DYNAMIC ADHESIVE WETTABILITY OF WOOD

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(Received February 2000)

ABSTRACT

Adhesive wettability of wood is usually evaluated by contact angle measurement. Because of liquid penetration and spreading on the wood surface, the contact angle changes as a function of time. In this study, a wetting model was developed to describe the dynamic contact angle process in which a parameter (K) can be used to quantify the adhesive penetration and spreading during the adhesive wetting process. By applying the wetting model, the adhesive wettability of sapwood and heartwood of southern pine and Douglas-fir was studied. Liquid wettability along and across the wood grain direction was also compared. Two resin systems, polymeric diphenylmethane diisocyanate (PMDI) and phenol-formaldehyde (PF), were evaluated. It was learned from this study that the wetting model could accurately describe the dynamic adhesive wetting process on wood surfaces. Through applying this model, it is shown that PMDI resin exhibited a better wettability on wood than PF resin. The adhesive is more easily wetted along the grain direction than across the grain direction. Species and drop location have no significant effect on the spreading and penetration rate (K-value). However, the interaction term between species and resin type shows a significant effect for the K-value. PMDI exhibits a greater K-value on the Douglas-fir surface, while PF resin shows a greater K-value on the southern pine surface. Heartwood shows a lower instantaneous contact angle than sapwood. Douglas-fir has a greater instantaneous contact angle than southern pine. The effect of species on the equilibrium contact angle is strongly dependent on the location of the drop on the wood surface. The equilibrium contact angle of Douglas-fir is smaller than that of southern pine for sapwood, but is greater for heartwood.

Keywords: Wettability, adhesive, wood, penetration, spreading.

INTRODUCTION

Wetting is a term to describe what happens when a liquid comes into contact with a solid surface. To obtain proper interfacial bonding and a strong adhesive joint, good adhesive wetting, proper solidification (curing) of the adhesive, and sufficient deformability of the cured adhesive (to reduce the stresses that occur in the formation of the joint) are important (Baier et al. 1968; Zisman 1962). Adhesive wettability is the ability of the adhesive to make intimate contact with a surface. In the 1960s and 1970s, much research effort was undertaken to study the wettability of wood (Collett 1972; Gray 1962; Herczeg 1965; Chen 1970; and Hse 1972) by determining the instantaneous or equilibrium contact angles at the solid/adhesive interface. Wetting refers to

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Wood and Fiber Science, 33(1), 2001, pp. 58–68

the manifestations of molecular interaction between liquids and solids in direct contact at the interface between them (Berg 1993). For adhesive wetting, these manifestations include:

1) The formation of a contact angle at the solid and adhesive interface,
2) Spreading of the adhesive over a solid surface, and
3) Adhesive penetration into the porous solid substrate.

Manifestation 1 (contact angle formation) is related to the thermodynamics of the liquid/solid interaction. Manifestation 2 (spreading) is due to the change of energy states on the solid surface, adsorption, and wetting kinetics. Theoretical discussions on the surface dynamic behavior of polymers can be found in Liu et al. (1995). Spreading is also related to the droplet shape and solid surface structure. Manifestation 3 (penetration) is mainly related to the surface structure of the solid. No liquid penetration occurs for nonporous materials. Both spreading and penetration cause the contact angle changes as a function of time.

Wood is a lignocellulosic and porous material. Penetration of the pores by liquid is an important factor in bond formation. Adhesive wetting on a wood surface includes all of the above three manifestations. Wood is also an anisotropic material. Adhesive wetting behavior may be different along and across the wood grain direction. In addition, the differences in components and structure for sapwood and heartwood may have an effect on adhesive wettability. In most of the previous studies on the thermodynamics of the liquid/solid interaction of wood, the instantaneous or equilibrium contact angles were usually used (Nguyen and Johns 1978; Herczeg 1965) neglecting the liquid penetration and spreading process. However, adhesive penetration and spreading are also important indices to evaluate wood adhesion. For example, adhesive penetration can be directly related to mechanical interlocking mechanism in adhesion theory. Therefore, the liquid wetting process,

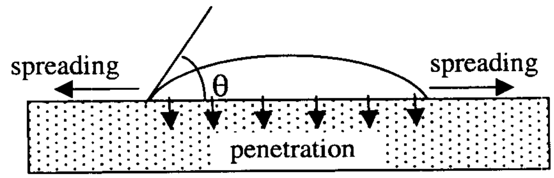

FIG. 1. Adhesive wetting on a porous material surface.

which includes all the information on the contact angle formation, spreading, and penetration, will be more meaningful in studying the adhesive wettability than comparing only the initial or equilibrium contact angles. Recently, researchers have realized the importance of measuring the contact angle change as a function of time in liquid wetting studies (Maldas and Kamdem 1998; Scheikl and Dunky 1998). However, there is no quantitative specification on the spreading and penetration ability for a liquid/solid system based on the wetting process. It will be more useful and easier for the comparison of adhesive wettability if the adhesive penetration and spreading on a solid surface can be quantified.

