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Vegetable Oils — Structure and Performance

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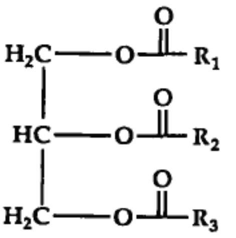
INTRODUCTION

Vegetable oils are found in the seed or fruit of various plants.[1,2] They are predominantly triacylglycerols (triglycerides) in which three fatty acid groups are esterified to a glycerol backbone (Figure 1).[3]



Triacylglycerol
(Triglyceride)

(R_1, R_2, R_3 = Fatty acid alkyl groups)

FIGURE 1 Structure of a triacylglycerol.

Vegetable oils have to be extracted or expressed from the plant tissue in the "crude" form. The "crude" vegetable oil, although predominantly a triglyceride, contains several minor components like steroids, pigments, waxes, etc. In most applications these minor components and other impurities are removed, using specific purification steps. Purification involves one or all of the following steps: refining (free fatty acid removal), bleaching (color removal), deodorization (free acid and peroxide removal), winterization (wax removal).[4]

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COMPOSITION

The physical and performance properties of a purified vegetable oil are largely influenced by the fatty acid groups present in the triacylglycerol (Figure 1).

Common vegetable oils contain a combination of saturated and unsaturated fatty acids (Table 1). The double bonds in unsaturated fatty acids generally have the *cis* configuration. Some vegetable oils also contain significant amounts of fatty acid groups with chemical functionality, in addition to the saturated and unsaturated fatty acids (Table 2). Examples of vegetable oils containing special functionality are castor and lesquerella oils (hydroxy functionality),[5] vernonia oil (epoxy functionality),[6] and meadowfoam oil (multiple double bonds separated by more than two carbon atoms).[7] Because of the presence of chemical functionality (Figure 5) these oils can be subjected to unique chemical modifications that can be exploited in lubricating applications.[8-10]

The chemical structures of various fatty acids found in vegetable oils are shown in Figures 2 to 5.

STRUCTURE/PERFORMANCE RELATIONSHIPS

Qualitative generalizations can be made about the structure–performance relationships for common vegetable oils. Thus, it can be seen from Table 3 that oxidative stability increases with decreasing unsaturation, while the reverse holds true for low temperature properties. Because of this, the use of either highly saturated or highly polyunsaturated vegetable oils in lubricant applications is limited.

In contrast to these extremes, a special class of oils, containing a high oleic content (≥75% oleic) and low polyunsaturated fatty acid content (linoleic and/or linolenic), displays good oxidative stability with acceptable low temperature properties.[11,12] This makes them well suited for use in lubricants compared to conventional vegetable oils.

PERFORMANCE PROPERTIES

Basic physical properties of various vegetable oils are shown in Table 4. General performance properties of interest in lubricating applications are shown in Table 5 while Table 6 shows friction and load bearing properties. Note that the data in Tables 4 to 6 are without additives.

Table 7 shows the oxidative stability of vegetable oils in the presence of antioxidants.[13] These data indicate how oxidative stability increases with decreasing unsaturation — decreasing iodine value.

APPLICATIONS

Vegetable oils are mainly consumed in foods. However, they also serve as the primary feedstock for the oleochemical industry and are gaining popularity as lubricating base oils.[14,15]

Vegetable oils are obtained from renewable resources and are biodegradable. Thus they offer specific environmental benefits over mineral oil-based lubricants. This is significant in applications where the lubricant is "lost" in the environment, e.g., chain bar lubricants and hydraulic fluids for farm machinery.[16]

In addition to environmental benefits, vegetable oils also have certain performance advantages over conventional mineral oil base stocks. These include low volatility, high flash points, viscosity index, and excellent lubricity.

The primary drawback of conventional vegetable oils is their lower oxidative stability relative to mineral oils and certain synthetic esters. However, with recent advances in breeding technology, it is becoming possible to alter the physical properties of conventional vegetable oils by changing fatty acid profiles. A specific example pertaining to lubricant applications is the improvement of oxidative stability by increasing the oleic content in various oils.[17,18]

TABLE 1
Fatty Acid Percentage Compositions for Common Vegetable Oils[a]

		Saturated Fatty Acids										Monounsaturated Fatty Acids				Polyunsaturated/Other Fatty Acids[a]			
	Vegetable Oil	Cap-roic	Cap-ric	Cap-rilic	Lau-ric	My-ristic	Palm-itic	Stea-ric	Ara-chidic	Behe-nic	Tetra-decanoic	Palm-itoleic	Oleic	Gad-eolic	Eru-cic	Lin-oleic	Lin-olenic	Other	Iodine Value[b]
No.	No. of carbon atoms: double bonds	6:0	8:0	10:0	12:0	14:0	16:0	18:0	20:0	22:0	24:0	16:1	18:1	20:1	22:1	18:2	18:3		
1	Medium chain triglycerides	2	66	31	1														5–9
2	Palm kernel oil - stearin fraction	0.1	2.4	3.2	55.2	19.9	8.1	3.3	0.1				6.9			0.8			6–10
3	Coconut oil	0.5	7.1	6	47.1	18.5	9.1	2.8	0.1	0.0			6.8			1.9	0.1		7–12
4	Tucum oil	0.2	2.8	2.1	51.7	22	6.4	2.0	0.1				10.3			2.4			10–14
5	Baribasu oil	0.4	6	5.1	42.2	16.8	9.3	3.5	0.1				14.2			2.4			13–18
6	Palm kernel oil	0.2	3.3	3.4	48.2	16.2	8.4	2.5	0.1				15.3	0.1		2.3			14–19
7	Palm kernel oil – olein fraction	0.2	4.3	3.7	42.6	12.4	8.4	2.5	0.1				22.3	0.1		3.4			25–31
8	Cocoa butter					0.1	26.3	33.8	1.3	0.2		0.4	34.4	0.1		3.1			33–40
9	Palm oil – stearin fraction				0.7	1.5	55.8	4.8	0.4	0.1			29.6			7.2	0.1		45–50
10	Palm oil				0.1	1	44.4	4.1	0.3	0.1		0.2	39.3			10.0	0.4		50–55
11	Palm oil – olein fraction				0.2	1	39.8	4.4	0.4	0.1		0.2	42.5			11.2	0.2		56–60
12	Sunflower oil, high oleic (90% oleic)						1.6	2.3		0.6			89.5			5.5			80–85
13	Sunflower oil, high oleic (80% oleic)						3.7	5.4	0.4	0.1		0.1	81.3			9.0			80–85
14	Safflower high oleic (80% oleic)					0.1	3.6	5.2	0.4	1.2	0.3	0.1	81.5	0.2		7.3	0.1		80–85
15	Olive oil, virgin						13.7	2.6	0.4	0.1	0.1	1.5	67.5	0.3		12.7	0.6		80–90
16	Corn oil, high oleic (62% oleic)						7.0	2.4	0.4	0.1		0.1	62.8	0.1		25.7	0.7		80–90
17	Canola oil, high oleic low linolenic (75% oleic; 2% linolenic)						3.7	2.2		0.4			72.9	1.4		15.2	2.0		80–90
18	Canola oil, high oleic (75% oleic)							4.0					74.5			13.5	6.8		85–90

TABLE 1 (CONTINUED)
Fatty Acid Percentage Compositions for Common Vegetable Oils[a]

		Saturated Fatty Acids										Monounsaturated Fatty Acids				Polyunsaturated/Other Fatty Acids[a]			
	Vegetable Oil	Cap-roic	Cap-ric	Cap-rilic	Lau-ric	My-ristic	Palm-itic	Stea-ric	Ara-chidic	Behe-nic	Tetra-decanoic	Palm-itoleic	Oleic	Gad-eolic	Eru-cic	Lin-oleic	Lin-olenic	Other	Iodine Value[b]
No.	No. of carbon atoms: double bonds	6:0	8:0	10:0	12:0	14:0	16:0	18:0	20:0	22:0	24:0	16:1	18:1	20:1	22:1	18:2	18:3		
19	Peanut oil					0.1	10.0	2.5	1.3	3.1	1.7	0.2	48.4	1.5		31.0			84–100
20	Rice bran oil					0.1	16.2	1.7		0.2	0.3	0.2	39.4	0.7		38.4	1.7		84–100
21	Sesame oil					0.1	9.3	5.4	0.2	0.1		0.1	39.8	0.2		43.7	0.4		84–100
22	Rapeseed oil, high erucic (HEAR)					0.1	3.8	1.2	0.7		1.0	0.3	18.5	6.6	41.1	14.5	11.0	—[c]	100–115
23	Canola oil, low erucic, low glucosinolate (LEAR)					0.1	4.1	1.8	0.7	0.3	0.2	0.3	60.9	1.0	0.7	21.0	8.8		100–115
24	Cottonseed oil				0.1	0.7	21.6	2.6	0.3	0.2		0.6	18.6			54.4	0.7		100–120
25	Corn oil					0.1	10.4	2.0	0.1	0.1	0.2	0.1	26.3	0.3		59.0	0.3		118–128
26	Walnut oil					0.03	7.3	2.6	0.1	0.0		0.1	15.9	0.2		59.7	13.7		120–140
27	Soybean oil					0.1	10.6	4.0	0.3	0.3		0.1	23.2			53.7	7.6		123–139
28	Sunflower oil					0.1	7.0	4.5	0.4	0.7		0.0	18.7	0.1		67.5	0.8		125–140
29	Safflower oil					0.1	7.0	2.7	0.3	0.3	0.1	0.1	15.1	0.3		73.1	0.3		140–150
30	Linseed oil						5.4	3.5	0.2	0.3	0.1		19.9	0.3		17.9	51.2		170–190

[a] Data are based on gas chromatographic analysis and are sorted by iodine number ranges; percentages do not necessarily add up to 100 % since only prominent fatty acids are shown.

[b] Iodine value ranges are shown based on actual determinations and literature values (*CRC Handbook of Chemistry and Physics*; 1973–1974; 54th ed., D-189).

[c] 0.7% C20:2

TABLE 2

Fatty Acid Percentage Compositions for Vegetable Oils with Special Chemical Functionality[a]

		Common Fatty Acids					Special Functionality Fatty Acids									
	Vegetable Oil	**Palm-itic**	**Stea-ric**	**Oleic**	**Lin-oleic**	**Lin-olenic**	**Ricin-oleic**	**Lesque-rolic**	**Densip-olic**	**Auricolic**	**Vernolic**	**Meadow-foam Acids**	**Meadow-foam Acids**	**Meadow-foam Acids**	**Meadow-foam Acids**	**Iodine Value[b]**
No.	**Carbon Atoms: Double Bonds**	**16:0**	**18:0**	**18:1**	**18:2**	**18:3**	**18:1**	**20:1 14-OH**	**C18:2 12-OH**	**C20:2 14-OH**	**C18:1 12,13 Epoxy**	**20:1 Δ5[c]**	**22:1 Δ5[c]**	**C22:1 Δ13[c]**	**C22:2 Δ5,13[c]**	
A	Castor oil		1.8	3.5	4.2		89.2									86
B	Lesquerella oil		1.8	14.6	7.0	9.1		57.3	2	3.9						99
C	Meadowfoam oil			2.0	0.5							62.5	2.5	12.0	18.0	95
D	Vernonia oil	2.5	2.4	4.6	11.2						78.2					

[a] Data obtained by gas chromatographic analysis; percentages do not necessarily add to 100%, since only prominent fatty acids are shown.

