A dry subject

Bearings sans liquid lubricants find use in everything from computer printers to rocket engines.

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Dry bearings, as the name implies, work with little or no liquid lubrication. Compared with rolling-element bearings, dry bearings are simpler to design, less expensive to purchase and maintain, and better resist contamination.

Materials suitable for dry bearings include polymers and polymer composites, carbon graphite, ceramics, and wood. A basic understanding of the underlying physics of dry bearings should help with the selection process.

SOME DRY THEORY

Two bodies in dry, sliding contact, carry some of the total normal load, W (MN) through asperities in the softer material. This so-called real contact area, A (m^2) can be estimated by:

$$A = \frac{W}{p} \quad (1)$$

where p = yield pressure (MPa) for the softer asperities, which is typically about 3× higher than the material's tensile yield strength. Real contact area is a small fraction of nominal area. For example, an acetal bearing with an asperity yield pressure = 300 MPa under a bearing load of 3 MPa has an asperity contact area equal to 1.0% of gross projected area.

The force, F (MN) needed to displace an asperity of the softer material with shear strength, s (MN/m^2) in dry sliding contact with a rigid body is:

$$F = As \quad (2)$$

This asperity shearing can account for 90% or more of total friction force. Other factors that may contribute to friction force include the "lifting force" needed to raise asperities over roughness of mating surfaces, scratches by dirt and particles, internal material damping, and surface layers.

The coefficient of friction f, directly relates to shear strength and compressive strength, p_c (MN/m^2), by:

$$f = \frac{F}{W} = \frac{s}{p_c} \quad (3)$$

Both s and p_c typically key to the same material properties such as lattice structure and bond strength, so f often falls in a narrow range of about 0.20 to 0.35 for a variety of bearing materials varying several hundred fold in yield strength.

Low-shear-strength surface layers of polytetrafluoroethylene (PTFE) or solid lubricants can lower f to about 0.05. Conversely, f may exceed 10 when similar mating materials fuse together. Friction force typically drops with increasing sliding speed because there is less time for adhesion to take place between surfaces.

Bodies in sliding contact always wear, typically at a higher-than-normal rate during initial run-in. Surface finish, misalignment, and contaminant particles mostly influence wear rate until sliding wear tends toward a steady rate.

Steady-state wear depth, h (m) is directly proportional to sliding distance, d (m) and applied pressure, P (MN/m^2):

$$h = kPd \quad (4)$$

where k (m^3/N-m) is the wear factor for a given bearing material and set of operating conditions.

A key metric for plastic bearings called the PV factor characterizes a material's maximum wear rate and limiting temperature rise. PV (MN/m-sec) is simply the product of unit load, P (MN/m^2) on the bearing projected area and surface velocity, V (m/sec).

MODERATE TEMPERATURES, LIGHT LOADS

Nylon, acetal, PTFE, polyethylene, and polypropylene are the most commonly used thermoplastics.

TYPICAL LIMITS FOR DRY BEARING MATERIALS

Material	Max temperature, °C	*PV* limit, MN/m-sec (*)	Max pressure *P*, MN/m² (**)	Max speed *v*, m/sec (***)
Thermoplastics				
Nylon	90	0.09	5	3
filled	150	0.46	10	
Acetal	100	0.12	5	3
filled	-	0.28	-	
PTFE	250	0.04	3.4	0.3
filled	250	0.53	17	5
fabric	-	0.88	400	0.8
Polycarbonate	105	0.03	7	5
Polyurethane	120	0.05	-	
Polysulfone	160	0.18	-	
Thermosetting				
Phenolics	120	0.18	41	13
filled	160	0.53	-	
Polyimides	260	4	-	8
filled	260	5	-	8
Others				
Carbon-graphite	400	0.53	4.1	13
Wood	70	0.42	14	10

* To convert MN/m-sec to psi-fpm, multiply by 2.86×10^4
** To convert MN/m² to psi, multiply by 145.
*** To convert m/sec to fpm, multiply by 197.

