Effects of Sanding Process on Adhesion of Waterborne Paint Film on a Polypropylene Membrane Surface

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Abstract

In this article, the surfaces of 2D and 3D polypropylene (PP) membranes were sanded with different brush-type sanding belts and a waterborne primer and topcoat were applied; the effect of the sanding process on the adhesion of the waterborne paint film on a PP decorative membrane surface was tested. A contact angle meter was used to determine the effect of the sanding process on the hydrophilicity of a PP decorative membrane surface. A scanning electron microscope and a roughness tester were used separately to observe the changes in the surface microfeatures and the roughness on PP decorative membranes before and after the sanding process. A 3D profilometer was used to test the changes in the surface roughness and 3D microtopography on PP decorative membranes before and after the sanding process, and a crosscut tester was used to test the changes in the surface adhesion of waterborne paint film on PP decorative membranes before and after the sanding process so as to research the effects of different sanding parameters on the adhesion of waterborne paint films on PP decorative membrane surfaces. The research results showed that the surface sanding process could be used to decrease the surface contact angle, increase the roughness, and improve the wettability of PP decorative membranes. In general, under experimental conditions, a 400-grit sanding belt and two sanding passes were the suitable parameters for 2D PP decorative membranes, and a 320-grit sanding belt and two sanding passes were suitable for 3D PP decorative membranes.

The polypropylene (PP) decorative membrane is a typical surface decoration material for wood products. It has many advantages, such as superior plasticity, excellent decoration effect, good degradability, no chlorinated compounds or other substances that are harmful to health, and low cost and good flexibility compared with natural decorative veneer; therefore, it is widely used in edge banding of wood products and decorations of planes or special-shaped surfaces (Zhang 2012, Bai 2016, Li et al. 2017). With further diversification of consumer demand and increasing requirements for product quality, the 3D texture process and the ink spraying process on PP decorative membranes have become more popular in recent years; moreover, in order to improve the integrity and harmony and create a more realistic texture imitation between wood products and their PP decorative accessories, a new painting process on decorative membranes was proposed to solve the problems between wood accessories (such as door casings for wood doors with PP decorative surfaces and decorative panels for kitchen cabinets) and other parts (such as door panels); the problems include poor integrity, obvious color differences, and poor 3D texture imitation effects. However, as the PP decorative membrane has been based on a nonpolar polymer with low surface energy, high crystallinity, and good chemical stability but without polar groups in its molecular chains, and as certain additives were required in its preparation that were unfriendly to the adhesion of inks and coatings, these surface features should be modified in actual applications (Zhen et al. 2014, Dimitriou et al. 2016).

There are four common methods to improve the surface adhesion of PP materials: (1) introduce polar groups to polarize the surface, (2) improve the surface free energy, (3) improve the surface energy by removing weak boundary layers, and (4) improve the surface roughness of the PP decorative membrane to strengthen the mechanical bonding

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effect and enlarge the effective bonding areas with other materials (Chen et al. 2000, Cheng 2009).

In this article, based on these four methods, a brush-type belt sander was used to sand the surfaces of PP decorative membranes with different parameters to study physical changes, such as surface hydrophilicity, surface roughness, and micromorphology, on the surfaces of PP decorative membranes, and waterborne film adhesion changes of waterborne paints on PP decorative membrane surfaces before and after the sanding process.

This article can provide important theoretical references and data support for research on the effects of the sanding process to improve the adhesive properties of paints and inks on the surfaces of PP decorative membranes and benefit the industrial application of PP decorative membranes.

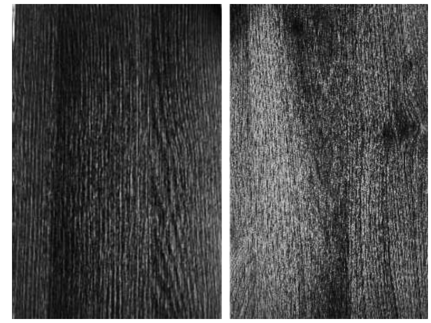

Figure 1.—Black walnut polypropylene (PP) decorative mask: (left) PP stereo mask and (right) PP planar mask.

