Development of an Elastomer with a High Static or Breakaway Friction Coefficient

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Synopsis

This paper reviews the literature concerning the measurement of friction coefficients (μ) for elastomers and summarizes our data measured under static or breakaway conditions against epoxy painted steel using ~ 176 psi contact pressure. Although largely related to missile launch system applications, the μ values presented are specific for interface pairs, normal loading force, and speed. Therefore, this article should serve as a starting point for those requiring specific friction data for selected elastomers.

INTRODUCTION

Over the last two decades we have paid considerable attention to the identification of polymer coatings with low static or breakaway friction coefficients for use in missile launch applications.[1] These efforts culminated in the use of sodium etched Teflon bonded to cast polyurethane and molded neoprene rubber components in the Poseidon and Trident missile launch systems and Armalon (Teflon-impregnated glass fabric) bonded to EPDM pads for the MX (now Peacekeeper) missile launch system.[2]

For a variety of applications, additional studies have been conducted to identify or develop materials with either high or low friction coefficients at a variety of contact pressures and surface speeds against polyurethane painted steel and graphite/epoxy composite.

Because of the wide range of available materials and test variables it was considered valuable to review much of the data available in the open literature by addressing the questions listed below:

What is a coefficient of friction?
How is friction measured?
What is the influence of test speed on friction?
What is the influence of polymer type on friction?
What is the influence of rubber compounding ingredients on friction?
What is the influence of hardness and crosslink density of rubber on friction?
What is the influence of shape factor on friction?
How does contact pressure or normal force influence friction?
What is the influence of contact time on friction?
How does aging of the rubber product influence friction?

An attempt is made to answer these questions and selected formulations and friction values, mainly those related to the development of rubber

compounds with high static or breakaway friction coefficients against graphite/epoxy, are presented.

DISCUSSION

What is a Coefficient of Friction?

Friction or resistance to sliding is generally represented by the letter F and is equal to the normal load (N) on the contacting surfaces multiplied by the coefficient of friction (μ), which is the sliding force divided by the normal force:

$$F = \mu N \qquad (1)$$

$$\mu = F/N \qquad (2)$$

As is readily apparent, μ is dependent upon the normal force used to measure the sliding force. Therefore, any discussions of friction should contain information pertaining to the normal force used in its measurement. At no time can the coefficient of friction be considered a material property, independent of the test method used in its measurement.

For most systems, the initial breakaway or static coefficient of friction is greater then the dynamic coefficient of friction as measured between contacting surfaces moving relative to each other. In general, most data in the literature are for dynamic applications. This is due to the fact that most work reported has been related to the tire industry, rheology of polymer melts such as extrusion, and automotive or rail car braking applications. However, for missile launch application the static or slip-stick characteristic of a material is of interest, particularly after long contact times at relatively low contact pressures.
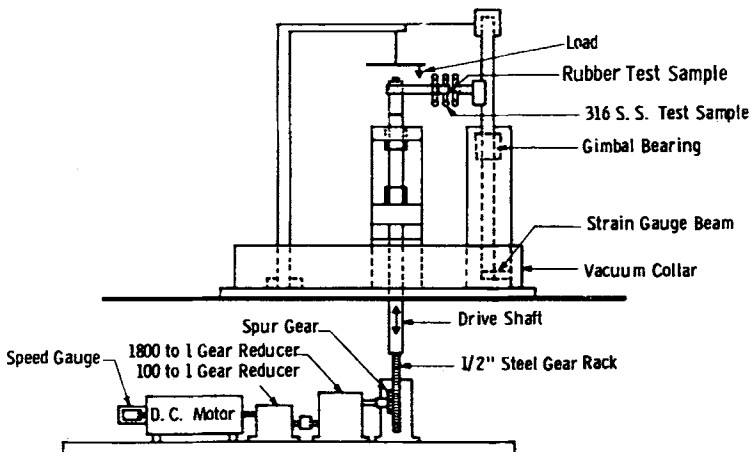

Fig. 1.   Schematic of apparatus for measuring breakaway force under ultra-low speed conditions.

How is Friction Measured?

The number of experimental test fixtures for measuring friction and friction coefficients seem to be limited only by the experimenter's imagination and cost limitation. However, all share the common features of a normal load placed on the materials in contact and a force transducer parallel to the direction of motion. The test setup used by D. Boes at Westinghouse R & D is shown in Figure 1. This equipment was used to collect much of the breakaway or static friction data presented in this article. Relative motion of the contacting surfaces can be varied from 0.003 to 0.060 in./min, but 0.060 in./min is a rate frequently used and is considered to be a static test.

Another test fixture for determination of μ static used by G. E. Rudd at Westinghouse R & D is shown schematically in Figure 2. In this fixture, referred to as a 2D (for two-dimensional) test fixture the blocks of rubber can be up to ~ 4" × 4" square and thickness can be varied from < 0.125" to 4".

