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Sliding Contact Damage Testing

SURFACE DAMAGE from sliding contact is related to the adhesion of the mating surfaces in contact. Adhesion is a major contributor to sliding resistance (friction) and can cause loss of material at the surface (i.e., wear) or surface damage without a loss of material at the surface (e.g., galling or scuffing). Adhesion is clearly demonstrated in sliding systems when a shaft seizes in a bearing.

The types of surface damage caused by sliding contact include adhesive wear, galling, and fretting. These three damage mechanisms are all influenced by adhesion of the mating surfaces, but these categories also reflect the nature of the surface damage and the type of sliding contact. For example, galling is considered a severe form of adhesive wear that occurs when two surfaces slide against each other at relatively low speeds and high loads. Fretting is also a special case of adhesive wear that occurs from oscillatory motion of relatively small amplitude.

The third damage type, adhesive wear, is a little more ambiguous. Often adhesive wear is defined by excluding other forms of wear. For example, if no abrasive substances are found, if the amplitude of sliding is greater than that in fretting, and if the rate of material loss is not governed by the principles of oxidation, adhesive wear is said to occur. In most cases, however, adhesive wear involves a transfer of material from one surface to another. Adhesive wear also occurs typically from the sliding contact of two surfaces, where interfaces in contact are made to slide and the locally adhered regions must separate, leaving transferred material. Breakout of this transferred material will form additional debris. This separation of material results in a wide range of wear rates, depending on the type of contact and the adhesion between the mating surfaces.

This article describes the methods for evaluation of surface damage caused by sliding contact. The first section, "Adhesive Wear," describes wear testing from long-distance sliding of nominally clean and dry (unlubricated) surfaces. This is followed by sections on test methods for galling and fretting wear, which are more unique forms of adhesive wear and surface damage. Additional information on sliding contact damage can be found in *Friction, Lubrication, and Wear Technology,* Volume 18 of *ASM Handbook.*

Adhesive Wear

W.A. Glaeser, Battelle

Adhesive wear typically occurs from sliding contact and is often manifested by a transfer of material between the contacting surfaces. As an example, Fig. 1 shows bronze transfer to a steel surface under sliding contact. Transfer can be minute and only visible in the microscope. Deformation wear, or plastic deformation of a thin surface layer during sliding contact, can also fall under the definition of adhesive wear. Adhesive wear can occur along with abrasive or chemical wear conditions. A transfer layer can build up on the harder surface of a sliding pair in the form of a mechanically mixed material (Ref 1). The transfer layer can also contain compacted wear debris. This layer will tend to break out and form wear debris.

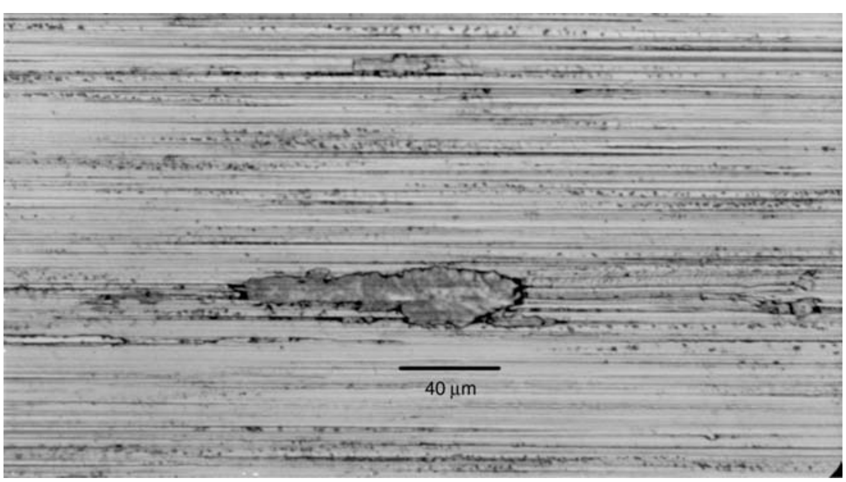


Fig. 1 Bronze transfer to a steel surface after adhesive wear during sliding contact

Adhesive wear is a function of material combination, lubrication, and environment. For instance, austenitic stainless steels (AISI 304, 316, etc.) sliding against themselves are very likely to transfer and gall with severe surface damage. Other materials that are prone to adhesive wear include titanium, nickel, and zirconium. These materials make very poor unlubricated sliding pairs and can wear severely in adhesive mode even when lubricated. Other metals are apt to show adhesive wear when dry sliding contact occurs. Rubber tends to bond to smooth, dry surfaces (glass and polymers) by weak van der Waals forces and slide in a stick-slip mode that involves adhesion.

A gaseous environment is an important factor in promoting adhesive wear. The lack of oxygen and water vapor in a wear environment can aggravate adhesive wear. High vacuum conditions as found in outer space will make adhesive wear likely. Wear tests run in simulated space conditions (10^{-10}) torr reveal tendencies for various material combinations to develop adhesive wear in that environment (Ref 2).

Adhesive wear testing can be carried out with a variety of sliding contact systems. These include four-ball, block-on-ring, pin-on-disk, crossed cylinders, flat-on-flat, and disk machines. Examples are shown in Fig. 2.

