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Effect of water drying conditions on the surface property and morphology of waterborne UV-curable coatings for engineered flooring

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ABSTRACT

UV-curable coatings are widely used on wooden materials such as flooring and furniture, because they have excellent properties, including high hardness, gloss, mar and chemical resistance, and are also environmental friendly, containing no solvents. Recently, waterborne UV-curable coatings have been studied as a viable alternative, since solvents are added to spray applications to lower viscosity. We investigated the effects of water drying conditions on the surface properties and morphology of waterborne UV-curable coatings at the flash-off step. Temperature conditions studied were 22 °C, 50 °C, and 80 °C, with various drying times. We evaluated surface properties such as pendulum hardness, pencil hardness, and adhesion strength. Also observed was surface morphology, comparing surface properties using optical microscopy after drying and UV-curing. Insufficient drying caused cracking, peeling and blistering at the surface of a cured coating. Sufficient drying was very important for the best application and ideal surface morphology of waterborne UV-curable coatings.

1. Introduction

Coating industries increasingly face stricter environmental legislation and consumer concern over environmental impacts. Coating technology has changed from traditional solvent-borne coatings to environmental friendly coatings. UV-curable coatings have many advantages, including a very fast curing time at ambient temperature, low curing energy and no solvent system. Because of these attributes, the applications of UV-curable coating technology have been extended from wooden flooring to printing inks, adhesives, photoresists and the automotive industry [1–4]. However, organic solvents are added to UV-curable coatings in order to lower the formulation viscosity. Generally, UV-curable coatings have a higher than adequate viscosity for spray applications. Some monomers are used as reactive diluents, but they have limited thinning power. Recently, waterborne UV-curable coatings have been researched in an effort to meet environmental concerns over organic solvents by replacing organic solvents with water. This type of coating does have some drawbacks, such as poor blocking or chemical resistance. But, waterborne systems can extend the application range of UV-curing systems by thinning viscosity and can make up the disadvantages of waterborne systems by crosslinking (Fig. 1). In this way, waterborne UV-curable coatings can incorporate the advantages of both technologies and overcome the weaknesses [5–7].

In the formulation of waterborne UV-curable coatings, water served as the solvent for thinning viscosity. Tack-free films were acquired after a flash-off step (water drying step). In the waterborne system, adhesion strength between coatings and substrates was improved by adding another hydrophilic group. However, it is not easy to convert a UV-curable resin to an aqueous system. Also, the properties of the waterborne system are weaker than traditional solvent systems. Because of this, there have not been many studies about waterborne UV-curing coatings [8–12]. There are several methods to make waterborne UV-curable coatings; polyurethane dispersion is most commonly used. The dispersion is prepared by introducing an ionic group or hydrophilic group into the polyurethane acrylate backbone. This method has many advantages, including the excellent properties of polyurethane and the high molecular weight of prepolymer. It can be acquired the tack-free film, which is easy to handle after the flash-off step.

Previous studies focused on the curing kinetics and properties of 100% UV-curable coatings [13–16]. The weathering of UV-curable coatings was applied to wooden substrates and studied by investigating its curing behavior, hardness and viscoelasticity

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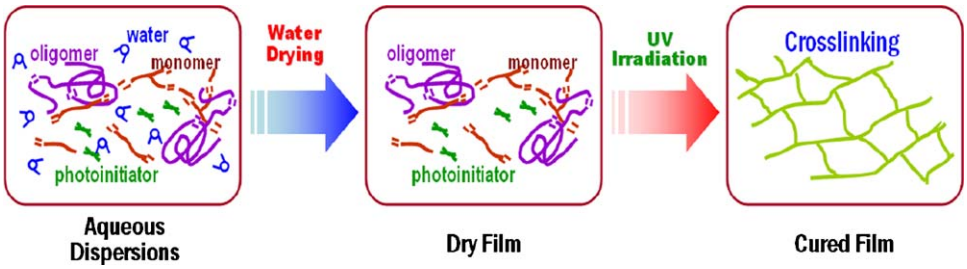

Fig. 1. Two-step reaction of waterborne UV-curable coatings.

[17–21]. In this study, we investigated the effect of the flash-off condition, including drying temperature and time, on the surface property of cured coatings. We evaluated surface properties such as hardness and adhesion strength, and observed the surface of cured coatings using an optical microscope to find out the optimum condition of the flash-off step.