Materials and Methods

Materials, reagents, and instruments

- Black walnut 3D PP decorative membrane and 2D PP decorative membrane: Both purchased from Guangdong Tian'an Decoration Materials Co., Ltd, as shown in Figures 1a and 1b; thickness was 0.05 mm, density was 0.91 g/cm^3, and only the former's surface was uneven and relatively rough, while the latter's surface was flat and smooth without lines.
- Waterborne topcoat (YBW500X): A one-component waterborne topcoat with a viscosity of 16 s, provided by Tianjin Yubei Paint Co., Ltd.
- Brush-type belt sander: Jointly developed by the Wood Products Office of the Research Institute of Wood Industry of the Chinese Academy of Forestry and Qingdao Shengfu Machinery and Equipment Co., Ltd; provides a feeding speed within the range of 0 to 12.3 m/min.
- JC2000-type static drop contact angle tester: Jointly developed by Shanghai Zhongchen Resin Technical Apparatus Co., Ltd, and the Laboratory of the Research Institute of Wood Industry of the Chinese Academy of Forestry.
- ANEST Iwata W-200-151g gravity spray gun: Purchased from Shenzhen Heye Xingtai Spraying Tools Co., Ltd; nozzle diameter was 1.5 ψmm, and air supply rate was 200 liters/min.
- S-4800 cold field emission scanning electron microscope: Manufactured by the Hitachi Company.
- ContourGT-K 3D microtopography profilometer: Manufactured by the Bruker Company.
- Water curtain–type coating chamber.
- Paint Film crosscut tester: A paint surface tester equipped with a QFH crosscut tester and 3M adhesive tape with a measurement accuracy of 0.02 mm, a measurement range of ½ mm, and a resolution of 0.01.
- Surtronic 3+ contact-type roughness tester: Manufactured by the Taylor/Hobson Company and equipped with a standard probe; probe tip measurement radius was 5 m, and sampling length was 12.5 mm.

Methods and test characterization

Experimental determination for surface wettability.—Determination of the surface contact angle considered matching the mesh size of the abrasive belt with the surface microfeatures and roughness of the PP film according to the pre-experimental tests: (1) sand 3D PP decorative membranes longitudinally in one, two, and three passes with brush-type belt sanders equipped with 240-, 320-, and 400-grit sanding belts, respectively (at a sanding roller speed of 900 rpm and a feeding speed of 8 m/min with a sanding belt length of 90 mm); (2) sand 2D PP decorative membranes longitudinally in one, two, and three passes with brush-type belt sanders equipped with 320-, 400-, and 600-grit sanding belts, respectively (sanding roller and the feeding speeds the same as above); and (3) measure the contact angles of PP decorative membranes with the static drop method and with distilled water and di-iodomethane as testing liquids. A PP decorative membrane sample was fed directly into the contact angle tester. The contact angle was measured with the same testing liquid and was decreased gradually over time. A photo was taken within 1 to 2 seconds immediately after applying the testing liquid, and the contact angle in the photo was measured with the tangent method; the measurement was repeated 20 times at each of 10 points, and then the average of these measurements was taken as the result (Peng and Zhang 2018, 2019).

Determination of surface free energy used the Young-Good-Girifalco-Fowkes equations to calculate the materials' surface energies with the solids of low surface energy as a reference (Young 1805, Owens and Wendt 1969, Wolkenhauer et al. 2008, Sheng et al. 2012):

$$\gamma_L(1+\cos\theta) = 2\left[(\gamma_S^d\gamma_L^d)^{1/2} + (\gamma_S^P\gamma_L^P)^{1/2}\right] \quad (1)$$

$$\gamma_S = \gamma_S^d + \gamma_S^p \quad (2)$$

where γ_L and γ_S are surface energies of the liquid and solid, respectively; γ_L^d and γ_L^p are the dispersion and nondispersion forces (polar force) of the liquid's surface, respectively; γ_S^d and γ_S^p are the dispersion and nondispersion forces (polar force) of the solid's surface, respectively; and θ_1 and θ_2 represent contact angles. The values for γ_L^d and γ_L^p are 21.8 $\times 10^{-7}$ and 51.0×10^{-7} J cm^{-2}, respectively. The 2D and 3D PP surface energies were calculated based on the above formula.

Experimental determination for surface microtopography.—PP decorative membranes were sanded longitudinally with two passes using brush-type belt sanders equipped with different sanding belts and the sanding parameters described in the previous section. The surface characteristics of 2D PP decorative membranes were observed before and after the sanding process with atomic force microscopy (AFM), and the surface roughness and 3D microtopography of 3D PP decorative membranes were determined before and after the sanding process with a 3D profilometer. The test steps were as follows: (1) paste double-sided adhesive tape with dimensions of 10 by 10 mm on the top of the sample table, (2) cut 2D PP decorative membranes into test pieces with dimensions of 10 by 10 mm and gently attach them to the sample table, and (3) observe them with AFM (Ma and Ma 2018). Test pieces were prepared and attached with 3D PP decorative membranes as previously described and then scanned with a 3D profilometer under the following conditions: scanning frequency of 0.5 Hz, ×20 objective lens, scanning ranges of 0.24 by 0.18 mm and 96 by 72 μm, and white-light mode (Samyn et al. 2016). The 3D profilometer was driven by a motor to change the distance between the objective lens and the test pieces so as to move the interference fringes to carry out the scanning process. The surface roughness of 3D PP decorative membranes was also measured with the 3D profilometer.