The equipment used by Schallamach,[3] shown in Figure 3, can be used to determine either μ static or μ dynamic.
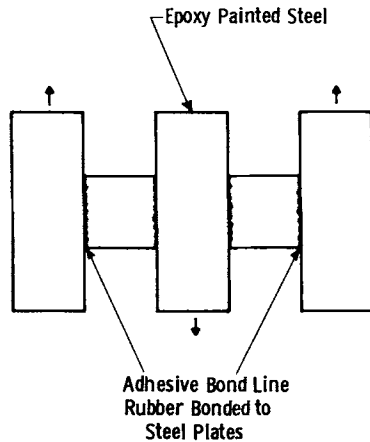
Fig. 2.   Double shear test fixture for measuring friction.
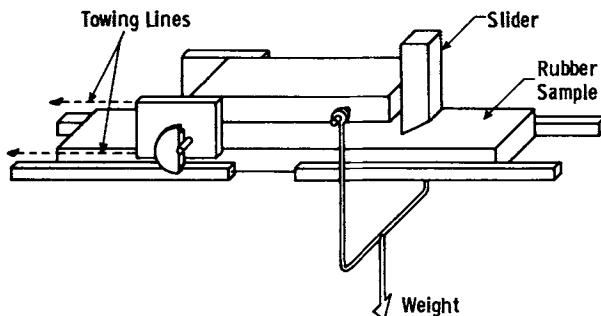
Fig. 3.   Sketch of the experimental layout used by Schallamach.[3]

What is the Influence of Test Speed and Temperature on Friction?

In general, as the testing speed changes, and therefore the temperature at the contact surface increases due to frictional heating, the coefficient of friction changes quite markedly. This is shown graphically by Figure 4 for a "pinhead" glass, used in bathroom windows, against acrylonitrile rubber.[4] In the form of Figure 4, this graph presents a somewhat confusing picture of the relationship between friction, velocity, and temperature. However, using the Time-Temperature Superposition Principle, and shifting the curves along the horizontal axis to form a Master Curve at 20°C, the velocity dependence of friction coefficients can be developed as shown in Figure 5.[4]

Construction of such Master Curves has a sound theoretical base as supplied by Schallamach.[5] It is interesting to note that construction of such curves for natural rubber is generally not possible, since natural rubber has a tendency to crystallize, and therefore the data between $-26°C$ and $-40°C$ will not fit the transformation as depicted by Eq. (3)

$$\log_{10} a_T = \log_{10}\left[f(T - T_s)\right] = \frac{-8.86(T - T_s)}{101.5 + (T - T_s)} \qquad (3)$$

where T is the test temperature and T_s is a temperature approximately 50°C above the glass transition temperature. For natural rubbers, a continuous
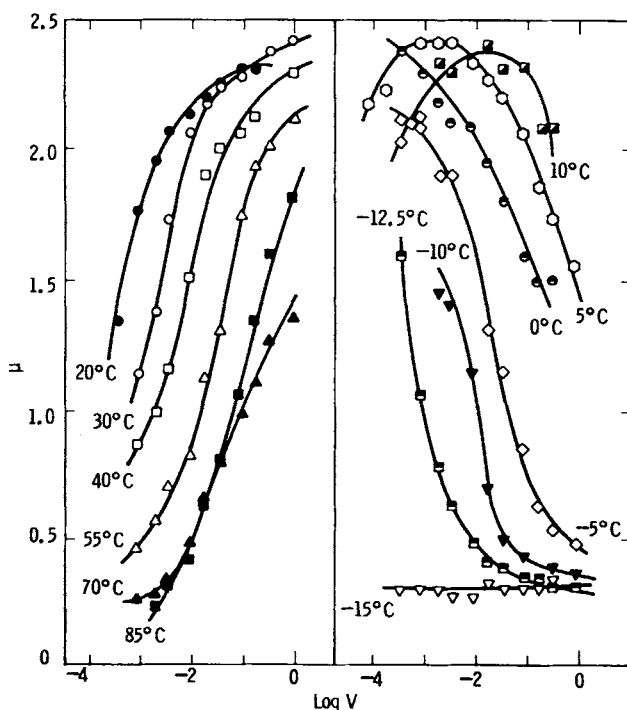

Fig. 4. Coefficient of friction on pin-head glass of unfilled acrylonitrile-butadiene rubber at various temperatures, as function of sliding velocity cm/s. From Ref. 4.
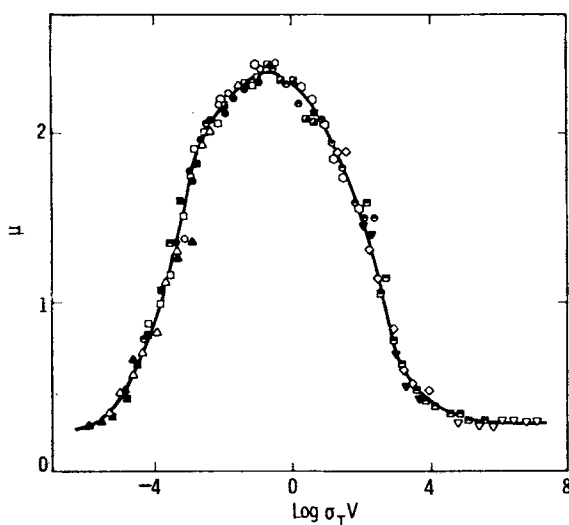
Fig. 5. Master curve for coefficient of friction of acrylonitrile-butadiene rubber at 20°C, derived from the graphs in Figure 4, from Ref. 4.

