Article

Study on the painting methods, amount and thermal properties of waterborne acrylic paint on bamboo-laminated lumber for furniture

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Abstract: In order to understand the finishing effect of Waterborne Acrylic Paint under different painting methods and amount, bamboo-laminated lumber for furniture was coated with waterborne acrylic paint, then the effects of different painting methods and amount on the drying rate, smoothness, hardness, adhesion and wear resistance of the paint film were investigated. Further, the mechanism of film formation was described by thermal property analysis using thermogravimetry and differential scanning calorimeter. The results show that different painting methods have little effect on film properties, the drying time of primer and topcoat are not affected by them, which is 8/8.5 min for primer surface/solid and 6.5/7 min for topcoats. The film surface hardness and adhesion can reach B and 0 grade, the best wear resistance of the film is 51.24 mg·100 r^{-1} when using one-layer primer one-layer topcoat. Different coating amount has great influence on film properties, the drying speed of the film increases with the increase of the painting amount. The film properties reach the best when the painting amount is 80 g/m^2, while too little painting amount leads to the decrease of hardness, and too much leads to the wear resistance weaken. Thermal analysis of the primer and topcoat show that water decomposition occurs at 100 °C and thermal decomposition of organic components occur at 350 °C. Topcoats have better thermal stability than primers higher than that of topcoat, the topcoat displayed better thermal stability than the primer.

Keywords: waterborne acrylic paint; painting method; painting amount; film properties bamboo-laminated lumber

1. Introduction

Waterborne paints (WBPs) use water as a solvent or dispersion medium which have the advantages of non-toxic, safe, environmental friendly compared with traditional paints [1–3].

In recent years, as awareness of people regarding environmental protection national environmental protection policies increases, the proportion of WBPs used in furniture, interior decoration, construction and other industries is increasing year by year, and WBPs will gradually replace traditional organic paints. With the continuous development of WBPs industry, it plays an increasingly important role in the development of bamboo. At present, bamboo and wood furniture is still mainly painted with organic solvents. In the future, WBPs will be more and more widely used in bamboo furniture [4–6]. "Three parts paint and seven parts painting process" [7–10] highlights the significance of the painting process (including the method and amount) to the film properties. Some scholars have studied the painting process and adhesion mechanism of water-based paint [11,12], But in generally speaking, at present, some scholars have done some research on the painting method and amount of water-based

paint, but they mainly focus on wood painting [13–15], there is little research on the painting of bamboo waterborne paint.

In this paper, bamboo-laminated lumber for furniture was coated with waterborne acrylic paint. The effects of different painting methods (one-layer primer one-layer topcoat, one-layer primer two-layer topcoat, two-layer primer one-layer topcoat and two-layer primer two-layer topcoat) and amount (60, 80, 100, 120 g/m^2) on the drying rate, smoothness, hardness, adhesion and wear resistance of the paint film were investigated. Further, the thermal properties of the paint were analysed using thermogravimetry and differential scanning calorimeter to study on the mechanism of film formation. It can provide the theoretical basis for the painting of bamboo, moreover, these can be used as a reference for waterborne painting of bamboo in furniture production.

2. Materials and methods

2.1. Materials

Bamboo-laminated lumber with the density about 0.8 g/cm^3, consisting of side-pressured carbonised Moso bamboo (*Phyllostachys edulis*) sheets, was cut into (100 × 100 × 10) mm^3 in size, the number of the samples was about 30. The bamboo-laminated lumber surface remained uncoated, and the moisture content was controlled under 10%.

Waterborne acrylic paints were bought from Zhejiang Feida new material Co., Ltd which consist of primer (D) and topcoat (M). Main parameters of the paints are showed in **Table 1**.

Additional materials used in this paper include gauze strips, absorbent cotton, a high-grade drawing pencil from a Chinese brand, qualitative filter paper and scotch tape.

Table 1. Main performance parameters of waterborne acrylic paints.

Paints	pH value	Clour	Particle size(nm)	Viscosity (mPa·s)	Polymer dispersity index	Solid content (/%)
Primer (D)	7	Light yellow	221.8	15.7	1.000	29
Topcoat (M)	7	Milky white	925.2	30.8	1.000	38

2.2. Major equipment

Painting equipments: special wool brush for WPBs, sandpapers (240 #, 320 # and 400 #) and electronic scales.

Analytical equipment: Paint film drying time tester (type QGS, produced by Zhongya Cangzhou Zhongya Test Instrument Co., Ltd), pencil hardness tester (type QHQ-A, produce by Zhejiang Airuipu Test Instrument Co., Ltd), wear-resisting instrument (type JM-IV, produced by Pushen Testing Instrument (shanghai) Co., Ltd), super-depth-of-field microscope (type PA53, produced by Shenzhen Huaxian Optical Instrument Co., Ltd), thermalgravimetric analyser (TG for short, type DSC 214 Polyma, produced by NETZSCH-Gerätebau GmbH) and differential scanning calorimeter (DSC for short, type 209F1, produced by NETZSCH-Gerätebau GmbH).

