Application Parameters of Water Transfer Printing on Wood-based Panel Surfaces

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Optimum application values of the Water Transfer Printing (WTP) technique were determined on various wood-based panel surfaces. For this purpose, 8-mm-thick, glossy white, acrylic-coated medium-density fiberboard (MDF) panels (high gloss panels), polyvinyl chloride (PVC)-coated MDF panels, MDF Lam ready-to-use panels, and cellulosic, polyurethane, acrylic, and water-based paint applied MDF panels were used. An automatic immersion system with pool was designed and produced. A 30-µm-thick carbon patterned WTP film was applied on sample panel surfaces prepared with the help of this device at four immersion angles (0º, 15º, 30º, and 45º), four immersion speeds (50 cm/min, 100 cm/min, 150 cm/min, and 200 cm/min), and four immersion times (5 to 10 s, 20 to 30 s, 50 to 60 s, and 80 to 90 s). The optimum parameters of the WTP technique regarding the temperature and relative humidity of the application environment, water temperature, laying method, dissolution time, amount of activator, spray gun angle and tip clearance, air pressure, as well as immersion angle, speed, and time were determined using the measurement and observation method. According to the optimum parameters obtained in the study, the WTP technique was successfully applied to all wood-based panel surfaces.

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INTRODUCTION

Wood materials have an important place in human life. Wood has a wide range of uses. Today, innovations in the wood industry in parallel with developments in economic, cultural, and social life, along with population growth are increasing the consumption of wood-based materials (Altınok 1995). Despite the fact that the extent of world forests remains the same and is even decreasing, the rapid increase in the population and the consumption of forest products per capita necessitates better utilization of forests (Özen and Kalaycıoğlu 1980). In addition, because solid wood material has become less available in Turkey, its price has risen and there are still some problems encountered during the usage of solid wood; thus there is a need to use wood-based panel products instead of solid wood material (Akkılınç 1998; Güller 2001). Especially with the discovery of synthetic adhesives and their use in production, there is a tendency to utilize forest residues, some plant stems and fibers, and to obtain wood-based panels that have wood-like characteristics but do not perform exactly like the original wood materials. As a result, wood-based panels, such as particleboard, medium-density fiberboard (MDF), and oriented strand board (OSB), are produced (Güller 2001; Kılıç 2006; Budakçı 2008).

However, in general, uncoated wood-based panels do not make sense in the furniture and decoration industry as a single product, and they are not suitable for quality furniture production. For wood-based panels to be used in furniture production and as interior fittings, panel surfaces and edges should be covered with various coatings or painted (Budakçı 2010). Liquid (varnish/paint) or solid surface coatings (wood, laminate, PVC, melamine resin-impregnated papers, *etc.*) are preferred for coating the panels used in the production of decoration elements, such as furniture, paneling, and ceiling coverings, in the woodworking industry. These materials applied to the panel surfaces improve the physical and mechanical properties of the panels, provide a decorative appearance, increase the aesthetic value of the product, give the natural appearance and warmth of the wood material, provide color and pattern unity on the panel surfaces, and prevent the release of formaldehyde, which is a volatile organic compound (VOC). Such coverings are used for many reasons such as prevention. Today, when these coating materials are insufficient, different printing techniques, water transfer printing (WTP), screen printing, ultraviolet (UV) pattern printing, *etc.*, are used to increase the variety in the product range.

In recent years, it is seen that the WTP technique has been used to camouflage the upper surfaces of weapons and related war equipment used in the defense industry, in accessories such as pendulums, chests, armbands, rims, and covers in the automotive industry, and in increasing the aesthetic value of many plastic, metal, composite-based items used in interior design (Du *et al*. 2013; Panozzo *et al*. 2015; Zhang *et al*. 2015).

The film used in the WTP technique has a water-soluble poly(vinyl acetate) (PVAc)-based composition. The WTP film is formed by printing pigments in the desired pattern and color on this film structure. Water and cellulosic thinner-based activator liquid are used so that the coating film can dissolve and adhere to the 3D object. The pattern-bearing PVAc part of the WTP film is laid in a pool filled with warm water. The pattern-printed part ensures the homogeneous dissolution of both the color pigments and the carrier PVAc structure with the help of the activator. The product, which is planned to be printed on the dissolving WTP film, is immersed in water smoothly and then removed from the water, and the coating process of the surfaces of the materials is completed (Kalyon Garage 2020; Liquidprintone 2022; Teknik 2022).

No protective coating is required on plastic material surfaces before WTP technique. However, the application of WTP on metal or wood material surfaces requires painting. There are disturbing amounts of roughness and protrusions on the upper surfaces of newly processed wood or metal panels on the machine bench. These panel surfaces must be sanded, a primer coat applied, and a top coat painted. Thus, WTP coating can be applied perfectly on a smooth surface. Otherwise, when WTP coating is applied to unpolished panels, faulty surfaces are encountered (Bilgiustam 2022). Le Borgne *et al.* (2019) argue that hidden circuits can be produced in three-dimensional electronic circuits using current-conducting paints in the printing film used in the WTP technique. In this coating method, an expensive facility is not needed and the coating process is easy to apply, which indicates that such a method has not been used before on complex 3D surfaces. Sun *et al*. (2019) report that they have succeeded in producing solar cells on the glass layer using the WTP technique and they have obtained suitable efficiency from these cells. Zhang *et al*. (2016) state that applying the WTP technique on copper material has advantages such as simple equipment, operation at room temperature, and low electricity consumption. In addition to its many features and advantages, because the WTP application is a low-cost method for the sector is another prominent factor (Du *et al.* 2013; Zhang *et al.* 2015).