Master Curve for friction has been obtained only on dusted silicon-carbide paper. Crystallization appears, therefore, to predominantly affect the adhesion component of friction as opposed to the hysteresis component. These data are shown in Figure 6. Examples of Master Curves for noncrystallizing rubber are shown in Figure 7.[5]

These results have been explained by the existence of two different friction mechanisms. One of them is molecular adhesion of the type envisaged in the example of natural rubber. This is the only mechanism operative for friction of rubber on smooth glass. The other process is mechanical energy loss due to
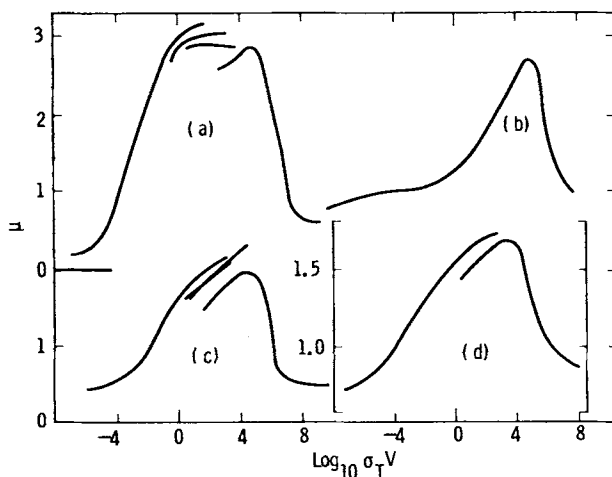

Fig. 6. Master curves for NR at 20°C; unfilled rubber on glass (a), on dusted silicon carbide paper (b), and on clean silicon carbide paper (c); filled with 50 phr HAF on clean silicon carbide paper (d). From Ref. 4.
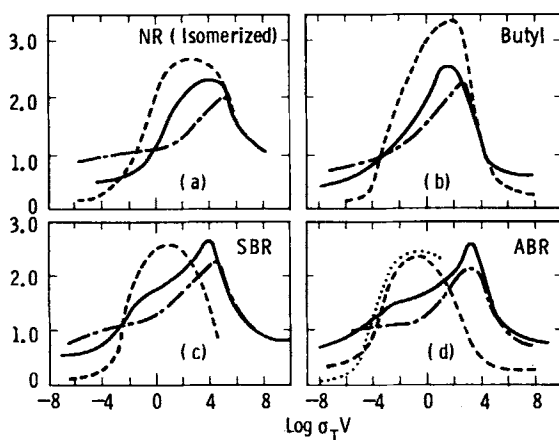
Fig. 7.   Master curves for coefficient of friction of noncrystallizing unfilled gum rubbers at 20°C on various tracks. (——) nondusted silicon carbide; (— · —) dusted silicon carbide; (-----) pinhead glass. From Ref. 4.

gross deformation of the rubber surface by track asperities, as in the silicon-carbide paper example. These energy losses or hysteresis losses, according to Greenwood and Tabor,[6] are the single source of friction on a lubricated track. Because of adhesion friction on a dry track, deformations are much larger than on a lubricated surface, and therefore produce abrasion.

What is the Influence of Polymer Type on Friction?

As shown in the previous section, the values for coefficient of friction for natural rubber are highest for very low speeds of separation of the contacting surfaces, that is breakaway or static coefficient of friction, and decrease with increasing speed of separation. This conclusion appears to be universal regardless of base polymer type. Similar results are shown in Figure 8, for SBR-based rubber compounds containing different levels of styrene in the copolymer.[4]
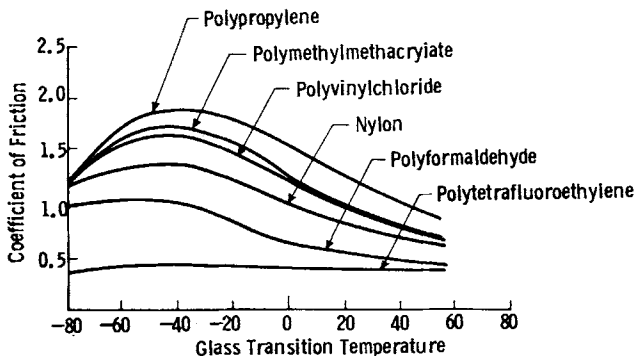

Fig. 8.   Coefficient of friction of SBR compounds with different stryene content (specified by their glass transition temperature) on various plastic tracks.
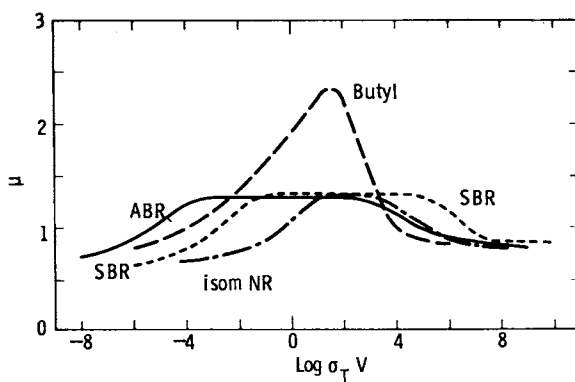
Fig. 9. Master curves for coefficient of friction of black-filled, noncrystallizing rubbers at 20°C on silicon carbide paper. From Ref. 4.

