FRICTION COEFFICIENT OF OVEN-DRY SPRUCE PINE ON STEEL, AS RELATED TO TEMPERATURE AND WOOD PROPERTIES

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ABSTRACT

The coefficient of friction ranged from 0.10 to 0.25 and was negatively correlated with temperature for tangential earlywood, tangential latewood, and radial surfaces pulled parallel and perpendicular to the grain and for transverse surfaces pulled parallel and perpendicular to the annual rings. For transverse surfaces pulled parallel to the annual rings, tangential latewood surfaces pulled parallel or perpendicular to the grain, and tangential earlywood surfaces pulled parallel to the grain, the coefficient also increased with increasing extractive content for a given temperature. No significant relationships were detected between the coefficient and wood specific gravity after the effects of temperature and extractive content had been accounted for.

The coefficient of kinetic friction of wood on steel is a fundamental property important in machining, since it affects the type of chip formed and hence the quality of the machined surface. In a previous paper (Lemoine et al. 1970), the coefficient for spruce pine wood (*Pinus glabra* Walt.) was shown to vary with specific gravity, extractive content, and moisture content of the samples. In the research reported here, the friction coefficient of four wood surfaces, pulled in two directions, was studied in relation to the temperature of the wood-steel interface and the specific gravity and extractive content of the sample. Spruce pine was again chosen for study because the Southern Forest Experiment Station is attempting to define its properties as an industrial raw material.

By stratifying wood into two specific gravities at each of two extractive contents and testing each at four temperatures, it was possible to isolate the independent relationship of each factor with the friction coefficient for all combinations of surface and direction of slide. Oven-dry wood was evaluated because it seemed impractical to maintain higher moisture contents in samples tested at elevated temperatures.

While others have investigated the subject, none appear to have stratified the samples to reveal the independent effects of wood variables. For this reason, and because of additional differences in method, it is difficult to compare the present data with those already in the literature.

PROCEDURE

A factorial experiment replicated three times was designed with variables as follows:

- Unextracted specific gravity (oven-dry weight and green volume)
  - Low: less than 0.45
  - High: more than 0.45
- Extractive content (per cent of oven-dry unextracted weight)
  - Extractive-free (0%)
  - Unextracted (content at test)
- Temperature of wood-steel interface
  - 76 F
  - 125 F
  - 175 F
  - 225 F

Twelve 1-inch cubes (six of each specific-gravity class) were prepared so as to accurately expose a radial, a transverse, and two tangential surfaces. One of the tangential surfaces was entirely of earlywood and one was entirely of latewood (Fig. 1). Three of the cubes in each specific-gravity class were extracted in acetone for 24 hr, benzene and ethanol (2 to 1) for 48 hr,

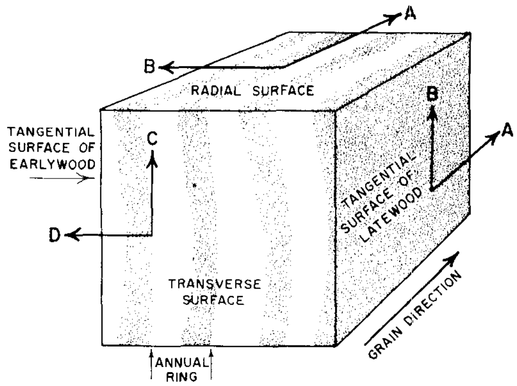

FIG. 1. Method of specimen preparation. The letters A, B, C, and D refer to the direction of slide. Direction A is parallel to the wood grain, while direction B is perpendicular. Direction C is parallel to the annual rings, while direction D is perpendicular.

and ethanol for 48 hr. The remaining three were not extracted. All specimens were then dried for 48 hr in an oven maintained at 221 F.

The horizontal force (F_h) required to slide a 1-square-inch surface subjected to a known vertical force component (F_v) was measured, and the coefficient of kinetic friction (μ) was calculated by the relationship:

$$\mu = F_h/F_v$$

An Instron testing machine was used to maintain a sliding velocity of 2 inches per min as well as to measure the horizontal force (Fig. 2). A thin copper wire was attached to the specimen and to a 1-lb load cell mounted on the movable crossarm of the testing machine. Movement of the crossarm thus provided a constant sliding velocity, while the load cell simultaneously measured the horizontal force component. A 1-lb weight was placed on the upper surface of the cube and it, plus the weight of the sample, was considered the total vertical force component.

An oil-hardened, tool steel plate was used as the stationary surface. Its surface roughness was 9 microinches RMS, and the specimens were pulled parallel to the grinding marks. The temperature of the plate was controlled by varying the voltage to electrical strip heaters attached to its lower surface.