No study has yet investigated the coating of solid wood material or wood-based panels (plywood, fiberboard, particleboard, *etc*.) used in the furniture industry using the WTP technique. Thus, this study aimed to calculate the optimum application values such as immersion angle, immersion speed, immersion time, *etc*., which should be considered in the coating of various wood-based panel surfaces using the WTP technique. For this purpose, 8-mm-thick, glossy white, acrylic-coated MDF panels, MDF panels (high gloss panel), PVC-coated MDF panels, MDF Lam ready-to-use panels, and cellulosic, polyurethane, acrylic, and water-based paint applied MDF panels were used. An automatic immersion system with pool was designed and produced with the support of the Scientific and Technological Research Council of Türkiye (TUBITAK) - 221O551 project. A 30-μm-thick carbon patterned WTP film was applied on sample panel surfaces prepared with the help of this device at four different immersion angles (0º, 15º, 30º, and 45º), four different immersion speeds (50, 100, 150, and 200 cm/min), and four different immersion times (5 to 10 s, 20 to 30 s, 50 to 60 s, and 80 to 90 s). In the study, the temperature, relative humidity of the application environment and the temperature, laying method, dissolution time, amount of activator, spray angle, pressure, *etc*., of the materials used in the WTP technique were investigated. Optimum parameters related to the values were attempted to be determined by means of measurements and observations. The optimum parameters of the temperature and relative humidity of the application environment and the temperature, laying method, dissolution time, amount of activator, spray angle, pressure *etc*., of the materials used in the WTP technique were determined.

EXPERIMENTAL

Materials

In the study, first class and 8-mm-thick, glossy white color, acrylic-coated MDF panels (high gloss panel), PVC-coated MDF panels, MDF Lam panels, and raw MDF panels were selected to apply the WTP technique. All the samples had the dimensions of 520 × 310 mm^2 and were kept in an air-conditioning cabinet at 23 ± 2 °C and 50 ± 3% relative humidity, according to the principles specified in TS EN 322 (1999), until they reached a constant weight and until the moisture content was to 10%. (Fig. 1a).

(a) (b)

Fig. 1. (a) Air conditioning of the samples, **(b)** Lacquer paint application on raw MDF surfaces

Bright white cellulosic, polyurethane, acrylic, and water-based lacquer paint was applied to the raw MDF panel surfaces in accordance with ASTM D3023 (1998) principles before WTP technique (Fig. 1b).

In lacquer application, cellulosic primer (312-1029; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), cellulosic topcoat (311-1033; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), two-component polyurethane primer (602-1420; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), two-component polyurethane topcoat (601-1691; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), two-component acrylic primer (702-1035; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), two-component acrylic topcoat (701-1400; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye), one-component water-based primer (A32-1000), and two-component water-based topcoat (A25-1518; Durmus Yasar ve Ogullari /DYO, İzmir, Türkiye) were selected (DYO 2022). Solid matter ratios and the manufacturer's recommendations were taken into account in determining the amount of paint to be applied to the panel surfaces. Information on some application and technical properties of the paints used in the study are given in Table 1.

Table 1. Some Application and Technical Properties of the Paints Used in the Experiments

Paint Type	Solid Content (%)	Density (g/mL)	Application Viscosity (sn/DIN Cup 4 mm/20 °C)	Amount of Paint to be Applied (g/m²)	Spray Gun Tip Clearance (mm)	Air Pressure (bar)
Acrylic Primer	62	1.35	20-21	150	1.8	2-3
Acrylic Topcoat	58	1.22	19-20	150	1.8	2-3
Cellulosic Primer	56	1.20	19-20	150	1.8	3-4
Cellulosic Topcoat	38	1.24	19-20	150	1.8	3-4
Water Based Primer	48	1.22	19-20	150	1.8	2-3
Water Based Topcoat	50	1.15	18-19	150	1.8	2-3
Polyurethane Primer	75	1.50	21-22	150	1.8	2-3
Polyurethane Topcoat	66	1.32	20-21	150	1.8	2-3

Two coats of primer and two coats of topcoat paint were applied to the sample panels. The amount of paint was 150 g/m^2 per coat. The amount was determined using an analytical balance with a sensitivity of 0.01 g. After the primer paint application, the samples were kept at room temperature for 24 h, and then they were sanded to achieve a smooth surface with 220-grit sandpaper. After the dust was cleaned, the topcoat paint was applied. Air pressure and spray gun tip clearance were adjusted according to the manufacturer’s recommendations, and the spray gun was moved 20 to 25 cm above the sample surface parallel to the surface at the same speed. This prevented the formation of faulty layers and the application of different amounts of lacquer paint (Budakçı 2003).

After the lacquer painting process was completed, the samples were kept in an air-conditioning cabinet at 23 ± 2 °C and 50 ± 3% relative humidity according to the principles specified in TS EN 322 (1999) until they reached a constant weight, and the moisture content was reduced to 9 to 10% again after painting (Fig. 2).

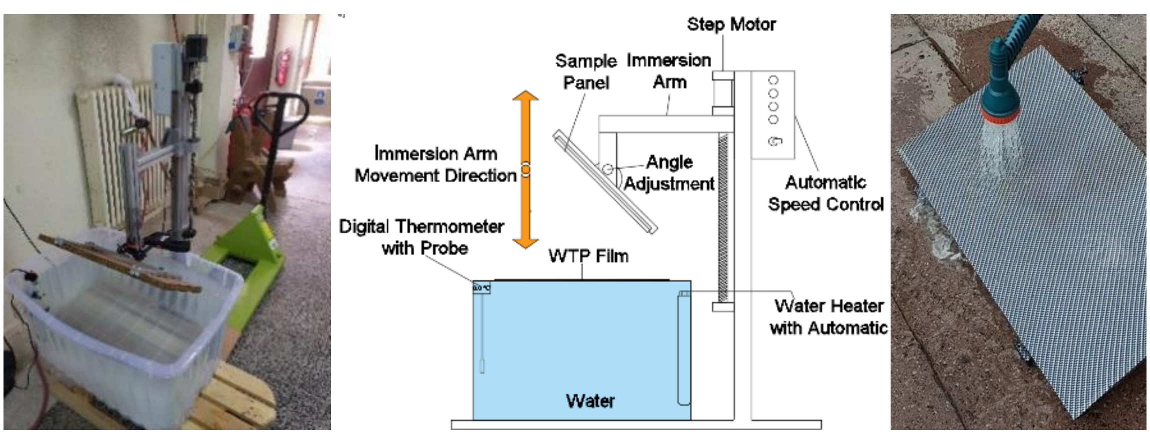
(a) (b)

Fig. 2. (a) Drying of the samples whose lacquer painting process is completed at room conditions, **(b)** Reconditioning of samples

Methods

WTP application

In the WTP application, the automatic immersion system with pool designed and produced with the support of TUBITAK - 221O551 project was used (Fig. 3.a.b). After the air conditioning of the surfaces of the sample panels was completed with this device, a 30-μm-thick, 40 × 60 cm^2 water-soluble PVAc -based carbon patterned WTP film was applied on sample panel surfaces at four different immersion angles (0º, 15º, 30º, and 45º), four different immersion speeds (50, 100, 150, and 200 cm/min), and four different immersion times (5 to 10 s, 20 to 30 s, 50 to 60 s, and 80 to 90 s).