What is the Influence of Compounding Ingredients on Friction?

Although the literature examined does not dwell much on this subject area, the influence of carbon black has been reported for selected rubbers and these data are given in Figure 9.[4] Addition of carbon black to rubber does not displace the curves along the velocity axis, but flattens the maximum in μ values to plateaus, with the exception of butyl rubber. Two effects most probably contribute to the difference of filled and unfilled compounds. First, the distribution of relaxation times is broadened by the addition of filler, as deduced by Ferry[7] from Payne's data.[8] This, in turn, affects the hysteresis component of friction. Second, the true area of contact is smaller with filled rubber, because of the greater hardness imparted by the filler. Therefore, the adhesion mechanism is reduced in importance. Although no data were found on the influence of other compounding ingredients, it appears reasonable and will be shown later, that the addition of oils, plasticizers, processing aids, or other materials with low surface energies that can diffuse or bloom on the rubber surface, will reduce the friction coefficient of the material.

What is the Influence of Hardness and Crosslink Density of Rubbers on Friction?

In a similar way to the addition of carbon black, it is speculated that increased crosslink density in the rubber will lead to reduced friction coefficient. This is because a high crosslink density gives rise to a harder rubber. Hence, for maximum static friction coefficients, it is concluded that little or no oil should be included in the compound formulation, and the crosslink density should be kept as low as practically possible, consistent with having physical properties that meet specification limits.

What is the Influence of Shape Factor?

Although nothing specific regarding the influence of shape factor on friction coefficients was found in the literature, our work does suggest that μ values should be compared on samples with similar shape factors. Shape factor is defined as the loaded area divided by the force-free area[9] or:

$$S = LW/(2t(L + W)) \tag{4}$$

where: L = sample length
         W = sample width
         t = sample thickness

This in effect leads to high shape factors at high loads, and the greater the shape factor, the higher the effective hardness and the lower the measured friction coefficient, as explained previously.

How Does Contact Pressure Influence Friction?

Contact pressure and shape factor are not independent variables as alluded to in the previous section, since shape factor increases with increasing contact pressure. It is also true that as sample hardness increases, μ decreases. This is shown in Figure 10[10] for Adiprene polyurethane polymers and in Figure 11 for natural rubber tire tread compound,[5] but our experience shows this to be true for other materials as well.

