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VARIABILITY OF DRY FILM THICKNESS OF A COATING APPLIED BY ROLLER COATER ON WOOD IN A REAL INDUSTRIAL PROCESS

This study investigates variation in the dry film thickness (DFT) of a coating applied by roller coater on the surface of wood in real industrial conditions on a UV finishing line. It was examined how DFT is influenced by the temperature of the liquid top coating, the position of the sample on the conveyor, and the position of the measurement point along the length of the sample. The three-way interaction between the temperature of the liquid top coating, position on the conveyor and position along the sample did not have a statistically significant impact on DFT. However, an increase in the temperature of the liquid top coating (from 24.1 to 24.8°C) caused a decrease in the viscosity of the coating and a significant reduction in DFT when samples were positioned closer to the coating supply hose or in the middle of the conveyor. When the temperature of the liquid top coating was lower, the variation in DFT at different positions across the conveyor was not significant. A higher temperature of liquid top coating led to significantly smaller DFT for samples closer to the supply hose and in the middle, compared with those further from the supply hose. It was also found that DFT was greater at the forward end than at the back end of a sample.

Keywords: wood, coating, roller application, UV finishing line, temperature of liquid top coating, dry film thickness of coating, position on conveyer, length of sample

Introduction

The dry film thickness of the coating (*DFT*) is one of the most important properties of a coated wood surface. The importance of *DFT* is reflected in its impact on almost all of the properties of the coated wood surface: adhesion [Gurleyen et al. 2017]; scratch resistance [Jaić et al. 2010; Keskin et al. 2010; Banecki 2011]; hardness [Alimam et al. 2016; Gurleyen et al. 2017]; hiding power [Franco and Graystone 2009; Goldschmidt and Streitberger 2007]; leveling ability, coating permeability [Franco and Graystone 2009]; moisture

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uptake [Gupta et al. 2016]; resistance to abrasion [Jaić et al. 2010; Jaić and Palija 2013; Keskin and Tekin 2011]; resistance to cold liquids [Jaić and Palija 2013]; resistance to dry and wet heat; water repellency, preservative leaching, surface checking of wood [Nejad 2011]; gloss [Fletcher 2002; Gupta et al. 2008; Palija et al. 2014]; indoor air pollution [Stachowiak-Wencek et al. 2014]; etc. For this reason, it is necessary to achieve sufficient and uniform *DFT* on the wood surface. Conventional coatings are applied in liquid state on the wood surface, and *DFT* is governed by the solid content and the spreading rate of the coating [Franco and Graystone 2009]. The application process affects the spreading rate as well as the uniformity of the applied quantity of coating across the surface of the object. The main advantage of mechanical over manual application processes is the uniformity of the coating film on the surface of the object. When the *DFT* is small, it is especially important to apply an equal quantity of coating across the surface to ensure total coverage of the substrate or of the previous layer of coating. Accordingly, most industrial coating application processes will use several layers to build the desired total thickness of dry film.

Roller coaters are used to apply coating materials on flat surfaces with high transfer efficiency and high productivity. The quantity of applied material varies from a few grams per m^2 to about 100 g/m^2 (depending on the construction of the coater). They are particularly suitable for the application of radiation curing products, as their high viscosities and solid content allow the achievement of good results in terms of film thickness and surface homogeneity [Franco and Graystone 2009]. Roller application is especially suitable for the finishing of parquet boards, where it is possible to set up several roller coaters in a line, followed by ultraviolet (UV) lamps, and to achieve complete finishing of multiple layers of coating within a few minutes or less. The application rate is adjusted by means of the distance between the applicator and dosing rollers and their speeds, as well as the conveyor speed and the viscosity of the coating material. If the conveyor speed and the speeds of rotation of the rollers are constant, the application rate is controlled by adjusting the distance between the applicator and dosing roller, with the viscosity of the liquid coating fixed at an appropriate value. However, for finishing on a real industrial production line, the viscosity of the liquid coating is maintained within a certain range and periodically checked. Since the friction between the applicator and dosing rollers generates heat [Bonner 2014], roller coaters are often equipped with a cooler unit that regulates the temperature of the dosing roller to ensure small variation in the temperature and viscosity of the liquid coating. In addition, the temperature of the liquid coating can be adjusted by heating the reservoir of coating material. However, the temperature varies to some extent, and this is reflected in the viscosity of the liquid coating and can also affect the applied quantity of coating material and *DFT* [Bonner 2014; Klumpp n.d.].