2. Experiment

2.1. Materials

The UV-curable oligomer was an aliphatic polyurethane acrylate copolymer dispersion (LUX 285, Alberdink Boley GmbH). Solid contents were about 40%. Irgacure 500 (Ciba Specialty Chemicals) was used as a photoinitiator. It was added to LUX 285 at a typical concentration of 5 wt%. Then the formulation was mixed using a homogenizer (Nihonseiki Kaisea Co. Ltd.) at a speed of 2000 rpm for 5 min. This formulation was named L285-I500. Glass plates and engineered flooring were used as substrates. Fig. 2 shows the structure of the laminate and engineered floorings [22].

2.2. Experiment

2.2.1. Curing process

Waterborne UV-curable coatings were cured through two-step process as shown in Fig. 1. Because water was used as diluents in this system, it needed the flash-off step, where water is evaporated before UV-curing. During aqueous dispersion to dry film, physical entanglement occurred, then tack-free film could be acquired because of the large molecular weight of the prepolymer [23–27]. In the second step, after UV light irradiated the dried film, a photoinitiator was activated and made radicals. Formed radicals broke the acrylate double bond of the monomers and oligomers, which resulted in crosslinking. After UV-curing, coatings were completely cured. Waterborne UV-curable coatings were applied on the glass plates and engineered flooring using an application at 40 μm thickness. Drying time was measured according to different drying temperatures of 22 °C, 50 °C and 80 °C before UV-curing. Then dried films were cured by a UV-lamp (medium pressure mercury lamp: 100 W/cm, main wave length: 365 nm). Total radiated UV-dose was 1000 mJ/cm^2.

2.2.2. Surface property of cured coatings

The hardness of cured coatings was measured by pencil hardness according to ASTM D 3363-05. Pendulum hardness was also measured according to the König method (ASTM D 4366) using a pendulum hardness tester (Ref. 707PK, Sheen Instruments Ltd.) at 22 ± 1 °C and 50 ± 2% R.H. The results of pencil and pendulum hardness were then compared with each other [28]. To evaluate adhesion strength between coatings and substrates, the cured coatings were peeled off according to ASTM F 2296-4 using a cross-hatch cutter (Ref. 750/2, Sheen Instruments Ltd.). The area of peeling off was then evaluated with an image analyzer.

2.2.3. Surface morphology of cured coatings

Surface morphology of cured coatings was observed using an optical microscope (BX50, Olympus) with 4 × 10 magnitude to compare the surface property of cured coatings.

3. Results and discussion

3.1. Drying rate

The UV-curable dispersion (LUX 285) was applied to the glass plate at 40 μm thickness and dried under different drying temperatures in order to investigate the drying rate. Water was dried at ambient temperature (22 °C) and under oven conditions (30 °C, 40 °C, 50 °C, 60 °C, 80 °C and 100 °C). The remaining water was measured by gravimetry upon water drying as shown in Fig. 3. The water drying rate was increased with increasing temperatures. At ambient temperature, the drying rate of the UV-curable dispersion declined continuously during 5 min, and after 5 min, the remaining water was nearly zero. But with oven conditions over 30 °C, the water was dried fast from the

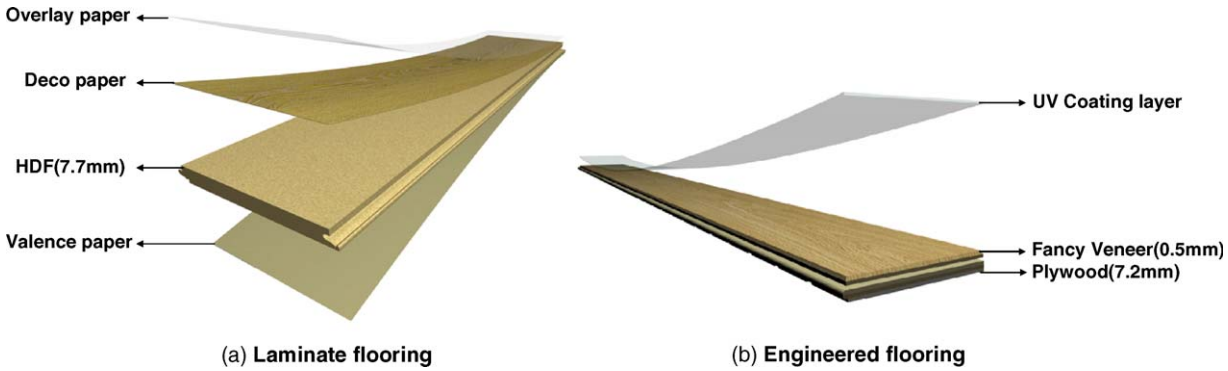

Fig. 2. Structures of laminate and engineered floorings [22].