The objectives of this study are:

1. To develop a model to describe the adhesive wetting process in which a parameter can be used to quantify adhesive penetration and spreading;
2. By applying the model, to quantitatively evaluate the adhesive wettability of different adhesive types on different wood surfaces.

WETTING MODEL

In the liquid wetting process, the contact angle change as a function of time is a decreasing function. When a liquid drop is placed on a porous surface, in addition to forming a contact angle at the liquid/solid surface, liquid penetration together with liquid spreading also occurs (Fig. 1). At the initial stage of the wetting process, the contact angle of a liquid drop decreases quickly. As time elapses, the contact angle decreases more slowly, and finally attains relative equilibrium. For an ideal liquid and solid system, the penetration and spreading rate depends on the drop shape (contact angle) at a particular moment in time which can be expressed as:

$$\frac{d\theta}{dt} = -K\theta \quad (1)$$

in which K is the contact angle change rate constant.

As the contact angle change rate decreases because of less spreading and penetration and tends to be zero at infinity, a limitation term should be added to Eq (1):

$$\frac{d\theta}{dt} = -K\theta \cdot \left(1 - \frac{\theta_i - \theta}{\theta_i - \theta_e}\right) \quad (2)$$

in which θ_i represents the instantaneous (initial) contact angle, θ_e represents equilibrium contact angle. In Eq (2), K is then a constant referred to the intrinsic relative contact angle decrease rate.

Reorganizing Eq. (2), we have the following expression:

$$\frac{d\theta}{dt} = K\theta \cdot \left(\frac{\theta_e - \theta}{\theta_i - \theta_e}\right) \quad (3)$$

After integration, the final expression of the wetting model is:

$$\theta = \frac{\theta_i\theta_e}{\theta_i + (\theta_e - \theta_i)\exp\left[K\left(\frac{\theta_e}{\theta_e - \theta_i}\right)t\right]} \quad (4)$$

The rate of contact angle change is related to the rate of the liquid penetration and spreading on the solid surface. Therefore, the intrinsic relative contact angle change rate constant (K) in Eq. (4) can also be referred to as the penetration and spreading constant. The physical meaning of the K-value represents how fast the liquid spreads and penetrates into the porous structure of wood. By knowing the K-value, spreading and penetration in adhesive/solid systems can be quantified. According to Eq. (4), simulation was used to plot contact angle changes as a function of time at different K-values assuming an instantaneous contact angle of 80 degrees and an equilibrium contact angle of 30 degrees (Fig. 2). The higher the K-value, the faster the contact angle reaches equilibrium, and the faster the liquid penetrates and spreads. When K = 0, the equilibrium contact angle will be equal to the instantaneous contact angle, and no spreading and penetration will occur. When K is larger than a certain number, the liquid can be regarded to wet out the solid surface instantly (the instantaneous contact angle is zero). To obtain a K-value for a particular liquid/solid system, a nonlinear curve-fitting method can be used to fit the empirical data in Eq. (4).

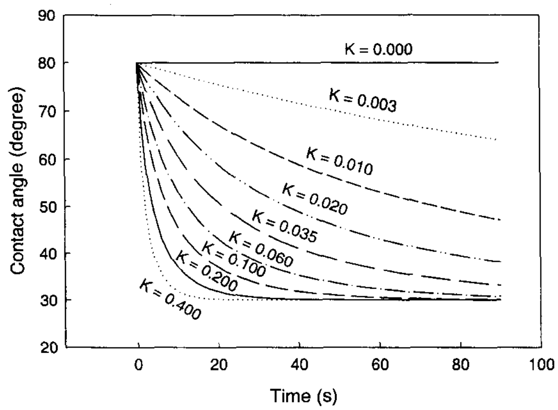

FIG. 2. Contact angle changes as a function of time at different K-values (θ_e = 30°; θ_i = 80°).

MATERIALS AND METHODS

Two adhesive resins commonly used in the wood composite industry were evaluated in the wetting experiments, phenol-formaldehyde (PF) and polymeric diphenylmethane diisocyanate (PMDI). The PF resin was obtained from Neste Resins Corporation, Springfield, Oregon, and the PMDI resin (Mondur 541) was obtained from Bayer Corporation, Pittsburgh, Pennsylvania. The major specifications of the two resins are shown in Table 1. The resin surface tensions shown in Table 1 were characterized using dynamic contact angle (DCA) measurements. The surface tension measurements were made on a Cahn DCA-322 instrument using clean glass slide microscope covers.