Adhesive wear testing (sliding contact wear, no lubrication, slow motion, heavy load) may be chosen deliberately to investigate the resistance of a material to excessive wear and material transfer for a given application. Adhesive wear can also occur unexpectedly in a sliding contact test and should be recognized from the wear morphology. Typical wear scars associated with adhesive wear are shown in Fig. 3 and 4. Figure 4(a) shows a scanning electron microscope (SEM) micrograph of an embedded steel particle in an aluminum bearing surface; the particle is identified by the energy-dispersive x-ray spectrometry (EDX) pattern for iron shown in Fig. 4(b). The test can be designed to determine load capacity or effects of temperature on the onset of adhesive wear. These data would then be used in the design of a bearing or gear system that could operate safely in the conditions simulated in the test.

Adhesive Wear Terms

Adhesive wear from sliding contact occurs from the transference of material from one surface to another due to a process of solid-phase welding (Ref 3). Particles that are removed from one surface are either permanently or temporarily attached to the other surface. There are also a number of other terms used to describe adhesive wear conditions, defined as follows.

Asperity refers to an isolated high spot in a given surface-roughness profile or a protuberance in the small-scale topographical irregularities of a solid surface.

Cold welding is the bonding of surface contact points after localized softening or melting caused by the frictional heating of contacting asperities during sliding.

Galling is a severe form of scuffing and is often associated with gross damage to the surfaces or failure. The usage of the term galling has different intents, and therefore its meaning must be ascertained from the specific context of the usage. Galling can be considered to be a severe form of adhesive wear, where cold welding of asperities causes heavy transfer of surface material.

Scuffing is the formation of severe scratches in the sliding direction. Also referred to as *scoring,* scuffing is considered a milder form of galling. It occurs when cold-welded junctions leave hardened protrusions, which tend to plow and scratch the softer mating surface much like abrasion.

Seizure is the stopping of relative motion as a result of interfacial friction or by gross surface welding. Seizure is an adhesive wear condition, where cold welding and material transfer result in loss of clearance between mating surfaces.

Wear coefficient is a nondimensional number that is typically defined as the proportionality k factor in the Archard wear formula (Ref 4):

$$W = kLD/H$$

where W is wear volume, L is normal load or force, D is distance of sliding, H is hardness, and k is wear coefficient.

This equation *assumes a linear process;* that is, wear is proportional to the applied load and distance, and inversely proportional to hardness. This equation is used extensively in developing data from wear tests. As an example, assume a pin-on-disk wear test is run using a copper pin. The operating conditions are as follows (a detailed description of the calculation and use of the wear coefficient can be found in Ref 5):

Normal load, N (kgf)	19.6 (2)
Disk speed, rpm	80
Track diameter, mm (in.)	32 (1.3)
Test duration, h	2
Pin weight loss, mg (grains)	23.1 (0.35)
Hardness of pin, HV	80
Density of copper, g/cm^3 (lb/in.^{3})	8.9 (0.3)

The wear coefficient is calculated as follows:

$$W = 23.1/8.9 = 260 \text{ mm}^3$$

$$D = \pi \times 32 \times 80 \times 120 = 9.65 \times 10^5 \text{ mm}$$

$$k = 2.60 \times 80/9.65 \times 10^5 \times 2 = 1.08 \times 10^{-4}$$

Wear Life Determination. Assume a 10 mm diam copper pin electrode rides against a rotating steel surface running at 100 rpm and the allowable shortening of the pin due to wear is 10 mm. The pin load is 1 kg. The track diameter is 70 mm. What is the approximate life of the pin?

$$k = 1.08 \times 10^{-4}$$

$$\text{Pin wear volume} = \pi \times 100 \times 10 = kLD/H$$

$$D = (3.14 \times 10^3 \times 80)/1.08 \times 10^{-4} = 2.32 \times 10^9 \text{ mm}$$

$$D = \pi \times 70 \times 100 \times \text{time}$$

$$\text{Time} = 2.32 \times 10^9/2.2 \times 10^4 = 1.05 \times 10^5 \text{ min, or } 1750 \text{ h}$$

Specific wear is similar to wear coefficient, except that the hardness factor is not included. This is often used when determining the wear properties of materials of similar hardness.