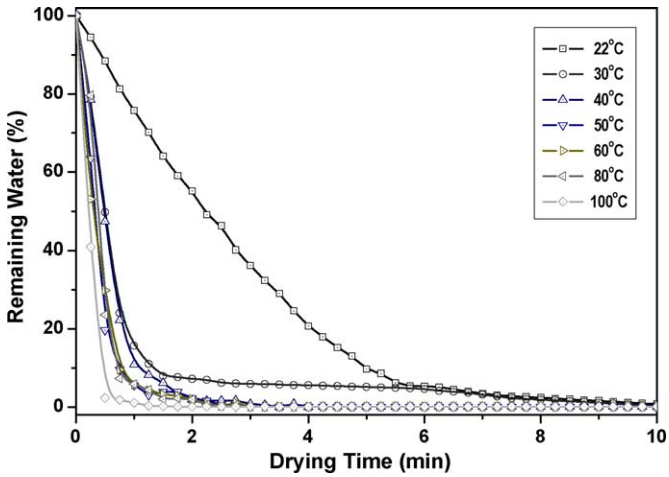

Fig. 3. Water drying rate according to drying temperature of the UV-curable dispersion (LUX 285) coated on a glass plate.

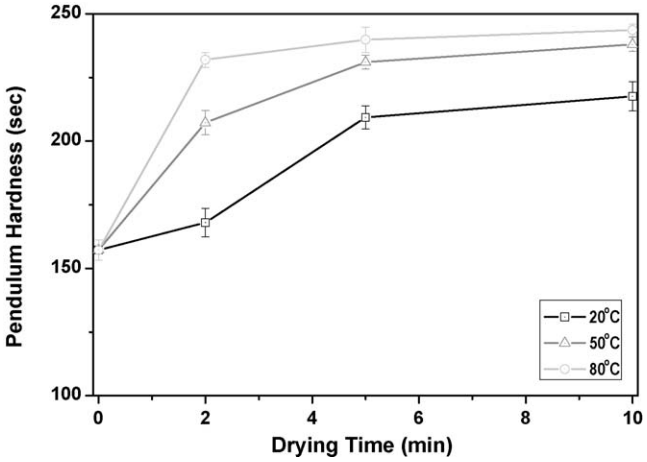

Fig. 5. Pendulum hardness according to drying temperature and time of waterborne UV-curable coatings (L285-I500).

beginning and residual water was nearly zero after 2 min at 30 °C. The higher temperature water was dried at, the faster the residual water was decreased. After only 1 min at 80 °C, the residual water was nearly zero [10,11,29]. Because of these results, three temperatures were selected as the drying temperatures for this study: ambient temperature (about 22 °C), 50 °C and 80 °C. At each temperature, a UV-curable dispersion was dried for different lengths of time. 0 min, 2 min, 5 min and 10 min were selected as drying times.

The water drying rate of the UV-curable dispersions, according to substrates at ambient temperature, is seen with Fig. 4. Without the photoinitiator, LUX 285 was applied to the glass plate and engineered flooring at 40 μm thickness each. The water drying rate on the glass plate was faster than that of the engineered flooring. On the glass plate, the UV dispersion was almost dried after 10 min and the remaining water was nearly zero. But on the engineered flooring, the water was removed continuously and the remaining water almost reached the zero percent after 15 min of drying. The difference in the substrates' surface tension and the interactions between the dispersion and the substrate caused this result. The critical surface free energy of glass plate is approximately 73 mN/m [30]. The surface free energy of engineered flooring was measured with a goniometer (SEO 300A, Surface & Electro-Optics Corp.) at 23 ± 1 °C and 55 ± 3% R.H. The contact angles of water, formamide and diiodomethane on the engineering flooring were 45.6°, 35.8°, and 19.4°, respectively. The surface free energy calculated based on the acid-based theory was 50.3 mN/m and was almost same the surface free energy of some woods [31]. Lower surface free energy of engineered flooring caused the poor wetting and some water was soaked into fancy veneer layer. This caused the low rate of water drying in engineered flooring. Thus, the water drying conditions should be adjusted according to the type of substrate it would be applied to.