Two wood species, Douglas-fir (*Pseudo-*

TABLE 1. *Specifications of the PF and PMDI resins used in the experiments.*

Specification		PF	PMDI
Color		Pale red-brown to maroon	Dark brown to black
Solubility in water		Insoluble to infinitely soluble	Not soluble
Specific gravity		1.10–1.30	1.24
Viscosity (25°C) (cps)		197	200
% NaOH		7.5–7.7	
Nonvolatile content (%)		56.7	100
Surface free energy*	Advancing	51.95	41.24
(mJ/m^2)	Receding	71.79	50.28

* The surface energies of the resins were characterized using dynamic contact angle analysis.

tsuga menziesii) and southern pine (*Pinus* spp.), were examined. All the contact angle measurements were conducted on the radial surface of the wood specimens. The specimens were cut into a dimension of about 1 inch by 1 inch so that the fresh wood surfaces were exposed. To reduce any surface aging effects, all specimens were kept in plastic bags in the absence of light during the time between the specimen preparation and contact angle measurements. Before measurements, surfaces of the specimens were smoothed using a razor blade. The following experiments were conducted on the contact angle change as a function of time for both wood species and two resins:

(1) Effect of wood grain direction. The contact angles along (//) and across (⊥) the wood grain were measured and compared. All the specimens for both species in this experiment were prepared from heartwood.
(2) Effect of wood location (heartwood and sapwood). In this experiment, the contact angle measurements were conducted across the wood grain direction for both southern pine and Douglas-fir species.

In the adhesive wetting measurements, a drop of adhesive (using a 0.005-ml microsyringe) was placed on the earlywood. A CCD camera connected to a videocassette recorder (VCR) was used to measure the adhesive sessile drop image. The drop shape change process was recorded by videotape. The recording was stopped after the drop shape stabilized (equilibrium contact angle was obtained). The contact angle of the adhesive drop was averaged from the contact angles of both ends of the drop measured using global lab image software. Seven data points were taken for each recorded drop to obtain a curve of contact angle vs. time. Ten to fourteen replicates were averaged for each sample. Representative images of the adhesive drops are shown in Fig 3. It is seen from Fig. 3 that the length of contact between the sessile drop and the solid surface increases as time elapses, and this increase is due to liquid spreading. It is also seen from Fig. 3 that the drop volume decreases as a function of time. The volume decrease is due to primarily liquid penetration into the porous structure of the wood surface. Therefore, these phenomena confirm the fact that the contact angle change as a function of time is caused by both liquid spreading and penetration into the substrate.

The wetting model (Eq (4)) was applied to these experimental data. The Marquardt-Levenberg algorithm was used to obtain the penetration/spreading constant (K-value) that provides the best fit between the equation and the data (Marquardt 1963). This algorithm seeks a K-value that minimizes the sum of the squared (SS) differences between the observed and predicted values of the dependent variable.

$$SS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad (5)$$

where y_i and $\hat{y}_i$ are the observed and predicted values of the dependent variable, respectively.