[b] Actual iodine values are shown.

[c] Indicates position of unsaturation.

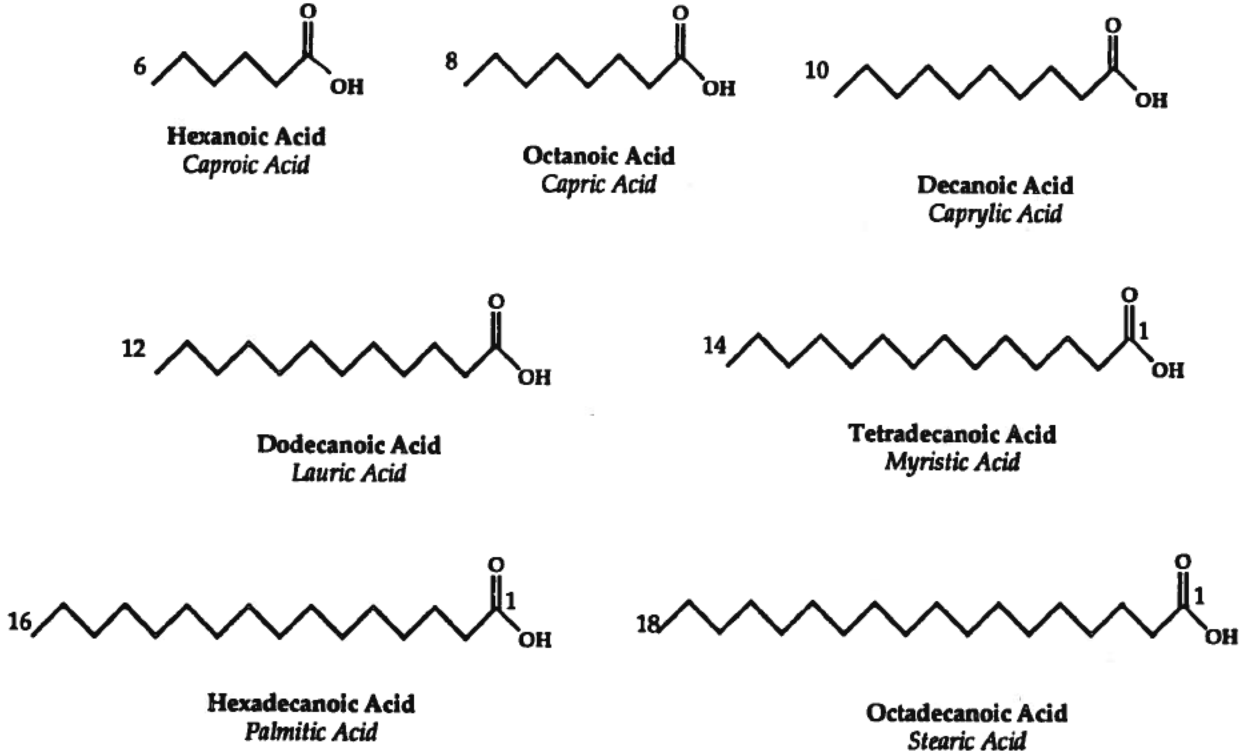
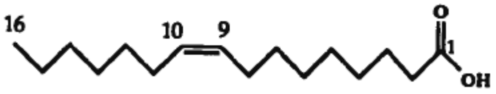


FIGURE 2 Structure of saturated fatty acids.

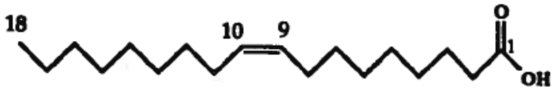
Icosanoic Acid
Arachidic Acid

Docosanoic Acid
Behenic Acid

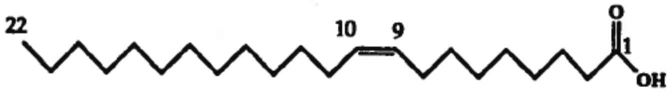
FIGURE 2 (continued).



cis-9-Hexadecenoic Acid
Palmitoleic Acid



cis-9-Octadecenoic Acid
Oleic Acid

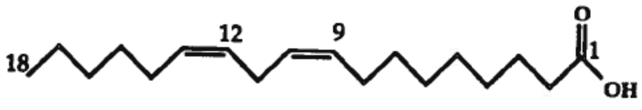


cis-9-Docosenoic Acid
Erucic Acid

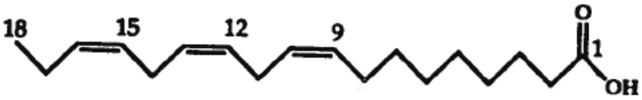
FIGURE 3 Structures of monounsaturated fatty acids.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the help provided by Mr. Rick Unger in performing several fatty analyses shown in Table 1 and the Lubrizol Corporation for supporting this work.

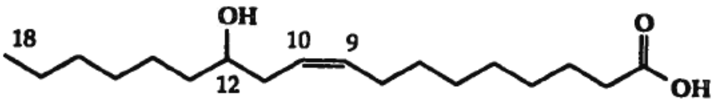


cis-9,12-Octadecadienoic Acid
Linoleic Acid

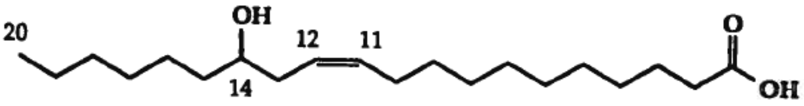


cis-9,12,15 -Octadecatrienoic Acid
Linolenic Acid

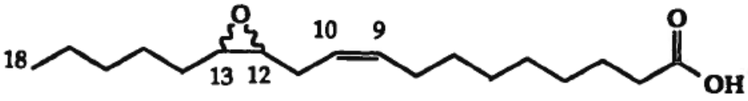
FIGURE 4 Structures of polyunsaturated fatty acids.



cis-12-Hydroxy-9-Octadecenoic Acid
Ricinoleic Acid - Castor Oil

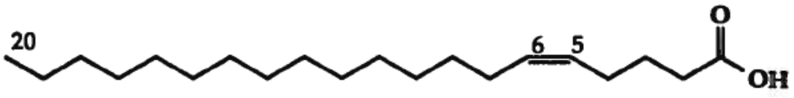


cis-14-Hydroxy-11-Icosenoic Acid
Lesquerolic Acid - Lesquerella Oil

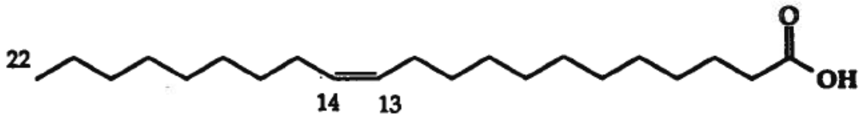


cis-12,13-Oxido-9-Octadecenoic Acid
Vernolic Acid - Vernonia Oil

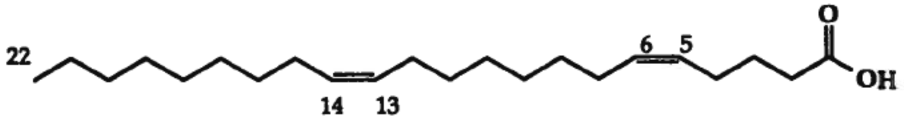
FIGURE 5 Structures of fatty acids with special chemical functionality.



cis-5-Icosenoic Acid
(Meadowfoam Oil)



cis-13-Docosenoic Acid
(Meadowfoam Oil)



cis-5,13-Docosadienoic Acid
(Meadowfoam Oil)

FIGURE 5 (continued).

TABLE 3
Qualitative Structure-Performance Relationships for Vegetable Oils[a]

	Predominant Fatty Acid		
Lubricant Property	**Saturated[b] (i.e., Coconut Oil)**	**Monounsaturated[b] High Oleic Oils**	**Polyunsaturated[b] (i.e., Soybean Oil)**
Oxidative stability	Excellent	Very Good	Poor
Low temperature properties	Poor	Good	Good
Viscosity index	~130	~200	~200

[a] Note that the designations poor–excellent are comparative for a data set containing vegetable oils only; mineral oils and certain saturated synthetic esters display better oxidative stability.

[b] Saturated fatty acids do not contain double bonds; monounsaturated fatty acids contain one double bond (oleic acid), and polyunsaturated fatty acids contain either two (linoleic acid) or three (linolenic acid) double bonds. See Figures 3 and 4 for structures: note the *cis* configuration of the double bond.

TABLE 4
Basic Physical Properties of Vegetable Oils[a]

No.[b]	ASTM Test Method No.: Vegetable Oil	Color[c] D1500	Flash Point COC D92 °C	Acid Number[c] D974	Kinematic Viscosity D2270 cSt @ 40°C	Kinematic Viscosity D2270 cSt @ 100°C	VI D2270	Pour Point D97 °C	Brookfield Viscosity D2983 cP @ −12°C/−25°C/ −35°C
23	Canola oil	L0.5	328	0.1	34	7.8	215	−21	1,360/solid/solid
18	Canola oil, high oleic (75% oleic)	L0.5	326	0.2	37.3	8.4	212	−21	1,470/solid/solid
17	Canola oil, high oleic, low linolenic	L0.5	325	0	38.6	8.6	210	−18	Solid/solid/solid
A	Castor oil	L0.5	>200	0.6	255.6	19.5	87	−33	37,500/solid/—
2	Coconut oil	L1.0	294	0.1	27.6	5.9		25	Solid/solid/solid
25	Corn Oil	L0.5		0.1	31.92	7.7	223	−15	2,210/solid/solid
16	Corn oil, high oleic (62% oleic)	L1.0	320	0	36.1	8.2	214	−18	4,520/solid/solid
24	Cottonseed oil								
B	Lesquerella oil	L3.0	230	0.2	115.4	14.2	124	−27	8,850/solid/—
30	Linseed oil								
C	Meadowfoam		320		48.9	10.3		6	Solid/solid/solid
1	Medium chain triglycerides[d]	L0.5	232	0.1	13.8	3.5	130	−21	Solid/solid/solid
15	Olive oil	L1.0		0.2	38.3	8.4	203	−9	Solid/solid/solid
19	Peanut oil	L0.5		0.01	36.9	8.3	212	3	Solid/solid/solid
22	Rapeseed oil, high erucic	L2.5		0.62	40.27	9.08	217	−18	1,360/solid/solid
20	Rice bran oil	L1.0		0.1	37.6	8.4	208	−6	Solid/solid/solid
29	Safflower oil	L0.5		0.03	30.2	7.5	231	−18	620/solid/solid
21	Sesame oil	L0.5		0.05	34.6	7.9	215	−6	Solid/solid/solid
27	Soybean oil	L0.5	320	0.07	31	7.6	227	−9	Solid/solid/solid
28	Sunflower oil	L0.5	325	0.04	31.6	7.7	226		4,040/solid/solid
13	Sunflower oil, high oleic (80% oleic)	L0.5	326	0.03	38.8	8.5	205	−12	Solid/solid/solid
12	Sunflower oil, high oleic (90% oleic)	L0.5	330	0.27	39.9	8.7	203	−15	Solid/solid/solid
26	Walnut oil	L2.5	257	20.9	27	6.9	232	−15	2,900/solid/solid

[a] Table is arranged alphabetically. Purified vegetable oils used as commercially available.

[b] Number shown corresponds to number in Table 1 (number) or letter in Table 2 (Alphabet).

[c] These properties are highly dependent on processing and subsequent storage conditions.

[d] Synthetic, commercial product.