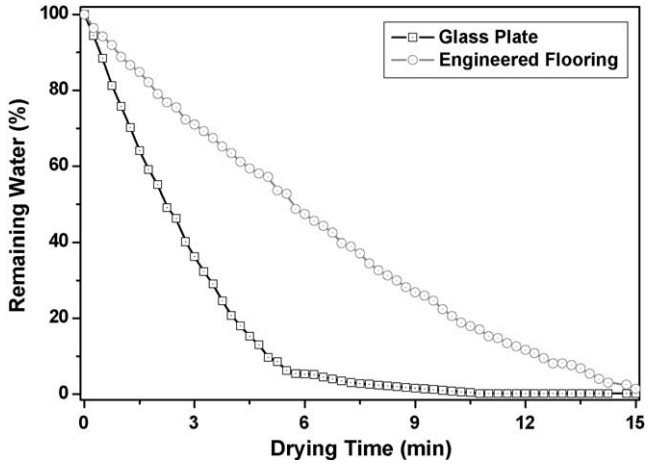

Fig. 4. Water drying rate of UV-curable dispersion (LUX 285) according to substrates at 22 °C.

3.2. Effect of drying condition on the property

3.2.1. Surface hardness

High hardness is one of the enhanced and important properties of UV-curable coatings. Thus, we compared pendulum hardness and pencil hardness of the cured coatings. Fig. 5 explicates the effect of water drying temperature and time on the pendulum hardness. At ambient drying condition, the pendulum hardness of the UV-cured coating without drying was about 150 s. After 5 min of drying and UV-curing, the pendulum hardness was increased to 200 s. The water drying temperature was increased to 50 °C, and the hardness was the same 200 s after 2 min. When dried at 80 °C, the hardness of the cured film was increased to maximum value of 240 s after 2 min.

With higher drying temperatures and longer drying times, pendulum hardness increased. Under insufficient drying conditions, water remained in the dried film and defects on the surface of the coating appeared during UV-curing. This causes the low hardness of coatings when treated with insufficient drying conditions. The pendulum hardness of several commonly used substrates is depicted in Fig. 6. The pendulum hardness of L285-I500 used in this study was between about 150 s and 250 s, which was high enough to use in the surface protecting coatings or on wooden flooring.

Fig. 7 shows the results of pencil hardness relating to the drying conditions. In the case of direct UV-curing without drying, remaining water in the dried film made a lot of defects, seen as holes, cracking and blistering. Pencil hardness could not be measured because of peeling during the measurement of pencil hardness. After 2 min of water drying and UV-curing, the pencil hardness was 2B at ambient drying. When the drying temperature was increased to 50 °C, the pencil hardness was H. The drying temperature was increased to 80 °C resulting in the pencil hardness becoming 3H, the maximum value. After 5 min of water drying, pencil hardness for all conditions was at

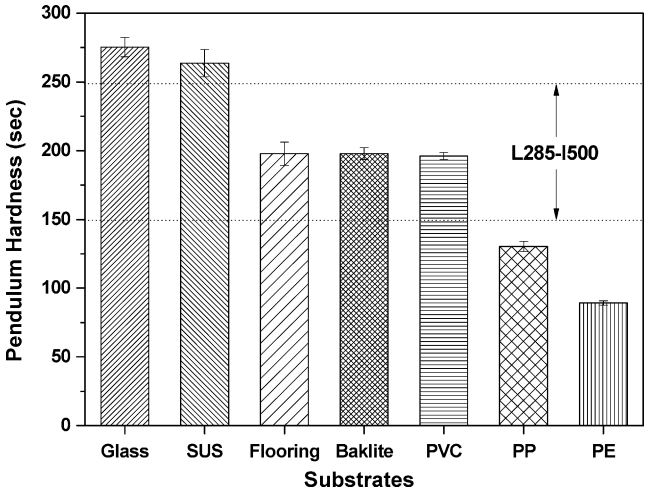

Fig. 6. Pendulum hardness of several substrates and waterborne UV-curable coatings (L285-I500).