It appears that these results are valid only as long as the sliding velocities are low enough for a frictional temperature increase to be negligible. Quite erroneous conclusions may be drawn from experiments in which this is not true, as is demonstrated by Figure 11. The graph shows the coefficient of friction and the simultaneous increase in temperature for a black-filled NR
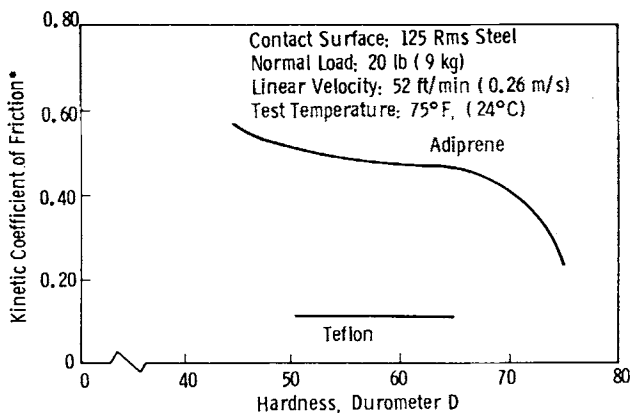
Fig. 10.   Effect of surface hardness on friction. Measured on an experimental dynamic friction tester based on an ice friction tester developed by Research Division of The Goodyear Tire & Rubber Co.
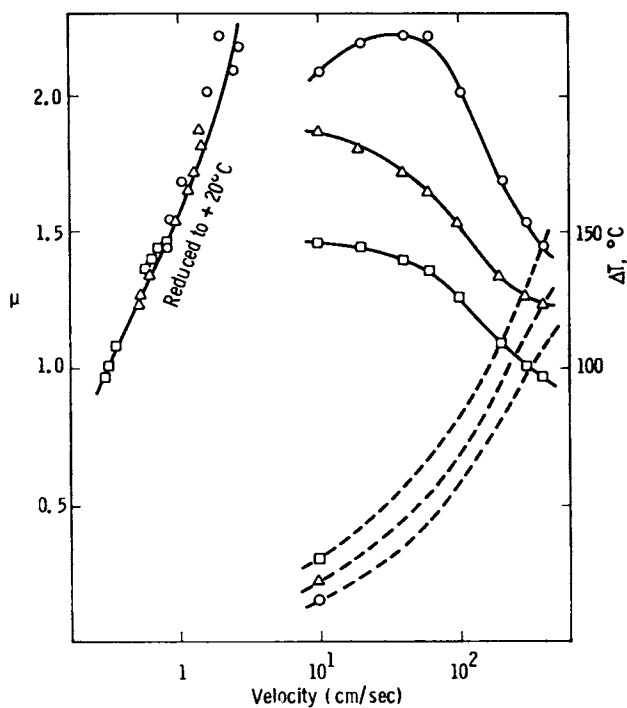
Fig. 11. Right-hand side: Coefficient of friction (full lines) and frictional temperature rise (broken lines) of a needle-thermocouple sliding on an NR tread compound. Left-hand side: Coefficient of friction reduced to 20°C. (O) normal load 34 g; (△) normal load 72 g; (□) normal load 154 g. From Ref. 13.
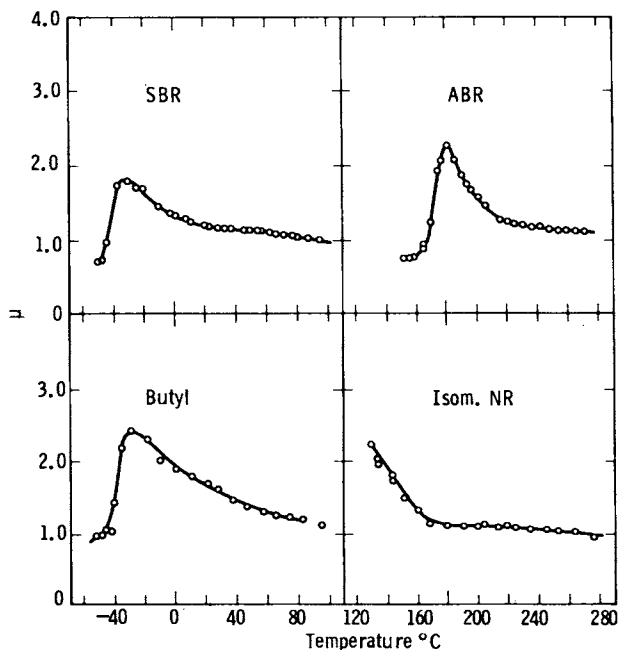
Fig. 12. Temperature dependence of coefficient of friction μ of noncrystallizing unfilled rubbers at 1 cm/s. From Ref. 5.
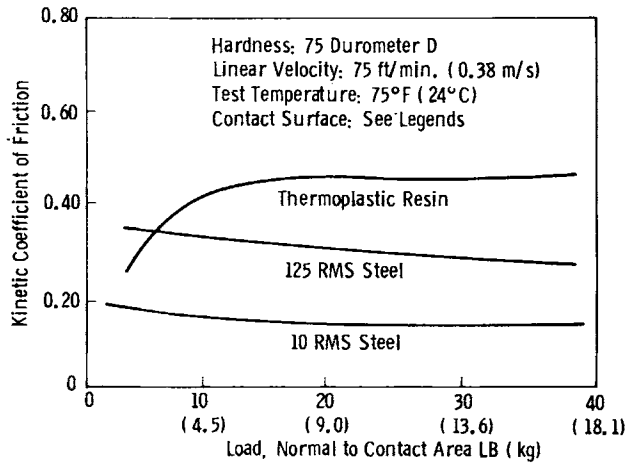
Fig. 13.   Effect of contact surface on lubricity of Adiprene.

compound at speeds up to 400 cm/s.[5] The friction coefficient is seen to decrease with increasing load in apparent agreement with the load dependence of friction.[11] If, however, the friction temperature rise is taken into account, and the data converted to a constant temperature, 20°C, all points fall on one continuous curve.[12] What at first appeared to be a load effect is actually a temperature effect. The data given in Figure 12[5] were collected for 1 cm/s (~ 0.03 ft/s) sliding velocity.

The nature of the contact surface is important in bearing applications. Figure 13 compares the kinetic coefficient of friction of an Adiprene polyurethane against steel machined to rms 10 and rms 125 finishes, as well as against a typical thermoplastic material. The least friction is experienced with the highly polished steel surface, while the highest friction coefficient is observed with the thermoplastic. Plastics do not dissipate heat from the contact area as well as metals, and it is this heat buildup that is responsible for the higher friction coefficient measured for the plastic. For applications where friction must be minimized, use of a mating surface that will dissipate the heat is desirable as is increased hardness of the polymer.

Other examples of decreased coefficient of friction with increasing pressure were found in the literature. The friction coefficient for Teflon was shown to decrease from 0.3 at low pressures to 0.1 at 900 atmospheres (13,000 psi).[13] For polyethylene, increased contact pressure decreased μ from 0.2 to 0.05.[14] When the polyethylene was kerosene soaked, the kerosene acted as a plasticizer or lubricant and μ values decrease further to 0.025.[14]

What is the Influence of Contact Time on Friction?