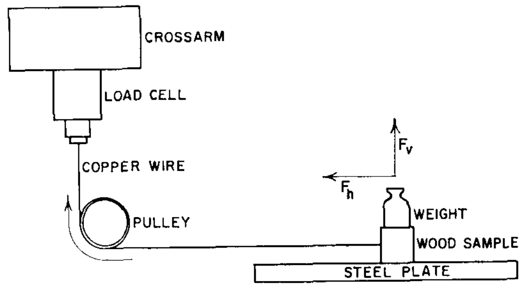

FIG. 2. Experimental setup.

Before each force determination, all wood surfaces were sanded in a figure-8 motion with a fresh sheet of 220-grit paper and cleaned with compressed air. Specimens were then heated for 30 min in an oven maintained at the same temperature as the steel plate (i.e., 76, 125, 175, or 225 F). Surfaces were tested in two directions. On the radial and tangential surfaces, specimens were pulled first parallel and then perpendicular to the grain (direction A and direction B in Fig. 1). On the transverse surface, they were pulled both parallel and perpendicular to the annual rings (direction C and direction D in Fig. 1). Three observations were made for each surface and direction of pull, and the results were averaged.

At the conclusion of the experiment, the extractive content and specific gravity of all specimens were determined by standard methods.

RESULTS

Table 1 summarizes the information on wood properties and coefficients of friction. Wood of low specific gravity averaged 0.395, while wood of high specific gravity averaged 0.504. The extractive content of unextracted samples averaged 1.31%; this value is low because the samples were from the outer portions of old stems.

Regression equations were developed for each surface and each direction of slide by stepwise introduction of the independent variables in order of their individual con-

TABLE 1. *Results of wood-property and friction-coefficient determinations*[1]

Specific gravity and temperature (F)	Parallel slide				Perpendicular slide			
	Tangential latewood	Tangential earlywood	Transverse	Radial	Tangential latewood	Tangential earlywood	Transverse	Radial
				Extractive-free samples				
Low specific gravity (av. 0.397)								
76	0.192	0.216	0.205	0.182	0.179	0.199	0.198	0.197
125	0.138	0.150	0.116	0.148	0.126	0.141	0.113	0.159
175	0.103	0.130	0.121	0.132	0.107	0.123	0.117	0.162
225	0.112	0.109	0.103	0.109	0.102	0.109	0.113	0.099
High specific gravity (av. 0.499)								
76	0.204	0.211	0.195	0.178	0.205	0.187	0.192	0.180
125	0.132	0.145	0.112	0.146	0.126	0.136	0.118	0.157
175	0.107	0.132	0.122	0.136	0.120	0.135	0.114	0.141
225	0.112	0.112	0.101	0.100	0.102	0.102	0.099	0.103
				Unextracted samples[2]				
Low specific gravity (av. 0.392)								
76	0.179	0.200	0.250	0.209	0.164	0.192	0.225	0.220
125	0.152	0.204	0.112	0.113	0.173	0.135	0.107	0.108
175	0.149	0.142	0.119	0.123	0.151	0.134	0.128	0.122
225	0.119	0.131	0.125	0.115	0.113	0.120	0.106	0.112
High specific gravity (av. 0.509)								
76	0.174	0.190	0.233	0.207	0.162	0.217	0.226	0.217
125	0.156	0.184	0.100	0.109	0.175	0.128	0.114	0.108
175	0.133	0.145	0.114	0.118	0.122	0.137	0.126	0.137
225	0.121	0.115	0.113	0.108	0.103	0.116	0.104	0.114

1 Each numerical value for the coefficient of friction is the average of three replications.
2 Extractive contents averaged 1.65% for samples of low specific gravity and 0.96% for samples of high specific gravity.

tribution to the cumulative R^2. All equations were of the type:

$$y = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots\ldots,$$

where y is the dependent variable, i.e., coefficient of friction; b_i, a regression coefficient; and X_i, an independent variable, e.g., temperature, specific gravity, or extractive content. Curvilinear effects and interactions of the independent variables on the friction coefficient were considered. All equations were tested at the 95% level of probability, and all variables were significant at that level.

Table 2 lists the multiple regression equations that most accurately describe the coefficient of friction in terms of temperature and wood properties for each surface and direction of slide. The effects of the variables are graphed in Figs. 3 through 6; these figures were obtained by substituting a range of values for the variables on the X-axis and fixing the remaining variables at the indicated levels.

Tangential surface of latewood

The coefficient of friction for a tangential surface of latewood pulled parallel to the grain was related to temperature, the square of temperature, and the product of temperature and extractive content. The equation accounted for 84% of the total variation with a standard error of 0.013.