2.3. Preparation of paint films

2.3.1. Different painting methods

In this section, a single-factor experimental method was used. Bamboo-laminated lumber was painted using four different painting method (including one-layer primer one-layer topcoat, one-layer primer two-layer topcoat, two-layer primer one-layer topcoat and two-layer primer two-layer topcoat) at room temperature, as shown in **Figure 1**. Moreover, amount of paint used to the primer and topcoat was maintained at (80 ± 5) g/m^2. Before the primer painting, the bamboo-laminated lumber was sanded with 240 # sandpaper until the surface became smooth (usually, the roughness is less than 10 μm). Before the topcoat coating, the surface was sanded with 320 # sandpaper until the surface was smooth (usually, the roughness is less than 5 μm). After painting, the samples were immediately dried in a temperature and humidity chamber, with conditions set at 50 °C, 20% relative humidity and 0 m/s wind speed. Once the paint film was completely dried, bamboo-laminated lumber was left in an indoor environment for a week to acclimate with the drying time and the paint film performance before testing.
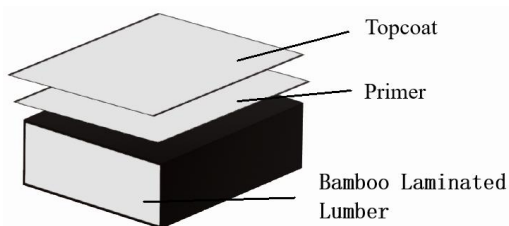

Figure 1. Painting process.

2.3.2. Different amounts of applied paint

In this section, the single-factor experimental method based on the result of the different painting methods and the optimal painting techniques was chosen, then four different amounts of paint (60 g/m^2, 80 g/m^2, 100 g/m^2 and 120 g/m^2) were applied to primer and topcoat for further examination.

2.4. Testing and Characterisation

The drying rate (including surface drying time and solid drying time) of the paint film were tested according to GB/T 1728-2020, the hardness of the paint film was tested according to GB/T 6739-2006(pencil scratches of different hardness6B-6H were used), the wear resistance (the Loss of film weight) and adhesion (the method of grid) were according to the GB/T 4893.8-2013standard [16,17]. Five parallel samples were tested, and the average was the final result.

Before testing, the completely dried paint film was needed to balance in a natural environment for one week. Each test was conducted at room temperature. Each experiment needs to be repeated five times and the experimental error was observed to below 10.0%.

The super-depth-of-field microscope was used to analyse the surface smoothness of the paint films.

The thermal properties of the liquid primer, topcoat and solid films were analysed using TG and DSC. The temperature range was 30–600 °C, with a heating rate of 10 °C/min.

3. Results and discussion

3.1. Effect of the painting method on the performance of paint films

3.1.1. Effect of the painting method on the drying rate of paint films

Table 2. Surface and solid drying time of the paint films with different painting methods.

Painting Methods	First Primer		Second Primer		First Topcoat		Second Topcoat	
	Surface Drying Time (min)	Solid Drying Time (min)	Surface Drying Time (min)	Solid Drying Time (min)	Surface Drying Time (min)	Solid Drying Time (min)	Surface Drying Time (min)	Solid Drying Time (min)
one-layer primer one-layer topcoat	8 (0.5)	8.5 (0.41)	/	/	6.5 (0.5)	7 (0.38)	/	/
one-layer primer two-layer topcoat	8 (0.5)	8.5 (0.41)	/	/	6.5 (0.5)	7 (0.38)	6.5 (0.58)	7 (0.51)
two-layer primer one-layer topcoat	8 (0.5)	8.5 (0.41)	6 (0.36)	6.5 (0.53)	6.5 (0.43)	7 (0.46)	/	/
two-layer primer two-layer topcoat	8 (0.5)	8.5 (0.41)	6 (0.36)	6.5 (0.53)	6.5 (0.43)	7 (0.46)	6.5 (0.41)	7 (0.42)

Note: standard deviations are provided in the brackets.

The drying time of paint film can be divided into surface drying and solid drying. Surface drying time refers to the paint surface has been dry, but it still contains water or volatile materials, solid drying refers to the moisture and the volatile materials of the paint have been completely dried.

Table 2 shows the paint films' surface and solid drying time under different painting methods. As shown, the four different painting methods had minimal effect on the film's drying time; the surface drying times for the primers (first and second) were 8 and 6 min, respectively, and the solid drying time were 8.5 and 6.5 min, respectively. Alternatively, the surface drying times of topcoats were 6.5 and 6.5 min, which the solid drying time of primers were 7 and 7 min. Notably, the effect of painting techniques on the drying time of the primer is greater than that of the topcoat. This could be because the first primer layer is in direct contact with the bamboo surface, resulting in the primer permeating into the bamboo surface and requiring a longer period for water evaporation. In contrast, when applying the second primer layer, moisture evaporated directly without permeating the surface. Additionally, a chemical reaction between the first primer and the bamboo surface could lead to a longer surface and solid drying time.