The aim of this research was to determine whether variation in the temperature of the liquid top coating applied by roller coater on a UV finishing line in real industrial conditions affected the *DFT*. In addition, for determined temperatures of liquid top coating, an examination was made of the uniformity of *DFT* along the width of the conveyor and the length of a sample.

Materials and methods

The study used 12 samples of three-layered engineered flooring with dimensions (l × b × d) 2280 × 198 × 14 mm. The upper (visible) layer of the samples was made of oak wood (*Quercus robur* L.) in the form of lamellas from tangential and radial cuts, arranged according to esthetic characteristics.

Sanding of samples and the application and curing of a UV-acrylic coating were performed on an industrial UV finishing line, consisting of:

- a sanding machine (for preparation of the samples);
- roller coaters (for application of the coating in layers);
- UV lamps (for curing of the coating after application of each layer);
- a sanding machine (for intermediate sanding of the coating).

Preparatory sanding of the samples was carried out with a wide-belt sanding machine (LSM 8, Heesemann, Germany) using abrasive belts with grit sizes P60, P80, P100 and P120. The sanding speed was set to 20 m/s, the conveyor speed was 16 m/min, and the sanding pressure was 6 bar.

Four layers of a transparent base coating material (IS 485 OR 124 sealer, Akzonobel) and one layer of a transparent top coating material (IL 485 OR LACK CLASSIC B, Akzonobel) were applied on the sanded surfaces of the samples using a separate roller coater for each layer of the coating (fig. 1).

Fig. 1. Roller coater for application of top coating layer

The roller coaters (fig. 2) consist of a steel applicator roller covered with 20 Shore rubber, with direct rotation, and a steel dosing roller with the reverse direction of rotation. The speeds of the applicator and dosing rollers were set to16 m/min and 1 m/min respectively. The cooler unit (gwk Gesellschaft Wärme Kältetechnik mbH, Germany, model Weco 06 KLE) was used to maintain the temperature of the dosing roller by means of cold water passing along the central axis of the roller.

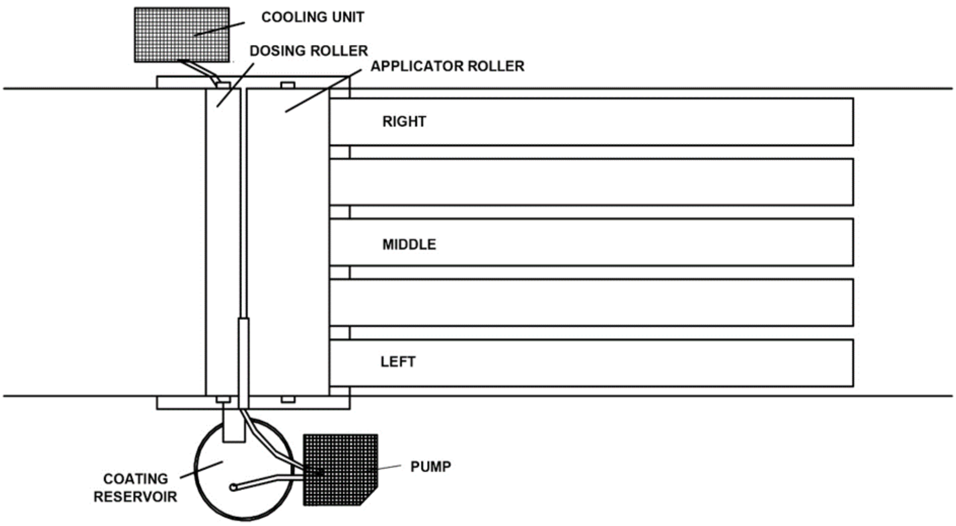

Fig. 2. Schematic illustration of the parts of the roller coater and positions of samples on the conveyor belt