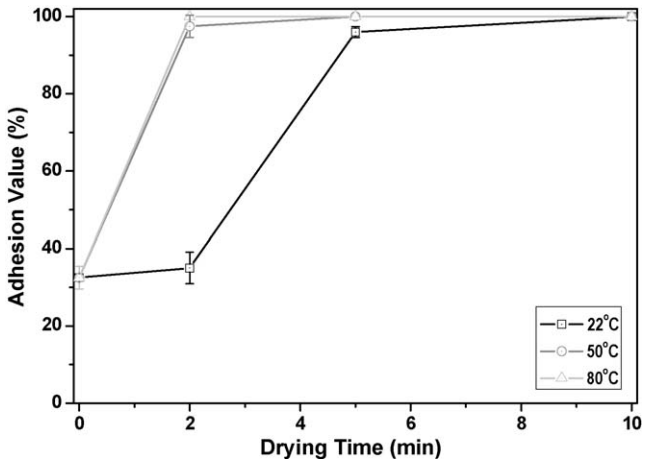

Fig. 8. Cross-cut test for the adhesion value of waterborne UV-curable coatings (L285-I500) coated on a glass plate.

maximum value. Fig. 5 shows that the results seen with the pencil hardness were paralleled in pendulum hardness results.

3.2.2. Adhesion strength

Fig. 8 describes the adhesion value between the cured coatings and glass plates according to water drying conditions. At ambient drying conditions, it took 5 min for the adhesion value to become greater than 90%. The adhesion value became greater than 90% after 2 min at 50 °C and 80 °C oven drying conditions. Fig. 9 depicts the adhesion value between the cured coatings and engineered flooring. After 10 min of drying, the adhesion value was very low at ambient temperature. Drying temperature was increased to 80 °C, and the adhesion value also increased. At 80 °C, the adhesion value became approximately 90% after 10 min of drying. As shown in Fig. 3, the water drying rate was faster on a glass plate than on engineered flooring, which is why there is a higher adhesion value with the glass plate. The remaining water caused defects and also reduced adhesion strength. Whatever substrate was used, the adhesion strength was increased as drying temperature and drying time increased. Any remaining water affected the adhesion strength, thus it is necessary to remove water during the flash-off step for superior properties.

3.3. Relationship between surface property and morphology

The optical image of the surface morphology at ambient drying conditions is shown in Fig. 10. In the case of UV-curing without water drying, cracking and blistering were found in all regions of the cured film. After 2 min of water drying, severe defects were again found. However, there were no defects on the surface of the cured films after 5 min and 10 min of water drying. With insufficient drying conditions, the remaining water was pushed out to the surface during UV-curing, resulting in the defects on the cured coatings and the lower surface hardness and adhesion strength.

Fig. 11 shows the surface morphology of the cured coating on the engineered flooring at ambient drying conditions. Due to low water drying rates on the engineered flooring, severe defects were observed until 10 min of drying. The optical image of the cured coating with flash-off at 50 °C is shown in Fig. 12. During 5 min of water drying, severe cracking and blistering were observed throughout the cured film. But after 10 min of water drying, a very clear coating was acquired. When the drying temperature was increased to 80 °C, a very clear coating could be obtained without defects after only 2 min of drying, as shown in Fig. 13. Increasing the water drying temperature and drying time resulted in improvements in the surface property and surface morphology

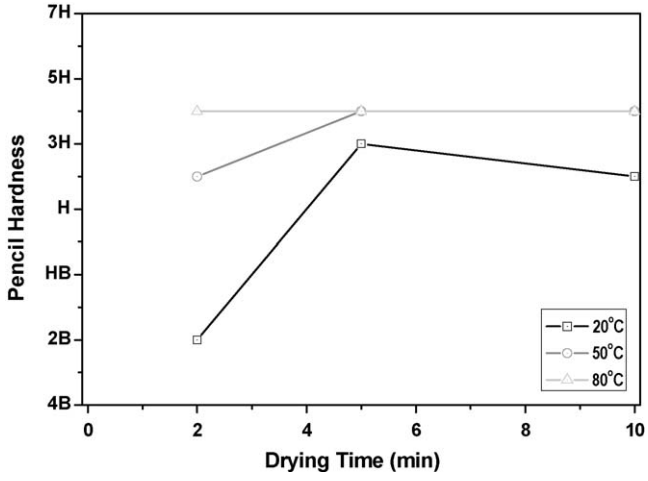

Fig. 7. Pencil hardness according to drying temperature and time of waterborne UV-curable coatings (L285-I500).