The surface roughness of 2D PP decorative membranes was measured with a surface roughness meter according to the requirements of GB/T 12472-2003, ''Geometrical Product Specifications (GPS)—Surface Texture Profile Method: Surface Roughness Parameters and Values for Wood Products'' and GB/T 3324-1995, ''General Technical Requirements for Wooden Furniture'' (Standardization Administration of China [SAC] 1995, 2003). To ensure that all test pieces of the 2D PP decorative membranes were measured at the same points both before and after the sanding process, the measurement points were marked in advance. Three different measurement zones were selected with an area of 15 by 15 mm in each of four groups of 2D PP decorative membranes separately; three measurements in each measurement zone were performed with the surface roughness tester, and the average of three measurements was taken as the result (Peng et al. 2012, Zhang et al. 2012).

Experimental determination for the adhesion of waterborne paint films.—Based on the results obtained from the previous two sections, the test steps were as follows: (1) sand PP decorative membranes with different sanding belts, (2) apply the waterborne topcoat to them, (3) dry them for 48 hours, and (4) measure the adhesion of the waterborne paint films before and after the sanding process for PP decorative membranes with the crosscut tester according to the requirements of GB/T9286-1998, ''Paints and Varnishes—Cross Cut Test for Paint Films'' (SAC 1998): use a 100-grid knife to apply force evenly and perpendicular to the surface of the template, draw at least six parallel cutting lines smoothly, and then cross the vertical cutting lines at 90° to draw six parallel lines to form a grid pattern. Clean the lines in the grid, then apply tape to the center of the grid and ensure that it is in full contact with the paint film. Lift the tape to form an angle of about 60° with the template, continuously and smoothly withdraw the tape, and then observe the peeling of the paint film in the grid. Take five test pieces for the measurement and then take the average as the result, as shown in Figure 2.

Results and Analysis

Effect of the sanding parameters on surface wettability

Effect of sanding parameters on surface contact angle.—The Wenzel model shows that the hydrophilicity of the material surface increases when the contact angle increases from 0° to 90° and that the hydrophobicity of the material surface increases when the contact angle increases from 90° to 180°. The changes in surface contact angles on 2D PP decorative membranes and 3D PP decorative membranes sanded under different process conditions are shown in Table 1. As shown, the contact angles of the water and the di-iodomethane on the unsanded surface of PP decorative membranes were relatively large at 89° and 65°, respectively. After the membrane was sanded with different sanding belts, the contact angles were decreased to different degrees due to different sanding meshes and passes. For 2D PP decorative membranes, under the experimental conditions, if a 320-grit sanding belt was used, the surface contact angle was decreased relatively slightly; when there were three sanding passes, the most dramatic decrease in the surface contact angle was observed. The contact angle of the water was decreased by 24.72 percent, and the contact angle of the di-iodomethane was decreased by 36.92 percent. However, in this case, there were local substrate exposures on 2D PP decorative membranes that might be caused by larger sanding meshes, rougher sanding particles, and more sanding passes. If a 400-grit sanding belt was used, the surface contact angle was noticeably decreased, especially after two sanding passes, and the most dramatic decrease in the surface contact angle was observed. The contact angle of the water was decreased by 31.46 percent, and the contact angle of the di-iodomethane was decreased by 53.85 percent; however, the decrease in the surface contact angle after three sanding passes was relatively less than that after two sanding passes because that excessive sanding process might decrease the tension of the water drops on the contact surface. If a 600-grit sanding belt was used, the surface contact angle on 2D PP decorative membranes was relatively larger than that sanded with a 400-grit sanding belt because the surface roughness might not be noticeably increased by sanding with a finer sanding belt. Therefore, 2D PP decorative membranes should be sanded in two passes with a 400-grit sanding belt. According to the results of the analysis of variance in Table 2, it can be concluded that for the planar PP film, the influence of the mesh number of the belt on its surface contact angle was extremely significant, and the effect of the number of sanding times was significant.

For 3D PP decorative membranes, the surface contact angles of the water and the di-iodomethane were relatively large before the sanding process and were about 81° and 52°, respectively. Similar to 2D PP decorative membranes, the surface contact angles on 3D decorative membranes sanded with different sanding belts were decreased to different degrees because of different sanding processes. In the

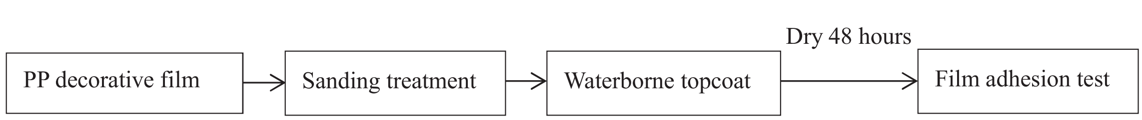

Figure 2.—Process and performance test of water coating adhesion of polypropylene (PP) mask after sanding.