The application rate of the coating material was set from 11 to 20 g/m^2, depending on the layer (table 1). The layers of the coating were cured by passing the coated samples through UV units (TRUV, Bürkle, Germany) under mercury (K 490 621, Bürkle, Germany) and gallium (K 491 842, Bürkle, Germany) UV lamps. Both types of UV lamps had different input powers, according to their position on the line (table 1). Intermediate sanding of the coating was performed following the application and curing of the first and the fourth layer of coating, using the wide-belt sanding machine with abrasive belts with grit sizes P180 and P240 respectively.

The temperature of the liquid top coating was measured using an infrared thermometer (model MS6530, Sinometer Instruments Manufacturer, China) at the discharge plate of the roller coater. The discharge plate is used to drain surplus material, which has not been applied to the surfaces of the samples, to a reservoir. The temperature of the liquid top coating was recorded during the production process.

Table 1. Application rate and type and input power of UV lamps for different coating layers

Number of coating layer	Average application rate (g/m²)	Number, type and input power of UV lamp		
		1st position[1]	2nd position[2]	3rd position[3]
1.	18	1x Hg UV lamp[4] (60 W/cm)	/	/
2.	20	1x Ga UV lamp[5] (80 W/cm)	1x Hg UV lamp (100 W/cm)	1x Hg UV lamp (100 W/cm)
3.	12	1x Ga UV lamp (100 W/cm)	1x Hg UV lamp (100 W/cm)	1x Hg UV lamp (110 W/cm)
4.	11	1x Hg UV lamp (80 W/cm)	/	/
5.	11	1x Ga UV lamp (100 W/cm)	1x Hg UV lamp (110 W/cm)	1x Hg UV lamp (110 W/cm)

[1,2,3]By distance from corresponding roller coater.
[4]Hg UV lamp – mercury UV lamp.
[5]Ga UV lamp – gallium UV lamp.

The viscosity of the liquid top coating was measured by an efflux method, using a DIN dip cup with 4 mm orifice (Byk-Gardner, Germany) in accordance with DIN 53211:1987. The value of the viscosity of the liquid top coating was expressed as the mean value of two measurements.

Based on the recorded temperatures of the liquid top coating, two groups of samples were identified. Each group consisted of 6 samples of the engineered flooring, 2 for each positon on the conveyor belt: left, middle and right (fig. 2).

DFT was measured by an ultrasonic gauge (model PosiTector 200 Series, DeFelsko, USA) without destruction of the coating, in accordance with EN ISO 2808:2011. For each sample 9 measurements of *DFT* were made (at 2 cm, 160 cm and 226 cm from the forward end of the board; fig. 3). For each temperature and each position on the conveyer (left, middle or right) 18 measurements of *DFT* were made, making 54 measurements for each temperature, and 108 measurements in total.