TABLE 5
Lubricant Performance Properties of Vegetable Oils[a]

	ASTM Test Method No.:	Copper Strip D130	Rust Test D665		Foam D892	Demulsibility D1401	Hydrolytic Stability D2619	RBOT D2272	Cincinnati Milacron (PartA)	
No.[b]	Vegetable Oil	3 Hrs @ 100, 121, 149°C	Part A — Distilled Water	Part B — Synthetic Sea Water	Seq I/II/III	ml oil/water/ emln. (min.)	Cu Wt. Loss (mg)/Cu App./ NNA Aq.	Minutes	Cu Rod/Fe Rod/Sludge/% Evapn	Color Change
23	Canola oil	1A/1A/1A	Fail severe	Fail severe	0,0/0,0/0,0	41/39/0 (15)	0.04/4A/3.9	10	3, 2, 7.3, 0	L1.0–L3.0
18	Canola oil, high oleic (75% oleic)	1A/1A/1A	Fail severe	Fail severe	0,0/0,0/0,0	40/40/0 (10)	0/1B/1.6	15	1, 1, 2.0	
17	Canola oil, high oleic, low linolenic	1A/1A/1B	Fail mod.	Fail severe	0,0/0,0/0,0	41/39/0 (15)	0.0/3A/0.02	12	7, 7, 4, 0	L1.0–L3.0
A	Castor oil	1A/1A/1A	Fail severe	Fail severe	470/180,30/0,400/10	0/20/60 (3)		29	4, 5, 12.5, 0.1	
2	Coconut oil						0.00/1A/0.12		5, 4, 0, 0	L1–L1.5
25	Corn oil	1A/1A/1A	Fail severe	Fail severe	0/0,0/0,0/0	43/37/0 (10)	0.00/2A/0.20	9	9, 4, 2, 3, –0.5	L1–L3.0
16	Corn oil, high oleic (62% oleic)	1A/1A/2B.	Fail severe	Fail severe	0,0/0,0/0,0	40/40/0 (10)		15	3, 4, 4.8, –0.3	
24	Cottonseed oil									
B	Lesquerella oil	1A/1A/1A	Fail severe	Fail severe	490/20,40,0/230.0	41/39/0 (30)	0.1/2B/3.3	17	2, 1, 14.8, 0	L1.5–L3.0
30	Linseed oil									
C	Meadowfoam					41/36/3 (30)		22	6, 2, 0.0, 1.0	L1.0–L 4.0
1	Medium chain triglyceride[c]	1B/1B/1B	Fail severe	Fail severe			0.0/4A/11.0	57	5, 4, 1.1, 3	L1–L1.5
15	Olive oil	1A/1A/1A	Fail severe	Fail severe	0,0/0,0/0,0	42/38/0 (15)	0.00/2E/0.09	13	9, 5, 1.3, 0.5	L1.0–L4.0
19	Peanut oil	1A/1B/1B	Fail severe	Fail severe	0,0/0,0/0,0	42/38/0 (10)	0.01/3A/0.02	14	9, 5, 1.3, –0.9	L1.0–L4.5
22	Rapeseed oil — high erucic	1A/1A/1A	Fail severe	Fail severe		20/11/49 (30)		13		
20	Rice bran oil	1A/1A/1A	Fail severe	Fail severe	10,0/0,0/0,0	40/40/0 (25)	0.03/3A/0.04	14	2, 1, 0.6, –0.8	L1.5–L3.5
29	Safflower oil	1A//1A	Fail medium	Fail severe	0,0/0,0/0,0	41/39/0 (20)	0.00/2A/0.02	12	8, 5, 263.4, –0.4	L1.0–L3.5
21	Sesame oil	1A/1A/1A	Fail medium	Fail severe	0,0/0,0/0,0	42/38/0 (10)	0.10/2E/0.09	14	3,4, 3.0, –0.8	L1.0–L1.5
27	Soybean oil	1A/1A/1A	Fail severe	Fail severe	0,0/0,0/0,0	40/40/0 (15)		13	4, 4, 0.9, 0.5	L1.0–L2.5
28	Sunflower oil	1A/1B/1B	Fail severe	Fail severe	0,0/0,0/0,0	41/30/9 (30)		9	4, 3, 1, 0.5	L1.0–L2.5
13	Sunflower oil, high oleic (80% oleic)	1A/1A/1A	Fail severe	Fail severe	0,0/0,0/0,0	40/40/0 (15)	0.02/1A/0.05	14	2, 2, 3.0	L1.0–L3.0
12	Sunflower oil, high oleic (90% oleic)	1A/1A/1A	Fail mod.	Fail severe	0,0/0,0/0,0	40/40/0 (10)	0.00/1B/0.03	16	1, 1, 1.8	L1.0–L3.0
26	Walnut oil					40/40/0 (5)		18		

[a] Table is arranged alphabetically. Purified vegetable oils used as commercially available.

[b] Number shown corresponds to number in Table 1 (Number) or letter in Table 2 (Alphabet).

[c] Synthetic, commercial product.

TABLE 6
Friction and Load Bearing Properties of Vegetable Oils[a]

	ASTM Test Method No.:	4-Ball Wear D2672	Shell 4-Ball EP D2783	Falex Wear D2670	Timken "OK" Load D2509/2782
No.[b]	Vegetable Oil	Scar Dia./Coeff. of Friction	Seizure/Weld/ LWI	No. Of Teeth[d] (Temp. Diff.)	"OK" Load (lbs)
23	Canola oil	0.87/0.07	63/126/24.5	54,59 (90,118)	22 (13300)
18	Canola oil, high oleic (75% oleic)	0.6/0.072	50/126/17.5	20,25 (86,83)	
17	Canola oil, high oleic, low linolenic	0.6/0.072	50/126/17.5	20,25 (58,64)	
A	Castor oil	0.51/0.04	63/126/22.2	29,29 (58,64)	30 (14500)
2	Coconut oil				
25	Corn oil	0.84/0.07	63/126/25.4	25,29 (90,79)	
16	Corn oil, high oleic (62% oleic)	0.6/0.07	63/126/26.2		
24	Cottonseed oil				
B	Lesquerella oil	0.63/0.05	63/126/25.4	41,37 (90,82)	30 (18127)
30	Linseed oil				
C	Meadowfoam	0.6/0.073			
1	Medium chain triglycerides[c]			18, 10 (—,—)	
15	Olive oil	0.61/0.08	63/126/21.6	16,24 (70,90)	
19	Peanut oil	0.63/0.07	63/126/21.5	20,14 (114,109)	
22	Rapeseed oil — high erucic				
20	Rice bran oil	0.75/0.11	63/126/21.2	21,5 (49, 65)	
29	Safflower oil	0.66/0.08	63/126/24.2	39,36 (87,89)	
21	Sesame oil	0.66/0.063		33,47 (88,100)	
27	Soybean oil	0.66/0.08		24,43 (98,106)	
28	Sunflower oil	0.69/0.08			15 (11538)
13	Sunflower oil, high oleic (80% oleic)	0.65/0.08	63/126/21.9	58,51 (103,113)	20 (13025)
12	Sunflower oil, high oleic (90% oleic)	0.65/0.09	63/126/21.9		20 (13528)
26	Walnut oil	0.57/0.09	50/126/17.8		

[a] Table is arranged alphabetically. Purified vegetable oils used as commercially available.

[b] Number shown corresponds to number in Table 1 (Number) or letter in Table 2 (Alphabet).

[c] Synthetic, commercial product.

[d] Duplicate tests.

TABLE 7
Oxidative Stability of Vegetable Oils[a]

	ASTM Method:	RBOT No Antioxidant D2272	RBOT With Antioxidant[c] D2272	
No.[b]	Vegetable Oil	Min for 25 lb Pressure Loss	Min for 25 lb Pressure Loss	Iodine Value[a]
1	Medium chain triglycerides[c]	57	325	7
2	Coconut oil	27	425	9
12	Sunflower oil, high oleic (90% oleic)	16	439	82
13	Sunflower oil, high oleic (80% oleic)	14	352	85
15	Olive oil	13	82	85
A	Castor oil	29	179	86
17	Canola oil, high oleic, low linolenic	12	195	87
18	Canola oil, high oleic (75% oleic)	15	158	90
16	Corn oil, high oleic (62% oleic)	15	68	90
19	Peanut oil	14	105	92
20	Rice bran oil	14	41	92
21	Sesame oil	14	37	92
C	Meadowfoam	22	60	95
B	Lesquerella oil	17	89	99
23	Canola oil	10	43	108
24	Cottonseed oil	13		110
25	Corn oil	9	42	123
26	Walnut oil	18	21	130
28	Sunflower oil	9	38	132
27	Soybean oil	13	28	141
29	Safflower oil	12	35	145
30	Linseed oil			180

[a] Data sorted by iodine value; iodine values shown represent the median of the range shown in Table 1.

[b] Number corresponds to Table 1 (number) or letter in Table 2 (Alphabet).

[c] Synthetic commercial product.[13]

NOTES AND REFERENCES

1. Olive oil is an example of a vegetable oil derived from a fruit.
2. Animal and dairy fats, although triglycerides, are not described in this monograph. Animal fats include tallow, lard, and chicken fat, and dairy fats include butter fat. The key feature in animal-derived oils is the presence of significant amounts of palmitoleic acid (3 to 4%), whereas in dairy fats it is the presence of small and medium chain fatty acid groups.
3. Jojoba oil is also not described in this monograph, since although it is commonly a vegetable oil, by source, it does not have the triglyceride structure; it is predominantly a simple monoester-oleyl oleate. "Jojoba Oil and Derivatives," Wisniak, J., *Prog. Chem. Fats Other Lipids*, 1977, 15, 167–218.
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14 Solid Lubricants

E. R. Booser

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These materials provide thin films between two surfaces to reduce friction and wear, generally for high temperatures, vacuum, nuclear radiation, aerospace, and other environments that preclude the use of conventional oils and greases. The wide range of solid lubricants can generally be classified as inorganic compounds, organic polymers, and metal films.[1-3] The inorganic compounds and polymers are commonly used in a bonded coating over chemical conversion coatings (See Section VII, Chapter 57) to provide lower friction and wear on metal surfaces.[4,5]

INORGANIC COMPOUNDS

Most important of this group listed in Table 1 are layer–lattice solids in which bonding between atoms in an individual layer is by strong covalent or ionic forces and those between layers are by relatively weak ionic forces. Molybdenum disulfide and graphite are the preferred choices; others which find occasional use are tungsten disulfide, tungsten diselenide, niobium diselenide, calcium chloride, calcium iodide, and graphite fluoride.[6]

Graphite is commonly used as a dry powder or as a dispersion in water, oils, greases, or solvents. The dispersions are used for lubricating tools, dies, and molds for metalworking and metal forming; with oxygen equipment; and for conveyors and other high temperature industrial applications. In vacuum or in atmospheres where no moisture can be absorbed, mixing with cadmium oxide, MoS_2, or organic binders will restore the film-forming ability of graphite.[1] Oxidation by air commonly sets a limit of about 550°C; above 100°C high friction may be encountered from water desorption.

Molybdenum disulfide has replaced graphite in many applications for its independence from the need for adsorbed vapors in providing lubrication, superior load capacity, and more consistent properties.[1] MIL-M-7866 covers the most common grade.[5] Above 400°C, MoS_2 is oxidized to the trioxide which may be abrasive.