Table 1.—Effect of sanding treatment on the surface contact angle of polypropylene (PP) facing film.

Treated materials	Belt grit	Sanding times	Water contact angle (°)	Di-iodomethane contact angle (°)
PP planar film	Untreated		89	65
	320	1	71	49
		2	70	45
		3	67	41
	400	1	66	35
		2	61	30
		3	63	33
	600	1	69	43
		2	67	39
		3	66	38
PP stereo film	Untreated		81	52
	240	1	64	31
		2	63	30
		3	63	30
	320	1	60	27
		2	58	23
		3	59	26
	400	1	68	34
		2	69	36
		3	67	35

experiments, a sanding belt with smaller meshes was selected for 3D decorative membranes compared with that for 2D decorative membranes; that is, a rougher sanding belt was selected. Under the experimental conditions, the effects of the decrease in the contact angle (on 3D PP decorative membranes) with different sanding belts were ranked as follows: 400-grit < 240-grit < 320-grit. If a 3D PP decorative membrane was sanded in two passes with a 320-grit sanding belt, the decrease in the contact angle was smallest. The contact angle of the water was decreased to 58° with a maximum decrease ratio of 28.40 percent, and the contact angle of the di-iodomethane was decreased to 23° with a maximum decrease ratio of 55.77 percent. If a 400-grit sanding belt was used, the decrease in the surface contact angle was smaller because 3D PP decorative membranes might be sanded poorly with the finer sanding belt. Therefore, 3D PP decorative membranes should be sanded in two passes with a 320-grit sanding belt. It can be seen from Table 3 that for stereo PP membranes, the influence of the mesh number of the belt on the contact angle is extremely significant, but the influence of the number of sanding times is not obvious.

Effect of sanding parameters on surface free energy.—The changes in the surface free energy of 2D and 3D PP decorative membranes sanded under different process conditions are shown in Figures 3 and 4. Under the experimental conditions, the surface free energies of unsanded 2D and 3D decorative membranes were relatively small and were 35.88 and 39.19 mJ/mm^2, respectively; after they were sanded in different passes with different sanding belts, the surface tensions increased to different levels. Similar to the surface contact angle, if a 2D PP decorative membrane was sanded in two passes with a 400-grit sanding belt, the increase in the surface free energy was the largest, ranging from 35.88 (before the sanding process) to 47.12 mJ/mm^2 with an increase ratio of 31.35 percent, which might be caused by the increase of the dispersion force. If a 3D PP decorative membrane was sanded in two passes with a 320-grit sanding belt, the surface free energy was noticeably increased from 39.19 (before the sanding process) to 53.99 mJ/mm^2 with an increase ratio of 37.76 percent, which might also be caused by the increase of the dispersion force. The above results show that the sanding process was the main factor in changing the physical characteristics of PP decorative membranes, such as the increase in the roughness, the decrease in the contact angle, and the absence of chemical reaction.

According to the results of the analyses of variance in Tables 4 and 5, it can be concluded that for the planar PP film, both the influence of the belt's mesh number and the number of sanding times on its surface free energy are extremely significant. For the stereo PP membrane, the influence of the belt's mesh number on its surface free energy is extremely significant, but the influence of the number of sanding times is relatively small.

Effect of the sanding process on surface microtopography

Under the suitable conditions of the testing instruments, the surface microtopography of 3D PP decorative membranes was observed with a 3D profilometer, and the surface topography of 2D PP decorative membranes was observed with a scanning electron microscope. The surface micro-

Table 2.—Variance analyses of the contact angle of polypropylene planar film.[a]

Source of variance	Sum of squared deviations	df	Mean square	F	Significance
Belt mesh number	56.000	2	28.000	22.909	0.002
Sanding times	18.667	2	9.333	7.636	0.022
Error	7.333	6	1.022		
Total	63,845.000	12			

[a] $R^2 = 0.994$.

Table 3.—Variance analyses of the contact angle of polypropylene stereo film.[a]

Source of variance	Sum of squared deviations	df	Mean square	F	Significance
Belt mesh no.	121.556	2	60.778	117.214	0.000
Sanding times	1.556	2	0.778	1.500	0.296
Error	3.111	6	0.519		
Total	56,036.000	12			

[a] $R^2 = 0.996$.

Table 4.—Variance analyses of the surface free energy of polypropylene planar film.[a]

Source of variance	Sum of squared deviations	df	Mean square	F	Significance
Belt mesh no.	63.924	2	31.962	40.642	0.000
Sanding times	15.831	2	7.916	10.065	0.012
Error	4.719	6	0.786		
Total	19,831.679	12			

[a] $R^2 = 0.994$.