3.1.2. Effect of painting method on the mechanical properties of paint films

The mechanical properties of paint films, including hardness, adhesion and wear resistance, for the four different painting methods are shown in **Table 3**. The hardness of the films obtained using all these four painting methods was grade B and the adhesion was grade 0, indicating that the painting method has little effect on the hardness and adhesion of the film. In this experiment, the four-painting method's quality loss were 51.24, 71.27, 69.68 and 83.65 mg·100r^{-1}, respectively. The highest

wear resistance was achieved with the one-layer primer one-layer topcoat method, whereas the lowest was observed with the two-layer primer two-layer topcoat method. This may be because the thickness of the film increased with an increase in the paint layers, leading to poor wear resistance. Furthermore, large painting thickness might result in the film's pinhole and hanging, reducing its wear resistance.

Table 3. Mechanical properties of paint films in different painting methods.

Painting methods	Hardness (grade)	Adhesion (grade)	Loss of film quality (mg·100r^{-1})
one-layer primer one-layer topcoat	B	0	51.24 (2.06)
one-layer primer two-layer topcoat	B	0	71.27 (8.29)
two-layer primer one-layer topcoat	B	0	69.68 (10.46)
two-layer primer two-layer topcoat	B	0	83.65 (9.06)

Note: standard deviations are provided in the brackets.

3.1.3. Effect of painting method on the surface smoothness of paint films

The analysis of super-depth-of-field optical microscope is one of the key methods for surface characterization of composite materials. Its advantage lies in the non-destructive optical detection, and the super depth of field, which can observe the micro-area more clearly. The smoothness of the material surface can be directly seen through the super-depth-of-field optical microscope image.

Figure 2 shows a three-dimensional (3D) view of the surface of the paint films painted using the four different painting methods, which measured by the super-depth-of-field optical microscope.
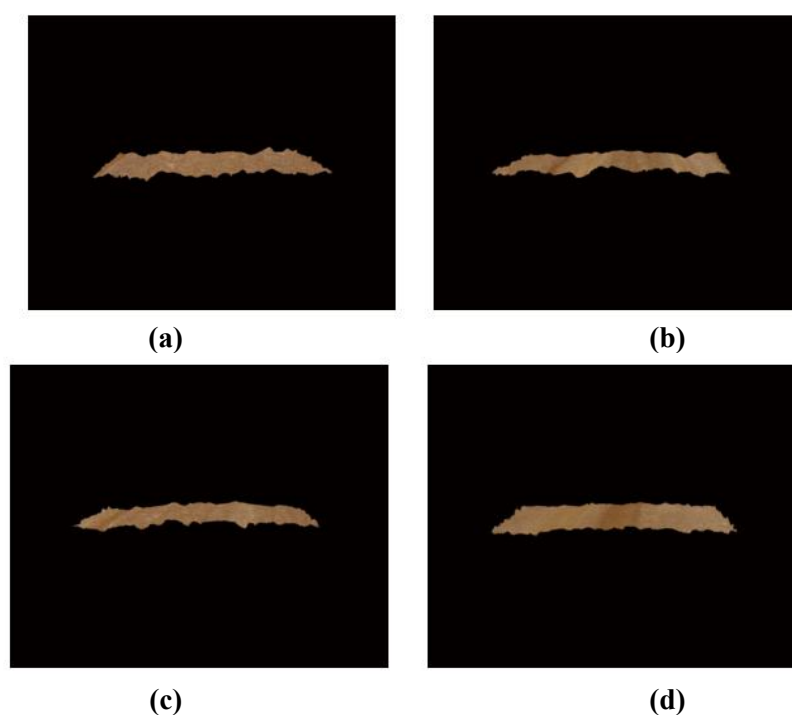

(a)   **(b)**

(c)   **(d)**

Figure 2. Surface smoothness of films in four painting methods was analysed using super-depth-of-field microscope. **(a)** one-layer primer one-layer topcoat; **(b)** one-layer primer two-layer topcoat; **(c)** two-layer primer one-layer topcoat; **(d)** two-layer primer two-layer topcoat.

The surface smoothness of the paint film increased with increasing paint layers. Hence, among the different painting techniques, two-layer primer two-layer topcoat had the best film surface smoothness. This is probably because the primer serves to fill gaps on the bamboo surface, while the topcoat fills gaps on the primer layer. As the number of paint layers increases, the remaining pores are filled, resulting in a smoother surface.

3.2. Effect of the different paint amount on the performance of paint films

3.2.1. Effect of different paint amount on the drying rate of paint films

The results of the mechanical properties of paint films for the four different painting methods show that the film with one-layer primer one-layer topcoat has the best mechanical performance. Consequently, in this section, bamboo-laminated lumber was painted using a one-layer primer one-layer topcoat with different amount of paint, and the surface and solid drying times of the paints are shown in **Table 4**.

Table 4. Surface and solid drying times of the paint films after applying different amounts of paint.

Amount of paint (g/m^2)	Primer		Topcoat	
	Surface Drying time (min)	Solid Drying Time (min)	Surface Drying time (min)	Solid Drying Time (min)
60	7 (0.39)	7.5 (0.43)	6 (0.31)	7 (0.34)
80	8 (0.5)	8.5 (0.41)	6.5 (0.5)	7.5 (0.38)
100	9 (0.64)	10 (0.58)	8 (0.52)	9 (0.36)
120	10 (0.34)	10.5 (0.29)	9 (0.63)	9.5 (0.56)

Note: standard deviations are provided in the brackets.

