties, we included these properties in this review, since they are important parameters when wood is used for construction elements, what can be a common situation when it is used in outdoor applications. It turned out that because of exposure of wood to the process of titania deposition, mechanical properties decreased (Table 3). As can be seen, the bending strength was dependent on the deposition reaction time. After 15min of treatment the bending strength decreased for 13.5%, and after 30-minutes for 16.8%.

Table 3

Bending strength (F_m) and modulus of elasticity (E_L) of the treated and untreated samples

Samples:	Control	15 min titania deposition process	30 min titania deposition process
F_m [N/mm ²]	98.4	85.1	81.9
Std.dev	15.0	11.9	12.4
E_L [N/mm ²]	13000	11400	11700
3 months	2300	1390	1830

Influence of artificial accelerated ageing on colour, gloss and hydrophobicity (Petrič *et al.* 2014)

As can be seen from Table 4, application of surface coating systems on the substrates, either without or with the TiO₂ deposits, quite substantially changed the appearance of wood, in terms of the ΔE colour difference value. In Table 5 there are presented the ΔE values of the coated specimens after 100, 200, 300, 400 and 500 hours of artificial accelerated ageing. From the data in Table 5 it can be seen that the specimens coated with the oil based finish, alkyd type coating or with the 2-K polyurethane coating, without TiO₂ deposits and without TiO₂ nanoparticles in the coating systems, even after only 500 hours of artificial ageing changed their colours quite substantially. From ΔE = 13.2 for the oil and alkyd based finishes to ΔE = 14.4 for the polyurethane type coating. On the other hand, the influence of TiO₂ deposits and of TiO₂ particles in the coating formulation was obviously dependent on the coating system. In the case of the polyurethane, we could not observe any substantial improvement of the colour stability. On the other hand, TiO₂ deposits on wood substantially decreased coloured changes of oiled specimens (ΔE = 5.3 and 4.6 at surfaces with deposits and oil or with deposits and oil with TiO₂, respectively). However, when the oil with TiO₂ particles was applied to the substrate, covered with TiO₂ deposits, the colour change was surprisingly even larger than in the case of the oil based finish without TiO₂ on the substrate without the deposits. This can lead to the conclusion that the TiO₂ deposits on the substrate are essential for colour stabilisation and not the titania particles in the oil. Somewhat different behaviour was observed at the alkyd type coating. The best result in terms of the colour stability during ageing was observed at the alkyd with nanoparticles, but applied to the non-modified substrate (ΔE = 4.5), followed by the formulation with nanoparticles, applied on the surface with titania deposits (ΔE = 5.6). This observation anticipates a kind of a synergistic activity of both the TiO₂ particles on wood as well as in the coating formulation.

Table 4

Changes of colours due to application of surface finishes and the values of L*, a* and b* of the coated samples prior to exposure to artificial accelerated ageing

The system	ΔE due to application of the coating	Colour of the coated sample		
		L*	a*	b*
OIL	5.54	75.08	8.33	38.16
Deposits + OIL	13.59	57.11	16.89	33.90
OIL(TiO ₂)	11.46	65.58	14.00	39.43
Deposits + OIL(TiO ₂)	7.13	62.61	15.04	30.81
ALKYD	3.81	74.94	8.49	38.18
Deposits + ALKYD	19.05	68.15	10.20	31.11
ALKYD(TiO ₂)	13.83	76.28	7.97	20.95
Deposits + ALKYD(TiO ₂)	6.51	71.73	8.26	15.94
PU	1.82	74.85	8.38	34.21
Deposits + PU	5.81	61.51	13.69	28.81
PU(TiO ₂)	17.69	77.32	7.61	16.27
Deposits +PU(TiO ₂)	17.76	70.69	9.02	11.38