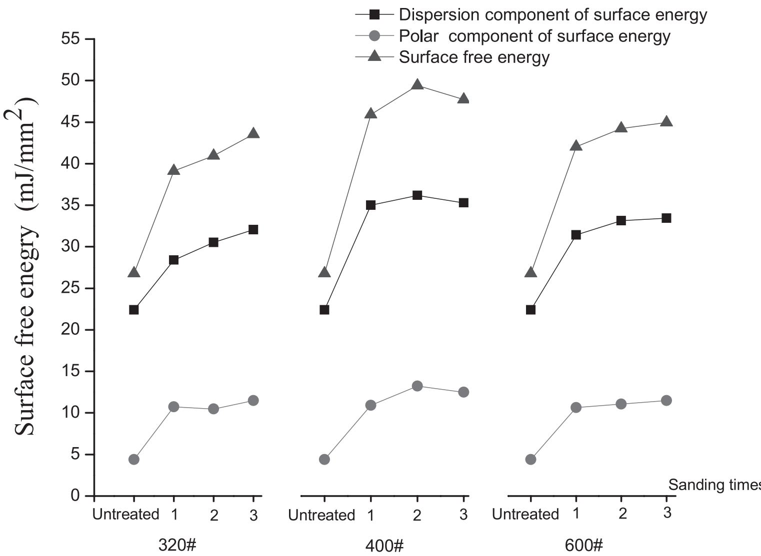

Figure 3.—Surface free energy of polypropylene planar film.

topography and the roughness of a 3D PP decorative membrane sanded with different sanding belts are shown in Figures 5a through 5d and Table 6. Before the sanding process, the 3D PP decorative membrane had a relatively smooth surface with a surface roughness of 2.318 μm only; after it was sanded with 240- to 320-grit sanding belts, the surface roughness was increased to different levels. When a 320-grit sanding belt was used, the surface roughness was increased to 4.618 μm with an increase ratio of 99.22 percent because the membrane was soft with a low density and there were strong bending and centripetal forces on sand grains on the supporting material of the sanding belt to press the exposed sanding grains into the membrane so as to form a strong friction with the surface of the test piece and increase the surface roughness. When a 400-grit sanding belt was used, the surface roughness of 3D PP decorative membrane decreased to 3.196 μm with a decrease ratio of 30.79 percent compared with that after sanding with a 320-grit sanding belt because the sanding belt was finer, the grinding force imposed by the sanding belt on the membrane was smaller, the sanding capacity was smaller, and the surface roughness was noticeably decreased. This conclusion was basically consistent with that of the surface contact angle on 3D PP decorative membranes.

The surface microtopography and the roughness of 2D PP decorative membranes sanded with different sanding belts are shown in Figures 6a through 6d and Table 7. The unsanded surface of 2D PP decorative membranes was relatively smooth with local round and continuous tissues and a surface roughness of only 1.698 μm. When sanded in two passes with a 320- to 400-grit sanding belt, the surface roughness increased with the meshes; it was observed under a scanning electron microscope that the 2D PP decorative membrane was uneven with local flocculent and reticular structures. When a 400-grit sanding belt was used, the surface roughness of the membrane increased to 3.061 μm

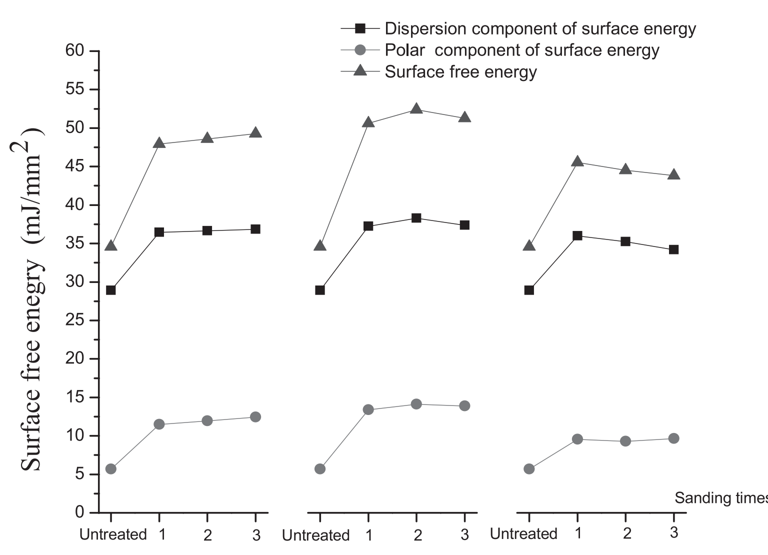

Figure 4.—Surface free energy of polypropylene stereo film.