When a polymer surface is kept in static contact with another polymer surface for long times at high contact pressure, or for short times at low contact pressures and high temperatures, there is an opportunity for polymer chains to diffuse across the interface and lead to very high interfacial bond strengths that approach the tensile strength of the base compounds. An entire body of work has been carried out in this area by Soviet scientists.[15] In addition, extender oils, plasticizers, antioxidants, etc., can diffuse from one

material to the other across the contacting interface.[16, 17]

When a rubber or polymer surface is in contact with metallic surfaces, painted surfaces, or composite surfaces, the ability of polymer molecules to diffuse into the hard surface is reduced. The bond strength that develops, often called "stiction," is generally low. Stiction is also influenced by the contact pressure. Generally the lower the contact pressure the lower the stiction force.

One other area of concern, when contacting cured rubber with hard surfaces for long periods of time (days to months), is the diffusion of oil or plasticizer from the bulk material to the surface of the material, in particular the interface. This can cause a reduction in μ which can result in failure of items which rely on retention of high μ values over time.

Some experimental results on the diffusion (or squeezing) of oil and plasticizer from rubber compounds held under 400 psi contact pressure against a steel surface will be described later in this paper, but it appears that these results corroborate work previously reported in the literature with regard to diffusion of oils from rubber compounds.[16, 17]

How Does Aging of the Rubber Product Influence Friction?

Although nothing specific was found in the literature regarding the influence of elastomer aging on friction, changes in friction would depend on the influence of aging on the rubber. That is, if the rubber softens and becomes more fluid on aging, it would be expected that friction would increase (i.e., the adhesive component of friction would increase). If the rubber hardens, the friction would be expected to decrease or stay about the same. One example of the influence of 10-year aging on friction is described in the next section.

EXPERIMENTAL RESULTS

Development of High Breakaway Friction Materials

Based upon the results shown in Table I (measured at ~ 176 psi contact pressure) for formulations 1 and 2, it can be seen that higher shape factors yield lower coefficients of static friction, thus once again confirming the theory that harder materials and high normal loads reduce the measured μ values. In addition, comparing the friction results for formulations 1 and 5 (SBR), it is also shown (Table II) that removing the oils and plasticizers from the compound formulation increases the measured μ value (0.96 with vs. 1.47 without oil and plasticizer) against epoxy painted steel. The results are not so different for the CR compound of Table I (compare results for formulation 2 with 4). However, the reason for this may be that the processing oil used in the CR formulations is more compatible with the polymer to begin with and the tendency to bloom to the surface is low. Also, the improvement in friction coefficient derived by reducing the surface lubricity, may not have been great enough to offset the increase in hardness that results from the removal of the plasticizers. This may not be the case for the SBR, since even after removal of the plasticizers, it is still softer than the CR compound with plasticizers. Further consideration of this topic is given in the next section.

In order to determine how the coefficient of friction changes as a function of aging, a neoprene rubber compound used in the vertical support pads for the

TABLE I

Summary of Breakaway Friction Values for Rubber Against Epoxy-Painted Steel

Rubber compound	Sample dimensions W × T (Ins.)	Shape factor[a]	Face load (lbs)	Normal pressure (psi)	Friction coeff. (μ)	Tensile strength (psi)	100% Modulus (psi)	Elongation (%)	Tear strength (Pli)	Hardness shore A	Source	Comments
Form #1	0.25 × 0.08	1.34	10.6	176	0.96	1015	247	344	181	57	WEC R & D	SBR, R & D formulation
Form #1	0.5 × 0.08	2.34	20	160	0.68	1015	247	344	181	57	WEC R & D	SBR
Form #2	0.25 × 0.08	1.34	10.6	176	1.28	2446	641	348	241	70	WEC R & D	CR, R & D formulation
Form #2	0.5 × 0.08	2.34	20	160	0.65	2446	641	348	241	70	WEC R & D	CR
Form #4	0.25 × 0.08	1.34	10.6	176	1.30	2770	1226	244	213	80	WEC R & D	Same as Form #2, but no oil
Form #4	0.25 × 0.08	1.34	10.6	176	0.99						WEC R & D	Same as Form #4, but surface abraded
Form #5	0.25 × 0.08	1.34	10.6	176	1.47	2142	447	308	202	65	WEC R & D	Same as Form #1, but no oil
Form #5	0.25 × 0.08	0.78	10.6	176	1.22						WEC R & D	Same as Form #5, but surface abraded
Form #6	0.25 × 0.08	0.78	10.6	176	1.26	2339	1745	145	165	90	WEC R & D	Neoprene w/sulfur cured
Form #7	0.25 × 0.08	0.78	10.6	176	1.52	2484	1928	340	158	90	WEC R & D	Neoprene w/NA-22 cured
Form #8	0.25 × 0.08	0.78	10.6	176	1.49	2423	1048	238	211	80	WEC R & D	Neoprene w/FB sulfur cured
Form #9	0.25 × 0.08	0.78	10.6	176	1.02	2668	967	258	188	80	WEC R & D	Neoprene s/FB/NA-22 cured
Form #10	0.25 × 0.08	0.78	10.6	176	1.37	2519	744	310	250	78	WEC R & D	Neoprene w/sulfur cured
Form #11	0.25 × 0.08	0.78	10.6	176	1.13	2654	847	260	202	79	WEC R & D	Neoprene s/NA-22 cured
Form #12	0.25 × 0.08	0.78	10.6	176	1.14	2037	221	558	218	60	WEC R & D	Butyl 268
7041	0.25 × 0.25	0.25	10.6	176	0.61					65	c	NBR/BR blend
7020	0.25 × 0.25	0.25	10.6	176	0.84					80	c	CR/SBR/BR blend

