2d. Coefficients of Friction

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Symbols

f_K coefficient of kinetic or sliding friction
f_R coefficient of rolling friction
f_s coefficient of static friction
P frictional resistance to rolling
r radius of roller
W load

2d-1. Static and Sliding Friction. All surfaces encountered in experience are more or less rough in the sense that as bodies move on them they exert forces parallel to the surface and in such direction as to resist motion. Such forces are termed "frictional." Frictional force is proportional to the normal thrust between body and surface; however, the coefficient of proportionality, known as the coefficient of friction, can for the same body and surface vary a great deal depending on the nature of the contact and the motion. It is customary to define

$$f_s = \frac{\text{magnitude of maximum frictional force}}{\text{magnitude of normal thrust}} \qquad \text{(2d-1)}$$

as the *coefficient of static friction* if motion is just on the point of starting. On the other hand, f_K, called the coefficient of *kinetic or sliding friction*, is the value of the ratio in Eq. (2d-1), when motion has once been established. In general $f_K < f_s$ for the same body and surface or the same two surfaces.

The friction between surfaces is dependent upon many variables. These include the nature of the materials themselves, surface finish and surface condition, atmospheric dust, humidity, oxide and other surface films, velocity of sliding, temperature, vibration, and extent of contamination.

In many instances the degree of contamination is perhaps the most important single variable. For example, Table 2d-1 lists values for the static coefficient of friction f_s for steel on steel under various test conditions.

TABLE 2d-1. COEFFICIENTS OF STATIC FRICTION FOR STEEL ON STEEL

Test condition	f_s	Ref.*
Degassed at elevated temp. in high vacuum	Weld on contact	20
Grease-free in vacuum	0.78	1
Grease-free in air	0.39	8
Clean and coated with oleic acid	0.11	1
Clean and coated with solution of stearic acid	0.013	21

* References follow Table 2d-4.

The most effective lubricants for nonfluid lubrication are generally those which react chemically with the solid surface and form an adhering film that is attached to the surface with a chemical bond. This action depends upon the nature of the lubricant and upon the reactivity of the solid surface. Table 2d-2 indicates that a fatty acid such as those found in animal, vegetable, and marine oils reduces the coefficient

TABLE 2d-2. COEFFICIENTS OF STATIC FRICTION AT ROOM TEMPERATURE

Surfaces	Clean	Paraffin oil	Paraffin oil + 1% lauric acid	Degree of reactivity of solid
Nickel	0.7	0.3	0.28	Low
Chromium	0.4	0.3	0.3	Low
Platinum	1.2	0.28	0.25	Low
Silver	1.4	0.8	0.7	Low
Glass	0.9	....	0.4	Low
Copper	1.4	0.3	0.08	High
Cadmium	0.5	0.45	0.05	High
Zinc	0.6	0.2	0.04	High
Magnesium	0.6	0.5	0.08	High
Iron	1.0	0.3	0.2	Mild
Aluminum	1.4	0.7	0.3	Mild

of friction markedly only if it can react effectively with the solid surface. Paraffin oil is almost completely nonreactive. The data are taken from ref. 22.

It is generally recognized that coefficients of friction reduce on dry surfaces as sliding velocity increases. Dokos (ref. 4) has measured this for steel on steel. It is difficult to screen out the effect of temperature, however, which also increases with sliding velocity so that frequently, under these conditions, both variables are present. Table 2d-3 gives values which are the average of four tests at high contact pressures.

TABLE 2d-3. COEFFICIENTS OF FRICTION, STEEL ON STEEL, UNLUBRICATED

Velocity, in./sec	0.0001	0.001	0.01	0.1	1	10	100
Coefficient of friction f_K	0.53	0.48	0.39	0.31	0.23	0.19	0.18

Table 2d-4 presents typical values of the coefficients of static and sliding friction for various materials under a variety of conditions.