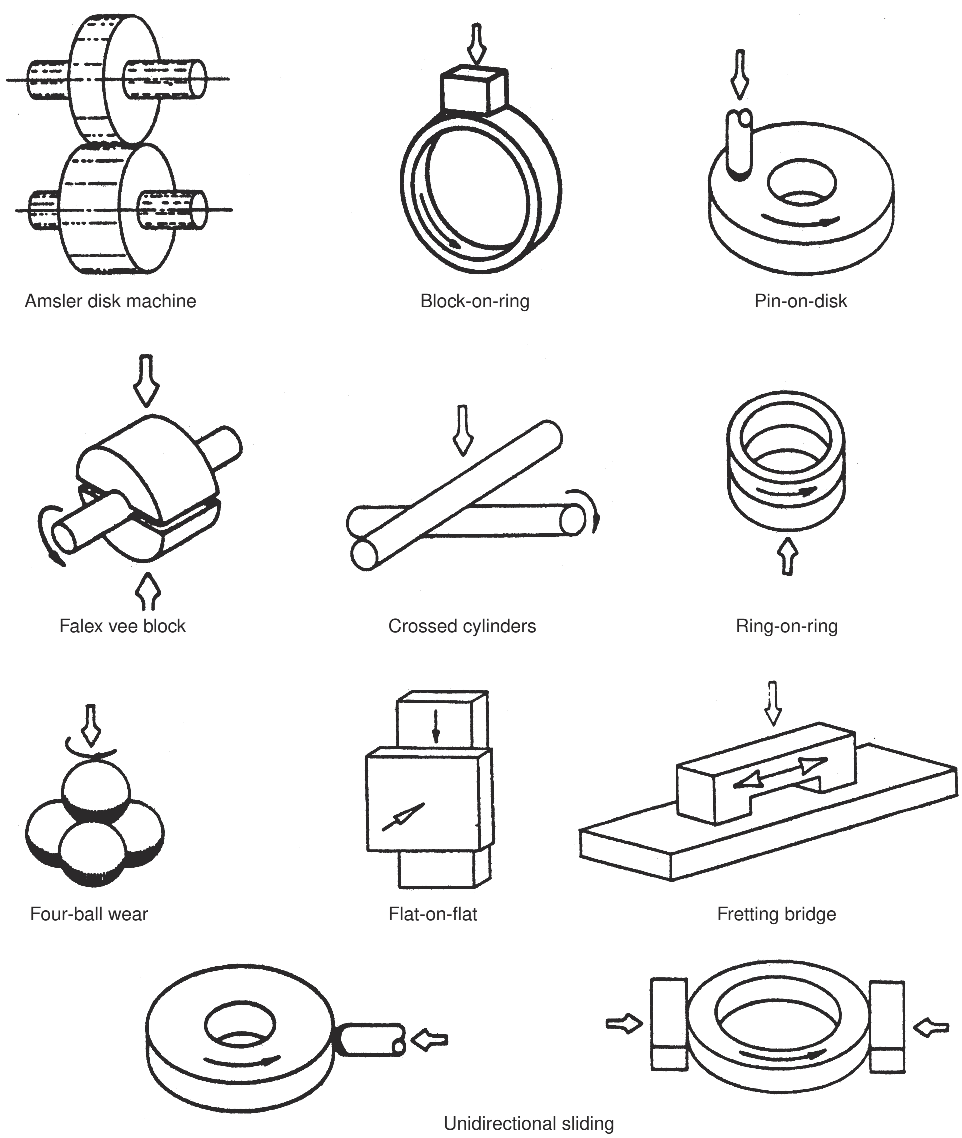


Fig. 2 Diagrams of contact types for various test machines

Selecting Standard Adhesive Wear Tests

Generally, adhesive wear testing involves sliding contact between unlubricated parts. For instance, such testing might help identify a material combination for a slow-moving brake or clutch system. Testing also could assist in operating a sleeve bearing in a high vacuum or oxygen and water-vapor-free environment. The purpose might be to estimate the wear life of such an operating system. The wear coefficient can be obtained from an appropriate wear test apparatus, and the maximum wear loss can be specified.

Simulation of Operating Conditions. In selecting a standard wear test, it is important that the test come close to simulating the prospective operating conditions of the mechanism of concern. The test should simulate the following conditions:

- Contact
  - Point contact (ball-on-flat, ball-on-ball, crossed cylinders)
  - Line contact (roller-on-flat; roller-on-roller, axes parallel)
  - Flat-on-flat
  - Conforming (sleeve or journal bearing)
- Velocity and load (high speed, low load; low speed, high load; low speed, low load)
- Temperature
- Vibration
- Gaseous environment

Contact conditions can be selected from a number of wear test configurations as are shown in Fig. 2. These are taken from standard wear tests, and many can be found in ASTM specifications. The Amsler and Falex vee block represent line contact systems. Point contact is represented in pin-on-disk, crossed cylinders and four-ball tests, while flat-on-flat is shown in ring-on-ring, fretting bridge, and flat-on-flat configurations.

The following ASTM standards apply to the configurations shown in Fig. 2:

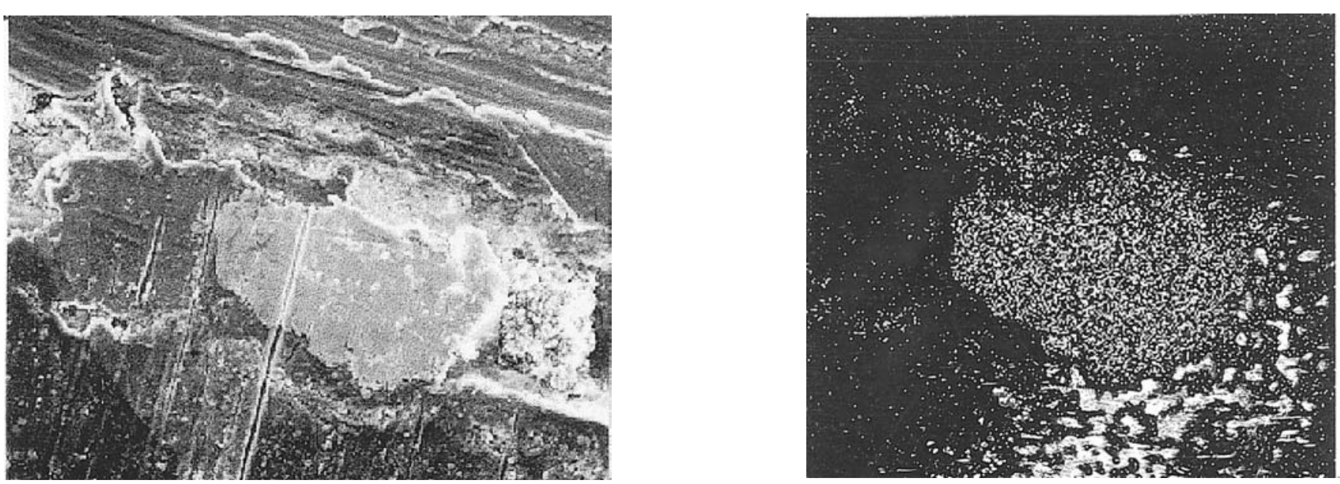
Test	ASTM No.	Title
Block-on-ring	G 77	Standard Test Method for Ranking Resistance of Materials to Sliding Wear, Using Block-on-Ring Test
Crossed cylinders	G 83	Standard Test Method for Wear Testing with a Crossed Cylinder Apparatus
Pin-on-disk	G 99	Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus
Falex vee block	D 2670	Standard Test Method for Measuring Wear Properties of Fluid Lubricants (Falex Pin and Fee Block Method)
Four-ball	D 4172	Standard Test Method for Wear Preventive Characteristics of Lubrication Fluid (Four-Ball Method)