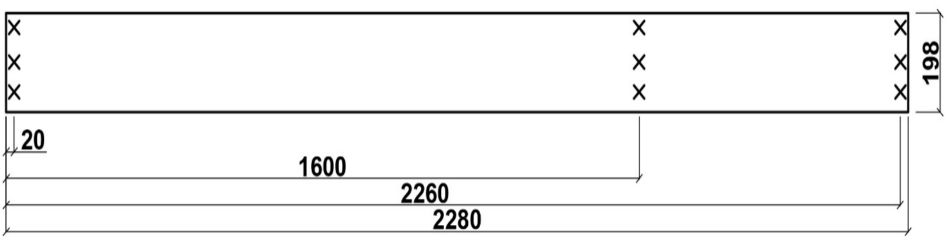

Fig. 3. Positions of *DFT* measurement points along the length of a sample

Statistical analysis of the results was performed with IBM SPSS Statistics 21 software, using descriptive statistics and analysis of variance (three-way ANOVA). The principle of ANOVA is based on the *F* statistic, which calculates the ratio of the variability between the variables being compared (systematic variance) and the variability within variables (unsystematic variance, referred to as error). Three-way ANOVA was used to test the effect of each variable (temperature of liquid top coating, position on conveyer and measuring position along the length of the sample) on *DFT*, as well as to identify any significant interaction effect between variables. The assumption of normality of *DFT* results was assessed for all possible combinations of observed variables (a total of 18 groups) using the Shapiro-Wilk test, and the homogeneity of variances was assessed using Levene's test of homogeneity of variance. When the interaction effect between variables was statistically significant, a simple main effect analysis was performed using all simple pairwise comparisons with a Bonferroni adjustment applied. For variables that were not involved in statistically significant interaction, main effect analysis was performed. When ANOVA showed a statistically significant difference between sample groups in the simple main effect and main effect analysis, a Tukey HSD post-hoc test was applied. All tests were performed at a confidence level of 95% ($p < 0.05$).

Results and discussion

Table 2 shows the results of measurements of the temperature and viscosity of the liquid top coating during the application process, for the defined groups of samples.

Table 2. Temperature and viscosity of the liquid top coating

Group of samples	t (°C)	Viscosity by efflux method with DIN dip cup (4 mm) (s)
I	24.1	18.6
II	24.8	17.0

The results showed that an increase in the temperature of the coating caused a decrease in the viscosity measured by efflux time, which was expected [Šućur 2013].

Table 3 shows the descriptive statistics of *DFT* for the groups of samples.

Table 3. *DFT* depending on temperature of liquid top coating, position on the conveyor and measurement position along the length of the sample

Group of samples	Position on conveyer	Position along length of sample (cm)	*DFT* (µm)				
			mean	*Min*	*Max*	*Sd*	S^2
I (t = 24.1°C)	Left	2	78.3	72	89	7.6	57.5
		160	78.8	68	89	7.9	63.0
		226	69.3	65	73	3.3	10.7
	Middle	2	78.2	74	81	2.7	7.4
		160	75.7	74	79	2.0	3.9
		226	75.5	73	79	2.2	4.7
	Right	2	79.5	73	85	4.3	18.3
		160	77.5	68	89	7.0	48.3
		226	75.3	69	85	6.2	37.9
II (t = 24.8°C)	Left	2	76.3	70	89	6.9	47.9
		160	71.0	66	76	4.0	16.0
		226	67.3	64	73	3.6	12.7
	Middle	2	70.3	61	77	5.6	31.1
		160	67.2	64	70	2.0	4.2
		226	66.3	62	70	3.3	10.7
	Right	2	77.2	64	86	8.4	69.8
		160	76.3	69	88	8.0	63.5
		226	79.2	70	87	6.6	43.0

Min – minimum, *Max* – maximum, *Sd* – standard deviation, S^2 – variance.

As the values of *DFT* were not normally distributed for all groups of measurements formed according to the considered variables, a transformation of the data was performed according to the formula:

$$DFT_{transf} = \frac{1}{DFT + 1} \quad (1)$$

The data for DFT_{transf} was normally distributed for each group. Basic descriptive statistics for DFT_{transf} are shown in table 4.

As regards position on the conveyor, the samples placed in the middle of the conveyor had the lowest values of standard deviation for *DFT* and DFT_{transf}, regardless of the temperature of the liquid top coating and the measurement position along the length of the sample. Accordingly, the greatest uniformity of *DFT* was achieved for samples placed centrally on the conveyor. The homogeneity of variances was not violated, and the results of three-way ANOVA are given in table 5.