Table 4 shows that the shortest drying time occurs when the amount of paint applied is 60 g/m^2 and that the drying time is longest when the amount of paint applied is 120 g/m^2. The drying time for surface or solid drying were different among the four different painting amounts, showing the following trend: the drying time increases as the amount of paint applied increases. The thickness of the paint increases with the amount of paint, and thus the heat required for water evaporation also increases, which results in a slower drying rate. Additionally, as the amount of paint applied increases, internal molecular motion is relatively difficult, which leads to a slower drying rate. However, a smaller amount of applied paint is not necessarily better as too little paint can weaken the bond between the paint film and the substrate, leading to insufficient adhesion. When the amount of painting reaches a certain degree, the performance of the paint film can meet the requirement.

Figure 3 shows the moisture curves of the primer and topcoat painting tinplate at different paint amounts. As seen in **Figure 3**, the moisture volatilisation rate, which represents the drying rate of the paint film, increases first and then decreases rapidly and then tends to zero, at approximately 2 min, the water volatilisation rate reaches its highest value, furthermore, the drying rate decreases gradually with an increase in the amount of paint. The moisture volatilisation reaches the saturation point fastest, so that the drying time of the film is the shortest. The results in **Figure 3** are consistent with those in **Table 4**. The smaller the amount, the thinner will be the painting, and faster

will be the surface water evaporation rate in comparison to the paint film's curing speed. When the paint thickness increases, the curing layer on the film's surface affects water evaporation. The drying speed of the paint film is affected by the coordination of moisture volatilisation and curing speed of the paint film, a high number of film-forming substances in the paint reduces the rate of water leaving the film's surface, which results in a decrease in the drying rate.
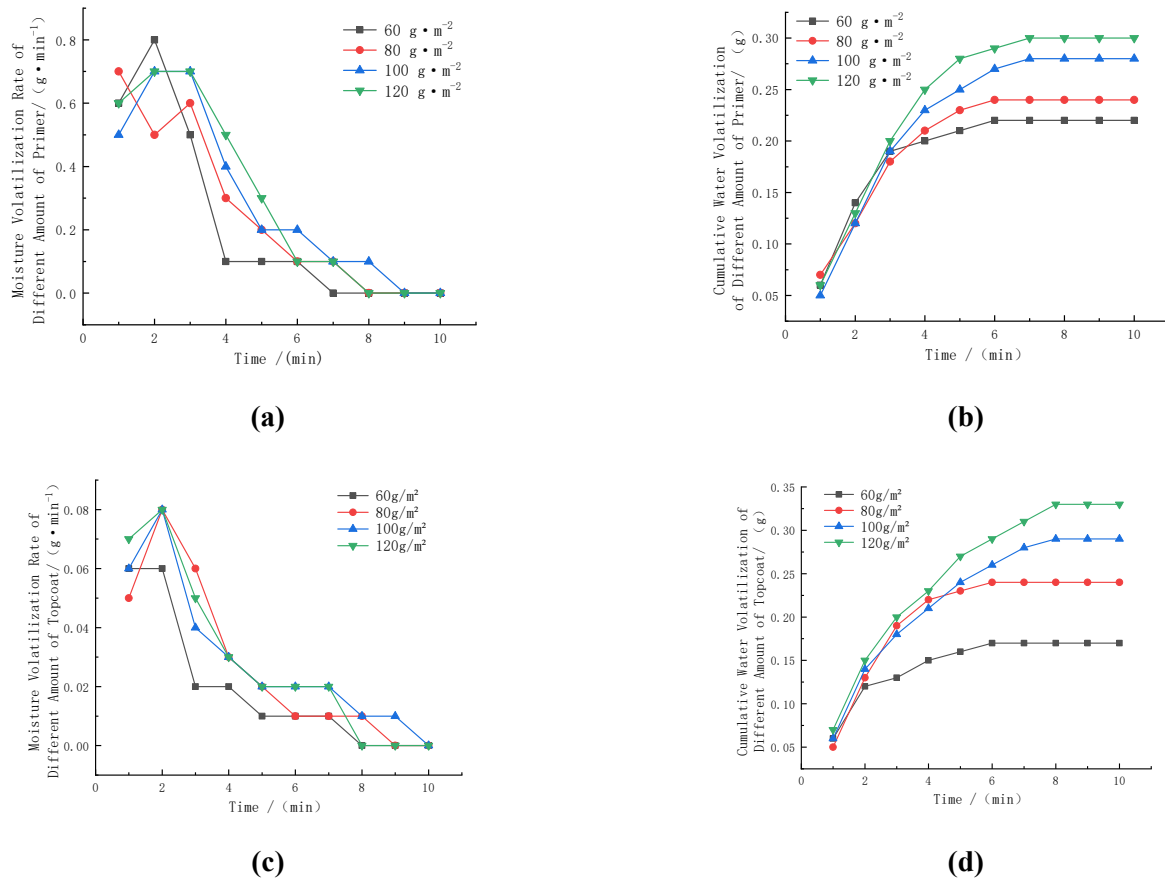

(a)

(b)

(c)

(d)

Figure 3. Moisture curves of primer and topcoat painting tinplate in different paint amounts. **(a)** the water volatilisation of primer; **(b)** the cummlative water volatilisation of primer; **(c)** the water volatilisation of topcoat; **(d)** the cummlative water volatilisation of topcoat.