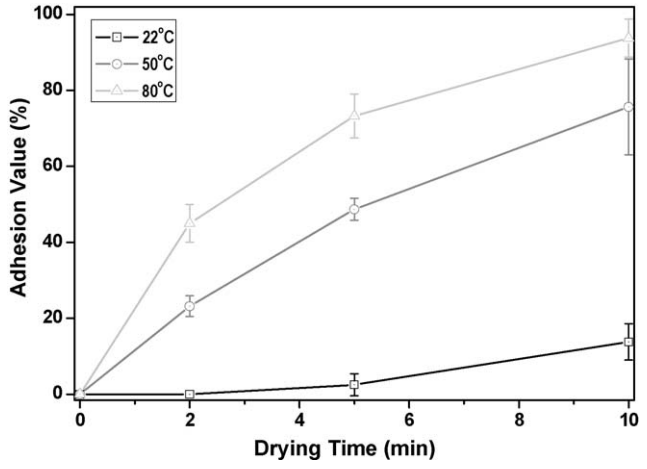

Fig. 9. Cross-cut test for the adhesion value of waterborne UV-curable coatings (L285-I500) coated on engineered flooring.

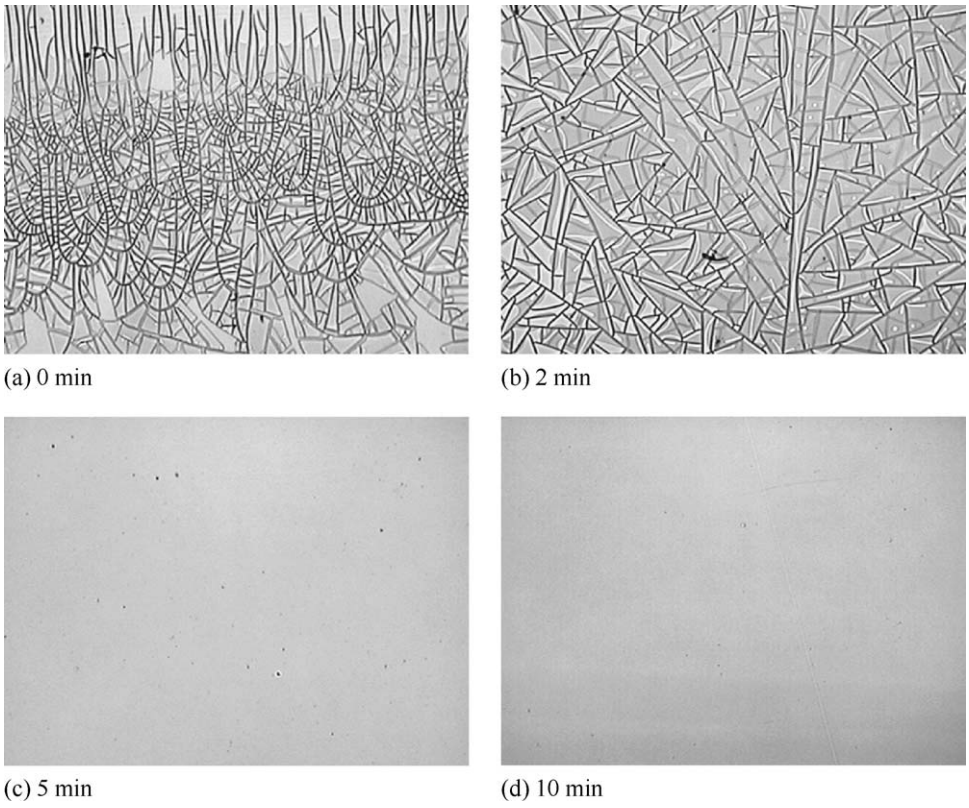

Fig. 10. Surface image of waterborne UV-curable coatings (L285-I500) coated on a glass plate at 22 °C.