TABLE 2d-4. COEFFICIENTS OF STATIC AND SLIDING FRICTION*

Materials	Static friction		Sliding friction	
	Dry	Greasy	Dry	Greasy
Hard steel on hard steel	0.78(1)	0.11(1,a)	0.42(2)	0.029(5,h)
		0.23(1,b)	....	0.081(5,c)
		0.15(1,c)	....	0.080(5,i)
		0.11(1,d)	....	0.058(5,j)
		0.0075(18,p)	....	0.084(5,d)
		0.0052(18,h)	....	0.105(5,k)
				0.096(5,l)
				0.108(5,m)
				0.12(5,a)
Mild steel on mild steel	0.74(19)	....	0.57(3)	0.09(3,a)
				0.19(3,u)
Hard steel on graphite	0.21(1)	0.09(1,a)		
Hard steel on babbitt (ASTM 1)	0.70(11)	0.23(1,b)	0.33(6)	0.16(1,b)
		0.15(1,c)	....	0.06(1,c)
		0.08(1,d)	....	0.11(1,d)
		0.085(1,e)		
Hard steel on babbitt (ASTM 8)	0.42(11)	0.17(1,b)	0.35(11)	0.14(1,b)
		0.11(1,c)	....	0.065(1,c)
		0.09(1,d)	....	0.07(1,d)
		0.08(1,e)	....	0.08(11,h)
Hard steel on babbitt (ASTM 10)	....	0.25(1,b)	....	0.13(1,b)
		0.12(1,c)	....	0.06(1,c)
		0.10(1,d)	....	0.055(1,d)
Mild steel on cadmium silver	....	....	....	0.097(2,f)
Mild steel on phosphor bronze	....	....	0.34(3)	0.173(2,f)
Mild steel on copper lead	....	....	....	0.145(2,f)
Mild steel on cast iron	....	0.183(15,c)	0.23(6)	0.133(2,f)
Mild steel on lead	0.95(11)	0.5(1,f)	0.95(11)	0.3(11,f)
Nickel on mild steel	....	....	0.64(3)	0.178(3,x)
Aluminum on mild steel	0.61(8)	....	0.47(3)	
Magnesium on mild steel	....	....	0.42(3)	
Magnesium on magnesium	0.6(22)	0.08(22,y)	.	

* Numbers in parentheses indicate references to data sources; letters identify lubricant in following list.

TABLE 2d-4. COEFFICIENTS OF STATIC AND SLIDING FRICTION (*Continued*)

Materials	Static friction		Sliding friction	
	Dry	Greasy	Dry	Greasy
Cadmium on mild steel	....	....	0.46(3)	
Copper on mild steel	0.53(8)	....	0.36(3)	0.18(17,a)
Nickel on nickel	1.10(16)	0.28(22,y)	0.53(3)	0.12(3,w)
Brass on mild steel	0.51(8)	0.11(22,c)	0.44(6)	
Brass on cast iron	....	....	0.30(6)	
Zinc on cast iron	0.85(16)	....	0.21(7)	
Magnesium on cast iron	....	....	0.25(7)	
Copper on cast iron	1.05(16)	....	0.29(7)	
Tin on cast iron	....	....	0.32(7)	
Lead on cast iron	....	....	0.43(7)	
Aluminum on aluminum	1.05(16)	0.30(22,y)	1.4(3)	
Glass on glass	0.94(8)	0.35(22,y) 0.1(22,q)	0.4(3)	0.09(3,a)
Carbon on glass	....	....	0.18(3)	
Garnet on mild steel	....	....	0.39(3)	
Glass on nickel	0.78(8)	....	0.56(3)	
Copper on glass	0.68(8)	....	0.53(3)	
Cast iron on cast iron	1.10(16)	0.2(22,y)	0.15(9)	0.070(9,d)
Bronze on cast iron	....	....	0.22(9)	0.077(9,n)
Oak on oak (parallel to grain)	0.62(9)	....	0.48(9)	0.164(9,r) 0.067(9,s)
Oak on oak (perpendicular)	0.54(9)	....	0.32(9)	0.072(9,s)
Leather on oak (parallel)	0.61(9)	....	0.52(9)	
Cast iron on oak	....	....	0.49(9)	0.075(9,n)
Leather on cast iron	....	....	0.56(9)	0.36(9,t)
Teflon on Teflon	0.04(22)	....	0.04(22,f)	
Teflon on steel	0.04(22)	....	0.04(22,f)	
Fluted rubber bearing on steel	....	....	....	0.05(13,t)
Laminated plastic on steel	....	....	0.35(12)	0.05(12,t)
Tungsten carbide on tungsten carbide	0.2(22)	0.12(22,a)		
Tungsten carbide on steel	0.5(22)	0.08(22,a)		