3.2.2. Effect of amount of paint on the mechanical properties of paint films

Table 5. Mechanical properties of the paint films when different amount of paint is applied.

Painting amount (g/m²)	Hardness (grade)	Adhesion (grade)	Loss of film quality (mg·100r⁻¹)
60	2B	0	75.41 (6.77)
80	B	0	51.24 (2.06)
100	B	0	83.16 (6.71)
120	B	0	89.65 (3.68)

Note: standard deviations are provided in the brackets.

Table 5 shows the hardness, adhesion and wear resistance of paint films for four different painting amounts. It can be observed that when the amount of paint applied

is 60 g/m^2, the paint film's hardness is lowest, with a grade of 2B, indicating that the amount of paint affects the hardness of the film. As the paint amount increases, the hardness of the film will be improved. However, once the hardness reaches a certain level, the amount of applied paint no longer affects the film's hardness. Here, the paint film's hardness was B grade for the other three painting amounts. The adhesion of the paint films was grade 0. During painting, a large one-time paint amount can lead to film uniformity issues, and painting becomes difficult due to paint hanging as a result of a large amount. The highest wear resistance for the paint film was observed when the amount of paint applied was 80 g/m^2, whereas the lowest wear resistance was found at 120 g/m^2. The reason could be that when using a large amount of paint, part of the paint cannot penetrate the substrate and accumulate on its surface, making it more susceptible to wear. However, if the amount of paint is too small, it cannot form enough paint nails between the paint and bamboo, reducing the effect of the force and making it easy to wear. Therefore, the amount of applied paint 80 g/m^2 is appropriate for wear resistance.

3.2.3. Effect of amount of applied paint on the surface smoothness of paint films

Figure 4 shows the 3D view of the paint film surfaces when applying four different paint amounts. As can be seen from the figure, the flatness of the paint film surface gradually increases with an increase in the amount of applied paint. This may be because, when the paint amount is small, the paint cannot completely cover the pores existing on the surface. Therefore, an increase in the coating amount can effectively fill the pores, hence, the surface smoothness of the film is highest when the paint amount was 120 g/m^2.
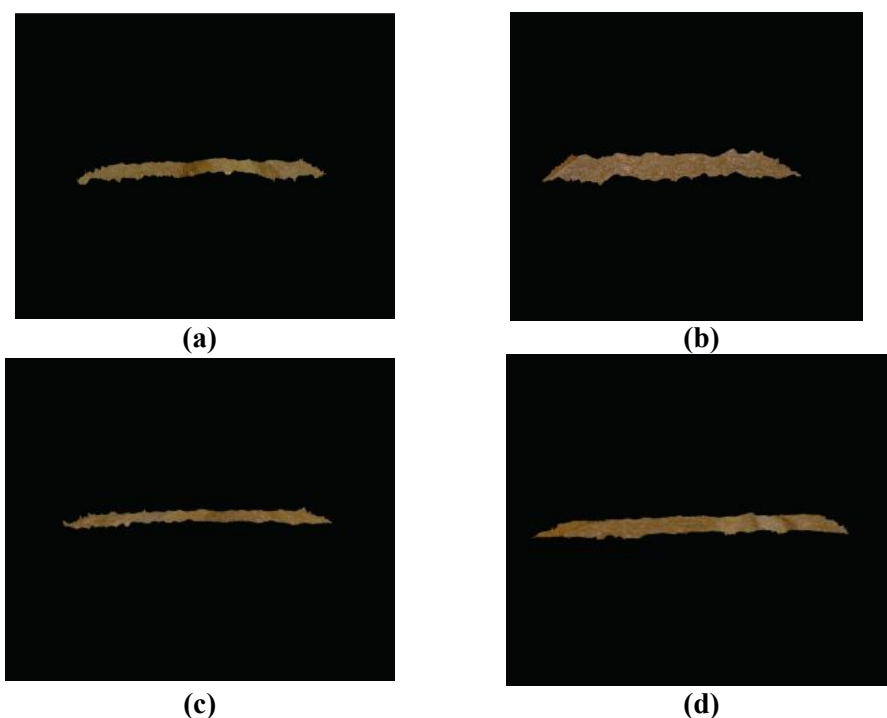

Figure 4. Super-depth-of-field microscope analysed the surface smoothness of the films in the four painting methods (**(a)**, **(b)**, **(c)**, **(d)** are the amount of applied paint 60 g/m^2,80 g/m^2 ,100 g/m^2 and 120 g/m^2).

3.3. Thermal properties analyses of the paints and paint films

3.3.1. Analyses of TG and DTG

TG analysis is a thermal analysis method which can show the relationship between the mass of a substance and temperature or time at a programmed temperature. By analyzing the thermogravimetric curves, the thermal stability, thermal decomposition and the intermediate products can be known.