For temperatures above 550°C, classes of materials that have shown promise are oxides formed on nickel-base and cobalt-base superalloys, and fluorides such as CaF_2, BaF_2, LiF, and MgF_2 applied as ceramic-bonded coatings, by fusion bonding, or as components of plasma-sprayed composite coatings.[6]

Various soft inorganic materials without a layer-lattice structure also find some use as solid lubricants: lime as a carrier in wire drawing, talc and bentonite as fillers for grease in cable pulling,

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TABLE 1
Common Solid Lubricants

Material	Acceptable Usage Temperature, °C				Av Friction Coefficient, *f*		Remarks
	Minimum		Maximum				
	In Air	In N_2 or Vacuum	In Air	In N_2 or Vacuum	In Air	In N_2 or Vacuum	
Molybdenum disulfide, MoS_2	–240	–240	370	820	0.10–0.25	0.05–0.10	Low *f*, carries high load, good overall lubricant, can promote metal corrosion
Polytetrafluoroethylene (PTFE)	–70	–70	290	290	0.02–0.15	0.02–0.15	Lowest *f* of solid lubricants, load capacity moderate and decreases at elevated temp
Fluoroethylene–propylene copolymer (FEP)	–70	–70	200	200	0.02–0.15	0.02	Low *f*, lower load capacity than PTFE
Graphite	–240		540	Unstable in vacuum	0.10–0.30	0.02–0.45	Low *f* and high load capacity in air, high *f* and wear in vacuum, conducts electricity
Niobium diselenide, $NbSe_2$			370	1,320	0.12–0.40	0.07	Low *f*, high load capacity, conducts electricity (in air or vacuum)
Tungsten disulfide, WS_2	–240	–240	430	820	0.10–0.20		*f* not as low as MoS_2 temp capability in air a little higher
Tungsten diselenide, WSe_2			370	1,320			Same as for WS_2
Lead sulfide, PbS			480		0.10–0.30		Very high load capacity, used primarily as additive with other solid lubricants
Lead oxide, PbO			650		0.10–0.30		Same as for PbS
Calcium fluoride–barium fluoride eutectic, CaF_2–BaF_2	430	430	820	820	0.10–0.25 above 540°C 0.25–0.40 below 540°C	Same as in air	Can be used at higher temp than other solid lubricants, high *f* below 540°C
Antimony trioxide, Sb_2O_2							High load capacity, used as corrosion inhibitor in MoS_2 lubricants

From Lipp, L. C., *Lubrication Engineering*, 32, 574–584, 1976. Reprinted by permission of Society of Tribologists and Lubrication Engineers. All rights reserved.

zinc oxide in high load capacity greases, and milk of magnesia for bolts. Toxicity has led to diminished use of basic white lead and lead carbonate.

ORGANIC POLYMERS

Various polymers provide self-lubricating properties when applied as thin films, as bearing materials, and as binders for lamellar solids.[1,3,4,7] Coatings are typically applied in powder or dispersion form (in thicknesses from 25 μm and upward) and then fused to the surface to provide lubricity, wear resistance, or release properties. PTFE is outstanding in this group and is effective from about –200 to 250°C in providing a coefficient of friction in the 0.03 to 0.1 range. Chapter 52, in Section VI, provides details on the properties of polymers and their composites.

TABLE 2
Properties of Soft Metals

Metal	Mohs Hardness	Melting Point, °C
Gallium		30
Indium	1	155
Thallium	1.2	304
Lead	1.5	328
Tin	1.8	232
Gold	2.5	1,063
Silver	2.5–3	961

From Peterson, M. B., Murray, S. F., and Florek, J. J., *ASLE Trans.*, 2, 225–234, 1960. With permission.

METAL FILMS

Table 2 lists soft metals which in many ways are ideal solid lubricants.[8] They have low shear strength, can be bonded to metal substrates, have good lubricity, and offer high thermal conductivity. Metal films are applied by electroplating, evaporation, sputtering, or ion plating.

Finding use as bolt lubricants are electroplated silver and copper, as are commercial formulations incorporating powders of nickel, silver, copper, and lead. Tin, zinc, copper, and silver coatings are used as lubricants in metalworking where use of lead has been eliminated for its toxicity.[9] Silver films are used in a variety of sliding and rolling contacts in vacuum and at high temperatures since silver is unique in forming no alloys with steel and is soft at high temperatures. While gallium is above its melting point under most conditions, it has been effective when applied as a coating in vacuum.

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52 Friction, Wear, and PV Limits of Polymers and Their Composites

Thierry A. Blanchet

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INTRODUCTION

Table 1 provides *representative* values describing the tribological behavior of polymers and composites in dry, unlubricated sliding contact with finished metallic surfaces under ambient room temperature conditions. Data are provided for static and kinetic coefficient of friction, steady-state rate of wear (expressed as volume loss per distance slid, per normal load), and the limiting product of apparent contact pressure P and sliding velocity V under which the material may be safely employed. (When multiplied by the friction coefficient, the product PV dictates the rate of frictional heat dissipation per unit area, and therefore the contact temperatures at the sliding interface. Since for any given material critical temperatures exist, a limiting PV therefore exists). The effects of addition of a single hard particulate or solid lubricant filler to composites of these polymer matrices are also given. Loading levels of filler materials are either denoted by volume percent (v%) or weight percent (w%). Though more than one filler type is often employed, space does not permit the additional listing here of the numerous composites of matrix and two or more filler materials.

The tabulated data originate from a broad variety of sources, including national laboratories, universities, and corporations, and were collected from publications in peer-reviewed professional journals, conference proceedings, and product bulletins. In most cases an effort was made to present single representative or average values for each composite system. When separate investigators reported very different behavior for very similar materials, both sets of data are presented. Such variations may result from slight differences in test materials, or from system differences involving counterface roughness and chemistry, load, speed, and contact kinematics, and atmosphere and temperature. Slight variations in these material or sliding system attributes may lead to significant tribological differences, as illustrated in the following examples.

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TRIBOLOGICAL PROPERTIES OF POLYMERS

SLIDING SPEED

As polymers are viscoelastic materials and can be thought of as possessing characteristic stress relaxation times, sliding speed can be likened to an imposed strain rate. Therefore kinetic friction coefficient usually increases with increasing sliding speed.[29] It may be for this reason that so many of the kinetic coefficients of friction reported from Reference 1, for example, exceed the static coefficients of friction, as kinetic friction in this case was measured at a speed of 0.25 m/s. (Kinetic friction at lower speeds is quite likely often less than the reported static friction.) At extremely high speeds, kinetic friction coefficient may eventually decrease with increasing speed from frictional heating and softening.[29]

As friction force often activates wear mechanisms, Blanchet and Kennedy[25] have noted a transition in wear rate of PTFE from $10*10^{-15}$ m^3/Nm to $500*10^{-15}$ m^3/Nm upon a small increase in sliding speed from 8 to 10 mm/s at room temperature. PV limit can also change significantly with sliding speed. For example, Theberge[19] has shown that the PV limit of a polystyrene/silicone composite, $0.32*10^6$ N/ms at 0.5 m/s, becomes as low as $0.035*10^6$ N/ms as speed is increased to 5 m/s. PV limits within Table 1 were generally determined at a speed of 0.5 m/s.

TEMPERATURE

Relaxation time of polymers decreases with increasing temperature.[52] As a result, decreases in ambient temperature often have effects equivalent to the increases in sliding speed.[25,29,40] As PV limits are based upon the attainment of a critical temperature at the sliding interface, increases in ambient temperature will result in decreases in PV limit. Above the melt temperature, molecules have adequate thermal energy to move about freely as a viscous fluid. As temperature decreases below the melt temperature T_m, semicrystalline polymers will develop regions (crystallites) of three-dimensional order with a corresponding sharp decrease in free volume. The lack of crystallization in amorphous polymers having structure not conducive to ordering instead experience gradual reductions in free volume with decreasing thermal energy. Equally important property changes take place at the glass transition temperature. The disordered regions of semicrystalline polymers (as well as the entirety of amorphous polymers) lose sufficient thermal energy to become glassy below T_g, and the polymer therefore transforms from being rubberlike and ductile to rigid and brittle.

NORMAL LOAD

Due to the lack of proportionality between real area of contact and normal load for polymers, the coefficient of friction in sliding contacts with smooth counterfaces tends to decrease with increasing load. For example, Janczak et al.[41] have shown the coefficient of sliding friction of an EPDM composite rubber to decrease from $\mu = 1.1$ to half that value as apparent contact pressure is increased from 0.1 to 0.6MPa.

CONTACT KINEMATICS

Entrapment of debris within a sliding contact can greatly affect its subsequent wear behavior. Likelihood of either entrapment or ejection of debris depends greatly on the type of sliding motion and on the degree of mutual overlap existing between the two contacting bodies. Debris entrapment becomes particularly likely in small amplitude oscillatory contacts. Abarou et al.,[28] for example, have shown the wear rate of a PA 6/6 composite to increase 50-fold as mutual overlap coefficient MOC was increased from 0.33 to 0.8.

COUNTERFACE ROUGHNESS

Counterface surface roughness greatly affects the relative degree of adhesive and abrasive contributions to resultant friction and wear behavior of polymers. Generally, a minimum will exist. For example, at a surface roughness of $R_a = 0.1$ μm, the friction coefficient of HDPE will be less than $\mu = 0.2$. As surface roughness is either decreased to $R_a = 0.01$ μm or increased to $R_a = 1.0$ μm, the coefficient of friction can exceed $\mu = 0.3$. For LDPE, wear rate experiences a minimum of less than $10*10^{-15}$ m^3/Nm at $R_a = 0.025$ μm. As roughness is decreased from this value to $R_a = 0.01$ μm, wear rate increases to $180*10^{-15}$ m^3/Nm, while as roughness is increased to $R_a = 1.3$ μm, wear rate increases to $500*10^{-15}$ m^3/Nm.[30] Data tabulated here are from tests utilizing finished (polished or lapped) counterfaces, and data obtained under abrasive wear conditions utilizing abrasive papers, gauzes, or other rough counterface materials have been omitted.

TRANSIENT RUN-IN

The wear rates, as reported, are understood to be steady-state values. A very different rate of wear may exist at the initiation of sliding, gradually approaching a roughly constant value as steady-state conditions are attained after a few hundred meters of sliding. Generally, wear rate during this transient run-in period will be greater than that attained during steady-state. However, in instances involving counterfaces that are initially very smooth, wear rate may instead increase with time and level at a higher rate of steady-state wear as sliding roughens the counterface.[30] Relative importance of transient and steady-state wear behavior will depend specifically upon the application and the anticipated sliding distance.

COUNTERFACE SURFACE CHEMISTRY/ATMOSPHERE

Friction and wear behavior can also be affected by interactions occurring between the polymer body and the counterface surface. Surface films which may exist and reform upon the counterface depend upon the counterface material as well as the atmosphere or environment in which sliding occurs. For similar surface roughnesses, the wear rate of a 10% graphite powder-filled PTFE increased over 30-fold if a steel counterface was replaced by aluminum.[1] Data tabulated here are primarily from sliding contacts involving steel counterfaces under ambient air atmospheres.

MOLECULAR WEIGHT/CRYSTALLINITY

Hu and Eiss's study of PTFE[31] illustrates the potential effect of molecular weight and crystallinity on polymer wear. For a PTFE of lower crystallinity (<40%), a ten-fold decrease in molecular weight from $17.3*10^6$ resulted in a 17% increase in wear. For a low molecular weight PTFE ($1.7*10^6$), a decrease in crystallinity from 37 to 25% resulted in a 14% increase in wear. Polymer crystallinity may vary considerably depending on thermal processing conditions.