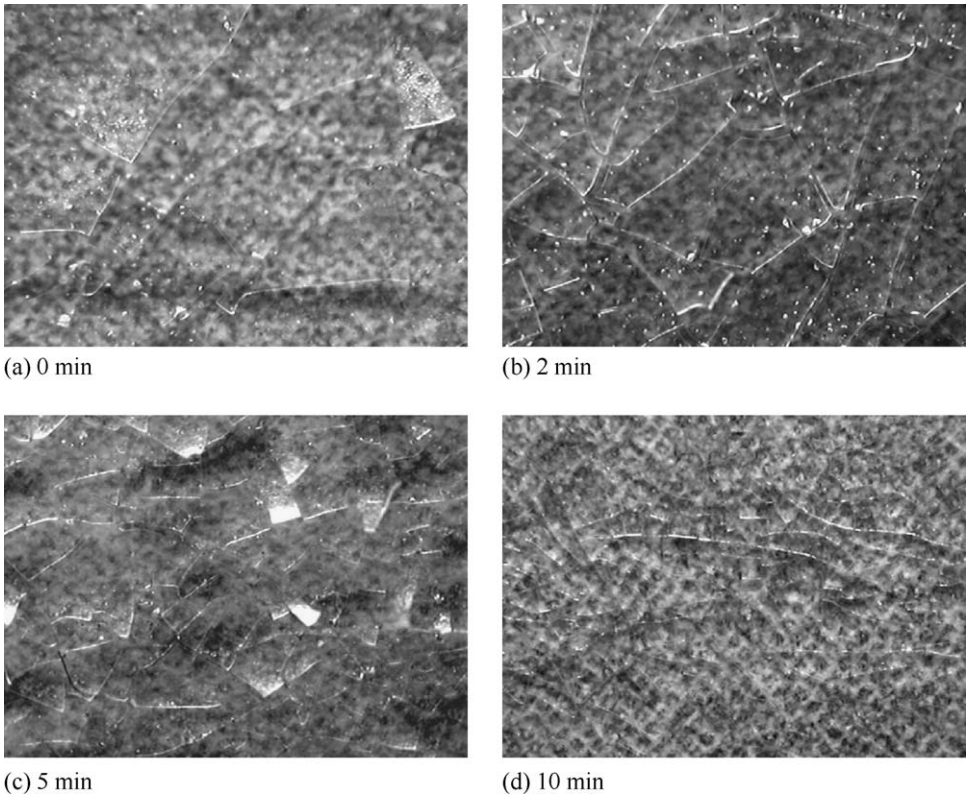

Fig. 11. Surface image of waterborne UV-curable coatings (L285-I500) coated on engineered flooring at 22 °C.