Sample	Size	S										Description
7061	0.25 × 0.25	0.25	10.6	176	0.68					75	c	IR/Br blend
6601	0.25 × 0.25	0.25	10.6	176	1.00					75	c	EPDM
25639	0.25 × 0.78	0.78	10.6	176	0.56					50	c	NR
84JG205	0.25 × 0.08	0.78	10.6	176	0.72					80	c	NBR brake shoe material
WE #5	0.25 × 0.08	0.78	10.6	176	1.19	1465	595	183	101	68	c	Lab Mix WEC Form #5
WE #4	0.25 × 0.08	0.78	10.6	176	1.35	2631	712	306	224	75	c	Lab Mix WEC Form #4
Trident Pad 82	0.25 × 0.09	0.69	10.6	176	1.02						c	2-Yr-Old Neoprene rubber
Trident Pad CR	0.25 × 0.09	0.69	10.6	176	0.7						c	10-Yr-Old Neoprene rubber
Trident Seal CR	0.25 × 0.15	0.41	10.6	176	0.96						c	10-Yr-Old Neoprene rubber
EPDM	0.25 × 0.25	0.27	20	333	0.60	1300	350	190	80	70	c	Cut from face sheet of pad
CR	0.25 × 0.25	0.33	20	160	0.27						c	CR
SBR[b]	0.5 × 0.25	0.33	20	160	0.38	945	524	270	112	75	c	SBR
Adiprene L-100/BD	0.5 × 0.5	0.17	20	160	0.72						c	Polyurethane
Adiprene L-100/BD	0.25 × 0.25	0.25	10.6	176	0.93						c	Polyurethane
3508	0.5 × 0.5	0.37	20	160	0.75						c	Phenolic/asbestos composite
3508	0.25 × 0.25	0.25	10.6	176	0.79						c	Phenolic/asbestos composite
114	0.5 × 0.5	0.37	20	160	0.82						c	Phenolic/cotton composite
Pu #1	0.25 × 0.25	0.37	10.6	176	0.72						c	Polyurethane
114	0.25 × 0.25	0.37	10.6	176	0.68						c	Phenolic/cotton composite

[a]$S = LW/(2T/(L + W))$, $L = 0.25$ in. for all tests.
[b]Tensile properties measured on 0.25 in. thick samples.
[c]Commercially supplied specimens.

TABLE II
High Friction Elastomer Formulations

Formulation → Ingredient ↓	1	2	4	5	6	7	8	9	10	11	12
SBR 500	100			100							
Neoprene WHV		25	25	1			75	75	100	100	
Neoprene W		75	75		100	100	25	25			
Neoprene FB											
Butyl 268											100
Reogen	2										
Stearic Acid	1	1	1	1	1.33	1.33	1	1	1	1	
Zinc Oxide	5	5	5	5	6.65	6.65	5	5	5	5	5
Agerite D	1			1							
Parflux	7										
Sundex 790	7	10									
N347											50
N550	20	50	50	20	66.5	66.5	50	50	50	50	
N762	25			25							25
Amax	1.25			1.25							
Sulfur	2.25	1.25	1.25	2.25	1.6625		1.25		1.25		1
Methyl Tuads	0.2			0.2							
Maglite D		4	4		5.32	5.32	4	4	4	4	
Agerite Stalite S		2	2		2.66	2.66	2	2	2	2	
Wingstay 100		1	1		1.33	1.33	1	1	1	1	
Chorowax LV		15									
Dixie Clay		20	20		26.6	26.6	20	20	20	20	
Unads		0.6	0.6		0.798		0.6		0.6		
NA-22						1.33		1		1	
TDEDC											0.5
MBT											0.5
ZDMDC											1.5
Zinc Stearate											1

TABLE III
Friction for Compound 4[a] as a Function of Postcure

Postcure (h @ 300°F)	Friction coeff.[b], (μ)
0	1.3
Control	
0.5	1.47
1.0	1.33
4.0	1.23

[a]See Table I for control μ and Table II for formulation.
[b]Normal pressure 176 psi.