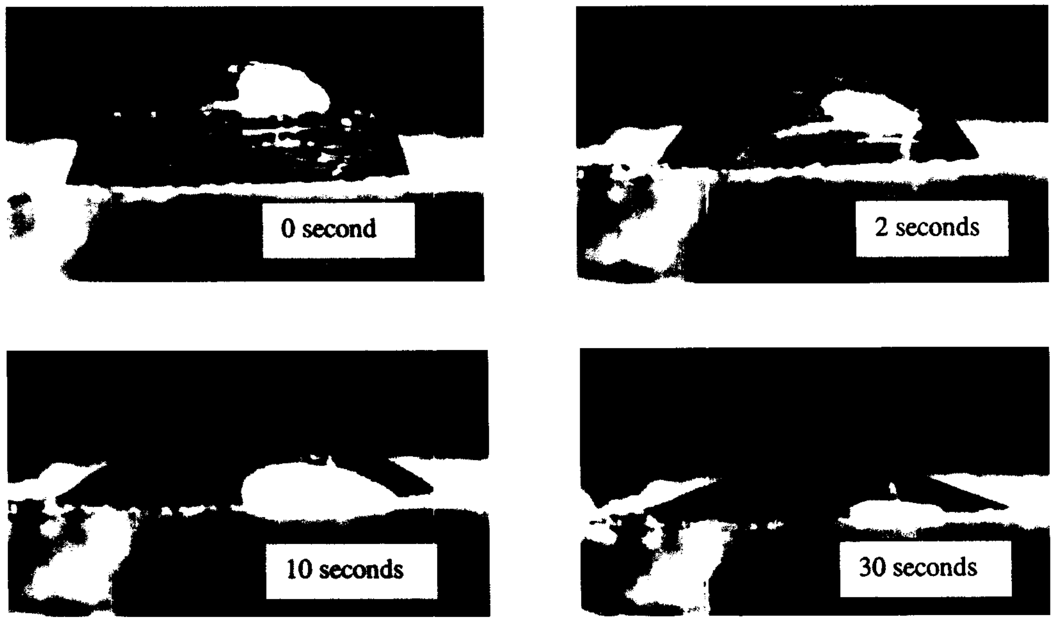

FIG. 3. Images of the same sessile drop of PF on treated Douglas-fir wood at different time intervals.

The asymptotic standard errors (SE) and the coefficients of variation (CV%) of the constant were calculated based on curve-fitting results. The K-value of wetting process for each individual adhesive drop was calculated. A three-way analysis of variance (ANOVA) on K-value, and instantaneous and equilibrium contact angles was conducted based on the results of the above two experiments. Resin type and wood species are included in both ANOVAs. The averaged contact angle data of each solid/liquid system was used to plot the relationship of contact angle versus time and the wetting model fit.

RESULTS AND DISCUSSION

Figures 4, 5, and 6 show the experimental data and the model fit of the contact angle decrease as a function of time for the different wood surfaces and two adhesive systems. It is seen from Figs. 4–6 that the wetting model provides an excellent fit to the experimental data. The penetration/spreading constants (K-values) of all the samples and their asymptotic standard errors (SE), and coefficients of correlation (R^2) of the model fit calculated using the Marquardt-Levenberg algorithm are shown in Table 2. As seen in Table 2, the R square values of the wetting model are over 0.95 for most of the wood surfaces examined. Coefficients of variation (CV) of the calculated K-values are less than 20%. Therefore, the developed wetting model can accurately describe the adhesive wetting process on the wood surface. Tables 3 and 4 show the results of three-way ANOVA of K-value and contact angles (instant and equilibrium) for the two different factor combinations, respectively. Based on these results, the adhesive wettability as a function of different wood surfaces and resins is discussed separately.

Adhesive type: PMDI vs. PF

It is seen from Tables 3 and 4 that resin type shows a significant effect (P-value < 0.001) on all the three parameters (K-value, θ_i, and θ_e) in the wetting model no matter what factor combination is used for the analysis. From the comparison curves plotted in Figs. 4–6, it is apparent that the resin type (PMDI and PF) has a more significant effect on the adhesive wetting process than the other parameters

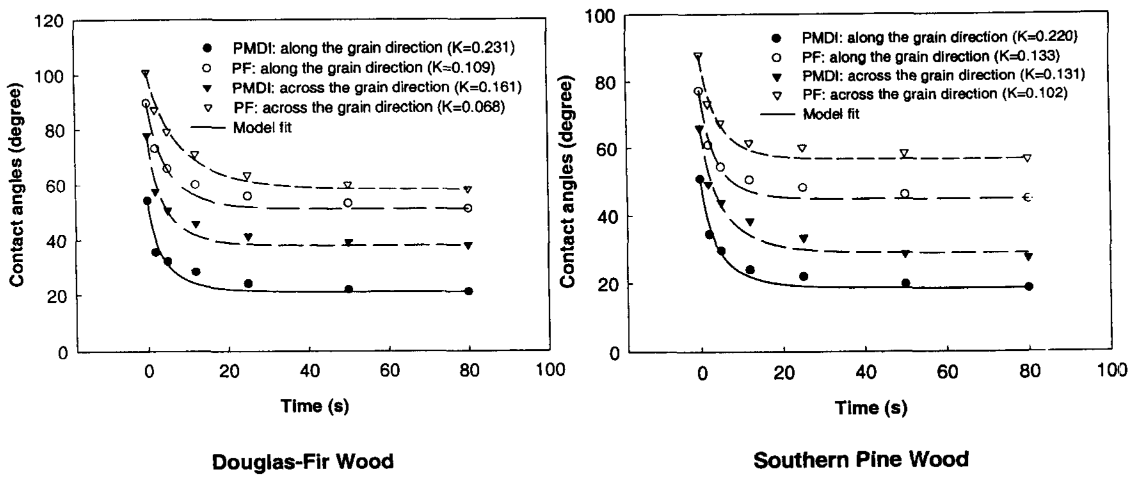

FIG. 4. Contact angle changes as a function of time on Douglas-fir and southern pine along and across the grain direction.