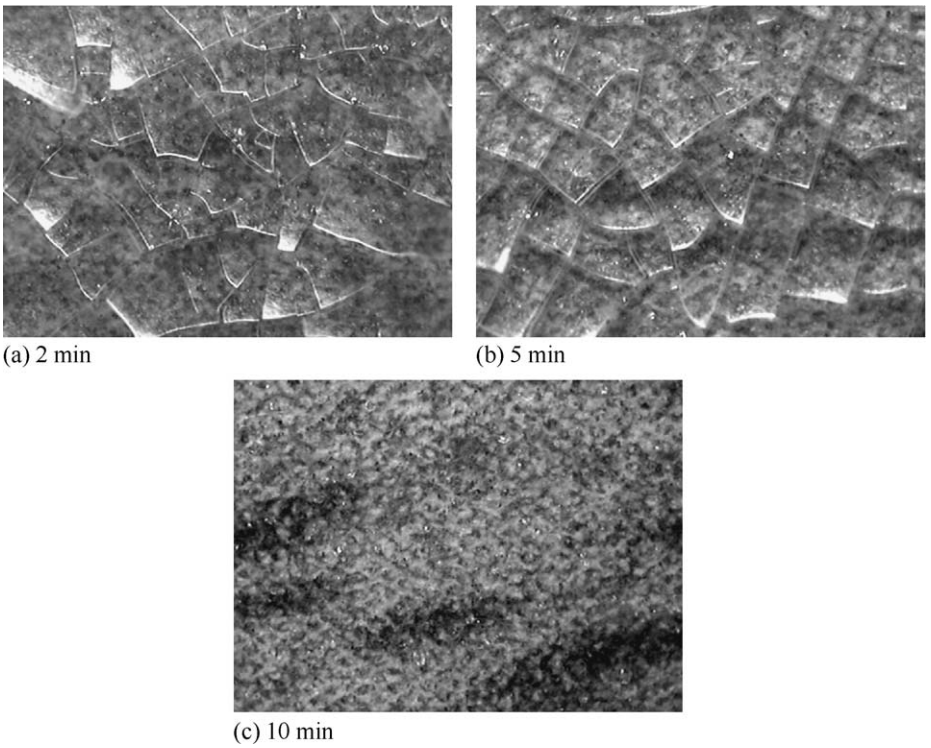

Fig. 12. Surface image of waterborne UV-curable coatings (L285-I500) coated on engineered flooring at 50 °C.

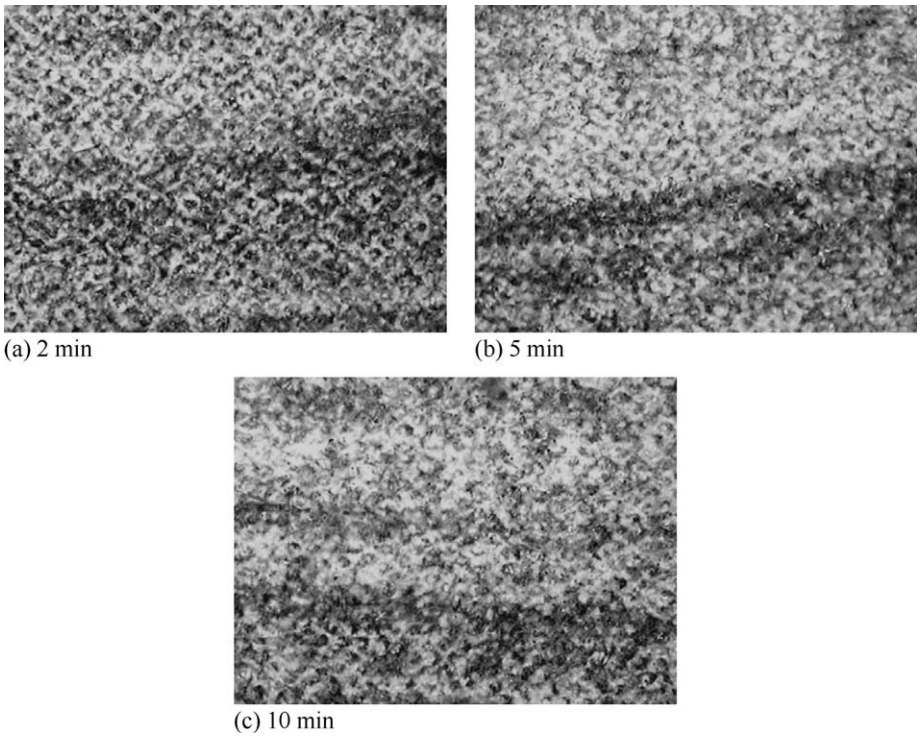

Fig. 13. Surface image of waterborne UV-curable coatings (L285-I500) coated on engineered flooring at 80 °C.

of the cured coatings. Therefore, adequate water drying temperature and time are important processing factors for waterborne UV-curable coatings.

4. Conclusion

The properties and morphology of waterborne UV-curable coatings according to varying water drying conditions were investigated. Increasing the water drying temperature and drying time increased the drying rate and enhanced the surface properties of pendulum hardness, pencil hardness and adhesion strength. Under insufficient drying conditions, the surface properties weakened. Defects such as cracking, peeling and blistering were observed on the surface of cured coatings. These defects were caused by the remaining water that could not evaporate during the flash-off step. Remaining water was flashed off in the UV-curing

step and caused severe defects and weak properties. On the engineered flooring, the surface properties were lower than on the glass plates. This result was caused by the low water drying rate on the engineered flooring. But when the drying temperature increased to 80 °C, it took only 2 min to dry sufficiently. Water drying conditions in the flash-off step are crucial for stable applications of the coating. Thus, water drying conditions should be considered when applying UV-cured coatings, including energy consumption and other factors like type of substrate and thickness.

Acknowledgement

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