Table 4. Transformed *DFT* depending on temperature of liquid top coating, position on the conveyor and measurement position along the length of the sample

Group of samples	Position on conveyer	Position along length of sample (cm)	DFT_{transf} (μm^{-1})	
			mean	Sd
I (t = 24.1°C)	Left	2	0.0127	0.00115
		160	0.0126	0.00126
		226	0.0139	0.00131
	Middle	2	0.0126	0.00044
		160	0.0131	0.00033
		226	0.0131	0.00042
	Right	2	0.0125	0.00067
		160	0.0128	0.00111
		226	0.0132	0.00103
II (t = 24.8°C)	Left	2	0.0130	0.00107
		160	0.0139	0.00078
		226	0.0147	0.00074
	Middle	2	0.0141	0.00117
		160	0.0147	0.00044
		226	0.0149	0.00073
	Right	2	0.0129	0.00145
		160	0.0130	0.00128
		226	0.0125	0.00104

Sd – standard deviation.

Since ANOVA did not show a statistically significant three-way interaction between temperature of liquid top coating, position on the conveyer and measurement position along the length of the sample, two-way interactions were analyzed. These revealed a statistically significant interaction between temperature of liquid top coating and position on the conveyer.

An analysis was made of simple main effects of temperature on mean DFT_{transf}. The simple main effect of temperature of liquid top coating on mean DFT_{transf} was statistically significant for samples in the left position on the conveyer ($F(1.90) = 5.742$, $p = 0.019$) and for samples in the middle of the conveyer ($F(1.90) = 25.337$, $p < 0.05$), but not for samples in the right position

Table 5. Results of three-way ANOVA for DFT_{transf}

Factor	Degrees of freedom (df)	Mean squares (MS)	F statistic	Sig. (*p* value)
Temperature of liquid top coating (A)	1	1.78E-05	18.736	0.000
Position on conveyer (B)	2	7.91E-06	8.327	0.000
Measurement position along length of sample (C)	2	4.93E-06	5.183	0.007
Interaction (AB)	2	5.87E-06	6.174	0.003
Interaction (AC)	2	4.01E-07	0.422	0.657
Interaction (BC)	4	1.58E-06	1.662	0.166
Interaction (ABC)	4	7.10E-07	0.747	0.563
Error	90	9.50E-07		
Total	108			

The ANOVA table presents the computed *F* statistics for each of the independent variables (A, B and C), the interaction effects of two variables (AB, AC and BC) and the interaction effect of all three variables (ABC), and their statistical significances (column "Sig."). There are a total of seven *F* statistics (for seven factors), which represent the ratio of the individual mean model sum of squares (MS_M) and the mean error sum of squares (MS_E). MS_M was calculated as the ratio between the model sum of squares (SS_M) of each factor and the respective degrees of freedom (df_M[1]). MS_E was calculated as the ratio between the error sum of squares (SS_E) and the respective degrees of freedom (df_E[2]). SS_M reflects differences between the mean of each factor and the overall mean, and SS_E reflects the differences between the measured data and the overall mean that cannot be explained by the examined model. If $p < 0.05$, the critical *F* value for the given degrees of freedom is lower than the computed *F* statistic, meaning that the effect of the observed factor is statistically significant.

on the conveyer ($F(1.90) = 0.005$, $p = 0.946$). The significantly lower values of *DFT* (corresponding to higher values of DFT_{transf}) in the samples in group II indicated that with an increase in the temperature and a decrease in the viscosity of the liquid top coating (table 2), the applied quantity of the coating material decreased. This result is in agreement with recommended guidelines for the adjustment of parameters on the UV finishing line to ensure the homogeneity of the applied coating [Bonner 2014; Klumpp n.d.]. An increase in the temperature of the liquid top coating did not affect the *DFT* of samples on the right side of the conveyor. This may be related to the distance of the feeding hose, which

[1]For each independent variable; for each interaction of two variables and for the interaction of all three variables.
[2]Where *k* is the number of comparison groups and *N* is the total number of measurements.

supplies material to the gap between the application roller and the dosing roller. As the samples in this group (right position) were furthest from the supply hose, and at the same time closest to the cooling unit, it is assumed that this arrangement may reduce the effect of the increased temperature on the coating.