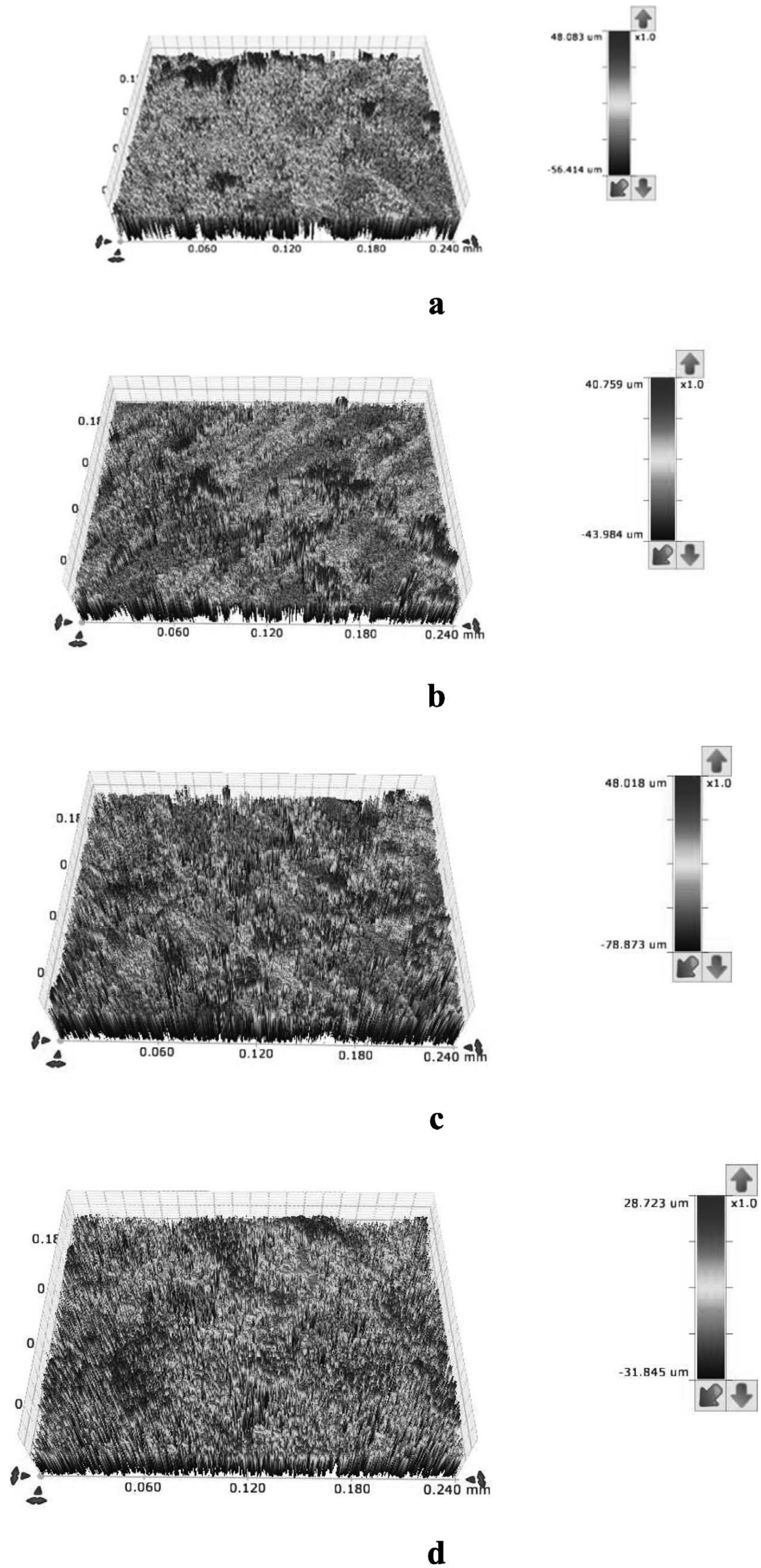

Figure 5.—Stereo shape of polypropylene stereo surface film under different sanding numbers: (a) unsanded, (b) 240-grit sanding belt, (c) 320-grit sanding belt, and (d) 400-grit sanding belt.

Table 5.—Variance analyses of the surface free energy of polypropylene stereo film.[a]

Source of variance	Sum of squared deviations	df	Mean square	F	Significance
Belt mesh no.	70.089	2	35.045	58.468	0.000
Sanding times	0.377	2	0.189	0.315	0.741
Error	3.596	6	0.599		
Total	24,577.154	12			

[a] $R^2 = 0.993$.

Table 6.—Surface roughness values of polypropylene stereo film under different belt diameters.

Belt grit	Roughness (μm)
Untreated	2.318
240	3.933
320	4.618
400	3.196

with an increase ratio of about 80.27 percent, but when a 600-grit sanding belt was used, the surface roughness increased to 2.698 μm with an increase ratio of only 58.89 percent. The meshes of the sanding belt used for the membrane were higher and the sanding grain size was finer than those used for 3D PP decorative membrane, and after the sanding process, the surface roughness of the membrane was slightly lower than that of the 3D PP decorative membrane.