These standards are also available in Ref 6.

Temperature and Friction. Wear tests should have continuous measurement of both specimen temperature and friction. Temperature can be measured by a thermocouple inserted in the stationary specimen near the contact surface. A number of standard tests found in ASTM specifications have friction measuring devices included in the description of the apparatus.

Velocity and Load. Archard's equation, as a general model of wear, assumes that wear is proportional to the applied load and sliding distance. Distance and velocity are related, and so wear is also proportional to velocity by

Fig. 3 SEM micrograph of adhesive wear of cast iron



(a) (b)

Fig. 4 Scar from adhesive wear. (a) SEM micrograph of wear scar on an aluminum bearing with embedded steel particle from the shaft. 200× (b) EDX pattern for iron in the particle. 200×

Archard's equation. Because it is desirable and economical to run wear tests as quickly as possible, both the load and the velocity can be increased to speed up a test. However, increasing these parameters will also increase the frictional heat generation and can lead to overheating. Overheating will change the wear mode (increasing galling and surface damage) and will result in misleading wear data. This is particularly important in wear testing of polymers. Polymers have low thermal conductivity and low melting and softening points compared to metals. Therefore, before embarking on a series of wear tests for statistical analysis, a set of preliminary tests should be run to establish the most efficient method, while keeping the wear mode as expected in the application.

Statistical Analysis of Wear Data

Data scatter is inherent in any testing, and using a statistical approach to the analysis of wear data is desirable. The method in ASTM G 83 (Ref 7) recommends sample sizes over 10. However, because 10 samples may not be possible owing to availability of samples and cost, ASTM G 83 does provide a method for analysis with sample sizes less than 10. The method uses the range of test results, where the range, R, is the difference between the highest and lowest test values for an initial set (2 to 10 samples) of measurements. For these small sample sizes, the standard deviation (s) can be calculated from the R value instead of from the root mean square value. For sample sizes from 2 to 10, the standard deviation is calculated from the range of the first few test results as follows:

$$s = R/d_2$$

where the values for d_2 are listed in Table 1 for different sample sizes.

Sample size (n) estimate can be derived from the relation:

$$n = 1.96\ \nu/e^2$$

where ν is the percent coefficient of variation = $(s/x) \times 100(\%)$, e is the sampling error, and x is the average for n tests. For example, if $s = 0.9$ mg and $x = 8$ mg, then the coefficient of variation is 11%. If an allowable sampling error (e) is selected as 10%, the sample size for 95% confidence limits should be $(1.9 \cdot 11/10)^2 = 5$.

The results of round-robin tests from several laboratories using block-on-ring test apparatus are reported in the appendix of ASTM G 77 (and also Ref 8). This reference shows the expected scatter in such wear tests.

Table 1 Factors for estimating standard deviation for sample sizes 10 and less

Sample size	d_2
2	1.128
3	1.693
4	2.059
5	2.326
6	2.534
7	2.704
8	2.847
9	2.970
10	3.078

Standard deviation $s = R/d_2$ for small sample size, where the range R is the difference between the highest and lowest test values for an initial set (2 to 10 samples) of measurements. Source: Ref 7

Measuring Wear

A wear test should be run long enough to produce measurable wear. What constitutes measurable wear depends on the measuring method. The easiest way to determine measurable wear is to measure weight loss. This is also the coarsest method. Weight loss must be sufficient to be uninfluenced by condensed moisture, contaminants such as dust and oil, and minute transfer. Dimensional change is a more sensitive method. If a well-defined contact geometry is used such as ball-on-flat, ball-on-ball, or ring-on-flat, a scar length can be translated to volume loss. Equations for calculating wear volume from scar dimensions are shown in Fig. 5.

Adhesive wear testing often involves some transfer from one surface to another. It is good practice to use two methods to measure wear: scar measurement and weight loss. The volumes determined from both methods can be compared, and effects of transfer, deformation, or pitting can be detected.

Galling

John H. Magee,
Carpenter Specialty Alloys

Galling is a severe form of adhesive wear or surface damage that occurs when the surface of two components slide against each other at relatively low speeds and high loads. Lubricants or coatings, designed to reduce friction and prevent galling, are sometimes either ineffective or cannot be used due to product contamination concerns. Thus, gross surface damage occurs and is characterized by localized material transfer or removal. This gross surface damage is known as galling and can occur after just a few cycles of relative movement between the mating surfaces. Severe galling can cause seizure of these parts.