The simple main effect of conveyor position on mean DFT_{transf} for samples in group II (t = 24.8°C) was statistically significant ($F(2.90) = 14.136$, $p < 0.05$), but for samples in group I (t = 24.1°C) it was not significant ($F(2.90) = 0.365$, $p = 0.695$). All pairwise comparisons were performed for the samples in group II. DFT_{transf} was 0.013 ± 0.001 μm^{-1} for the samples in the right position on the conveyor, which was significantly lower than DFT_{transf} for the samples in the middle (0.015 ±0.001 μm^{-1}, $p < 0.05$) and left position (0.014 ±0.001 μm^{-1}, $p = 0.006$) on the conveyor. There was no statistically significant difference in DFT_{transf} between samples in the left and middle positions. Although the DFT_{transf} values were significantly lower for the samples positioned furthest from the supply hose than for those in the middle or left position, the *DFT* values for the samples in the right position were in fact the highest (formula 1).

As regards the position of measurement along the length of the samples, no interaction was found with the temperature of the liquid top coating or with the position of samples on the conveyor. Therefore, main effect analysis was performed. There was found to be a statistically significant difference in DFT_{transf} values between different measurement positions (table 5). Tukey HDS post-hoc analysis showed that DFT_{transf} was significantly lower at 2 cm than at 226 cm from the forward end of the samples. No significant difference was found between the central measurement position (160 cm) and the terminal positions (2 cm and 226 cm) along the length of the sample (respectively $p = 0.215$, $p = 0.282$). The increase in DFT_{transf}, and accordingly the decrease in *DFT*, towards the back end of the sample can be explained by the large length of the samples, which may result in an uneven supply of the coating material, since the applicator roller was in contact with the surface of the sample over a distance of 228 cm. Also, since there was space between the samples along the length of conveyor (due to technological considerations), the material accumulated in the space between the applicator and dosing rollers prior to application of the coating at the forward end of the sample (at 2 cm), giving a slightly higher thickness of the coating film at the initial position.

The variation in *DFT* across the width of the conveyor and along the length of the samples may be related to the temperature profile of the coating material across the gap between the applicator and dosing rollers. This was observed in previous research, where the temperature variation of the coating material exceeded the total allowable temperature tolerance for that material [Bonner 2014]. In addition, the "occupancy" of the application roller depends on the length of the sample being processed, which affects the variation in *DFT* along the length of the sample. Therefore, the uniformity of the application rate of the roller coater should not be considered as absolute, but must be observed within the limits of the technological process. Variation in *DFT* may lead to insufficient coverage and protection of the wood surface, which can affect other properties of the coated wood. Accordingly, it is recommended to make regular checks of *DFT*, since the primary purpose of coating thickness measurement is to control the cost while ensuring adequate coverage [Beamish 2015].

Conclusions

Although roller coating application is often referred to in the literature as uniform, in real industrial processes some variation in the dry film thickness of the coating (*DFT*) is inevitable. This study has revealed that the most uniform rate of application of the coating material, expressed by the smallest deviation of *DFT*, was achieved when the samples were positioned in the middle of the conveyor. The position of measurement along the length of the sample was found to have a significant effect on *DFT* (based on DFT_{transf}) when results were compared from points 2 cm and 226 cm from the forward end of the sample. Analysis of the two-way interaction effect of the temperature of the liquid top coating and the position on the conveyor revealed that there was a difference in *DFT* (based on DFT_{transf}) at different temperatures of liquid top coating for samples in the middle and left positions on the conveyor. At higher temperatures of liquid top coating (24.8°C) *DFT* (based on DFT_{transf}) was higher for samples positioned on the right than for samples on the left and in the middle of the conveyor. At a lower temperature of liquid top coating (24.1°C) no significant difference in *DFT* (based on DFT_{transf}) was found among the samples occupying different positions on the conveyor.

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List of standards

EN ISO 2808:2011 Paints and varnishes – Determination of film thickness
DIN 53211:1987 Paints, varnishes and similar coating materials – Determination of flow time using the DIN flow cup

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