Table 5

ΔE values in dependence of artificial accelerated ageing

The system	ΔE after accelerated ageing				
	100 hours	200 hours	300 hours	400 hours	500 hours
OIL	6.56	9.03	8.24	7.99	13.25
deposits + OIL	1.75	3.67	2.22	2.79	5.28
OIL(TiO ₂)	5.94	9.09	13.89	16.53	22.43
deposits + OIL(TiO ₂)	1.09	1.77	2.10	2.46	4.57
ALKYD	7.04	9.48	10.08	10.49	13.19
deposits + ALKYD	6.26	9.55	10.28	10.87	14.14
ALKYD(TiO ₂)	3.99	4.20	5.07	5.03	4.47
deposits + ALKYD(TiO ₂)	2.22	3.01	3.76	4.65	5.58
PU	8.13	12.22	14.59	14.18	14.44
deposits + PU	6.99	11.11	12.09	12.45	14.19
PU(TiO ₂)	7.31	10.65	11.01	11.81	13.76
deposits + PU(TiO ₂)	7.21	10.00	10.50	11.00	12.40

* The best results are emphasised by grey background of the cells in the table

A decrease of gloss of the surface systems was also observed after artificial accelerated ageing of the oil and alkyd based surface systems. The polyurethane coating exhibited a relatively low gloss already before the exposure and any substantial influence of ageing on gloss was not observed in this case. Similarly to the influence of gloss, artificial accelerated ageing caused also the decrease of the contact angle of water (Table 6). From the data in Table 6 it is hard to draw some general conclusions on the influence of ageing on the contact angle of water. Also, some firm correlations with the changes of colour and gloss cannot be established. Nevertheless, it is possible to conclude that contact angles on the oiled surfaces were the least affected by ageing and those on the surfaces with the polyurethane, the most.

Table 6

Contact angle in dependence of artificial accelerated ageing*

The system	Contact angle of water (°)					
	Before exposure	100 hours	200 hours	300 hours	400 hours	500 hours
OIL	73.6	83.1	74.0	72.0	70.5	72.3
deposits + OIL	78.4	82.6	78.3	76.3	74.3	77.1
OIL(TiO ₂)	103.1	101.5	74.9	73.3	64.5	46.2
deposits + OIL(TiO ₂)	79.2	84.2	72.2	73.1	69.0	68.9
ALKYD	85.2	77.2	60.2	57.0	47.1	50.5
deposits + ALKYD	80.0	71.0	59.1	56.6	46.6	50.5
ALKYD(TiO ₂)	78.2	90.8	77.9	86.2	55.8	56.3
deposits + ALKYD(TiO ₂)	74.1	76.5	68.0	52.2	41.8	51.0
PU	75.3	64.8	23.1	50.2	44.6	45.2
deposits + PU	74.4	64.2	49.9	29.4	45.6	34.9
PU(TiO ₂)	77.2	67.6	45.9	38.8	25.4	41.5
deposits + PU(TiO ₂)	83.8	68.5	49.8	38.8	29.4	30.4

* The best results are emphasised by grey background of the cells in the table

CONCLUSIONS

Data on influence of titania deposits on spruce wood on its wettability are quite ambiguous and should be clarified by additional research.

At TiO₂ modified samples, finished with acrylic, oil based or silane surface systems, the contact angle of water increased in comparison with the contact angle on the samples without TiO₂ deposits. The equilibrium moisture content of the samples increased due to modification in the TiCl₄/HCl solution. Also, both titania modified surface finished and non-coated wood exhibited increase in water vapour transmission and diffusion of the system. The process of titania particles deposition substantially decreased bending strength of the samples: after 15min of treatment the bending strength decreased for 13.5%, and after 30-minutes even for 16.8%. The results of artificial accelerated ageing of some surface systems on the basis of oil, alkyd and polyurethane type coats were quite promising. In the case of oil and alkyd based surface systems, application of the titania deposits on wood and of the TiO₂ nanoparticles in the coatings resulted in considerably low colour changes after 500 hours of ageing. On the other hand, at the polyurethane coating, a positive influence of the deposits and nanoparticles was not observed.

In general, it seems that the low temperature hydrothermal TiO₂ deposition process is an interesting alternative to conventional protection systems for wood in outdoor application. It has so positive as well as negative influence on surface properties of treated wood, either not finished with a surface coating or with a surface finish. We believe, that this promising technique for surface treatment of wood should be extensively investigated in future.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P4-0015 »Wood and lignocellulosic composites«.)

REFERENCES

- Bulian F, Graystone JA (2009) Raw Materials for Wood Coatings (2) – Solvents, Additives and Colorants Wood Coatings. Elsevier, Amsterdam.
- Daniel T, Hirsch MS, McClelland K, Ross AS, Williams RS (2004) Clear exterior finishes: Finding the balance between aesthetics and durability. JCT Coatingtech 1:36-49.