(a) (b) (c)

Fig. 3. (a) Automatic immersion system with pool, **(b)** Working principle, **(c)** Panel surface washing

In addition, the temperature of the environment (12 ± 1 °C, 20 ± 1 °C, and 27 ± 1 °C), relative humidity (45 ± 3%, 50 ± 3%, and 55 ± 3%), and different parameters, such as the temperature of the materials used in the WTP technique (20 ± 0.5 °C, 25 ± 0.5 °C, and 29 ± 0.5 °C), laying method, dissolution time (30 to 40 s, 70 to 80 s, and 110 to 120 s), amount of activator (2 mL, 4 mL, and 6 mL), as well as spray angle (75º, 90º, and 105º) and pressure (1.5 bar, 1.75 bar, and 2.5 bar) were also tried.

Following the WTP technique on the sample panel surfaces, the remaining gel layer was washed away with water without waiting. During washing, water at a temperature of 24 ± 2 °C was used. A pressure regulated water spray was used for the washing process. The pressure state of the water is set in the *“shower mode”* (slow flow and wide range) (Fig. 3.c). Washing took 6 to 7 min for the gel layer to separate from the panel surface. After washing, the panels were left to dry at room conditions (Li *et al*. 2022).

RESULTS AND DISCUSSION

The parameters related to the WTP technique applied to the sample panel surfaces were investigated under three main headings as ambient conditions, materials used, and factors related to the application.

Ambient Conditions

Temperature

Experiments were conducted at three different ambient temperatures (12 ± 1 °C, 20 ± 1 °C, and 27 ± 1 °C) to reveal the effect of ambient temperature on WTP film application (Fig. 4a and 4b).

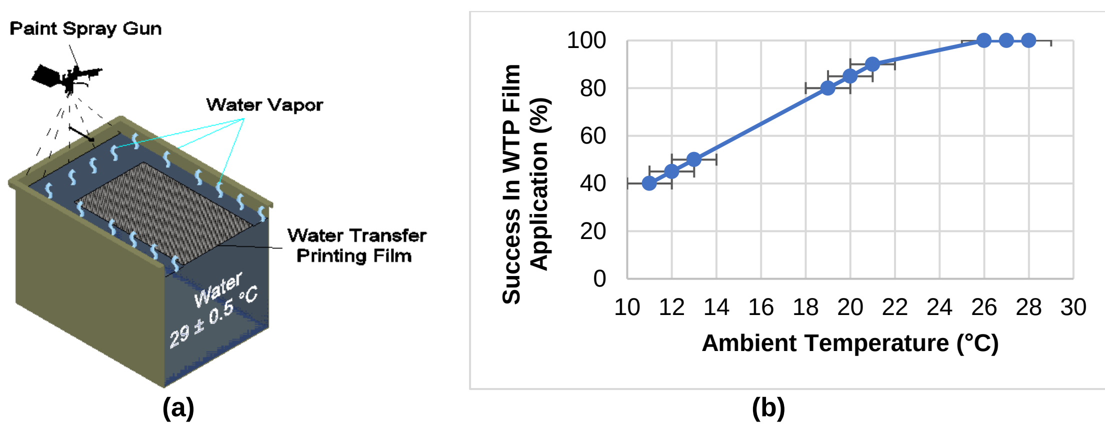


Fig. 4. (a) The pool where the WTP film will be laid and the formation of water vapor, **(b)** WTP film application and the ambient temperature relationship

According to Fig. 4.a, when the ambient temperature was decreased, water vapor formation increased on the water (29 ± 0.5 °C) in the pool where the WTP film will be laid. It was observed that when the ambient temperature was 27 ± 1 °C, the activator liquid effectively dissolved the WTP film (100%), and no water vapor was formed in the environment (Fig. 4.b). It was concluded that it is unnecessary to keep the ambient temperature above 28 °C. The activator liquid that is used to dissolve the WTP film at ambient temperatures of 12 °C and below did not dissolve the coating film properly by interacting with the dense water vapor formed in the application pool. The water vapor prevented the activator liquid from reaching the surface of the coating film. Therefore, erroneous results were obtained in the coating process of the samples.

Relative humidity

To reveal the effect of the relative humidity in the environment on the application of the WTP film, the ambient temperature was kept constant at 27 ± 1 °C in line with the data obtained, and experiments were conducted at three different relative humidity values (45 ± 3%, 50 ± 3%, 55 ± 3%) (Fig. 5).

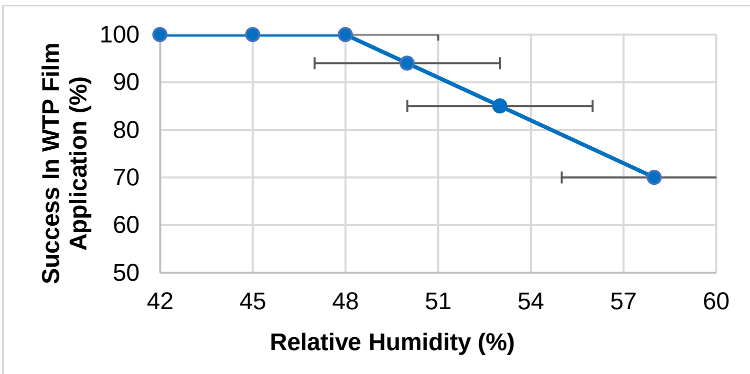
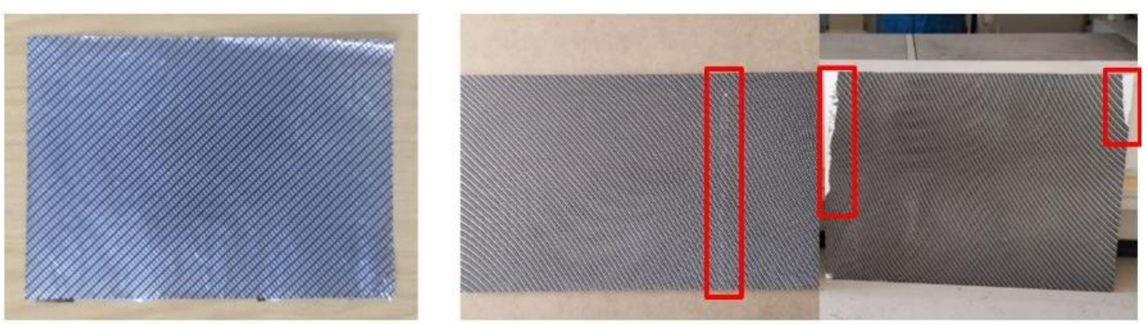