From Equation 1 and Fig. 3, the friction coefficient decreased with increasing temperature in a curvilinear manner for all levels of extractive content when samples were pulled parallel to the grain. The rate of decrease was small beyond 175 F. For a given temperature, the friction coefficient increased with increasing extractive content (EC); the effect was slightly greater at the higher temperatures. The correlation between extractive content and

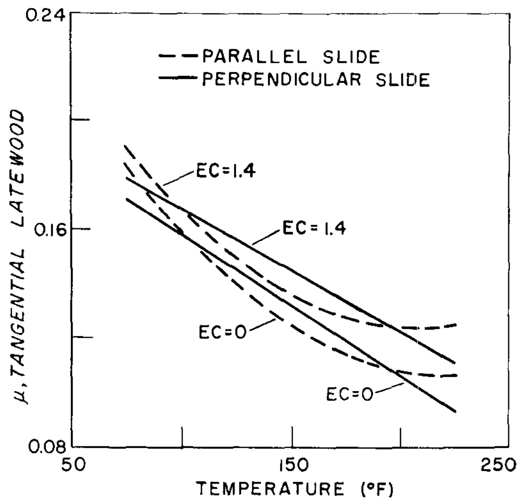

FIG. 3. Friction coefficient as related to temperature and extractive content (EC) for a tangential surface of latewood.

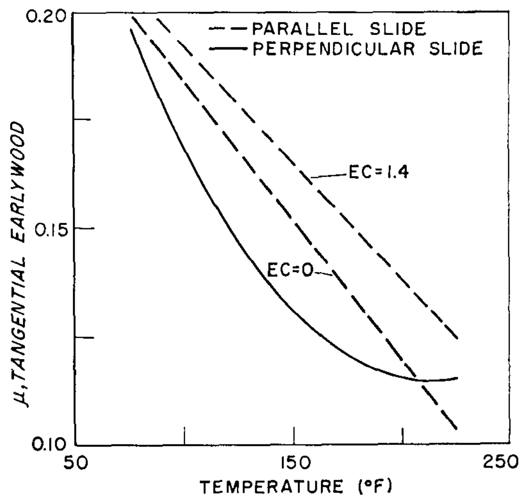

FIG. 4. Friction coefficient as related to temperature and extractive content for a tangential surface of earlywood.

temperature was low ($r = <0.001$). The values plotted for extractive content in Figs. 3 through 5 represent the two extremes of the range obtained in this study.

When samples were pulled perpendicular to the grain, the coefficient was a function of temperature and the product of temperature and extractive content (Equation 2, Fig. 3). The equation accounted for 76% of the total variation, and the standard

TABLE 2. *Multiple regression equations developed to estimate the friction coefficient*[1]

Parallel slide					Perpendicular slide				
Euation number	Variable	Coefficient	Cumulative R^2	Standard error of estimate	Equation number	Variable	Coefficient	Cumulative R^2	Standard error of estimate
				Tangential (latewood)					
(1)		b_0 0.28606			(2)		b_0 0.21254		
	T	b_1 -0.00162	0.710			T	b_1 -0.000530	0.696	
	T^2	b_2 0.00000368	0.794			(T)(EC)	b_2 0.0000675	0.755	0.017
	(T)(EC)	b_3 0.0000588	0.842	0.013					
				Tangential (earlywood)					
(3)		b_0 0.24665			(4)		b_0 0.31147		
	T	b_1 -0.000640	0.796			T	b_1 -0.00187	0.753	
	(T)(EC)	b_2 0.0000688	0.842	0.015		T^2	b_2 0.00000445	0.857	0.013
				Transverse					
(5)		b_0 0.43464			(6)		b_0 0.39126		
	T	b_1 -0.00378	0.540			T	b_1 -0.00310	0.615	
	T^2	b_2 0.0000104	0.814			T^2	b_2 0.00000825	0.833	0.018
	EC	b_3 0.00946	0.834	0.021					
				Radial					
(7)		b_0 0.30922			(8)		b_0 0.30418		
	T	b_1 -0.00193	0.680			T	b_1 -0.00170	0.617	
	T^2	b_2 0.00000468	0.788	0.017		T^2	b_2 0.00000376	0.671	0.024

[1] T = temperature of wood-steel interface in degrees Fahrenheit; EC = alcohol-benzene extractive content in per cent.