FILLER PARTICLE SIZE

Hard particulate fillers are often used to reduce wear of polymer matrices. If the filler particle size is too small, however (smaller than the wear debris that would be formed by the unfilled polymer), the filler will not be able to obstruct the polymer wear mechanism, and will be ineffective. As an example, Durand et al.[38] showed that as the size of alumina filler particles in an epoxy matrix decreased from 100 to 20 μm (roughly the thickness of debris formed by the unfilled matrix), wear rate increased from $40*10^{-15}$ m^3/Nm to $360*10^{-15}$ m^3/Nm (similar to that of the unfilled matrix). On the other hand, filler particles which are too large may block the redistribution of solid lubricant constituents throughout the sliding interface, and therefore can result in higher friction.[42]

FIBER ORIENTATION

Orientation will greatly affect the degree to which fibers may reduce the wear of the polymer matrix. To illustrate, Cirino et al.[20] have shown that wear rate of an aramid fiber-reinforced epoxy in which fibers are parallel to the sliding direction will be nearly eight times that if fiber were oriented normal to the sliding surface.

FILLER VOLUME FRACTION

The wear rate of polymer composites with hard particulates of fiber fillers is extremely dependent upon the level of loading of the filler. For most systems tabulated in Table 1, however, data for only a single volume fraction or weight fraction composite are given, as a result of limited space. The dependence of composite wear rate K_c on matrix volume fraction x_m and filler volume fraction x_f can typically be described by an inverse rule-of-mixtures:[43]

$$K_c^{-1} = x_m K_m^{-1} + x_f K_f^{-1}$$

where K_m and K_f are the wear rates of the matrix and filler, respectively. For a given system, values of K_f and K_m can be determined from the above equation, given composite wear data at any two different loading levels. (One of these levels may be the unfilled case. Weight fraction must be converted to volume fraction, using the densities of the filler and matrix.) Thereafter, wear rates of composites with loadings other than those tabulated may be estimated. At higher filler volume fractions ($x_f > 0.35$), particulates may no longer be well dispersed. The increasing occurrence of weak particle/particle interfaces may eventually result in increasing wear rate with increasing volume fraction,[44] deviating from this inverse rule-of-mixtures behavior.

For each data set in Table 1, a literature reference is provided. Since wide variation from the tabulated values exist, the reader is strongly advised to consult the corresponding reference and compare test conditions before further considering application of any material listed within this tabulation. Furthermore, it is assumed that the reader has available from other sources the compressive load limits and useful temperature ranges of the various polymer materials, as well as other nontribological characteristics which may affect their successful implementation in bearings applications.

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TABLE 1
Representative Tribological Properties of Polymers and Their Composites

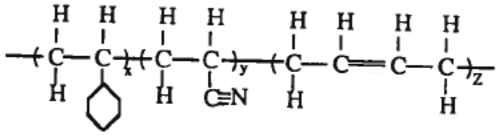
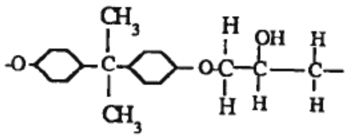
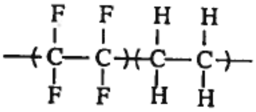
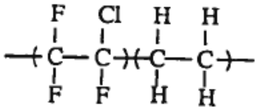
	Filler	Friction, Coeff.		Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
		Static	Kinetic			
Acrylonitrile Butadiene Styrene (ABS)	T_g = 100–125°C					50
						
	None	0.30	0.35	70	—	1
	30 w% Carbon fiber	0.17	0.19	2	—	3
	15 w% PTFE	0.13	0.16	6	0.14	1
	2 w% Silicone	0.11	0.14	1.6	—	1
Epoxy						51
						
	None	—	0.55	200	—	12
	30 w% Carbon fiber	—	0.42	2.1	—	12
	None	—	—	370	—	38
	5 v% ZrO_2	—	—	60	—	38
	5 v% SiC	—	—	20	—	38
	20 v% Al_2O_3	—	—	8	—	38
Ethylene tetrafluoroethylene (ETFE)	T_g = −120°C	T_m = 270°C				50
						
	None	0.50	0.40	100	—	1
	30 w% Glass fiber	0.17	0.18	0.2	—	1
	30 w% Carbon fiber	0.11	0.18	0.12	—	1
	30 w% PTFE	0.10	0.12	0.18	—	1
Ethylene chlorotrifluoroethylene (ECTFE)	T_g = −64°C	T_m = 240°C				49
						
	None	0.27	0.29	20	—	1
	10 w% PTFE	0.06	0.11	0.54	—	1
	15 w% Glass fiber	0.13	0.16	0.6	—	1
	20 w% Carbon fiber	0.15	0.17	0.36	—	1

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

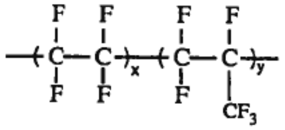
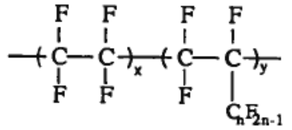
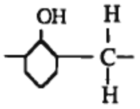
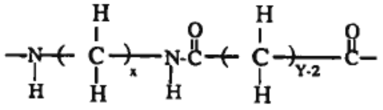
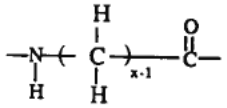
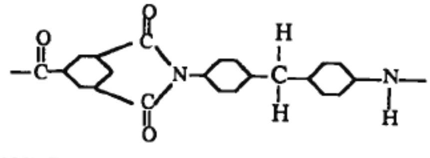
	Filler	Friction, Coeff.		Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
		Static	Kinetic			
Fluorinated ethylene propylene (FEP)	T_g = −100°C	T_m = 275°C				50
	 $-(CF_2-CF_2)_x-(CF_2-CF(CF_3))_y-$					
	None	0.11	0.16	22	—	1
	None	—	0.45	—	0.11	27
	None	—	0.2	—	—	17
	15 w% Glass fiber	0.11	0.12	0.5	—	1
	15 w% Carbon fiber	0.10	0.11	0.2	—	1
Perfluoroalkoxy (PFA)	T_g = 80°C	T_m = 304°C				50
	 $-(CF_2-CF_2)_x-(CF_2-CF(C_nF_{2n-1}))_y-$					
	None	0.12	0.15	25	—	1
	10 w% PAN carbon fiber	0.10	0.14	0.1	—	3
	15 w% Pitch carbon fiber	0.11	0.18	0.32	0.95	1
	20 w% Glass fiber	0.12	0.15	0.2	—	1
	10 w% PTFE	0.06	0.11	0.1	—	1
Phenol-formaldehyde (Phenolic)						46
						
	None	—	0.78	29	—	12
	None	—	—	—	0.18	23
	20 w% Carbon fiber	—	0.35	2.3	—	12
	20 w% Glass fiber	—	0.74	7.4	—	12
	30 w% Glass fiber	—	—	—	0.53	23
Polyamide X/Y (PA X/Y, Nylon X/Y)						49
Polyamide 6/6	T_g = 52°C	T_m = 265°C				
Polyamide 6/10	T_g = 40°C	T_m = 225°C				
Polyamide 6/12	T_g = 40°C	T_m = 215°C				
	 $-NH-(CH_2)_x-NH-CO-(CH_2)_{Y-2}-CO-$					
Polyamide 6/6 (PA 6/6, Nylon 6/6)	None	—	0.61	4.0	—	12
	30 w% Carbon fiber	—	0.35	2.5	—	12
	30 w% Glass fiber	—	0.44	4.4	—	12
	None	0.20	0.28	4.0	0.09	1
	30 w% Carbon fiber	0.16	0.20	0.4	0.95	1
	30 w% Glass fiber	0.25	0.31	1.5	0.35	1

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

	Filler	Friction, Coeff.		Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
		Static	Kinetic			
	20 w% Aramid fiber	—	0.25	1.2	—	45
	2 w% Silicone	0.09	0.09	0.8	0.21	1
	5 w% Graphite	0.15	0.20	1.1	—	1
	5 w% MoS_2	0.28	0.30	3.0	—	1
	20 w% PTFE	0.10	0.18	0.24	0.62	1
	None	—	0.57	16	—	21
	15 w% PTFE	—	0.13	0.5	—	21
Polyamide 6/10 (PA 6/10, Nylon 6/10)	None	0.23	0.31	3.6	0.07	1
	20 w% PTFE	0.12	0.20	0.3	0.62	1
	2 w% Silicone	0.10	0.12	0.92	0.14	1
	30 w% Glass fiber	0.26	0.34	1.6	0.3	1
	30 w% Carbon fiber	0.20	0.25	0.50	0.74	1
Polyamide 6/12 (PA 6/12, Nylon 6/12)	None	0.24	0.31	3.8	0.07	1
	20 w% PTFE	0.12	0.19	0.32	0.63	1
	2 w% Silicone	0.10	0.12	0.96	0.14	1
	30 w% Glass fiber	0.27	0.33	1.7	0.28	1
	5 w% MoS_2	0.33	0.33	2.9	—	1
Polyamide X (PA X, Nylon X)						49
Polyamide 6	$T_g = 40°C$	$T_m = 225°C$				
Polyamide 11	$T_g = 43°C$	$T_m = 190°C$				
Polyamide 12	$T_g = 42°C$	$T_m = 180°C$				



	Filler	Static	Kinetic	Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
Polyamide 6 (PA 6, Nylon 6)	None	0.22	0.26	4.0	0.07	1
	15 w% PTFE	0.13	0.15	0.6	—	1
	2 w% Silicone	0.10	0.12	1.0	0.14	1
	30 w% Glass fiber	0.26	0.32	1.8	0.3	1
	30 w% Carbon fiber	0.18	0.21	0.6	0.77	1
	5 w% Graphite	0.16	0.19	1.2	—	1
	5 w% MoS_2	0.28	0.30	3.2	—	1
Polyamide 11 (PA 11, Nylon 11)	None	—	—	7	—	36
	35 v% PbS	—	0.43	1.4	—	36
	85 w% Bronze	0.15	0.15	1.6	—	1
Polyamide 12 (PA 12, Nylon 12)	None	0.21	0.27	3.6	—	1
	15 w% PTFE	0.09	0.16	0.6	—	1
	2 w% Silicone	0.18	0.17	3.1	—	1
Polyamideimide (PAI)	$T_g = 275°C$					50



	Filler	Static	Kinetic	Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
	12% Graphite/ 3% PTFE	0.06	0.27	0.34	—	9
	12% Graphite/ 8% PTFE	0.02	0.19	0.12	—	9
	20% Graphite/ 3% PTFE	0.02	0.19	0.16	—	9

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

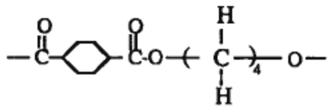
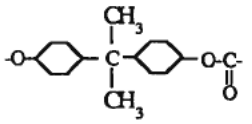
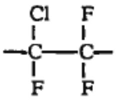
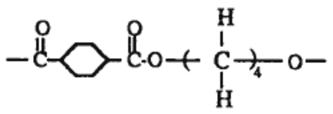
	Filler	Friction, Coeff.		Wear Rate	PV Limit	Ref.
		Static	Kinetic	($10^{-15}m^3/Nm$)	($10^6N/ms$)	
Polybutylene terephthalate (PBT Polyester)	T_g = 22–80°C	T_m = 236°C				49
						