Figure 5 shows the TG curves of the paints and films. The thermal decomposition processes of primer and topcoat are the same (**Figure 5**), which can be divided into two steps. Firstly, thermal decomposition occurred when the temperature reaches 100 °C, mainly due to water evaporation. Furthermore, the quality of the paints decreases rapidly, and at around 140 °C, the water has completely evaporated, transforming the liquid paints into solids, then the teds to be stabilised. Secondly, thermal decomposition occurred when the temperature reaches 350 °C, which corresponds to the thermal decomposition of polymers (organic components) in the solid paints, the quality of the paints decreases rapidly again, and thermal decomposition of the polymers was completed at approximately 400 °C [18]. The rate of paint weightlessness was 98%. Like liquid paints, the thermal decomposition process of primer and topcoat films can be divided into two steps. First is the evaporation of residual water and other additives in films, then, the rate of film weightlessness was not more than 25%. Second is the thermal decomposition of polymers in the films when the temperature reaches 340 °C. In these steps, the quality of the paints decreases rapidly, and the rate of weight loss is consistent with that of liquid paints, which is finally at 98% [19,20].
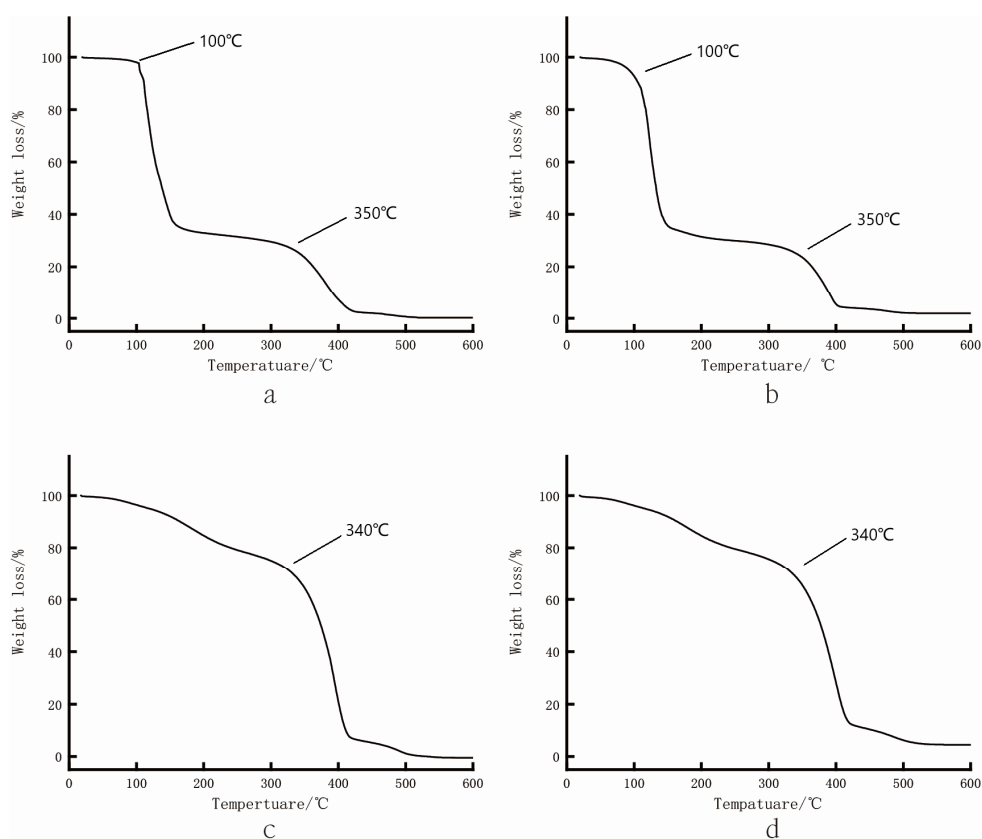

Figure 5. TG curves of paints and films. **(a)** the primer; **(b)** the topcoat; **(c)** the primer film; **(d)** the topcoat film.

DTG is the first derivative of a TG curve to temperature or time. In the DTG curve, the vertical coordinate is the rate of mass change, the horizontal coordinate is the temperature or time.