evaluated. PMDI resin exhibits lower instantaneous and equilibrium contact angles than PF resin. Also, the contact angle of PMDI resin attains equilibrium faster than the PF resin. The lower contact angles for the PMDI resin were expected, given the fact that PMDI is 100% organic, while PF resin is an aqueous alkaline mixture. PMDI has a lower surface tension (41.2 mJ/m^2) than that of the PF resin (52.0 mJ/m^2) as shown in Table 1. According to Young's equation for the classical case of the three-phase line of solid, liquid, and its vapor, the relationship between the contact angle and surface tensions is,

$$\cos \theta = \frac{\gamma_{SV} - \gamma_{LV}}{\gamma_{LV}} \tag{6}$$

in which γ_{SL}, γ_{LV}, and γ_{SL} are the interfacial free energies of liquid-vapor, solid-vapor, and solid-liquid, respectively. From Eq. (6), a higher solid surface tension or a lower liquid surface tension will form a lower contact angle in the solid/liquid system. The lower contact angle of PMDI resin indicates that it has a

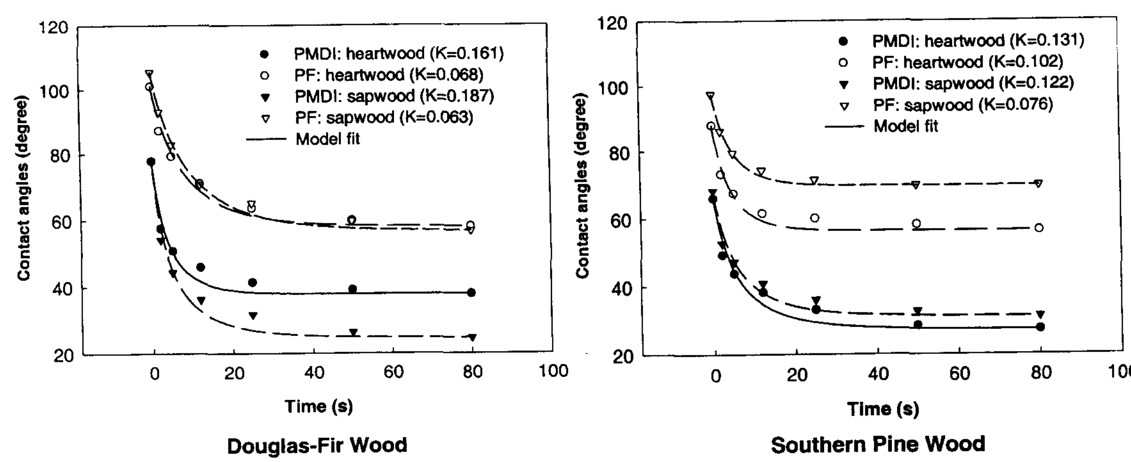

FIG. 5. Contact angle changes as a function of time on sapwood and heartwood across the grain direction.

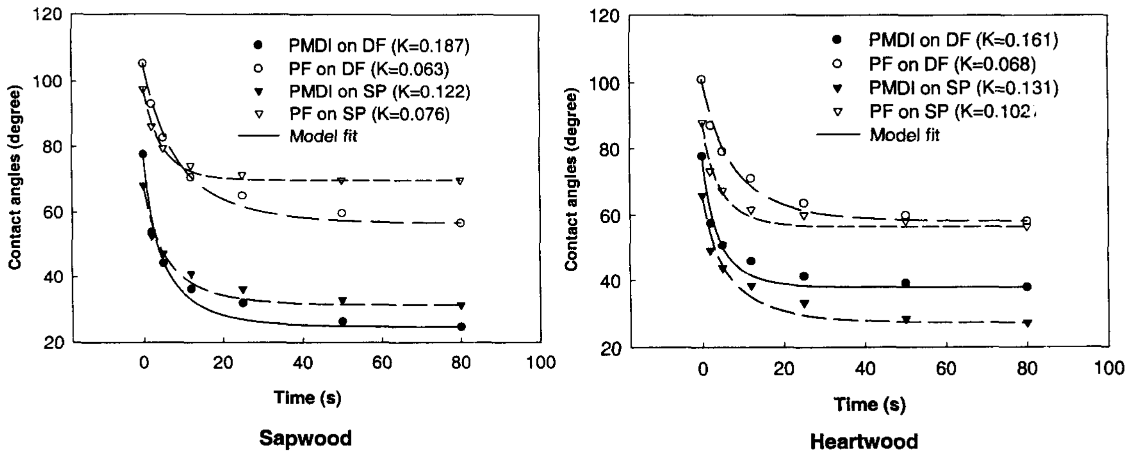

FIG. 6. Contact angle changes as a function of time on Douglas-fir and southern pine across the grain direction.