Acetal and ultrahigh-molecular-weight polyethylene are good for injection-molded housings, bearings, gears, and other machine elements in appliance, automotive, and many industrial applications.

PTFE (polytetrafluoroethylene) has a low coefficient of friction ranging from 0.04 to 0.10 at temperatures from cryogenic to 250°C. PTFE has limited utility when used in neat form, however. To avoid cold flow, for example, sliding speed should not exceed about 0.3 m/sec and maximum load, about 0.04 MN/m². Also, conventional petroleum and synthetic oils don't adequately wet PTFE. Oil actually accelerates wear by interfering with normal back-and-forth exchange of PTFE wear fragments between the bearing and its transfer layer on a steel surface.

Incorporating 15% PTFE powder in thermoplastic composites lowers coefficient of friction by 50% compared with the unfilled composite, reducing wear rate by a factor of 10 or more in some cases. The addition of inorganic or metal powders, graphite, and glass fibers to PTFE cuts wear rate by several orders of magnitude. Interestingly, filled PTFE maintains the same low friction coefficient as neat PTFE.

PTFE fabric handles loads to 400 MN/m² (60,000 psi) at low speeds and semistatic conditions. Interweaving a secondary fiber such as polyester, glass, or cotton with the PTFE lets the fabric bond to a steel support backing. Bearings made with the method find use in automotive ball and socket joints, bridge bearings, and aircraft controls.

Bearings of phenolic resins filled with cotton fibers, cellulose, or graphite work in small appliances, business machines, and instruments. Such bearings may be simple holes in phenolic or polyester structural elements. Bearings with small-bore sizes (below 50-mm diameter) can be injection molded, though high processing costs of the material limit use for larger bearings such as in industrial and marine applications.

Polyimide molding compounds incorporating graphite and other fillers are used in ball bearing retainers, bearing seals, aircraft bushings, and pis-

Thermosetting resins such as phenolics, polyesters, and polyimides, also serve as bearing materials. Injection-molded acetal and nylon work for inexpensive, small bearings subjected to light loads such as those in household appliances, office machines, small industrial equipment, toys, and instruments.

Polyamide nylons need little or no lubrication, have low friction, and operate with low noise. A thin layer of the material applied to steel backing, or the addition of fillers such as inorganic powders or glass fibers, minimizes cold flow under load.

SELECTING A PLASTIC BEARING

Estimate the radial wear in a nylon bushing supporting a 10-mm-diameter shaft running at 900 rpm for 1,000 hr under a load, P = 0.5 MN/m² (70 psi) based on projected area.

Nylon's wear factor, $k = 4.010 \times 10^{-15}$ m³/N-m, and sliding distance, $D = 1.70 \times 10^5$ m, gives a wear depth, h = 3.4 mm. Should this amount of wear be unacceptable, filled nylon (k = 0.24) reduces wear depth to 0.2 mm..

FRICTION AND WEAR FACTORS FOR PLASTIC BEARINGS

	Wear factor *k*, 10^{-15} m^3/N-m		Kinetic friction coefficient	
Material	**No filler**	**Filled**[a]	**No filler**	**Filled**[a]
Nylon 6,6	4.0	0.24[b]	0.61	0.18[b]
PTFE	100	0.14[c]	0.05	0.09[c]
Acetal resin	1.3	0.49	0.21	0.34
Polycarbonate	50	3.6	0.38	0.22
Polyester	4.2	1.8	0.25	0.27
Poly (phenylene oxide)	60	4.6	0.39	0.27
Polysulfone	30	3.2	0.37	0.22
Polyurethane	6.8	3.6	0.37	0.34

a. With 30 wt % glass fiber, unless otherwise noted ; b. 20% PTFE; c. 15% glass fiber; Considerable variability in material properties can be expected so users should consult suppliers on specific materials. In any case, test designs before production to establish actual performance.

ton rings at temperatures to 260°C. Polysulfones and polyphenylene sulfide also work in this temperature range.

Plastics, porous-metal, and rubber bearing materials have largely replaced lignum vitae and oil-impregnated maple and oak, though wood bearings are still found in food and chemical-processing machinery, ship-propeller shafts, conveyors, and hydraulic pumps and turbines. Such applications use water or other low-viscosity working fluid and operate at relatively low speeds and temperatures below 70°C.