Figure 6 shows the DTG curves of the paints and films. DTG indicates the weight loss rate. As seen in **Figure 6**, the first peak of the DTG curves for the primer occurred at approximately 110 °C, whereas it appeared at about 130 °C for the topcoat. Similarly, in the DTG curves of the films, the temperature of the peak of the primer film was 400 °C, which is lower than that of the topcoat film. Simultaneously, the thermal loss rate of the primer was higher than that of the topcoat, and all of these results show that the thermal stability of the topcoat was better.
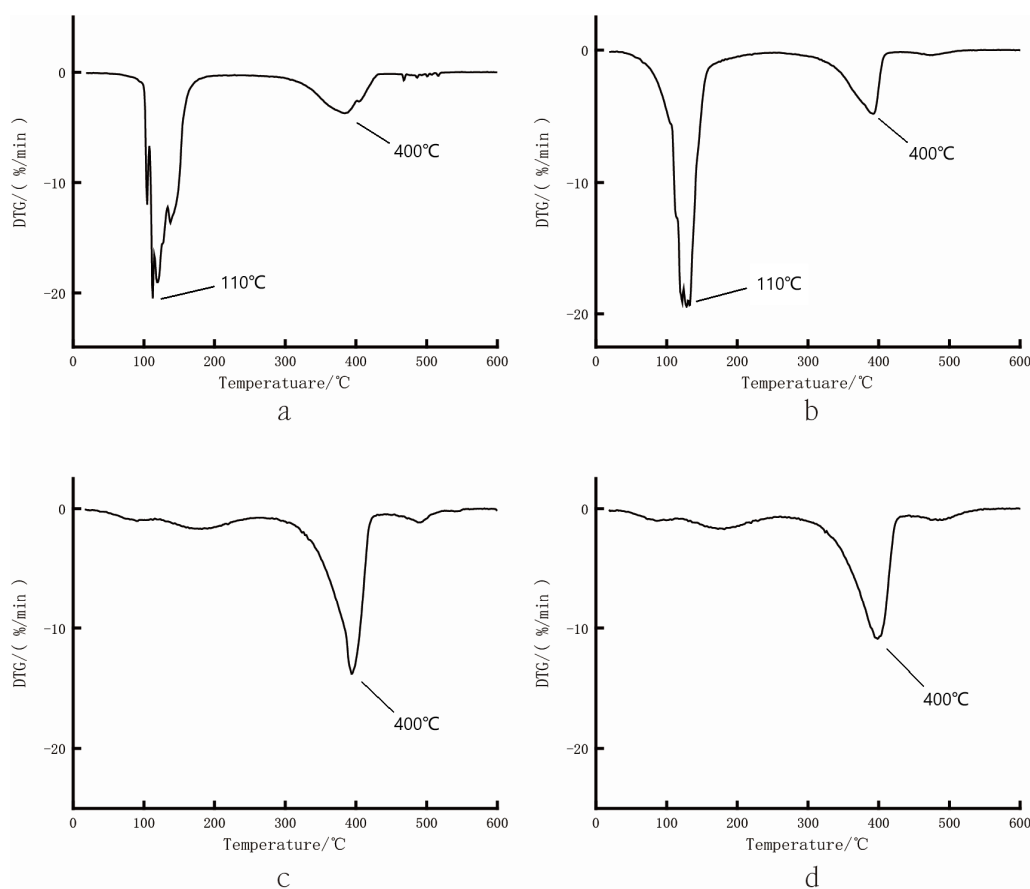

Figure 6. DTG curves of paints and films. **(a)** the primer; **(b)** the topcoat; **(c)** the primer film; **(d)** the topcoat film.

3.3.2. Analysis of DSC

Figure 7 shows the DSC curves of the paints and films. DSC curves are consistent with the results of TG, the DSC curves of primer and topcoat. Firstly, it is mainly the thermal decomposition of water and additives at 100–200 °C. Secondly, it is mainly the thermal decomposition of polymers (organic components) in the paints at 350–550°C. In the DSC curves of films, there is no peak between 100–200 °C as there is no water decomposition, besides, there are two peaks between 400–500 °C, at about 410 °C and 450 °C, respectively.
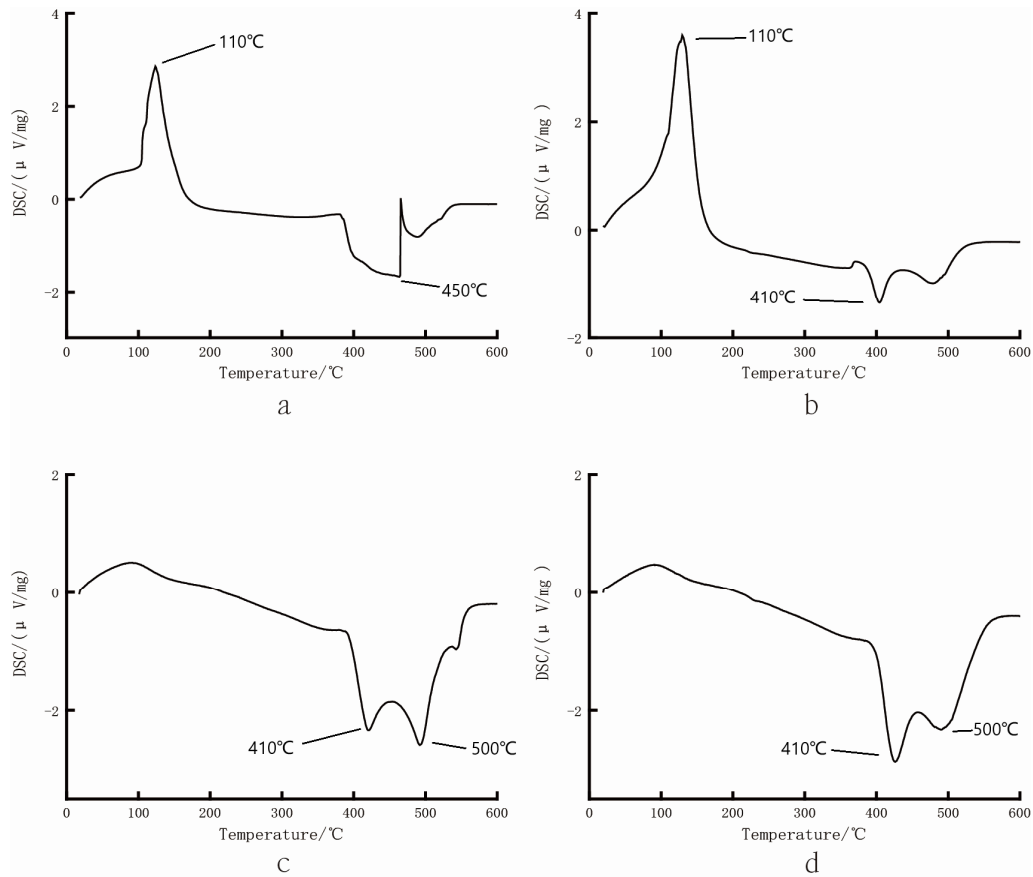
Figure 7. DSC curves of paints and films. **(a)** the primer; **(b)** the topcoat; **(c)** the primer film; **(d)** the topcoat film.