TABLE 2. *Contact angles and K-values on different wood surfaces with PF and PMDI resin systems.*

			Contact angles			K-values			
Species	Surfaces	Resins	θ_i (degree)	θ_e (degree)	Percent decrease (%)	Value (1/s)	SE ($\times 10^{-2}$) (1/s)	CV (%)	R^2 model fit
SP	Heart //	PMDI	50.9 (4.3)	18.3 (3.9)	64.1	0.220 (0.077)	0.037	16.9	0.97
		PF	77.2 (5.9)	44.5 (4.6)	42.4	0.133 (0.037)	0.021	15.3	0.96
	Heart ⊥	PMDI	65.4 (7.1)	26.5 (7.5)	59.5	0.131 (0.038)	0.025	18.5	0.95
		PF	88.0 (6.9)	56.4 (7.7)	35.9	0.102 (0.048)	0.013	14.6	0.96
	Sap ⊥	PMDI	68.2 (4.1)	31.3 (10.4)	54.1	0.122 (0.039)	0.016	14.8	0.97
		PF	98.5 (9.6)	69.0 (8.2)	30.0	0.076 (0.030)	0.012	17.3	0.99
DF	Heart //	PMDI	54.1 (5.9)	21.0 (5.8)	61.2	0.231 (0.112)	0.046	19.6	0.94
		PF	89.6 (4.5)	51.0 (5.4)	43.1	0.109 (0.056)	0.014	16.2	0.96
	Heart ⊥	PMDI	77.8 (6.9)	37.8 (8.6)	51.4	0.161 (0.068)	0.023	14.9	0.96
		PF	101.0 (7.0)	58.0 (5.5)	42.6	0.068 (0.028)	0.009	14.7	0.98
	Sap ⊥	PMDI	77.6 (9.0)	24.7 (3.6)	68.2	0.187 (0.057)	0.023	12.8	0.97
		PF	105.4 (4.9)	56.7 (7.9)	46.2	0.063 (0.017)	0.008	17.7	0.99

SP: southern pine; DF: Douglas-fir.
θ_i: Instantaneous contact angle; θ_e: Equilibrium contact angle (measured at 80 s).
PF: Phenol formaldehyde; PMDI: Polymeric diphenylmethane diisocyanate.
SE: Asymptotic standard error; CV: Coefficient of variation.
//: Along the grain direction; ⊥: Across the grain direction.

TABLE 3. *Three-way Analysis of Variance (ANOVA) for the K-value, instantaneous and equilibrium contact angles based on grain direction along with resin type and wood species.*

Source of variance	Degree of freedom	Mean square (MS)			*P*-value		
		K-value	θ_i	θ_e	K-value	θ_i	θ_e
Resin type	1	0.127	1.31×10^4	1.28×10^4	<0.001	<0.001	<0.001
Species	1	<0.001	1.90×10^3	559.05	0.812	<0.001	<0.001
Grain direction	1	0.062	4.16×10^3	2.18×10^3	<0.001	<0.001	<0.001
Resin type × species	1	0.012	111.66	40.34	0.045	0.116	0.350
Resin type × grain direction	1	0.009	292.48	42.52	0.079	0.012	0.338
Species × grain direction	1	<0.001	108.43	16.26	0.910	0.122	0.552
Resin type × species × grain direction	1	0.001	85.06	207.61	0.624	0.170	0.036
Residual	66	0.003	44.10	45.55			

θ_i: instantaneous contact angle; θ_e: equilibrium contact angle (measured at 80 s).

more intimate contact on the wood surface than that of the PF resin (Manifestation 1).