TOO HOT? TRY CARBON GRAPHITE

Consider carbon graphite when operating temperatures exceed what plastics can handle. A wide range of mechanical properties can come out of carbon-graphite composites made by high-pressure molding of graphite powder mixed with petroleum coke, lamp black and coal-tar pitch, followed by curing at temperatures to 1,440°C.

The resulting porous structure is impregnated with phenolic or epoxy resins, copper, babbitt, bronze, glass, or silver to give the desired strength, hardness, and wear properties. Common uses include pump bearings for water, gasoline, and solvents; conveyor and furnace bearings that operate at temperatures to 400°C; and in food, drug, and other machinery that can't tolerate oil and grease contamination.

Shaft surfaces should be hardened tool steel, chrome plate, high-strength bronze, and carbide and ceramic overlays with 0.25 μm or better surface finish. Tests of carbon-graphite bearings run dry at speeds from 0.05 to 47 m/sec (10 to 9,200 fpm) show a coefficient of friction = 0.16 to 0.20 and a wear factor = 14×10^{-16}m/N (70×10^{-10} in.^{3}-min/ft-lb-hr). Those considering carbon-graphite bearings should first build and test prototypes before starting production.

METALS AND ALLOYS

Various alloys of iron, cobalt, nickel, chromium and molybdenum can withstand operating temperatures from 500 to 850°C. Among these are nitrided and tool steels, stellites with large chrome carbides in a cobalt matrix, and cobalt or nickel-based tribaloys.

These alloys develop hardness by what is called an intermetallic, laves phase rather than by massive carbides. Above transition temperatures, a protective, smooth oxide surface rapidly forms in air to minimize metal-to-metal contact and wear. Steel, for example, has a transition temperature of 185°C. The transition temperatures for other common bearing alloys are: cobalt (350°C); molybdenum (460°C); titanium (575°C); chromium (630°C); nickel (630°C).

Wear-resistant steel alloys can operate at tem-

CERAMICS FOR BEARING AND SEAL APPLICATIONS

Property	Hot-pressed alumina Al_2O_3	Cold-pressed alumina AD999	Silicon carbide α-SiC	Silicon Nitride Si_3N_4	Partially stabilized zirconia PSZ MS
Density, g/cm^3	3.9-3.98	3.96	3.10	3.21	5.5-6.05
Hardness, kg/mm^3	2,050	1,500	2,800	1,500	1,050
Modulus of elasticity, GPa	380-400	390	410	325	150-220
Tensile strength, MPa	260	220	-	524	689
Flexural strength, MPa	260	276	-	524	689
Compressive strength, MPa	2,760	2,070	3,900	3,000	1,850
Fracture toughness K_{IC}, MPa-m$^{1/2}$	3-3.2	3	4.6	6-7	10-12
Thermal shock resistance, TSR	-	3-4	10	20	0.6
Max. use temperature in air, °C	2,000	1,760	1,650	1,300	900-1,400

peratures to about 500°C, while superalloys of cobalt, nickel, chromium, and molybdenum can work in the 750 to 850°C range. Some cobalt alloys, for example, form an oxide surface layer that dramatically reduces fretting and wear for limited sliding of seals and other surfaces in gas turbines, above the 350°C cobalt transition temperature.

Solid lubricants and soft metal coatings also help minimize wear during limited sliding and oscillating motion of high-temperature alloy seal and bearing surfaces in furnaces, gas turbines, rocket engines, and other aerospace applications.

HOT, HOT, HOT CERAMICS

Ceramics such as aluminum oxide (Al_2O_3) and silicon carbide (SiC) are used extensively as bearings and seals for high-temperature applications. Hybrid ball bearings, for example, combine silicon nitride (Si_3N_4) balls with tool-steel raceways. Si_3N_4 also works for mechanical seal faces. Partially stabilized zirconia ($ZrO_2 + Y_2O_3$ or MgO) is of current interest for low-heat-rejection diesel engines.