Materials	Sliding friction, dry
Nylon 6.6 on mild steel (no fibers)	0.40(23)
Nylon 6.6 on mild steel (30% by wt. carbon fibers)	0.35(23)
Copper-graphite (high copper) on hard steel	0.40(23)
Copper-graphite (low copper) on hard steel	0.25(23)
Carbon-graphite(low graphite) on hard steel	0.50(23)
Carbon-graphite (high graphite) on hard steel	0.25(23)
Carbon-Teflon on hard steel	0.30(23)
Carbon-copper-Teflon on hard steel	0.29(23)

Lubricant References for Table 2d-4

a. Oleic acid
b. Atlantic spindle oil (light mineral)
c. Castor oil
d. Lard oil
e. Atlantic spindle oil plus 2 per cent oleic acid
f. Medium mineral oil
g. Medium mineral oil plus $\frac{1}{2}$ per cent oleic acid
h. Stearic acid
i. Grease (zinc oxide base)
j. Graphite
k. Turbine oil plus 1 per cent graphite
l. Turbine oil plus 1 per cent stearic acid
m. Turbine oil (medium mineral)
n. Olive oil
p. Palmitic acid
q. Ricinoleic acid
r. Dry soap
s. Lard
t. Water
u. Rape oil
v. 3-in-1 oil
w. Octyl alcohol
x. Triolein
y. 1 per cent lauric acid in paraffin oil

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2d-2. Rolling Friction. Rolling is frequently substituted for sliding friction. The resistance to motion is substantially smaller than for sliding under nonfluid film conditions. The frictional resistance to rolling under the action of load W may be designated as P in Fig. 2d-1. The coefficient of rolling friction is then defined as

$$f_R = \frac{P}{W} \qquad (2d\text{-}2)$$

The frictional resistance P to the rolling of a cylinder under load is applied at the center of the roller and is inversely proportional to the radius r of the roller and proportional to a factor k, a function of the material and its surface condition. Thus

$$P = \frac{k}{r} W \qquad (2d\text{-}3)$$

If r is in inches, values of k may be taken as follows: hardwood on hardwood, 0.02; iron on iron, steel on steel, 0.002; hard polished steel on hard polished steel, 0.0002 to 0.0004. Noonan and Strange suggest, for steel rollers on steel plates: surfaces well

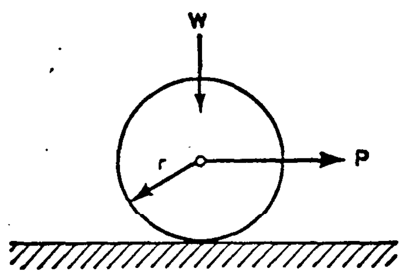

FIG. 2d-1. Rolling friction.

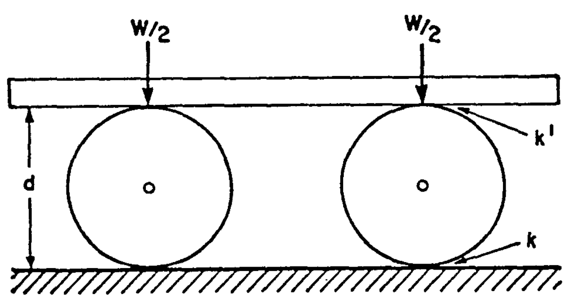

FIG. 2d-2. Load carried on rollers.

finished and clean, 0.005 to 0.001; surfaces well oiled, 0.001 to 0.002; surfaces covered with silt, 0.003 to 0.005; surfaces rusty, 0.005 to 0.01.

If the load is carried on rollers as in Fig. 2d-2, and k and k' are the respective factors for lower and upper surfaces, the force P is

$$P = \frac{(k + k')W}{d} \qquad (2d\text{-}4)$$

A comprehensive survey of rolling friction may be found in the following references presented at the annual meeting of the American Society of Mechanical Engineers, December 1 to 5, 1968.

Hersey, M. D.: Rolling Friction: I, Historical Introduction, Paper 68-LUB-B.
Hersey, M. D., and M. S. Downes: Rolling Friction: II, Cast Iron Car Wheels, Paper 68-LUB-C.
Hersey, M. D.: Rolling Friction: III, Review of Later Investigations. Paper 68-LUB-D.