PMDI resin exhibited greater K-values than PF resin for all the wood surfaces (Table 2). For example, the K-value of PMDI on the southern pine heartwood along the grain direction (0.220) is 65% greater than that of PF resin (0.133), while the K-value of PMDI on the Douglas-fir heartwood along the grain direction (0.231) is 112% greater than that of PF resin (0.109). The greater K-values of PMDI resin indicate its faster penetration and spreading on the wood surface compared to the PF resin (Manifestations 2 and 3). It is also seen in Table 2 that compared to the PF resin, PMDI resin has a larger percent decrease in contact angle from initial to equilibrium (51–85% vs. 30–67%). This trend is another indication that PMDI exhibits better spreading and penetration behavior than PF resin. Therefore, given the fact that the PF and PMDI used in this study have a similar viscosity (Table 1), considering the three adhesive wetting manifestations, it can be concluded that PMDI resin exhibits better wettability than PF resin and should form more intimate contact with the wood surface. The mechanical and physical properties of wood composites are highly dependent on how well the wood elements are bonded together. The bonding strength of wood composites is highly dependent on adhesive wettability of wood. The better the ad-

TABLE 4. *Three-way Analysis of Variance (ANOVA) for the K-value, instantaneous and equilibrium contact angles based on the location of wood along with resin type and wood species.*

Source of variance	Degree of freedom	Mean square (MS)			*P*-value		
		K-value	θ_i	θ_e	K-value	θ_i	θ_e
Resin type	1	0.104	1.31×10^4	1.74×10^4	<0.001	<0.001	<0.001
Species	1	0.003	2.11×10^3	43.26	0.243	<0.001	0.420
Location	1	<0.001	375.23	10.46	0.729	0.012	0.691
Resin type × species	1	0.025	4.14	289.56	<0.001	0.788	0.039
Resin type × location	1	0.003	182.14	465.52	0.245	0.077	0.010
Species × location	1	0.004	100.13	1.24×10^3	0.187	0.188	<0.001
Resin type × species × location	1	<0.001	11.75	20.25	0.733	0.650	0.580
Residual	71	0.002	56.58	45.55			

θ_i: instantaneous contact angle; θ_e: equilibrium contact angle (measured at 80 s).

hesive wettability, the higher the bonding strength of wood composites. Previous publications have shown that composites bonded with PMDI resin exhibit better physical and mechanical properties than those bonded using PF resin at the same resin content (Sun et al. 1994; Shi and Wang 1997). The results of this study partially explain this phenomenon. In addition to chemical bonding, the better wettability of the PMDI resin also appears to contribute to improved bonding.

Grain direction: along vs. across

Wood is an anisotropic material. The mechanical and physical properties along and across the grain directions are different. This nature of wood material is also presented in the adhesive wetting process on the wood surface. Figure 4 shows a comparison of contact angle change as a function of time in the two wood grain directions (along and across) of southern pine and Douglasfir heartwood. An obvious difference was found on the adhesive wetting behavior between the two wood grain directions. From the results of the ANOVA shown in Table 3, the P-values for the grain direction factor are all less than 0.001 for both K-value and contact angles, indicating that the grain direction has a significant effect on the adhesive wettability. As shown in Table 2 or Fig. 4, both the instantaneous and equilibrium contact angles are lower along the grain direction than that across the direction for the same specimens (about 22–44% lower for the PMDI resin and 11–21% for PF resin). The K-values of the adhesive wetting along the wood grain direction are always greater than that across the grain direction (the differences are about 0.07–0.09 liter/s for PMDI and 0.03–0.04 liter/s for PF). Based on the fact of lower contact angles and greater K-values, it can be concluded that the adhesive has a better wettability along the grain direction than that across the grain direction. The difference in the adhesive wettability measured as a function of grain direction is most likely due to the wood surface structure causing the liquid spreading difference. The longitudinal tracheids, which are the principal elements of wood structure for softwoods, have a length of 3–5 mm along the grain direction compared to a width of only 35–50 μm (Rowell 1994). On the cut wood surface, the tracheid lumens are exposed. During the adhesive wetting process, the liquid drop put on the surface will spread much easier along the tracheid lumen in the grain direction than that across the lumen because of capillary effects. The greater K-value and lower contact angles along the grain direction are mainly because of its greater spreading along the tracheid lumen on the wood surface. Therefore, when measuring contact angles on wood, the grain direction on the surface cannot be ignored.