Fig. 5. Relationship between WTP film application and relative humidity

Figure 5 shows that the WTP film application was flawlessly completed (100%) when the relative humidity in the workshop was 45 ± 3%. When the relative humidity was 50% and above, the cut WTP film lost its smoothness by changing its shape with the effect of the increasing moisture (Fig. 6a). When the wrinkled film was straightened and the water was laid on the surface, it was observed that air bubbles formed between the film layer and the water surface, and the edges folded. Thus, a defective coating process had taken place (Fig. 6b).



(a) (b)

Fig. 6. (a) The moist WTP film; **(b)** Defects on the sample panel as a result of the coating application with the moist film

Factors Related to the Materials Used

Water temperature

To determine the water temperature in the immersion pool used in the application of the WTP film, experiments were carried out at three different water temperature values (20 ± 0.5 °C, 25 ± 0.5 °C, and 29 ± 0.5 °C) (Fig. 7).

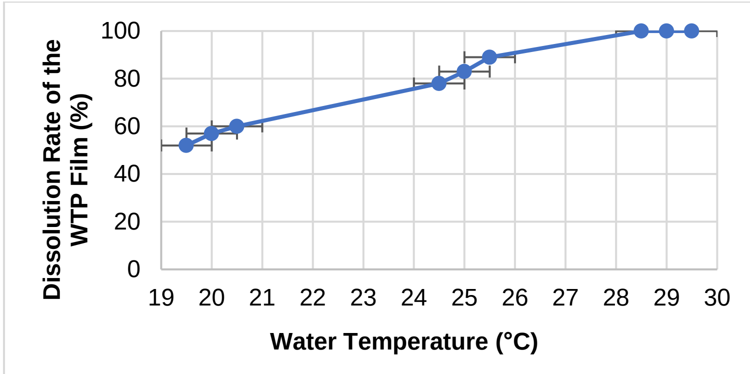


Fig. 7. Effect of water temperature on dissolution rate of the WTP film

According to Fig. 7, when the water temperature in the pool was 29 ± 0.5 °C, the PVAc structure of the WTP film dissolved completely and a smooth coating process was achieved. It was observed that the WTP film did not dissolve completely on the water surface at values below this temperature. It was also found that there was no need to increase the water temperature more than 29 °C as it leads to unnecessary energy consumption. Similar studies in the literature reported that the water temperature was kept at 30 to 35 ℃ (Du *et al.* 2013; Water Transfer Printing 2022). One study revealed that the water transfer process was better when the water temperature was between 30 and 40 ℃ (Wang *et al.* 2022).

Laying method

It was observed that during the free laying of the WTP film on the water surface in the pool, the upper surface of the film melted in the opposite direction as a result of water splash and collapsed into the water. Because the coating film was not laid on the water surface smoothly, at an equal time and speed, there was an air gap between the coating film and the water (Fig. 8a). This problem was solved by using a 5-cm diameter cylindrical plastic auxiliary apparatus and applying it to the water surface at a constant speed of 100 cm/min (Fig. 8b).

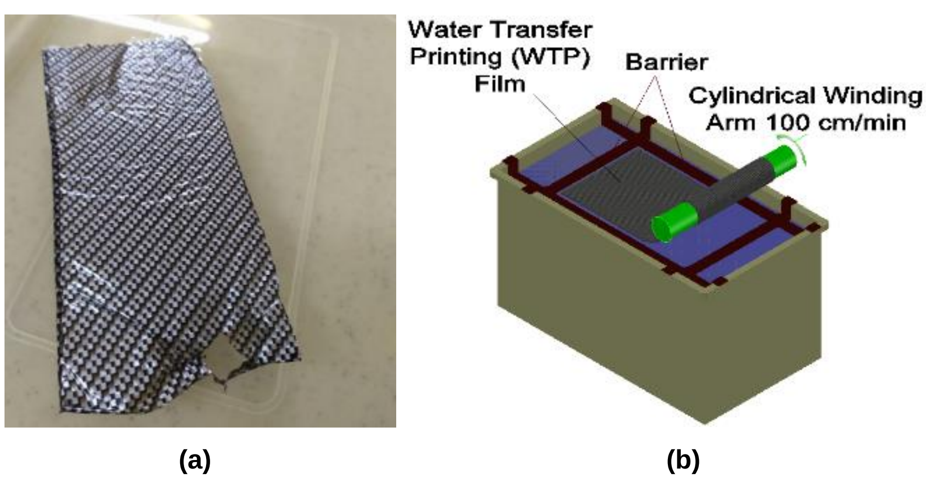
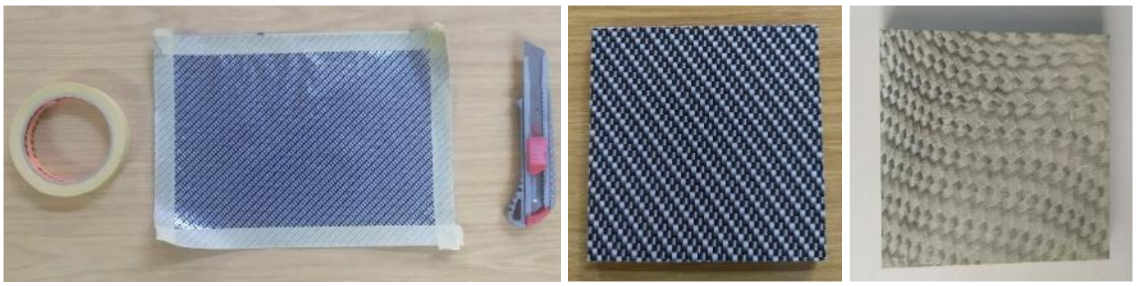