Effect of the sanding process on waterborne paint films and adhesion

As shown in Figure 7, the sanding process could improve the adhesion of waterborne paint film on PP decorative membranes significantly. The adhesion of the paint film on unsanded 2D PP decorative membranes was relatively poor and was about Grades 4 to 5 under the experimental conditions, with peeling of large blocks of paint film on the unsanded surface. When a 2D PP decorative membrane was sanded with a 320-grit sanding belt, the adhesion of paint film increased to Grade 3, but there was peeling of local paint film, which could meet the requirements for actual production. When a 2D PP decorative membrane was sanded with a 400-grit sanding belt, the adhesion of waterborne paint film increased mostly to Grade 2, and there was no obvious peeling, which could meet the requirements for actual production. And when a 600-grit sanding belt was used, the adhesion of waterborne paint film on 2D PP decorative membranes decreased to Grade 3 again. This conclusion was consistent with the previously mentioned conclusions that after the sanding process for PP

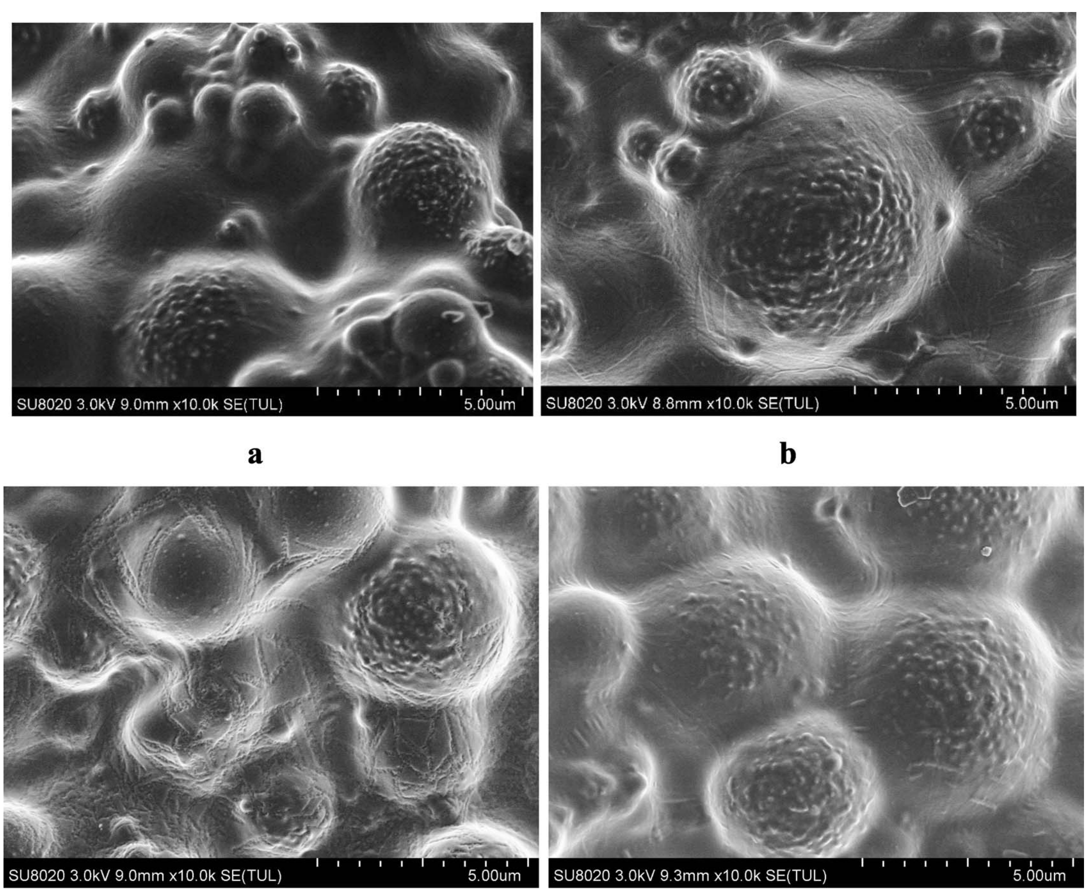

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Figure 6.—Scanning electron micrograph of the surface of polypropylene planar surface mask under different sanding orders: (a) unsanded, (b) 320-grit sanding belt, (c) 400-grit sanding belt, and (d) 600-grit sanding belt.

Table 7.—Surface roughness values of polypropylene planar films under different belt sizes.

Belt grit	Roughness (μm)
Untreated	1.698
320	2.698
400	3.061
600	2.352

decorative membranes, the surface contact angle was decreased, the surface roughness was increased, and the surface wettability was increased, all of which would benefit the mechanical bonding of waterborne paint film on PP decorative membranes.