When galling takes place, mated surfaces typically show distinct junctions where severe plastic deformation has occurred (Fig. 6). These contact surfaces contain areas where asperities, or surface protrusions, from one surface have bonded together with those on the other surface. Under low stresses, these junctions are minute and break apart with movement resulting in adhesive wear debris. However, higher stresses produce much larger junctions and galling (Ref 11).

Components that encounter galling conditions include threaded fasteners from a typical bolt/nut connection to large threaded tubular used in oil exploration. Valve parts have mating surfaces that are designed to encounter infrequent sliding movement. Galling damage on these surfaces affects valve performance, for example, leaking. The interface of a roller and side plate on a continuous chain-link conveyor belt can gall when lubrication is not used. This is an important design consideration for the conveyance of food and drug products because lubricants are prohibited due to contamination concerns (Ref 12).

The term galling has also been used to describe surface damage caused during metalworking. Metalworking processes include rolling, extrusion, wire drawing, deep drawing of sheet, and press-forming operations. Insufficient lubrication sometimes causes metal transfer and galling. In Japan, the term galling is used mainly to describe damage in sheet metalforming processes. Tests to characterize this gross surface damage usually involve production equipment or laboratory simulation of various plastic metalworking processes. Additional information can be found in Ref 13 and in *Friction, Lubrication, and Wear Technology,* Volume 18 of *ASM Handbook.*

This section describes in detail the ASTM G 98 button-on-block galling test. The purpose of this test is to rank material couples resistant to galling. Several variations of this test are also discussed that either increase the severity of the test or attempt to quantify the surface damage using profilometry. Data obtained from button-on-block testing are very useful in screening materials for prototype testing.

This section also describes prototype testing of threaded fasteners. Three threaded connection tests are discussed as examples of prototype tests designed to closely simulate field service for a specific application. This type of testing tends to be expensive, but vital before use in-service. Also, these tests can be used to solve a specific galling problem.

Button-on-Block Galling Test

In the 1950s, a simple button-on-block test was developed to evaluate the galling resistance of material couples (Ref 14). A specific version of this test is defined in ASTM G 98 (Ref 6, 15). This test is generally performed on bare metals; however, nonmetallics, coatings, solid lubricants, and surface-modified alloys can be tested as well.

The button-on-block test uses available laboratory equipment capable of maintaining a constant, compressive load between two flat surfaces. Both a Brinell hardness tester and a tension-test machine have been used to perform this test. Also, Falex Corporation, a designer and manufacturer of wear test equipment, has an apparatus specifically designed for button-on-block testing.

For bare metal evaluations, both galling specimens (button and block) are ground with abrasive paper or machine ground with an abrasive wheel. Both test surfaces should have a surface finish between 0.25 and 1.1 μm (10 and 45 μin.) for the arithmetic average surface roughness (R_a). Specimen flatness should be maintained at 0.33 mm/m (0.004 in./ft) to ensure 100% contact between the specimens during testing. The only critical dimension for either specimen is the button diameter that constitutes the contact area. The standard diameter is 13 mm (0.5 in.); however, other button diameters can be used. If a different diameter is used, then it should be reported since it can affect the test result. The block specimen must have sufficient area to accommodate at least one test; however, most users have found that a block length between 75 and 150 mm (3 and 6 in.) is ideal for this multiple sample test procedure. A reasonable block width is 19 mm (0. 5 in.), and a minimum width of 17 mm (0.625 in.) is necessary for testing a 13 mm (0.5 in.) button. Thickness is not critical.

Immediately prior to testing, both galling specimens are cleaned to remove machinery oils and metallic particles. The following cleaning technique is suggested for metals in ASTM G 98. First, ultrasonically clean the button and block in trichloroethane. Then, use a methanol