Fig. 8. (a) WTP film freely laid on the water surface; **(b)** Laying the WTP film on the water surface with the help of a cylindrical apparatus

In addition, before laying the film on the water surface, the edges of the WTP film prepared in the desired size were taped with 1-cm-wide paper tape (edge barrier) (Fig. 9a) and a side barrier was added to the pool surface (Fig. 8b) in activator application with a spray gun. This process prevented the disintegration of the coating pattern (Fig. 9b). Le Borgne *et al*. (2019) reported that the coating film on the water surface expands in the x and y axis and dissolves when the WTP process is performed on three-dimensional surfaces, and thus, a barrier should be used so that the WTP film on the water surface does not expand too much. If this is not done, shifts and distortions occur in the coating pattern as the film moves freely in the horizontal and vertical axis direction during the activator application (Fig. 9c).



(a) **(b)** **(c)**

Fig. 9. (a) WTP film edge tape application, **(b)** A sample WTP with edge barrier applied, **(c)** A sample faulty WTP with no edge barrier applied

Dissolution time

Measurements were taken at three different time intervals (30 to 40 s, 70 to 80 s, and 110 to 120 s) to reveal the effect of the dissolution time of the WTP film laid on the water surface in the immersion pool on the rate of dissolution (Fig. 10).

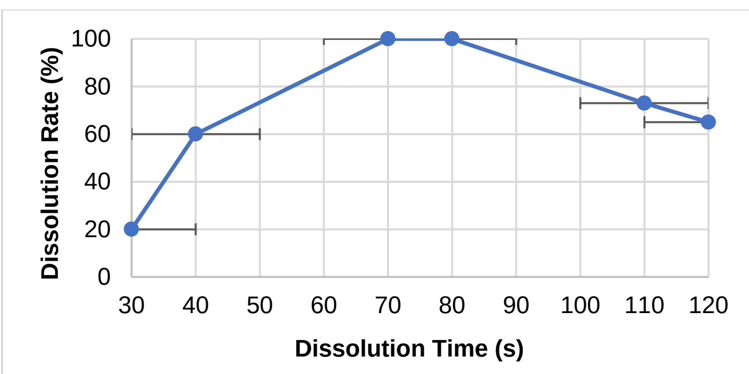
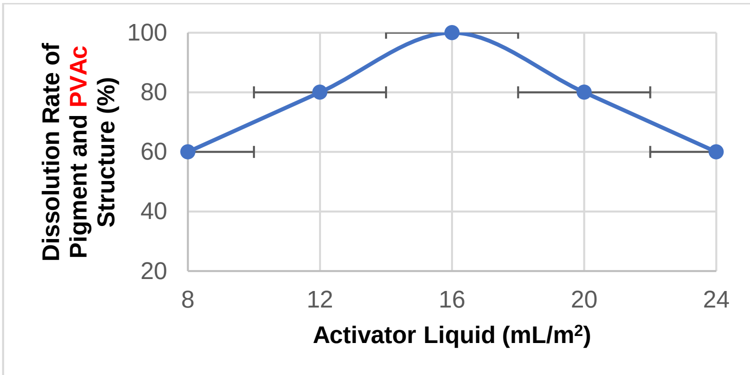


Fig. 10. Effect of dissolution time of the WTP film on dissolution rate

Figure 10 shows that the WTP film interacted with the prepared water and dissolved 100% in 70 to 80 s. It was observed that the coating film, which was kept in water for a shorter period of time, could not interact with the water sufficiently, and thus, the PVAc structure could not dissolve on the water surface. In contrast, when the coating film was kept on the water surface for longer than necessary, it dispersed and ruptured on the water surface.

Activator amount

Three different amounts of activator (8, 16, and 24 mL/m^2) were tested to ensure homogeneous dissolution of the PVAc structure forming the WTP film and the pigments on it (Fig. 11).



(a)

(b)

Fig. 11. (a) Effect of activator amount on the dissolution of WTP; **(b)** Excessive use of activator

As can be seen in Fig. 11, if the amount of activator was more than 16 mL, WTP film dissolved incorrectly and the pattern was transferred to the sample surfaces in a distorted manner during coating processes (Fig. 11b). It has been observed that when less activator liquid is used, the PVAc structure and pigments cannot completely dissolve, no matter how long the WTP film is kept on the water surface, and thus, they cannot adhere to the sample surfaces. Panozzo *et al*. (2015) reported that the amount of activator is critical for the success of the hydrographic coating process. If the amount is too small, the ink/pigments do not adhere to the object, and when too much activator is applied to the surface, the color scheme of the film shifts along the surface of the object. The results are in agreement with the literature.

Spray gun tip clearance and air pressure

Three different diameters of spray gun tips (1.3, 1.6, and 1.8 mm) and three air pressures (1.5, 1.75, and 2.5 bar) were tested to determine the effect of the spray gun tip clearance used in the application of the activator liquid and the air pressure on the WTP film (Fig. 12). The distance of the spray gun to the WTP film was kept at 25 cm.