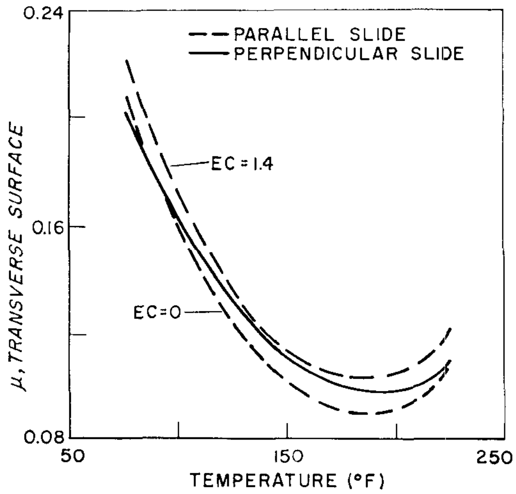

FIG. 5. Friction coefficient as related to temperature and extractive content for a transverse surface.

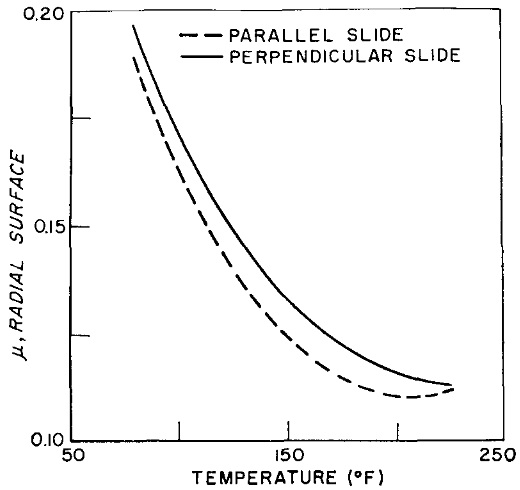

FIG. 6. Friction coefficient as related to temperature for a radial surface.

error was 0.017. The correlation with temperature was negative. The level of this relationship increased with increasing extractive content, while the slope decreased slightly.

Mean friction coefficient values for the interaction of temperature and extractive content of tangential latewood surfaces are given in the following tabulation. By analysis of variance, the interaction was significant at the 0.05 level.

Temperature (F)	*Parallel slide*		*Perpendicular slide*	
	Extracted	*Unextracted*	*Extracted*	*Unextracted*
76	0.198	0.177	0.192	0.163
125	0.135	0.154	0.126	0.174
175	0.105	0.141	0.114	0.137
225	0.112	0.120	0.102	0.108

Tangential surface of earlywood

For samples pulled parallel to the grain, the friction coefficient for tangential earlywood was a function of temperature and the product of temperature and extractive content. These factors accounted for 84% of the total variation; the standard error was 0.015.

As indicated by Equation 3 and Fig. 4, the coefficient was a negative linear function of temperature. For a given temperature, the coefficient increased with increasing extractives, the effect being somewhat greater with increasing temperature.

For samples pulled perpendicular to the grain, the coefficient was a curvilinear function of temperature only (Equation 4, Fig. 4). This factor accounted for 86% of the variation, and the standard error was 0.013. The negative effect of temperature was slight above 175 F.

Mean coefficients for tangential surfaces of earlywood were:

Temperature (F)	*Parallel slide*		*Perpendicular slide*
	Extracted	*Unextracted*	
76	0.214	0.195	0.199
125	0.147	0.194	0.135
175	0.131	0.144	0.132
225	0.111	0.123	0.112

Transverse surface

For a transverse surface pulled parallel to the annual rings, the coefficient was a function of temperature, the square of temperature, and extractive content (Equation 5). The equation accounted for 83% of the variation, and the standard error was 0.021.

As charted in Fig. 5, the coefficient decreased with increasing temperature to a minimum at about 185 F, then increased. For a given temperature, the coefficient increased with increasing extractives.

When the transverse surface was pulled perpendicular to the annual rings, the coefficient was a curvilinear function of temperature only (Equation 6). This factor accounted for 83% of the variation, and the standard error was 0.018. As in samples pulled parallel to the rings, the coefficient decreased with increasing temperature to a minimum at approximately 185 F, then increased (Fig. 5).

Means for transverse surfaces were:

Temperature (F)	*Parallel slide* *Extracted*	*Unextracted*	*Perpendicular slide*
76	0.200	0.242	0.210
125	0.114	0.106	0.113
175	0.121	0.117	0.121
225	0.102	0.119	0.105

Radial surface

The coefficient for the radial surface was a curvilinear function of temperature for both directions of slide (Equations 7 and 8). No other factors were significant after the effect of temperature had been considered. The equation for parallel slide accounted for 79% of the total variation with a standard error of 0.017. The values for perpendicular slide were 67% and 0.024 respectively.

As plotted in Fig. 6, friction decreased with increasing temperature for both directions of slide.

Means at each temperature were:

Temperature (F)	*Parallel slide*	*Perpendicular slide*
76	0.194	0.203
125	0.129	0.133
175	0.127	0.141
225	0.108	0.107

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