As shown in Figure 8, the sanding process could improve the adhesion of waterborne paint film on 3D PP decorative membranes significantly. The adhesion of unsanded 3D PP decorative membranes was relatively poor and was about Grade 4 only, and there was serious peeling of the paint film. When a 3D PP decorative membrane was sanded with a 240-grit sanding belt, the adhesion of the paint film noticeably increased to about Grade 2, and there was a small amount of peeling of the paint film, which could meet the requirements for actual production. When a 3D PP decorative membrane was sanded with a 320-grit sanding belt, the adhesion of the waterborne paint film increased mostly to Grade 1, and there was no peeling. Therefore, after a 3D PP decorative membrane was sanded and applied with waterborne paint, the adhesion of the waterborne paint film could be noticeably increased to meet the requirements for actual production because after the sanding process, the contact angle would be decreased and the surface roughness would be increased so as to improve the adhesion of the waterborne paint film on PP decorative membranes. With a 400-grit sanding belt, the adhesion of waterborne paint film on 3D PP decorative membranes would be about Grade 3 only.

Conclusions

First, the sanding process could noticeably improve the surface wettability of 2D and 3D PP decorative membranes

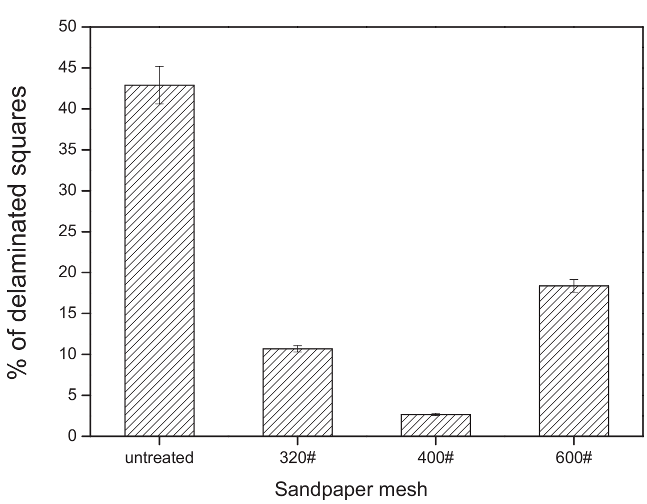

Figure 7.—Painting film adhesion on the surface of polypropylene stereo membrane by sanding.

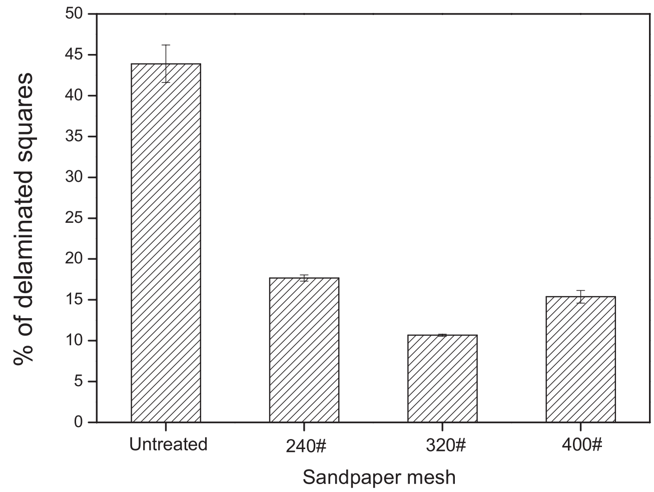

Figure 8.—Painting film adhesion on the surface of polypropylene planar membrane by sanding.

and decrease the surface contact angle effectively. After the optimized sanding process, the contact angle could be decreased by 31.46 percent for water and 53.85 percent for di-iodomethane on 2D PP decorative membranes as well as 28.40 and 55.77 percent on 3D PP decorative membranes; the surface free energy could be increased by 31.35 and 35.76 percent on 2D and 3D PP decorative membranes, respectively; and, finally, the surface roughness could be increased by 80.27 and 99.22 percent on 2D and 3D PP decorative membranes, respectively.

Second, the optimized surface sanding process parameters were using a 320-grit sanding belt and two sanding passes for 2D PP decorative membranes and a 400-grit sanding belt and two sanding passes for 3D PP decorative membranes. Under these conditions, the surface roughness of 2D and 3D PP decorative membranes was noticeably increased, followed by a decrease in the contact angle and then an increase in the surface free energy.

Finally, the sanding process could increase the adhesion of waterborne paint film on PP decorative membranes. The adhesion of waterborne paint film could be increased from Grades 4 to 5 to Grade 2 on 2D PP decorative membranes and from Grade 4 to Grade 1 on 3D PP decorative membranes. This study could provide the technical support for the industrial application of PP decorative membranes as decorative accessories of wood products.

Acknowledgments

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