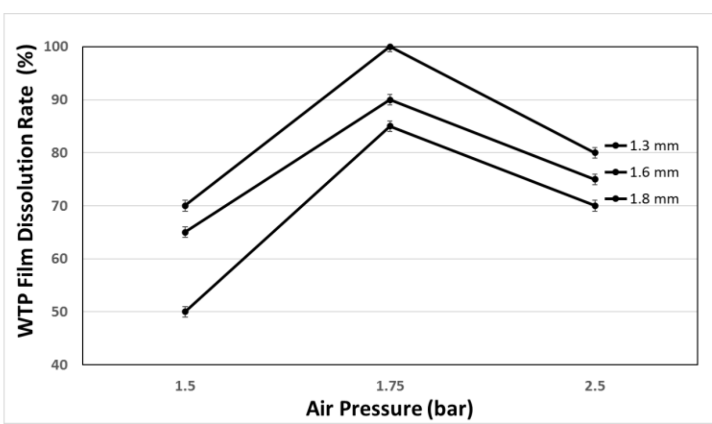
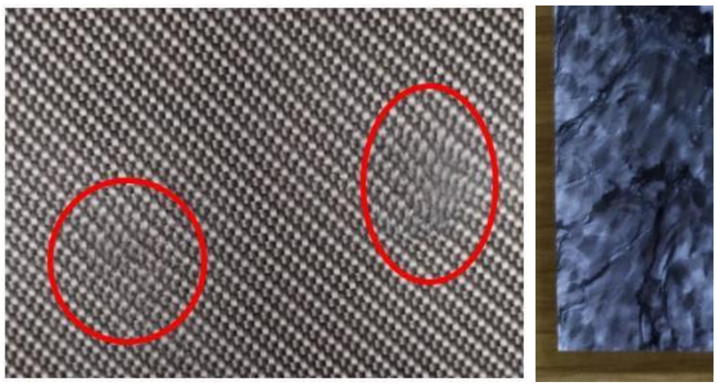


Fig. 12. The effect of air pressure and spray gun tip clearance on the dissolution of the WTP film

At all air pressure values used in the experiments (1.5, 1.75, and 2.5 bar), the WTP film was deteriorated because of spraying large amounts of activator liquid from the 1.6- and 1.8-mm diameter gun tips onto the coating surface (Fig. 13a). The best results were obtained at 1.75 bar pressure and 1.3-mm diameter gun tip clearance (Fig. 12). It has been observed that at 1.5 bar air pressure, the activator liquid cannot be sufficiently sprayed on the surface of the WTP film. In contrast, 2.5 bar air pressure causes changes in the position of the WTP film, the pattern deteriorates and folds over, and the activator liquid is used more than necessary (approximately 5 times) (Fig. 13b).

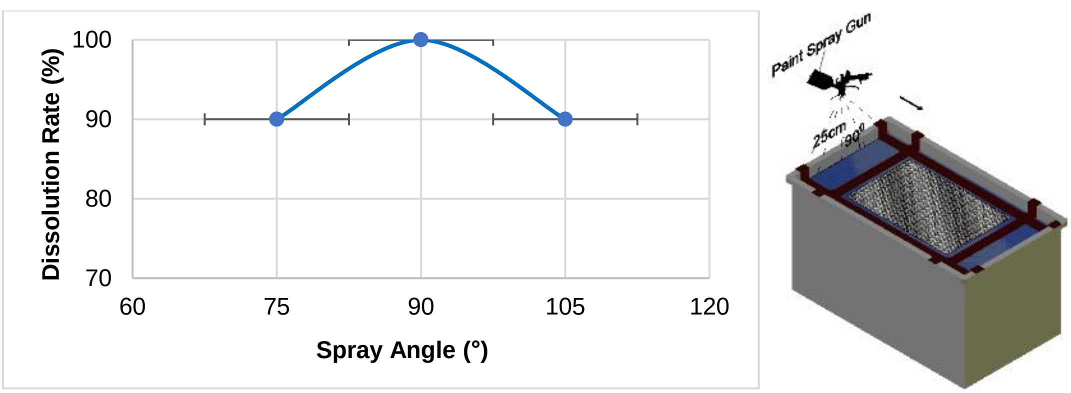


(a) (b)

Fig. 13. (a) Distortions in the WTP film; **(b)** Other faults

Spray gun angle

Depending on the ideal spray gun tip clearance (1.3 mm) and pressure (1.75 mm) values obtained in the study, experiments were carried out at three different spray angles (75º, 90º, and 105º) to reveal the effect of the activator liquid on the dissolution of the WTP film (Fig. 14a).



(a) (b)

Fig. 14. (a) Effect of spray angle on the dissolution rate of the WTP film; **(b)** 90º spray application

The study revealed that the PVAc structure and color pigments that made up the WTP film dissolved 100% when the activator liquid was applied at a 90º spray angle (Fig. 14.b). When sprayed at 75º and 105º, the application could not be continued because there was insufficient dissolution. In the trials during the application, the coating film could not be completely dissolved when the right-angle value changed during spraying. However, when the coating application continued on the panel, faulty surfaces were encountered. As a result, the coating film and wood-based panel were wasted.

During the application of the activator liquid with a spray gun, the authors ensured there were no water and oil residues in the air coming from the compressor. Otherwise, defective WTP surfaces were encountered again (Fig. 15).

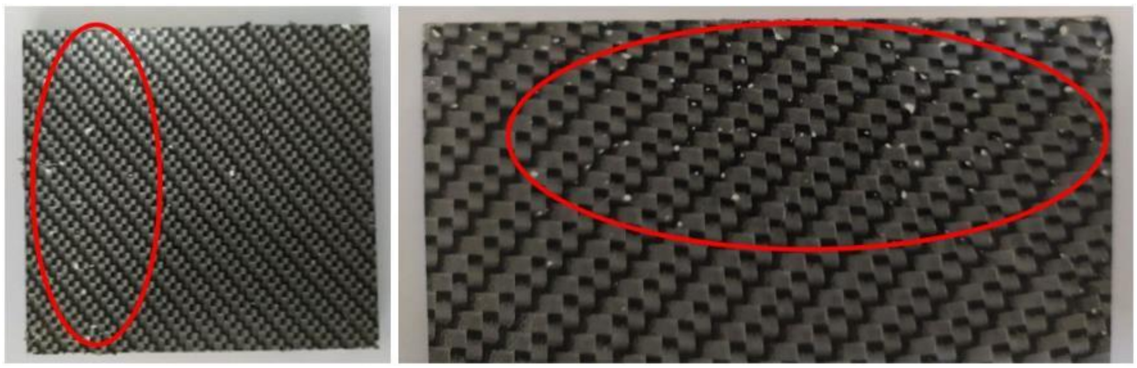


Fig. 15. Examples of faulty coatings that occurred due to water and oil residues in the spray air

Factors Related to the Application

Immersion angle

To determine the effect of the immersion angle on the WTP film application, experiments were conducted at four different angles (0º, 15º, 30º, and 45º).