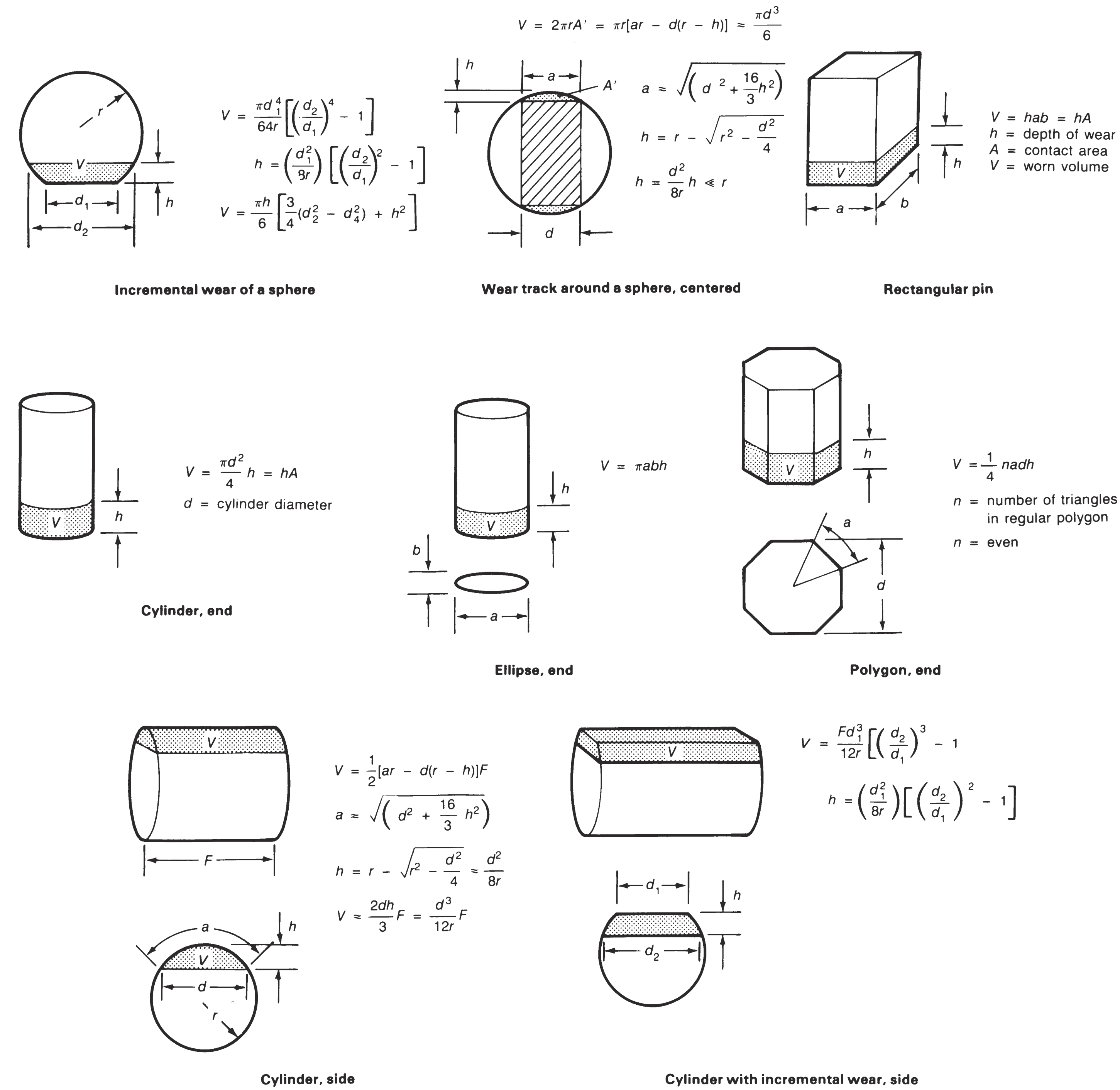


Fig. 5 Wear volume calculations for various shapes in contact with a flat surface. Source: Ref 9

rinse to remove any traces of trichloroethane residue. Materials with open grains (powder metals or hardfaced alloys) must be dried to remove all traces of the cleaning solvent that may be entrapped in the material. Note that because the use of trichloroethane is being discouraged, any nonchlorinated, non-film-forming cleaning agent and solvent can be used as a substitute.

Once cleaned, the specimens are mounted in the loading device, and a light compressive load, for example, 110 N (25 lb), is applied to make sure the button is properly seated on the block. The button-on-block test setup is shown in Fig. 7. A selected compressive load is then placed on the button specimen. This results in a specific compressive stress for a 13 mm (0.5 in.) button sample. The selected load is dependent on educated judgment of the galling resistance of the mated couples, that is, light loads for poor galling resistance and heavy loads for excellent galling-resistant couples. Stress cannot exceed the compressive yield strength of the button material.

Once loaded, the button is rotated slowly one revolution (360°) using either an open-end wrench, an adjustable wrench, or some other special tool for rotating by hand. A mechanized system may also be used to rotate one specimen relative to the other. The latter may allow torque measurement during testing. Actual sliding time should be between 3 and 20 s. Rotation direction, clockwise or counterclockwise, is not specified in ASTM G 98; however, it should be noted. The compressive load is then removed, and the mated surfaces are visually examined for galling. If specimens appear smooth and undamaged, to the unaided eye, the procedure is repeated at a higher load with an untested button specimen at a new location on the block sample. A burnished surface does not constitute a galled surface, nor does a scored surface. At least one of the contacting surfaces must exhibit torn metal. Galling has a distinct, macroscopic appearance with protrusions of metal above the original surface (Fig. 6).

If galling has occurred, testing is done at a lower load with a new button and block location to establish an interval between the highest nongalled stress and galled stress. This interval is used to define the threshold galling stress (TGS) and should be no greater than 34.5 MPa (5 ksi) for threshold stresses greater than 138 MPa (20 ksi) and no greater than 21 MPa (3 ksi) for threshold stresses of 138 MPa (20 ksi) or less. If galling is questionable or borderline, the test is repeated at a higher load to confirm the previous test result.

A typical series of galling tests is shown in Fig. 8. The reported TGS for the example is 34.5 MPa (4.5 ksi). Since the galling stress is based on the button diameter contact, the button impression on the block should be measured to determine if full contact occurred. At light loads, that may not be the case.

Experience has shown that galling is most prevalent in sliding systems that are slow moving and operate intermittently. The movement of threaded components or the opening and closing of valve components are classic examples that this test method attempts to simulate. This test method has proved valuable in screening materials for further prototypical testing that more closely simulates actual service conditions. The button and block material do not have to be the same material and hardness. When dissimilar, the selection of the button material should be the same as the sliding component being screened for the specific application.

Table 2 lists threshold galling stress data for a variety of material couples using the button-on-block test. Additional data can be found in Ref 12. This test is most popular for galling-prone materials, such as stainless steels.