- Deka M, Humar M, Rep G, Kričej B, Šentjunc M, Petrič M (2008) Effects of UV light irradiation on colour stability of thermally modified, copper ethanolamine treated and non-modified wood: EPR and DRIFT spectroscopic studies, *Wood Science and Technology* 42:5–20.
- EN ISO 11341 1A (2005) Paints and varnishes - Artificial Weathering and Exposure to Artificial Radiation - Exposure to Filtered Xenon Arc Radiation.
- Esteves B, Marques VA, Domingos I, Pereira H (2013) Chemical changes of heat treated pine and eucalypt wood monitored by FTIR (2013) *Maderas Ciencia y Tecnología*, 15:245-258
- Fufa SM, Jelle BP, Hovde PJ, Rorvik PM (2012) Coated wooden claddings and the influence of nanoparticles on the weathering performance. *Progress in Organic Coatings* 75:72–78.
- Godnjavec J, Znoj B, Veronovski N, Venturini P (2012) Polyhedral oligomeric silsesquioxanes as titanium dioxide surface modifiers for transparent acrylic UV blocking hybrid coating. *Progress in Organic Coatings* 74:654–659.
- Hayoz P, Peter W, Rogez D (2003) A new innovative stabilization method for the protection of natural wood, *Progress in Organic Coatings* 48(2-4):297–309.
- ISO 7724-2:1984 (1984) Paints and varnishes - Colorimetry - Part 2: Colour measurement.
- ISO 7783-1 (1999) Paints and varnishes – Determination of water vapour transmission rate – Part 1: Dish method for free films.
- Križan J (2017) Protection of wood against UV-light with titanium dioxide and coatings: B. Sc. thesis. University of Ljubljana.
- Petrič M, Delić F, Kričej B, Pavlič M, Pori P, Šernek M (2014) Resistance of spruce wood with TiO₂ surface deposits and a colourless finish against UV. Proc of the PRA's 9th international wood coatings congress, Amsterdam, Netherlands pp. 1-10.
- Pori P, Vilčnik A, Pavlič M, Kričej B, Straže A, Gorišek Ž, Rozman N, Orel B, Petrič M (2012) Hydrophobic properties and water-vapour transmission of surface treated and non-treated wood, modified with TiO₂. In: Proc of the „Wood is good - with knowledge and technology to a competitive forestry and wood technology sector” 23rd international scientific conference, Zagreb (Croatia), pp. 155-162.
- Pori P, Vilčnik A, Orel B, Petrič M (2014) Hydrophobic properties of wood surface modified by hydrothermal (telethermal) deposition of TiO₂ nanocrystals. In: Agenda and abstracts: moving towards a sustainable bioeconomy. University of Guelph, Ontario, p. 245.
- Pori P (2016) Protection of wood against UV radiation with nano-coatings (PhD thesis). University of Ljubljana, Slovenia.
- Pori P, Vilčnik A, Petrič M, Sever Škapin A, Mihelčič M, Šurca Vuk A, Novak U, Orel B (2016) Structural studies of TiO₂/wood coatings prepared by hydrothermal deposition of rutile particles from TiCl₄ aqueous solutions on spruce (*Picea Abies*) wood 372:125-138.
- Rassam G, Abdi Y, Abdi A (2012) Deposition of TiO₂ nano-particles on wood surfaces for UV and moisture protection, *Journal of Experimental Nanoscience* 7:468–476.
- SIST EN ISO 2813 (1999) Paints and varnishes – Determination of specular gloss of non metallic paint films at 20°, 60° and 85° ISO 2813:1994, Including Technical Corrigendum 1:1997.
- Sow C, Riedl B, Blanchet P (2011) UV-waterborne polyurethane-acrylate nanocomposite coatings containing alumina and silica nanoparticles for wood: mechanical, optical, and thermal properties assessment. *Journal of Coating Technology Research* 8:211-221.
- Todaro I, D'Auria M, Langerame F, Salvi AM, Scopa A (2015) Surface characterization of untreated and hydro-thermally pre-treated Turkey oakwoods after UV-C irradiation, *Surface and Interface Analysis* 47:206–215.