3.3.3. Analysis of the film-forming mechanism

In the thermal analysis results of paints, regardless of primer or topcoat, the first step is the decomposition of water and additives. Hence, the film forming of paint on the bamboo-laminated lumber can be divided into the following stages, as seen in **Figure 8**. First, particles are dispersed in the emulsion paint, then in stage I, water evaporates, and particles pack tightly. In stage II, particle mix together, and finally in state III, the mixed particles form the film [21].
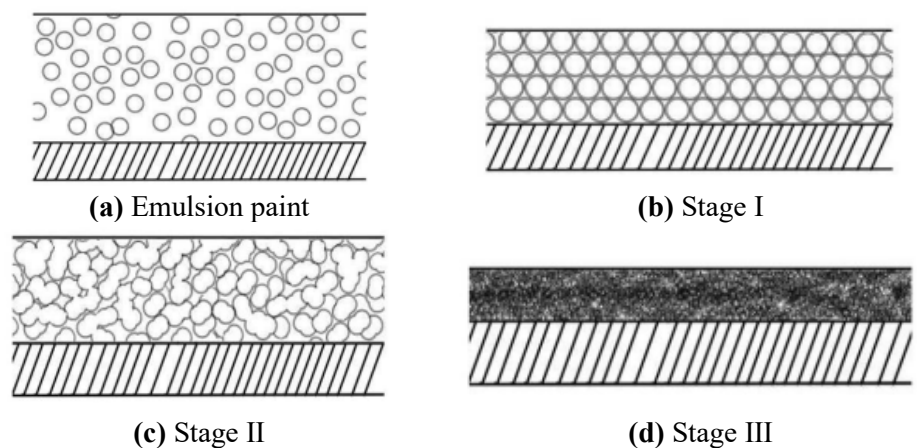

(a) Emulsion paint   **(b)** Stage I

(c) Stage II   **(d)** Stage III

Figure 8. Diagram of film formation. **(a)** Emulsion paint: Particles are dispersed; **(b)** Stage I: Water evaporates and particles pack tightly; **(c)** Stage II: Particles mix together; **(d)** Stage III: Film formation.

We know that waterborne acrylic paint is one of the water-soluble paints, so the particles of the paint are dispersed uniformly (emulsion paint). The water in the pants evaporates when painting on the bamboo-laminated lumber (stage I). With the further evaporation of water, the average contact number and contact area of latex particles increase, and the irreversible interaction between particles from disordered state at contact interface deforms, and the density of arrangement increases, the local and the whole reaches the most compact accumulation state, at this stage the force further causes the latex particles to fuse and deform (stage II). Then, the force or surface tension produced by the shrinking surface plays a leading role, and the molecular chains at the polymer interface diffuse, infiltrate and entangle each other, and the boundary of the particles is fully fused, macroscopically, it can form continuous paint film with certain mechanical properties (stage III).

4. Conclusions

In this study, bamboo-laminated lumber for furniture was coated with waterborne acrylic paints and the effects of four different painting methods and amount on the drying rate, smoothness, hardness, adhesion and wear resistance of the paint film were investigated. These results can be used as a reference for waterborne bamboo painting in furniture production. The conclusions are as follows.

(1) The painting method has little effect on the drying time, flatness, hardness and adhesion of the paint film; however, it had a certain influence on wear resistance. In this paper, the flatness of the films is relatively similar when using different painting methods. The drying times of the surface and solid of the primer are 8 and 8.5 min, respectively, whereas those of the topcoat are 6.5 and 7 min, respectively. The hardness and adhesion of the paint films are grade B and grade 0, respectively. The paint film exhibits the best wear resistance ($51.24 \ mg \cdot 100 \ r^{-1}$) when painted with one-layer primer one-layer topcoat.

(2) The amount of applied paint remarkably influenced the drying time and flatness of the paint film. As the amount increased, the surface/solid drying time of the paints also increased, and the flatness of the paint film increase first and then decrease. When the amount of applied paint is 80 g/m^2, the film's adhesion, hardness and wear resistance were the best at grade 0, grade B and $51.24 \ mg \cdot 100 \ r^{-1}$, respectively.

(3) The thermal analysis results of the primer and topcoat show that water decompose at 100 ℃, while the thermal decomposition of organic components occurs at 350 ℃. The weight loss of the primer and topcoat are the same, but the thermal loss rate of primer is higher than that of topcoat. This indicates that the thermal stability of topcoat was better.

Conflict of interest: The authors declare no conflict of interest.

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