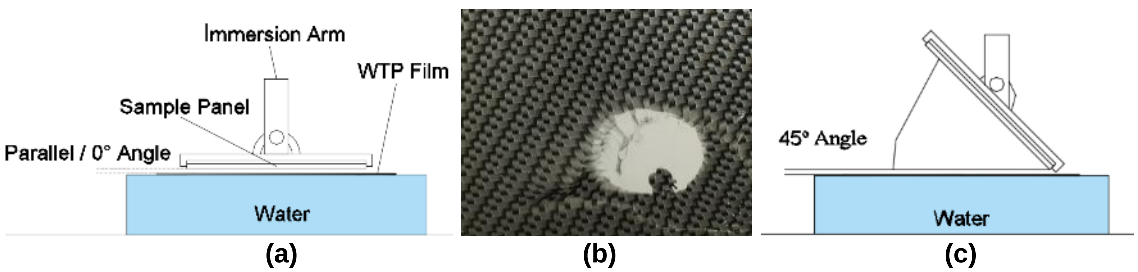
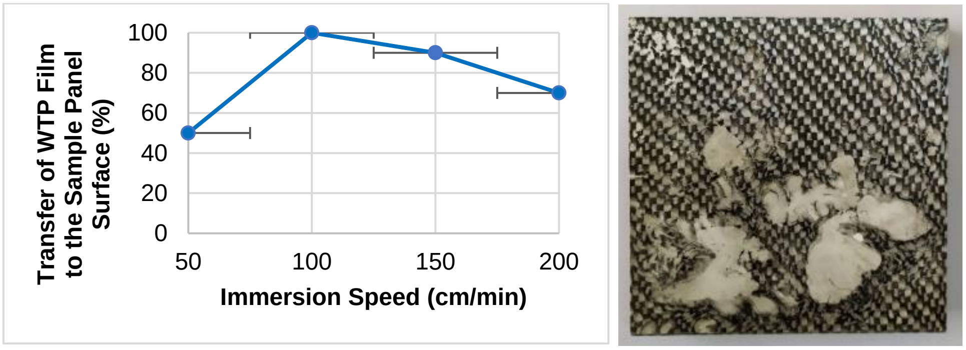


Fig. 16. (a) WTP film application with 0º immersion angle; **(b)** Incorrectly coated sample panel; **(c)** WTP film application with 45º immersion angle

When the samples were immersed on the water surface where the WTP film was laid at an angle of 0º as in Fig. 16a, air bubbles emerged between the coating film and the sample surfaces, and a faulty WTP process was observed (Fig. 16b). As a result of increasing the immersion angle by 15° levels, the smoothest WTP process was obtained at an immersion angle of 45° (Fig. 16c). Knoll *et al*. (2019) emphasized that the contact angle of the material immersed on the coating film on the surface of the water should be considered during the immersion of the material on the film layer. Panozzo *et al*. (2015) reported that the dissolving film layer was torn uncontrollably in places where the immersion angle of the object to be coated on the PVAc film surface was higher than 45°. The authors’ findings are compatible with the literature.

Immersion speed

To determine the effect of immersion speed on the WTP film application, experiments were conducted at four different immersion speeds (50 cm/min, 100 cm/min, 150 cm/min, and 200 cm/min) (Fig. 17a).



(a) (b)

Fig. 17. (a) The effect of immersion speed on the transfer to the sample surface; **(b)** WTP sample surface at an immersion speed of 150 cm/min

The study revealed that the samples were coated perfectly (100%) at an immersion speed of 100 cm/min. It was observed that when the immersion speed was set to 50 cm/min, the WTP film dissolved on the surface of the water could not adhere to the entire sample surface and too much deterioration occurred in the coating pattern (Fig. 17a). It was further observed that when the immersion speed was set to 150 cm/min, the water in the pool was shaken and dispersed the WTP film (Fig. 17b). At 200 cm/min immersion speed, the water in the pool splashed and scattered around.

Immersion time

Experiments were conducted at four different immersion times (5 to 10 s, 20 to 30 s, 50 to 60 s, and 80 to 90 s) to reveal the effect of immersion time on WTP film application (Fig. 18).

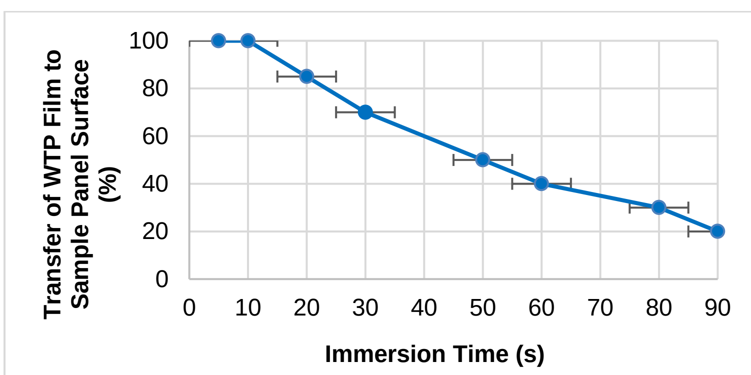


Fig. 18. Effect of immersion time on WTP film application

Figure 18 shows that the WTP film adhered 100% in 5 to 10 s, and as the immersion time was increased, the dissolved WTP film structure deteriorated and dispersed, precipitates into the water, and the adhesion decreased.

CONCLUSIONS

1. The study determined the optimum application parameters of the water transfer printing (WTP) technique on different wood-based panel surfaces. The ideal ambient temperature was 27 ± 1 °C; the ideal relative humidity was 45 ± 3%, and the ideal water temperature in the immersion pool was 29 ± 0.5 °C.
2. The measurements revealed that the WTP film should be laid on the water surface in the pool using an auxiliary apparatus at a constant speed of 100 cm/min, and the edges of the WTP film should be taped (edge barrier) with a 1-cm-wide paper tape.
3. Optimum values were obtained with WTP film dissolution time of 70 to 80 s, activator liquid amount of 16 mL/m^2, and 90º spray angle in the spray gun used for activator lquid application. In addition, 1.75 bar pressure and 1.3-mm diameter spray gun tip clearance were necessary to reach optimum values.
4. In the stage of coating wood-based panels with the dissolved WTP film, it was determined that the immersion angle should be 45º, the immersion speed should be 100 cm/min, and the immersion time should be 5 to 10 s.
5. According to the optimum parameters obtained in the study, the WTP technique was successfully applied to all wood-based panel surfaces.
6. Experts and researchers working in the sector may be recommended to examine the feasibility of the WTP application on raw wood-based panels and solid wood materials.
7. The biggest potential advantage of WTP coating for wood-based panel manufacturers is that such an application is not currently used in the furniture industry. This means that there is potential to attract new customers and high profits. WTP coating application, which is a new and remarkable type of coating, has been introduced to manufacturers for wood-based panel coating. This new technique in the furniture sector will likely increase interest in WTP coating technique.