Location on the wood cross section: heartwood vs. sapwood

Figure 5 shows the comparison of contact angle change as a function of time between heartwood and sapwood of two species (southern pine and Douglas-fir) measured across the wood grain direction. The effect of wood location on the adhesive wetting behavior is apparently not as significant as that of the adhesive type (PMDI and PF). Heartwood and sapwood have well-understood differences in structure and chemical components. For example, heartwood is normally infiltrated and encrusted with organic and sometimes inorganic extractives and dead parenchyma cells. In addition, encrusted pits in heartwood will greatly reduce wood permeability. Therefore, the heartwood is expected to have lower liquid penetration than that of sapwood. However, the rate of adhesive wetting is dependent on the combination of both adhesive penetrating into the wood structure and spreading on the surface. Because the difference in adhesive spreading ability between heartwood and sapwood is not known, the spreading and penetration constant (K) of the sapwood may not be necessarily greater than that of the heartwood. It is seen in Table 2 that the K-value of heartwood is slightly higher than that of sapwood except for the PMDI/Douglas-fir system. However, there is no significant difference in K-values between heartwood and sapwood based on the results of three-way ANOVA shown in Table 4 (*P*-value = 0.729). The analysis of variance indicates that wood location has a significant effect on the contact angles. As shown in Table 2, the instantaneous contact angle (θ_i) on heartwood is significantly lower than that on sapwood (*P*-value = 0.012 shown in Table 4). The difference in equilibrium contact angle (θ_e) between heartwood and sapwood is dependent on the wood species and resin type. As shown in Table 4, the *P*-values for the interaction terms of location with both species and resin type are less than 0.05. For southern pine species, the θ_e on sapwood is greater than that on heartwood. In contrast, a greater θ_e is shown on heartwood for Douglas-fir species. Greater differences in θ_e between heartwood and sapwood is shown for PF resin on southern pine (12.6°) and PMDI resin on Douglas-fir (13.1°).

Species: Douglas-fir vs. southern pine

Figure 6 shows a comparison of adhesive wetting behavior across the grain direction between Douglas-fir and southern pine for both sapwood and heartwood. Similar to the wood location, it is seen in Fig. 6 that the effect of the species on the adhesive wetting process is relatively insignificant compared to difference between PF and PMDI. No significant differences in K-values between the southern pine and Douglas-fir were found in the three-way ANOVA with *P*-values greater than 0.2 (Tables 3 and 4). However, the effect of species on the K-value interacts with the resin type (*P*-value = 0.045 in Table 3 and $<$0.001 in Table 4). As shown in Table 2, PMDI exhibits a greater K-value on Douglas-fir surface than on southern pine. In contrast, PF resin exhibits a greater penetration and spreading rate on the southern pine than on Douglas-fir. For the instantaneous contact angle, both Tables 2 and 3 show that there is a significant difference in θ_i between the two species. Douglas-fir has a greater θ_i than southern pine in all instances (Table 2). The effect of species on the θ_e is strongly dependent on the contact angle drop location on the wood surface. As shown in Table 4, the P-value of species × location for θ_e is less than 0.001. The equilibrium contact angle of Douglas-fir is smaller than that of southern pine for sapwood, but is greater for heartwood.

CONCLUSIONS

A wetting model was developed to describe the wood adhesive wetting process on the liquid/solid system. This model was applied to compare the adhesive wettability between two resin systems (PMDI and PF), grain direction (along and across), drop location on the wood surface (sapwood and heartwood), and wood species (southern pine and Douglas-fir). Dynamic contact angles of these materials were measured using a sessile drop method.

It was shown in this study that the wetting model could be used to accurately describe the adhesive wetting process (contact angle change as a function of time). The constant (K) in the model can be used to quantify the penetration and spreading rate of the liquid-solid system. PMDI resin has a lower contact angle (both instant and equilibrium) and a greater penetration and spreading constant compared to PF resin on all the wood surfaces evaluated in this study. The wood grain direction also affects the adhesive wetting process significantly. Both the instantaneous and equilibrium contact angles are lower along the grain direction than across the grain direction. The K-values of adhesive wetting along the wood grain direction are always greater than that across the grain direction. The differences in the adhesive wetting process between the two wood species and two surface locations (sapwood and heartwood) were not significantly different. There was no significant difference in K-value between heartwood and sapwood. A lower instantaneous contact angle was found on the heartwood. The difference in equilibrium contact angle between heartwood and sapwood is dependent on the wood species and resin type. The equilibrium contact angle on sapwood is greater than that on heartwood for southern pine, but is smaller for Douglas-fir. A greater equilibrium contact angle difference between heartwood and sapwood is shown for PF resin on southern pine and PMDI resin on Douglas-fir. The K-value between the southern pine and Douglas-fir is dependent on resin type. PMDI exhibits a greater K-value on the Douglas-fir surface, while PF resin shows a greater K-value on the southern pine surface. Douglas-fir has a greater instantaneous contact angle than southern pine. The effect of species on the equilibrium contact angle is strongly dependent on the contact angle drop location on the wood surface. Douglas-fir shows a lower equilibrium contact angle for sapwood and a greater angle for heartwood.

ACKNOWLEDGMENTS

This research was sponsored by the Office of Naval Research. Contract N00014-97-C-0395, under the direction of Mr. James J. Kelly. The authors would like to acknowledge Neste Resins Corporation at Springfield, OR and Bayer Corporation at Pittsburgh, PA, for providing the adhesive.

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