	None	0.19	0.25	4.2	—	1
	30 w% Carbon fiber	0.12	0.15	0.48	0.77	1
	30 w% Glass fiber	0.23	0.27	1.8	—	1
	20 w% PTFE	0.09	0.17	0.30	0.54	1
	2 w% Silicone	0.09	0.16	1.0	—	1
Polycarbonate (PC)	T_g = 65°C	T_m = 220°C				46
						
	None	0.31	0.38	50	0.018	1
	15 w% PTFE	0.09	0.15	1.5	0.70	1
	30 w% Glass fiber	0.23	0.22	3.6	—	1
	30 w% Carbon fiber	0.18	0.17	1.7	0.30	1
	None	—	0.6	34	—	12
	30 w% Carbon fiber	—	0.25	1	—	12
Polychlorotrifluoroethylene (PCTFE)	T_g = 45°C	T_m = 220°C				46
						
	None	0.28	0.28	—	—	17
	None	0.6	0.32	—	—	34
Polyether ester (Elastomeric polyester)	T_g = −70 to 20°C	T_m = 220°C				50
						
	None	0.27	0.59	20	—	1
	15 w% PTFE	0.22	0.25	0.8	—	1
	30 w% Carbon fiber	0.25	0.40	8	—	1
	2% Silicone	0.21	0.22	0.6	—	19

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

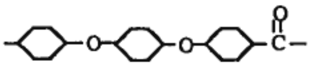
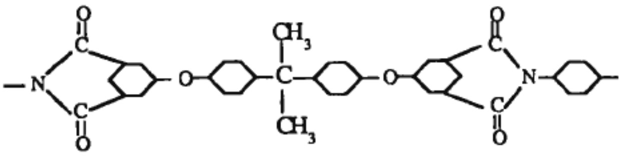
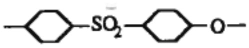
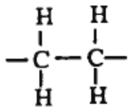
		Friction, Coeff.		Wear Rate	PV Limit	
	Filler	Static	Kinetic	($10^{-15}m^3/Nm$)	($10^6N/ms$)	Ref.
Polyetheretherketone (PEEK)	$T_g = 140°C$	$T_m = 343°C$				46
						
	None	0.20	0.25	4.0	—	1
	None	—	—	—	6	7
	30 w% Carbon fiber	0.19	0.13	1.2	—	1
	30 w% Carbon fiber	—	—	—	13.6	7
	30 w% Glass fiber	0.28	0.30	1.8	—	1
	20 w% PTFE	0.19	0.13	1.2	—	1
	None	—	0.5	14.5	—	21
	15 w% PTFE	—	0.18	0.5	—	21
Polyetherimide						
						
	None	—	0.43	38	—	21
	15 w% PTFE	—	0.22	2.4	—	21
	None	0.18	0.17	80	—	1
	30 w% Glass fiber	0.22	0.24	2.6	—	1
	30 w% Carbon fiber	0.20	0.22	1.4	—	1
Polyethersulfone	$T_g = 230°C$					50
						
	None	0.27	0.32	30	0.25	1
	15 w% PTFE	0.09	0.12	0.78	—	1
	30 w% Glass fiber	0.23	0.21	3	—	1
	30 w% Carbon fiber	0.17	0.15	1.6	0.35	1
Polyethylene (PE)	$T_g = -120°C$	$T_m = 137°C$				46
	 $-CH_2-CH_2-$					
Polyethylene-low density (LDPE)	None	0.28	0.28	—	—	17
	None	—	0.32	53	—	37
	30 v% Cu	—	0.35	2	—	37
Polyethylene-high density (HDPE)	None	0.15	0.15	—	—	17
	None	—	—	180	—	24
	20 w% PTFE	0.09	0.13	0.9	—	1
Polyethylene-high-molecular weight (UHMWPE)	None	—	0.2	0.1–1.6	—	32
	None	—	0.13	2.2	—	33
	None	—	0.22	0.25	—	26

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

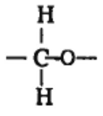
	Filler	Friction, Coeff.		Wear Rate ($10^{-15}m^3/Nm$)	PV Limit ($10^6N/ms$)	Ref.
		Static	Kinetic			
Polyethylene terephthalate (PET)	T_g = 70–120°C	T_m = 290°C				49
						
	None	—	—	3.2	—	24
	None	—	—	6.7	—	39
	None	—	0.68	21.7	—	21
	15 w% PTFE	—	0.15	0.7	—	21
Polyimide (PI)	T_g = 250–370°C					51
						
	None	—	—	—	4	23
	None	—	0.65	1.7	—	12
	30 w% Carbon fiber	—	0.35	0.4	—	12
	50 w% Graphite fiber	—	0.24	0.38	—	22
	30 w% Glass fiber	—	—	—	5	23
	None	0.35	0.29	2–9.6	—	8
	15 w% MoS_2	—	0.24	2.3	—	8
	15 w% Graphite	0.30	0.24	0.72	—	8
	15 w% Graphite	—	0.08	1.1	20.9	7
Polymethylmethacrylate (PMMA)	T_g = 105°C	T_m = 200°C				51
						
	None	0.3	0.3	—	—	17
	None	—	0.55	170	—	12
	30 w% Carbon fiber	—	0.25	0.5	—	12
	None	—	0.43	84	—	37
	20 v% Cu	—	0.66	53	—	37
Polyoxymethylene (POM, Acetal)	T_g = −85 to −50°C	T_m = 181°C				46
						
	None	—	0.45	2.1	—	21
	15 w% PTFE	—	0.22	0.4	—	21

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

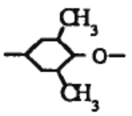
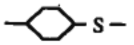
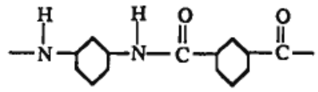
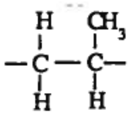
	Filler	Friction, Coeff. Static	Friction, Coeff. Kinetic	Wear Rate (10^{-15}m^3/Nm)	PV Limit (10^{6}N/ms)	Ref.
	None	0.14	0.21	1.3	0.12	1
	15 w% PTFE	0.08	0.16	0.4	—	1
	2 w% Silicone	0.08	0.11	0.4	0.42	1
	10 w% Graphite	0.16	0.22	1.2	—	1
	20 w% Carbon fiber	0.11	0.14	0.8	0.7	1
	30 w% Glass fiber	0.25	0.34	0.49	—	1
	30 w% Glass fiber	—	—	—	0.28	23
Polyphenylene oxide (PPO)	$T_g = 208°C$	$T_m = 260°C$				47,48
						
	None	0.32	0.39	60	0.018	1
	15 w% PTFE	0.10	0.16	2	—	1
	30 w% Glass fiber	0.26	0.27	4.6	—	1
Polyphenylene sulfide (PPS)	$T_g = 88°C$	$T_m = 285°C$				46
						
	None	—	0.7	38.5	—	21
	15 w% PTFE	—	0.3	2.8	—	21
	None	0.30	0.24	10.8	0.11	1
	20 w% PTFE	0.08	0.10	1.1	—	1
	40 w% Glass fiber	0.38	0.29	4.8	0.56	1
	30 w% Carbon fiber	0.23	0.20	3.2	0.7	1
Polyphthalamide (Aromatic Nylon, Aromatic PA)	$T_g = 250–400°C$					48,49
						
	None	0.20	0.21	17.8	—	2
	10 w% PTFE	0.05	0.10	0.16	—	2
	30 w% Glass fiber	0.19	0.21	1.0	—	2
	30 w% Carbon fiber	0.10	0.12	0.78	—	2
Polypropylene	$T_g = -18$ to $-10°C$	$T_m = 176°C$				46
	 $-\overset{H}{\underset{H}{C}}-\overset{CH_3}{\underset{H}{C}}-$					
	None	0.27	0.27	—	—	17
	None	—	0.48	22	—	12
	30 w% Carbon fiber	—	0.32	1.6	—	12
	20 w% PTFE	0.08	0.11	0.66	0.18	1

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

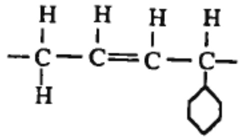
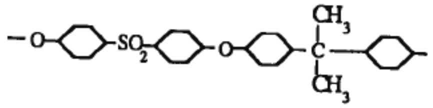
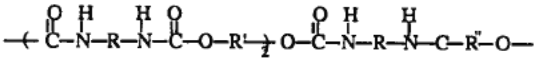
	Filler	Friction, Coeff. Static	Friction, Coeff. Kinetic	Wear Rate $(10^{-15} m^3/Nm)$	PV Limit $(10^6 N/ms)$	Ref.
Polystyrene (PS)	T_g = 100°C T_m = 240°C 					51
	None	0.28	0.32	60	0.05	1
	2 w% Silicone	0.06	0.08	0.74	0.32	1
	15 w% PTFE	0.12	0.14	3.5	—	1
Polysulfone	T_g = 185°C 					51
	None	0.29	0.37	30	0.18	1
	15 w% PTFE	0.09	0.14	0.92	—	1
	30 w% Glass fiber	0.24	0.22	3.2	—	1
	30 w% Carbon fiber	0.17	0.14	1.5	0.3	1
Polytetrafluoroethylene (PTFE)	T_g = 126°C T_m = 327°C 					5
	None	0.04	0.05	100	0.06	13
	15 w% Glass fiber	0.05	0.09	0.14	0.35	13
	25 w% Poly-oxybenzoate	0.05	0.13	0.1	0.63	13
	20 w% Poly-phenylene sulfide	0.05	0.13	0.08	0.34	13
	None	—	—	135	—	14
	30 w% FEP	—	—	6.3	—	14
	25 w% Polyester	0.04	0.09	0.06	—	10
	None	—	0.11	770	—	16
	30 v% Sn	—	0.08	130	—	16
	30 v% Al	—	0.17	100	—	16
	30 v% Ag	—	0.10	68	—	16
	30 v% Pb	—	0.11	53	—	16
	30 v% B_2O_3	—	0.06	10	—	16
	30 v% W	—	0.09	4	—	16
	30 v% Cu	—	0.13	3.5	—	16
	30 v% PbS	—	0.16	1.8	—	16
	30 v% Mo	—	0.11	1.8	—	16
	30 v% Zn	—	0.11	1.3	—	16
	30 v% Se	—	0.09	1.1	—	16
	30 v% Y_2O_3	—	0.14	1.0	—	16
	30 v% Ni	—	0.12	0.65	—	16
	30 v% SiO_2	—	0.10	0.5	—	16