Multiple-Rotation Button-on-Block Testing. A modification of the standard single-rotation test is a multiple-rotation procedure. This change is designed to simulate the action of valve components. Also, repetitive sliding across the same surface results in galling at lower stress values. Thus, alloys or coatings with good-to-excellent galling resistance can be evaluated. This procedure is especially useful for screening materials for service conditions known to be severe. One example of this multiple procedure is the triple-rotation test where the button is turned counterclockwise (360°), clockwise (360°), and counterclockwise (360°). This modified button-on-block test has been used to evaluate stainless steels with improved galling resistance and for testing solid lubricants, such as molybdenum-disulfide. Table 3 compares various stainless steels using the single- and triple-rotation tests. Most stainless alloys tested have significantly lower TGS values using the triple-rotation tests. Those who use cobalt-base alloys, hardfaced materials, and metallic coatings, should consider a multiple-rotation type of test procedure.

(a) (b)

Fig. 6 Galling test button specimens, after testing. (a) No galling exhibited. (b) Severe galling. Source: Ref 10

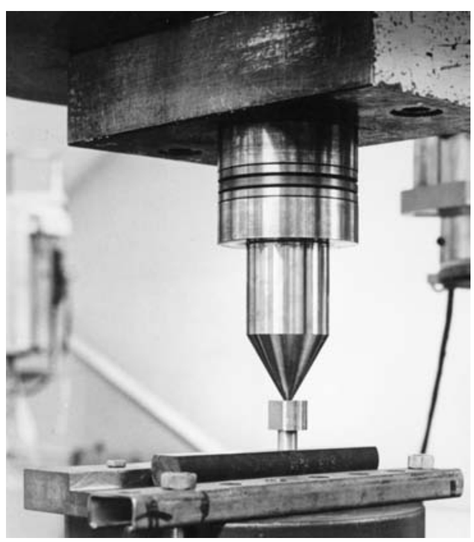


Fig. 7 Button-on-block galling test arrangement using a tension test machine. Source: Ref 16

Profilometry Evaluation of Galling Damage

Instead of a visual determination to assess galling damage, surface profilometry has been used. Several test procedures can be found in the literature (Ref 18–20). One example is a galling procedure that involves the twisting of a cylindrical 16 mm ($\frac{5}{8}$ in.) diameter pin against a block. Tests are performed at three selected loads. Cylindrical pins are slowly tested back and forth 10 times, through an arc of 120° at each load, using a new pin and block location per load. Scar profiles are measured using a profilometer. The difference in peak-to-valley amplitudes between the final roughness and

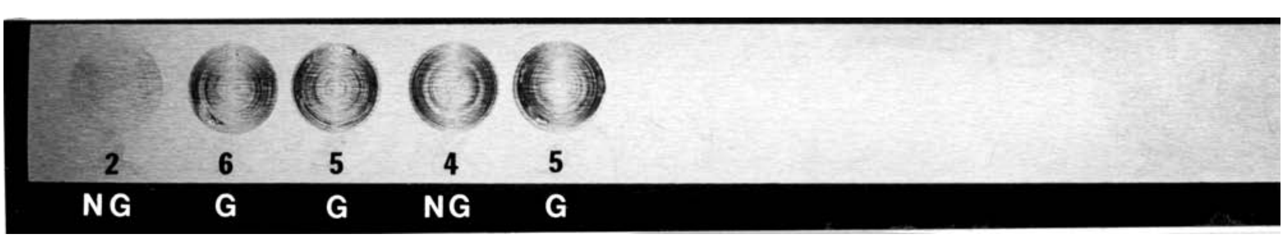


Fig. 8 Sequence of galling tests on block specimens. Source: Ref 17

Table 2 Galling resistance of selected material couples (metal A vs. metal B)

Contact metal A		Contact metal B		Threshold galling stress(a)	
Alloy	Hardness, HB	Alloy	Hardness, HB	MPa	ksi
Silicon bronze	200	Silicon bronze	200	28	4
	200	Type 304	140	304	44
A286 (S66286)	270	A286	270	21	3
AISI 4337	484	AISI 4337	415	14	2
AISI 1034	415	AISI 1034	415	14	2
Waukesha 88	141	Type 303	180	345+	50+
	141	Type 201	202	345+	50+
	141	Type 316	200	345+	50+
	141	S17400	405	345+	50+
	141	20Cr-80Ni	180	345+	50+
Type 201	202	Type 201	202	104	15
	202	Type 304	140	14	2
	202	S17400	382	14	2
	202	Nitronic 32	231	248	36
Type 301	169	Type 416	342	21	3
	169	Type 440C	560	21	3
Type 410	322	Type 420	472	21	3
Type 416	342	Type 416	372	90	13
	372	Type 410	322	28	4
	342	Type 430	190	21	3
	342	20Cr-80Ni	180	48	7
Type 440C	560	Type 440C	604	76	11
S17400	311	Type 304	140	14	2
	380	Nitronic 32	401	90	13
	435	Type 304	140	14	2
	400	S17700	400	21	3
	435	S17700	435	14	2
Nitronic 32 (S24100)	235	S17400	380	76	11
	401	Nitronic 32	401	235	34
	235	Nitronic 32	401	235	34
	235	Type 304	140	48	7
	401	Type 304	140	90	13
Nitronic 50 (S20910)	205	AISI 1034	205	14	2
	205	Nitronic 50	205	14	2
	321	Nitronic 50	321	14	2
	205	Nitronic 32	401	90	13
	321	Nitronic 32	235	55	8
	205	Type 304	140	28	4
Nitronic 60 (S21800)	205	Type 301	169	345+	50+
	205	Type 420	472	345+	50+
	213	S17400	313	345+	50+
	205	S17400	332	345+	50+
	205	Nitronic 50	205	345+	50+
	205	S13800	297	345+	50+
	205	S13800	437	345+	50+
	205	AISI 4337	448	345+	50+
	205	Stellite 6B	415	345+	50+
	205	A286	270	338+	49+
	205	20Cr-80Ni	180	248	36
	205	Ti-6Al-4V	332	345+	50+