Ceramic composites incorporating nickel, cobalt, molybdenum, or chromium, have better toughness, ductility, and shock resistance than pure ceramics. Plasma and other thermal-spray processes deposit wear-resistant ceramic coating powders of Al_2O_3, Cr_2O_3, TiN, WC, and TiO_2 on metal substrates (with or without added Co, Ni, or Cr) to improve mechanical properties.

These ceramics have low density, high compressive strength, fatigue and corrosion resistance, and retain mechanical properties at temperatures well above 1,000°C. Typical unlubricated coefficients of friction range from 0.5 to 1.0 and wear rates from 1×10^{-4} to 1×10^{-6} mm²/N-m.

Lubricants can lower wear rates into the 1×10^{-7} to 1×10^{-10} range or less. Candidate lubricants include oils, greases, water and water vapor, aqueous solutions, low-shear-strength solids, reactive vapors, and friction polymers. Consider vapor-phase lubrication and solid-lubricant films at temperatures above 250 to 300°C.

Cracking from thermal shock is always a concern with ceramic components that undergo a rapid rise in surface temperature. Relative thermal shock resistance (TSR) can be estimated from:

$$TSR = \frac{\sigma k}{E\alpha} \times 10^3 \qquad (5)$$

where

σ = tensile fracture stress, MPa
k = thermal conductivity, W/m°C
E = elastic modulus, MPa
α = thermal expansion coefficient, $°C^{-1}$

Materials with lower TSR values are more susceptible to thermal shock fractures than those with higher values. Partially stabilized zirconia, for example, has a TSR of about 0.6 and is highly sensitive to thermal shock. Silicon nitride's TSR of about 20 puts it at the top of the ceramics list, though it's still much lower than tool steel which has a TSR = 57.

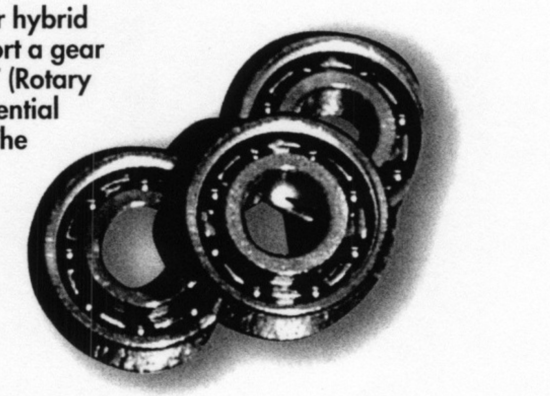
The addition of nickel, cobalt, molybdenum, or chromium to ceramic boosts toughness, ductility, and shock resistance. Plasma and other thermal-spray processes deposit wear-resistant ceramic coatings as powders of Al_2O_3, Cr_2O_3, TiN, WC, and TiO_2 on metal substrates (with or without Co, Ni, or Cr) to improve mechanical properties. ■

Bearings *are* rocket science

Custom hybrid ball bearings from **Pacamor Kubar Bearings** go in rocket-engine controls and withstand both cryogenic temperatures and the vacuum of space. The bearings support a shaft in rotary variable differential transformer gearheads from **Kearfott Guidance & Navigation Corp.** The RVDT supplies position feedback to an actuator that adjusts a throttle-control valve for an upper-stage rocket engine. The rocket booster, when completed, will be used to deploy satellites.

"The RVDT unit operates at –425°F, too cold for standard lubricants," says Kearfoot Engineering Manager Tony Patti. "In addition, the bearing must tolerate repeated oscillating motion."

PKB engineers spec'd bearings with a special PTFE-based retainer. This low-friction material has good chemical resistance, handles low and high temperatures, and provides limited lubrication. The use of dry-film lubricants and ceramic bearing balls further help the bearings survive the harsh environment. ■



Pacamor Kubar hybrid bearings support a gear shaft in a RVDT (Rotary Variable Differential Transformer). The RVDT actuator adjusts the throttle setting of an upper-stage rocket engine.

MAKE CONTACT

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