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

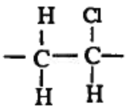
	Filler	Friction, Coeff.		Wear Rate	PV Limit	
		Static	Kinetic	($10^{-15}m^3/Nm$)	($10^6N/ms$)	Ref.
	30 v% Fe	—	0.13	36	—	16
	60 w% Stain-less steel	0.08	0.12	0.3	—	5
	None	0.1	0.23	—	0.06	35
	50 w% CdO	0.08	0.11	—	1.3	35
	None	—	0.21	300–800	—	15
	20 w% ZrO_2	—	0.57	1–2.5	—	15
	40 w% TiO_2	—	0.24	10–15	—	15
	20 w% MoS_2	—	0.22	5-40	—	15
	15 w% Graphite	—	0.21	4	—	15
	20 w% Graphite	0.06	0.08	0.22	0.8	4
	25 w% Carbon/ graphite	0.08	0.09	0.12	0.7	4
	None	—	—	500	—	25
	25 w% Glass fiber	—	—	0.5	—	25
	40 w% Bronze	—	—	0.2	—	25
	40 w% Bronze	0.05	0.13	0.1	0.44	6
	None	—	—	—	0.035	18
	None	—	0.25	460	—	12
	33 w% Graphite	—	0.32	0.7	—	12
	30 w% Carbon fiber	—	0.23	2.2	—	12
	25 w% Glass fiber	—	—	—	0.175	18
	30 w% Glass fiber	—	0.34	1.9	—	12
	30 w% Mica	—	0.25	7.1	—	12
	25 w% Asbestos fiber	—	0.25	3.0	—	12
	25 w% Coke flour	—	0.32	0.7	—	12
	25 w% Coke flour	0.09	0.11	0.16	0.62	4
	None	—	0.16	833	—	37
	30 v% Glass bead	—	0.2	2.5	—	37
	30 v% Cu	—	0.22	31.7	—	37
Polyurethane (Thermoplastic) (TPU)	T_g = −51°C					50



$$-\left(\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-R-\overset{\overset{H}{|}}{N}-\overset{\overset{O}{\|}}{C}-O-R'\right)_2 O-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-R-\overset{\overset{H}{|}}{N}-C-R''-O-$$

where, for example, R, R′, and R″ are based upon diisocyanate, polyglycol, and a glycol chain extender

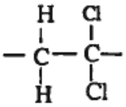
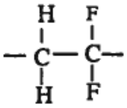
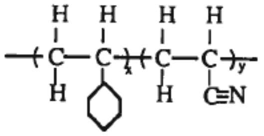
	None	0.32	0.37	6.8	0.053	1
	15 w% PTFE	0.27	0.32	1.2	—	1
	2 w% Silicone	0.25	0.31	1.1	—	1
	30 w% Glass fiber	0.30	0.34	3.6	—	1
Polyvinyl chloride (PVC)	T_g = 87°C	T_m = 212°C				46



$$-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-\underset{\underset{H}{|}}{\overset{\overset{Cl}{|}}{C}}-$$

	None	0.3	0.3	—	—	17
	None	—	0.45	440	—	12
	30 w% Carbon fiber	—	0.32	0.6	—	12

TABLE 1 (CONTINUED)
Representative Tribological Properties of Polymers and Their Composites

	Filler	Friction, Coeff.		Wear Rate	PV Limit	
		Static	Kinetic	($10^{-15}m^3/Nm$)	($10^6N/ms$)	Ref.
Polyvinylidene chloride	$T_g = -19°C$	$T_m = 198°C$				51
	 $-\overset{H}{\underset{H}{C}}-\overset{Cl}{\underset{Cl}{C}}-$					
	None	1.4–1.6	—	—	—	34
Polyvinylidene fluoride (PVDF)	$T_g = -40°C$	$T_m = 170°C$				50
	 $-\overset{H}{\underset{H}{C}}-\overset{F}{\underset{F}{C}}-$					
	None	0.21	0.24	20	—	1
	15 w% Carbon fiber	0.25	0.25	0.28	0.39	1
	25 w% Glass fiber	0.11	0.12	2.0	—	1
Styrene acrylonitrile (SAN)	$T_g = 115°C$					50
						
	None	0.30	0.35	70	—	1
	15 w% PTFE	0.13	0.16	6	0.14	1
	2 w% Silicone	0.11	0.14	1.6	—	1

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57 Bonded Solid Film Lubricants

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Development of bonded solid film lubricant products began late in the 1940s in the aircraft industry. Their use accelerated in the 1950s with the birth of the national space program and its need for lubricants in outer space subject to wide temperature extremes, radiation, vacuum, and other extreme environmental conditions. In the intervening years, bonded solid film lubricant technology has grown considerably and is now applied to a wide variety of industrial, automotive, military, and aerospace applications. The subject of solid lubricants is covered in Volume 2 of the *Handbook of Lubrication*.[1] Bonded solid film lubricants with inherent lubricating properties which are firmly bonded to the surface of the substrate are covered in Volume 3, the *Handbook of Lubrication and Tribology*.[2] This section will codify performance properties of many of these bonded solid film lubricants and the preferred pretreatments for different base metals.

SURFACE PREPARATION FOR SOLID FILM LUBRICANTS

Pretreatment of the metal substrate surface prior to the application of bonded solid film lubricants is the single most critical item affecting performance. Pretreatments are optimized for specific metals to modify surface roughness, hardness, and/or chemical reactivity to promote adhesion and enhance lubrication performance. Since solid film lubricants by themselves do not exhibit uniquely outstanding wear life, improper or inadequate pretreatment results in approximately 80% of most solid film lubricant failures.[3]

SURFACE PREPARATION FOR RESIN-BONDED SOLID LUBRICANTS

Ideal pretreatment processes for resin-bonded solid film lubricants fall into three basic operations: degreasing, grit blasting, and chemical treatment. Since each of these operations adds cost, it is often necessary to compromise performance. The design engineer must be careful that these compromises do not ultimately result in a poorly designed, non-cost-effective component.

Degrease

Degreasing is necessary to remove machining oils, corrosion inhibitors, and related solvent-soluble contamination. Failure to remove these contaminants usually results in poor adhesion of the solid

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film lubricant. Of three methods historically used, the preferred vapor degreasing is typically done in accordance with MIL-T-7003 in specially designed equipment using common solvents such as 1,1,1-trichloroethane, trichloroethylene, or perchloroethylene. Due to recent regulations regarding air quality and ozone-depleting substances, however, use of 1,1,1-trichloroethane has been eliminated. The other two solvents are under some scrutiny from a toxicity standpoint. Much new development is underway of aqueous degreasers as substitutes. Performance of various degreasers appears to be application specific. That is, some degreasing compounds work better with certain machine oils than others, and no effective control mechanism has been developed to determine when cleaning baths are depleted. Care must be taken in controlling these processes to ensure that parts are properly cleaned to avoid poor adhesion and catastrophic failure of the solid film lubricant.

Grit Blast

After vapor degreasing, abrasive blasting or grit blasting is recommended. For most metals, aluminum oxide is the preferred medium. A wide variety of mesh sizes are available; for most work, 220 mesh is preferred. Sand, starulite, walnut shells, peanut shells, and glass beads are also commonly used, particularly on some of the softer metals. The goal of grit blasting is to provide a uniform surface profile with a surface roughness of about 16 to 32 rms for most applications. Table 1 shows the effect of various grit sizes of aluminum oxide on aluminum, titanium, and stainless steel.

TABLE 1
Typical Grit Blast Finishes (rms) (Aluminum Oxide, 30–60 PSI, 30–60° angle)

Grit Size (Mesh)	Aluminum	Titanium	Stainless Steel
400	40–65	15–30	20–30
220	70–85	35–45	30–40
120	90–110	40–55	30–45
80	150–180	60–80	50–100

Chemical Treatment

The final operation necessary for optimum performance of bonded solid film lubricants is chemical treatment. Usually this represents a conversion coating, such as a phosphate for ferrous metals and zinc; anodize for aluminum, magnesium, or zinc; passivation for corrosion resistance steels; black oxide for copper and iron; chromate for copper, aluminum, cadmium, anodize metals, phosphated ferrous metals, and zinc; and various etchings for corrosion-resistant steels, ferrous metals, copper, zinc, and titanium.

Phosphate

The preferred phosphate process is described in DOD-P-16232 (see Table 2). Under this military specification, there are two primary phosphate types, zinc phosphate and manganese phosphate. Manganese phosphate provides a better wear-resistant base for solid lubricants, while zinc phosphate provides additional corrosion protection. Calcium/zinc phosphate, iron phosphate, and nickel/manganese phosphate are also used, but these are more applicable to paint systems.

After applying a phosphate, parts are dried under controlled conditions to eliminate trapping of water in the crystalline structure which would cause flash corrosion, poor adhesion, and possible hydrogen embrittlement. In the case of high-strength steels, including spring steels, trapped

TABLE 2
Phosphate Conversion Coating Pretreatments

Type	Market	Use	Advantage	Coating Weight (mg/ft)
Zinc (DOD-P-16232)	Military/commercial	SFL/paint	Corrosion/adhesion	600–2,000
Manganese (DOD-P-16232)	Military	SFL	Wear/adhesion	2,000–3,000
Calcium/zinc	Commercial	Paint	Corrosion/adhesion	100–400
Iron	Commercial	Paint	Adhesion/corrosion	25–100

hydrogen in the metal can potentially cause stress corrosion, cracking, and related failures. Therefore, it is important that the phosphated part be baked at a temperature which will eliminate any trapped hydrogen.

Anodization

Anodizing is a preferred conversion coating for such materials as aluminum and magnesium. In this process, a metal oxide coating is formed electrolytically as described in MIL-C-8625C. This military specification recognizes three fundamental types: chromic, sulfuric, or hard anodize. Hard anodize is a type of sulfuric acid anodize which leaves a much harder, more wear-resistant coating and is preferable for solid lubricants. Chromic acid anodize, which is best for corrosion protection, is being reduced in usage because of the toxicity of chrome.

Passivation generally involves treatment of the substrate metal with nitric acid. The purpose is to dissolve iron from the surface of corrosion resistant steels, making the surfaces nickel rich relative to the normal composition of the material. This eliminates any micro corrosion/oxidation which might occur prior to the application of the solid film lubricant. Passivation is typically done in accordance with MIL-STD QQ-P-35.

Miscellaneous Chemical Treatments

Black oxide is used on copper and to a lesser extent on iron, as covered by MIL-F-495 for copper and MIL-C-13924 for iron. This involves sulfide treatment of copper and caustic nitrate treatment for iron. This chemical conversion, while very inexpensive, does not provide the performance of a good phosphate on iron. Chromate conversion is also commonly used on copper, zinc, and phosphated ferrous metals. The purpose of this process is to treat the substrate with hexavalent chrome along with various activators, such as acetates, sulfates, and fluorides under a controlled pH. This process provides extra corrosion protection. However, the use of hexavalent chrome must be carried out with care due to its toxicity.

Finally, various enchants represent a cost effective pretreatment to provide metal surfaces with "tooth" to promote adhesion. However, use of enchants alone can represent a compromise in performance properties. For corrosion-resistant steels, ferric chloride solution at approximately 40% provides a good base for adhesion. On ferrous metals, a hydrochloric acid etch works well in place of grit blasting. However, care must be taken if hydrogen embrittlement is a consideration. Etching other metals can be accomplished as follows: aluminum with nitric acid and hydrofluoric acid, copper with sulfuric acid and nitric acid, zinc sulfuric acid and chromic acid, titanium with nitric acid and hydrofluoric acid.

SURFACE PREPARATION FOR INORGANIC BONDED SOLID LUBRICANTS

Pretreatment for inorganic bonded solid film lubricants is equally important as with resin-bonded products and generally follows the same guidelines of cleaning, degreasing, grit blasting, etc. Since inorganic solid film lubricants are generally used for high-temperature and chromating are usually avoided, since they decompose at temperatures in excess of 450°F and 300°F, respectively. Generally the preferred pretreatment is degreasing and grit blasting with aluminum oxide and, where applicable, passivation.

Inorganic solid lubricants are generally not used on low melting materials such as aluminum unless the application is for high vacuum where outgassing properties are of primary consideration, or where specific chemical resistance, such as liquid oxygen service, is of importance. Even then, the lubricant cure temperature may be excessive for the grade of aluminum.