Trident submarine launch system, stored at ambient condition for approximately 10 years, was tested for friction coefficient and compared with friction coefficient values for material only three years old. The results of this evaluation indicate a reduction in friction coefficient from 1.02 for three-year-old samples compared to 0.7 for the 10-year-old sample (Table I). This is most likely due to the stiffening of neoprene rubber with time due to crystallization and continued cure. In this case the primary cause is most likely continued cure, since crystallization is complete within a few months for TRT neoprene, and within hours for type W neoprene.[18]

Also, it was of interest to know how the friction characteristics of elastomers change as a function of abrasive wear. To address this issue, samples of both formulations 4 and 5 were abraded with sandpaper to remove the surface skin, followed by coefficient of friction measurements. The results indicate a decrease in friction for the SBR from 1.19 to 0.99 after abrasion, and for CR from 1.37 to 1.22 after abrasion. The exact reason for this observation is not totally clear, except that perhaps the actual contact area is decreased due to the resulting rough surface produced by abrasion, or exposure of oil in the bulk rubber after removal of the skin.

The effect of oven postcure on the friction properties of neoprene rubber was evaluated by postcuring samples of formulation 4 for 1, 2, and 4 h at 300°F. The samples were then tested for friction properties and compared against the control. The results of these tests, given in Table III, are somewhat ambiguous in that the postcured samples have a higher coefficient of friction than the control, yet the coefficient of friction seems to decrease as a function of postcure time. One might argue that the changes in friction as a function of postcure time are insignificant and within experimental error of the test procedure, yet one would expect to see a decrease in friction with postcure due to stiffening of the rubber upon further cure. However, these results indicate that if any real change in friction is occurring, it is not very large.

It appears that from a high friction perspective, either compound 4 or 5 (Table I) would be the best choice of all materials examined, depending upon what other requirements are imposed. However, a consideration of the desired mechanical properties, abrasion resistance, flame resistance, and ozone resistance as well as long-term aging characteristics are also important in any material selection process.

TABLE IV
Results of IR Scans of Exudate Squeezed from Rubber[a]

Sample ID	Relative amount of exudate[c]	IR analysis of exudate
Form #1 SBR (R & D)	4	Uncertain
Form #2 CR (R & D)	6	Paraffin wax
Form #4 CR (R & D)	0	Nothing observed
Form #5 SBR (R & D)	10	Petroleum oil
25639[b]	4	Pariffin wax
6601[b]	2	Paraffin wax
7020[b]	2	Uncertain
7041[b]	2	Misc. organics
7061[b]	10	Uncertain

[a] Rubber samples pressed under 400 psi of pressure for 30 min and exudate examined.
[b] Commercial material from Westinghouse Air Brake Co., courtesy of Mr. D. Ratloff.
[c] Samples rated on a scale from 0 to 10, with 10 being worst case and 1 being little exudate found.

Infrared Spectroscopy of Steel Surface in Contact With Various Rubbers

In some of our testing it was noted that both CR and SBR rubbers (procured commercially in sheet form) maintained a shear load for a few hours but then began to slide at a rate of 2–10 in./min. We speculated that under pressure the oil and/or plasticizer used in the rubber compounds was exuding to the surface from the bulk rubber, and the oil at the interface acted as a film lubricant lowering the coefficient of friction.

In order to verify this theory in a laboratory test, selected rubber samples were held in contact with a polished steel plate for 30 min at 400 psi. The steel surface was then flushed with chloroform, the liquid concentrated, and the concentrate placed on a KBr pellet for infrared analysis. This procedure was followed for the rubber samples listed in Table IV and the relative amounts of exudate were rated in a qualitative manner. It is interesting to note that samples with large amounts of exudate were the samples that slipped during full-scale testing against epoxy painted steel.

Although not unequivocally proven, it appears that oil/wax exudate contributed to reduced μ values and allowed slippage during the full-scale testing.

CONCLUSIONS

1. The coefficient of friction is comprised of two parts, hysteresis loss due to surface deformation and molecular adhesion at the material/substrate interface.
2. Test methodology and material properties such as hardness, influence the measured value of the coefficient of friction and as such the coefficient of friction cannot be considered an inherent material property.
3. Plasticizers, oils, and waxes that can exude to the interface have a profound effect on the measured frictional properties of polymers, in particular elastomers.
4. The higher the sliding speed during testing, the lower the measured value of the coefficient of friction.

5. Harder substrate pairs yield lower values of friction coefficients compared to similar materials that are softer, under otherwise identical test conditions.

6. Higher shape factors in part design will yield lower measured values for friction compared to the same materials using a design with a smaller shape factor. This is due to the mechanical stiffening associated with large shape factor values.

7. Higher normal loads yield lower measured friction values.

8. Rubber formulations developed by us and identified in Table II have measured coefficients of friction greater than 1.2 against epoxy painted steel, which is significantly greater than most materials identified in the literature or tested by us (Table I).

9. Abrasion of the rubber surface results in lower values of friction compared with the same material having a virgin surface.

10. The influence of long-term room temperature aging ($\sim$ 10 years) on friction is not known unequivocally. However, one example shows friction values for three-year-old material to be $\sim$ 1.02 while values for 10-year-old material were determined to be 0.7 and 0.96 on duplicate samples.

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