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REFERENCES CITED

Akkılınç, H. (1998). *Researching the Technological Features of Particleboards Veneered with Different Surface Materials*, M.Sc. Thesis, Istanbul University, Istanbul, Türkiye.

Altınok, M. (1995). *Dimensioning of Strength Members According to Stress Analysis in Chair Design*, Ph.D. Dissertation, Gazi University, Ankara, Türkiye.

ASTM D3023 (1998). "Standard practice for determination of resistance of factory-applied coatings on wood products to stains and reagents," ASTM International, West Conshohocken, PA, USA.

Bilgiustam (2022). "What is hydrographic (immersion) printing and how it is done," (https://www.bilgiustam.com/hidrografik-daldirma-baski-nedir-ve-nasil-yapilir/), Accessed 18 Oct 2022.

Budakci, M. (2003). *Pneumatic Adhesion Test Device Design, Production and Testing in Wood Varnishes*, Ph.D. Dissertation, Gazi University, Ankara, Türkiye.

Budakçı, M. (2008). *Determination of Adhesive Resistance of Wood Veneer and Artificial Resin Plate Adhesives,* Düzce University Scientific Research Project, Bolu, Türkiye, Project No: BAP 2005.06.01.227.

Budakçı, M. (2010). "The determination of adhesion strength of wood veneer and synthetic resin panel (laminate) adhesives," *Wood Research* 55(2), 125-136.

Du, Q., Zhang, L., and Zhang, J. Y. (2013). "The application profile of water transfer printing in the product design," *Applied Mechanics and Materials* 274(1), 216-219. DOI: 10.4028/www.scientific.net/AMM.274.216

DYO Boya (2022). "Furniture paints," (https://endustriyel.dyo.com.tr/sektorler/mobilya-boyalari/tds-msds-ve-sertifikalar), Accessed 18 Oct 2022.

Güller, B. (2001). "Wood composites." *Turkish Journal of Forestry* 2(1), 135-160.

Kalyon Garage (2020). "How is the watery pattern coating applied?," (https://www.kalyongarage.com/sulu-desen-kaplama/), Accessed 18 Oct 2022.

Kılıç, I. (2006). *Determination of Coating Adhesion Resistance in Some Wood Based Boards*, M.Sc. Thesis, Gazi University, Ankara, Türkiye.

Knoll, M., Offenzeller, C., Jakoby, B., and Hilber, W. (2019). "Screen printed sensors fabricated on non-planar surfaces by water transfer print," *Microelectronic Engineering* 209, 49-52. DOI: 10.1016/j.mee.2019.03.010

Le Borgne, B., Liu, S., Morvan, X., Crand, S., Sporea, R. A., Lu, N., and Harnois, M. (2019). "Water transfer printing enhanced by water-induced pattern expansion: Toward large-area 3D electronics," *Advanced Materials Technologies* 4(4), article ID 1800600. DOI: 10.1002/admt.201800600

Li, C., Xu, G., Wang, L., Li, J., and Lu, H. (2022). "Tribological properties of graphene oxide and polyethylene glycol composites under dry friction and oil lubrication conditions," *Journal of Applied Polymer Science* 139(15), article 51935. DOI: 10.1002/app.51935

Liquidprintone (2022). "What is hydrographic water transfer printing?," (https://www.liquidprintone.com/hydrographic-water-transfer-printing/), Accessed 23 Nov 2022.

Özen, R., and Kalaycıoğlu, H. (1980). "Particleboard industry lecture notes," Faculty of Forestry Publication, Karadeniz Technical University, Trabzon, Türkiye.

Panozzo, D., Diamanti, O., Paris, S., Tarini, M., Sorkine, E., and Sorkine-Hornung, O. (2015). "Texture mapping real-world objects with hydrographics," in: *Computer Graphics Forum* 34(5), 65-75. DOI: 10.1111/cgf.12697

Sun, L., Jiang, X., and Zhou, Y. (2019). "Efficient nonfullerene organic solar cells with active layers fabricated by water transfer printing," *Journal of Energy Chemistry* 37, 220-224. DOI: 10.1016/j.jechem.2019.04.001

Teknik, R. B. (2022). "What is hydrographic printing, how is it made?," (http://teknikressamm.blogspot.com/2016/05/hidrografik-baski-nedir-nasil-yapilir-su-transfer-baski-sulu-kaplama.html), Accessed 16 Oct 2022.

TS EN 322 (1999). "Determination of moisture content of wood-based boards," Turkish Standards Institute, Ankara, Türkiye.
Wang, H., Wang, J., Chen, D., Ge, S., Liu, Y., Wang, Z., Zhang, X., Guo, Q., and Yang, J. (2022). "Robust tattoo electrode prepared by paper-assisted water transfer printing for wearable health monitoring," *IEEE Sensors Journal* 22(5), 3817-3827. DOI: 10.1109/JSEN.2022.3141457
Water Transfer Printing (2022). "What is water transfer printing?," (https://watertransferprinting.com/faq/), Accessed 17 Oct 2022.
Zhang, Y., Yin, C., Zheng, C., and Zhou, K. (2015). "Computational hydrographic printing," *ACM Transactions on Graphics (TOG)* 34(4), article 131. DOI: 10.1145/2766932
Zhang, Y., Gui, Y., Meng, F., Li, L., Gao, C., Zhu, H., and Hao, Y. (2016). "Graphene water transfer printing for 3D surface," in: *2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS)*, Shanghai, China, pp. 13-16. DOI: 10.1109/MEMSYS.2016.7421545

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