Ceramic-Bonded Solid Film Lubricant

Since many ceramic-bonded solid film lubricants cure at temperatures around 1000°F or more, the preferred pretreatment is vapor degreasing followed by grit blasting. Since ceramic-bonded solid film lubricants are usually applied to corrosion-resistant materials such as Hastalloy and Waspalloy, passivation is usually not required. The main purpose of the pretreatment is to remove any oils, dirt, and loose debris, and to obtain the necessary surface roughness for optimal adhesion.

Sputtered and PVD Applied Films

Pretreatment for sputtered and physical vapor deposition-applied films generally involves degreasing/cleaning, often incorporating ultrasound. In some special cases, vapor honing is also done. Since vacuum-applied films are usually applied to very smooth surfaces, however, abrasive honing is usually accomplished with a slurry of very fine aluminum oxide, followed by subsequent cleaning in an ultrasonic bath. Once cleaned, the substrate is etched in the sputtering chamber by ion bombardment with an inert gas, such as argon. The argon plasma cleans the surface on an atomic level to provide the required adhesion.

BONDED SOLID FILM LUBRICANT COMPOSITIONS

Bonded solid film lubricants are composed of three primary elements: solid lubricant, resin binder, and ancillary additives such as solvents, corrosion inhibitors, flow agents, etc. The binders and additives are usually proprietary. The various binder types are usually selected not so much for their impact on lubricity as for their other properties: cure temperature, temperature range, and resistance to environmental factors such as resistance to radiation, chemicals, vacuum, and corrosion.

Solid lubricants are commonly selected from the list provided in Table 3. Molybdenum disulfide, graphite, and polytetrafluoroethylene are the most significant commercially. Some materials act synergistically with certain solid lubricants to enhance lubricity. The mechanism of this enhancement is not rigorously known, but is believed to be related to retardation of surface oxidation of the primary solid lubricant. The subject of solid lubricants is covered in the *Handbook of Lubrication.*[1]

BONDED SOLID FILM LUBRICANT PRODUCTS AND PROPERTIES

The aircraft/aerospace industry has attempted to codify the basic workhorse solid film lubricants which are commonly used throughout the industry in SAE specification AS 1701. Six product types in Table 4 cover a wide range of temperature applications. The primary purpose of these solid lubricants is to provide lubrication under the environments indicated.

Table 5[4] gives typical performance properties of a wide variety of solid film lubricants which meet various commercial or military specifications. Since many of these are used on threaded fasteners, the installation force and torque are listed for comparison purposes. Table 6 shows typical chemical resistance of these various generic products.

TABLE 3
Solids for Use in Bonded Lubricant Films

Material	Advantages	Disadvantages
MoS_2	High load-carrying <100,000 psi Low cost Most commonly used material	750°F Temp limit
WS_2	High load-carrying <100,000 psi	950°F Temp limit High cost Moisture is detrimental
Graphite fluoride	High temperature	High cost
Antimony trioxide	Synergy with MoS_2	Toxicity
Boric acid	High temperature, <600°F	Hydrolytic stability High friction
CaF_2/BaF_2	High temperature, >1,000°C	High friction at low temp
PbO	High temperature, <500°C	Toxicity
PbS	High temperature	Toxicity
$NBsA_2$	Electrical conductivity	Toxicity
Plastics PTFE Nylon Polyethylene	Good for light loads Good in fastener applications	Radiation resistance
Graphite	High temperature, <1250°F Moderate loads, <40,000 psi Good for light loads Inexpensive Commonly used.	Vacuum resistance Potential for galvanic corrosion
Soft metals Ag, An, Pb, Sn, Bi, Ga, In	High temperature, <1000°	High friction Limited use in sliding applications Some are toxic

For applications where lubrication is the primary performance requirement, products such as described in Table 4, type I, are used. This material also provides maximum fluid and chemical resistance of the organic resin-bonded types. However, it is heat cured to achieve these properties. For applications where the product must be air cured, Type II products are most commonly used. In Tables 5 and 6, these products are also described as "D" and "J", respectively.

It becomes obvious that no one type of coating, pretreatment, or metallurgy can solve all problems encountered by the design engineer. However, the preceding Tables indicate the performance of a number of common systems from which design engineers can select proper coating systems. Most solid film lubricant suppliers can supply products such as those listed in the preceding Tables. Always, however, the testing and prototyping of each specific system is necessary to fully qualify the coating system.

TABLE 4
AS 1701 Lubricant, Solid Dry Film

	Temperature Limit		Usage	Primary Lubricant	Binder	Max Cure Temp	Temperature Stability		Stress Corrosion Resistance
							± 15°F	(± 8°C)	
Type I	−65°F (−54°C)	+450°F (232°C)	General purpose: titanium, aluminum, low/high alloy steels	MoS_2	Epoxy/Phenolics	400°F (204°C)	450°F	(232°C)	Pass
Type II	−65°F (−54°C)	+450°F (+232°C)	General purpose: titanium, aluminum, low/high alloy steels	MoS_2	Epoxy	Air dry	750°F	(232°C)	Pass
Type III	−65°F (−54°C)	+750°F (+399°C)	Corrosion-resistant steels — heat corrosion-resistant steels, titanium alloys	MoS_2	Polyamide-imide	600°F (316°C)	750°F	(399°C)	Pass
Type IV	−65°F (−54°C)	+1400°F (+454°C)	Corrosion-resistant steels — heat, corrosion-resistant steels, waspaloy	MoS_2	Silicone	Air dry 24 h	850°F	(454°C)	Pass
Type V	−65°F (−54°C)	+850°F (+454°C)	Corrosion-resistant steels — heat, corrosion-resistant steels	MoS_2	Silicone	Air dry 24 h	850°F	(454°C)	Pass
Type VI	−365°F (−220°C)	+850°F (+454°C)	Corrosion-resistant steels — heat, corrosion-resistant steels, nickel based alloys, titanium alloys for use with fuels, oxidizers such as hydrazine, LOX, nitrogen tetroxide, UDMH	MoS_2	Phosphate, silicone, or silicate	500°F (260°C)	850°F	(454°C)	Pass

ABLE 5
erformance Properties of Common Solid Film Lubricant Products

	A	B	C	D	E	F	G	H	I	J	K	L	M		N
													1	2	
onformance spec	GM-6064 GM-6174	GM-6183	MIL-L-8937	MIL-L-46010A	N/A	N/A	PWA 550	DPM-5499	MIL-L-81329	MIL-L-23398	AMS2525A MIL-L-85645	AMS2526A MIL-L-85645	Hughes	760829	MIL-L-85614
olor	Colors	Clear	Gray/black	Gray/black	Gray/black	Gray/black	Gray/black	Gray/black	Gray/black	Gray/Black	Gray	Gray	Black	Gray/Black	Silver
nder resin	Phenolic	Epoxy	Phenolic Epoxy	Phenolic	Phenolic	Silicone	Silicone	Silicate	Epoxy	Proprietary	Proprietary inorganic	Proprietary inorganic	Epoxy	Phenolic	Phenolic
lid lubricant	PTFE	PTFE	MoS_2	MoS_2	Proprietary blend	Proprietary blend	MoS_2	MoS_2	MoS_2 graphite	MoS_2	Graphite	MoS_2	N/A	MoS_2	Aluminum
ire condition	300°F	300°F	300°F	375°F	300°F	250°F	Air dry	500°F	400°F	Air dry	300°F	300°F	350°F	300°F	300°F
iating Thickness	0.7 mil	0.7 mil	0.5 mil	0.5 mil	0.5 mil	0.5 mil	0.5 mil	0.5 mil	0.5 mil	0.5 mil	0.0001	0.0001	0.7 mil	0.5 mil	0.5 mil
sign environment	−100°F–+400°F	−100°F–+400°F	−365°F–+500°F	−365°F–+500°F	−365°F–+500°F		−100°F–+400°F	−365°F–+1,300°F	−365°F–+1,000°F	−365°F–+1,200°F	−365°F–+2,000°F	−365°F–+750°F	−365°F	+500°F	−365°F–+500°F
d use features	Automotive Corrosion Decorative Lubricity	Automotive Corrosion Decorative Lubricity	Aircraft Lubricity Corrosion	Aircraft Lubricity Corrosion	Nuclear Lubricity Corrosion	Prevailing torque nuts	High-temp Aircraft antiseize	High-temp Aircraft antiseize	High-temp Aircraft antiseize	Field application Lubricity Corrosion	Fine threads Lubricity	Fine threads Lubricity	Extreme corrosion resistance and lubricity		Interference fit Corrosion
ncil hardness ASTM D-3363	5H	3H	4H	2H	4H	5H	5B	5B	5B	2H	N/A	N/A		6H	4H
rasion (Taber)mg/1000 ycles ASTM D-1044	6.3	6.4	8.7	11.8	5.8	7.3	1.5	4.7	4.5	13.2	N/A	N/A		1.87	13.9
rrosion resistance to salt pray (hours) ASTM B-117	500	300	500	500	500	100	100	100	N/A	ND	N/A	N/A		2,500	350
tallation[b] (ft-lb)	20.5	19.7	26.7	24.2	20	16.5	20	13.8	18.6	23.6	55.	5	31.7	25	d
que (std dev)	3.4	3.1	2.6	2.0	0.1	1.7	0.1	1.3	1.7	2.3	2.3	1.69	1.58		—
ex wear life × 1000 cycles[c]	120		N/A	N/A	130	51	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
TM D-2714 Coefficient of iction	.08	.07	.06	.06	.08	.07	.07	.06	.06	.06	.06	.06	.06	.06	N/A

orrosion resistance was measured on standard 3 × 6 steel Q-Panels with zinc phosphate and 0.5- to 0.8-mil coating thickness applied. These results allow for rating of coating type. Actual performance on threaded fasteners will vary based on application hod and part shape.

stallation torque is determined on standard 1/4-20 bolts and nuts using PLI washers to determine when constant clamp load has been achieved.

dex wear life is determined at light load corresponding to 12,000 to 24,000 psi. Products containing MoS_2 will typically provide 300,000 to 500,000 cycles at >8–0,000 psi.

eets requirements of Boeing Material Specification BMS 10-85E.

TABLE 6
Chemical Resistance Properties

Test Fluid	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Lubricating oil, MIL-L-6082	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Lubricating oil, MIL-L-7808	○	○	○	○	○	○	○	○	N/A	○	○	○	○	○
Hydraulic fluid, MIL-H-8446	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Hydraulic fluid, MIL-H-5606	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Gasoline aviation, MIL-G-5572	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Trichloroethylene, O-T-634	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Lubricating oil, MIL-L-2104	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Turbine fuel (JP-4), MIL-J-5624	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Lubricating oil, MIL-L-23699	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Trichloroethane	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Methyl ethyl ketone	○	○	○	○	○	○	○	○	—	○	○	○	○	○
DC-550 fluid	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Skydrol 500	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Methylene chloride	○	○	○	○	○	○	○	○	—	○	○	○	○	○
Hydrochloric acid (15%)	●	○	●	○	●	●	●	●	○	●	N/A	N/A	○	●
Sulfuric acid (50%)	○	○	○	○	●	○	●	○	—	○	N/A	N/A	○	○
Nitric acid (10%)	○	○	○	○	●	●	●	○	—	●	N/A	N/A	○	○
Sodium hydroxide (25%)	●	○	●	○	○	○	●	●	—	○	○	○	○	○

Notes: ○ = PASS; ● = FAIR, ASTM D-2510 fluid resistance test required 24 h immersion of a coated specimen in the test fluid followed by tape adhesion testing. The product designations are the same as Table 4.

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