(a) Values shown are unlubricated threshold galling stress for the button-on-block galling test. Values given as 50+ indicate the samples did not gall. Source: Ref 14

Table 3 Threshold galling stress results for selected self-mated stainless steels

			Threshold galling stress			
			Single rotation(a)		Triple rotation	
Contact alloy	UNS No.	Hardness	MPa	ksi	MPa	ksi
Gall-Tough	S20161	95 HRB	104+	15+	104+	15+
		28 HRC	104+	15+	104+	15+
Nitronic 60	S21800	92 HRB	104+	15+	48	7
Nitronic 50	S24100	23 HRC	97	14	14	2
18-18 Plus	S28200	96 HRB	166	24	7	1
Type 303	S30300	85 HRB	138	20	<7	<1
Type 304	S30400	86 HRB	55	8	<7	<1
Type 420	S42000	49 HRC	55	8	14	2
Trimrita	S42010	50 HRC	104+	15+	21	3
Type 430	S43000	98 HRB	10	1.5	<7	<1
Custom 630	S44004	55 HRC	124	18	14	2
Custom 455	S45500	48 HRC	97	13	<7	<1
A 286	S66286	30 HRC	14	2	<7	<1

Button-on-block test, unlubricated ground finish. +, did not gall. <, galled at this stress. (a) ASTM G 98. Source: Ref 12

the initial roughness (measured in microns) is plotted versus load. Resistance to galling is quantified by the degree of damage (measured in microns) as shown in Fig. 9. This 10-turn test is designed to evaluate excellent galling-resistant materials such as Stellite alloy No. 6, against other materials. Damage measured by this test typically does not reach the level of surface damage observed in the button-on-block test, that is, macroscopic protrusions of metal above the surface. Note that when stainless steels, such as type 304, 316, and 410, are evaluated self-mated using this procedure, severe damage occurs at relatively low loads with only one or two twists possible before total seizure.

Pin-on-Flat Galling Test

A second example of a procedure that uses surface profilometry to measure galling damage is the pin-on-flat test (Ref 21). In this test, a spherically tipped pin slides in a straight line against a flat surface (Fig. 10). Unlike the procedures previously discussed, there is no twisting action, nor is the button surface flat. A single pass with a distance of 40 mm (1.5 in.) is employed at a speed of 2 mm/s (0.8 in./s) and a load of 130 N (30 lb). Surface finish of the specimens is produced by a 6 µm polish, and the pin diameter is 13 mm (0.5 in.). A pin tip radius of 25 mm (1 in.) is used. As with all galling evaluations discussed, specimens are thoroughly cleaned in an ultrasonic bath and then alcohol rinsed prior to testing.

The topography of the damage is measured on the flat specimen by means of a stylus profilometer. A series of parallel traces at a spacing of approximately 0.3 mm (0.012 in.) is taken over the entire length of the track. The

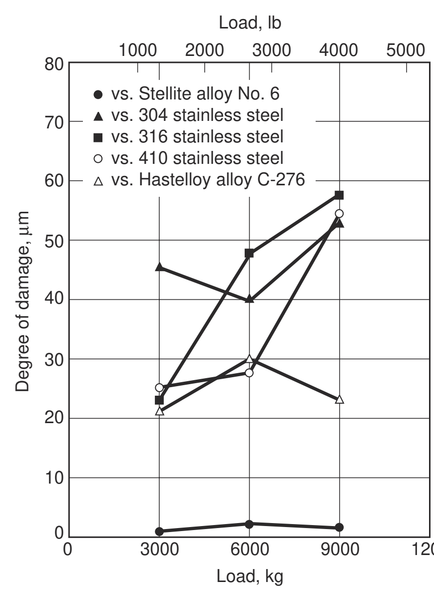


Fig. 9 Resistance to galling of Stellite alloy No. 6 (surface ground counterface) versus selected materials. Source: Ref 20

tracing direction is perpendicular to the sliding direction. Profile data are acquired in digital form, yielding a matrix of values that specify the elevation of points on the surface. A significant parameter, R_t, determined by these profilometry measurements, is the average maximum peak-to-valley distances (microns) for traces taken across the surface damage area. This parameter reflects the importance of the large protrusions and deep gouges that are characteristic of galling. Galling tendency of material is a function of the R_t value. Figure 11 plots damage severity (R_t) versus Knoop hardness for a wide variety of materials. The results show there is no overall correlation of damage severity with hardness. Aluminum-bronze, a known galling-resistant material, had no surface damage, while galling-prone alloys (such as type 410 stainless steel) had significant damage.

Threaded Connection Galling Tests

The galling tests described previously have been designed to rank material couples as a screening evaluation for prototype testing. Prototype tests tend to be more expensive and are designed for a specific application. Several threaded connections tests exemplify prototype testing (Ref 22–24). They are designed to determine if galling or seizure is a problem when inserting and removing threaded connections.

The first example involves evaluating a bolted joint design consisting of a socket head captive screw, a stainless flat washer, a helical lock washer, a stainless steel threaded insert, and a 19 mm ($\frac{3}{4}$ in.) thick drawer manifold to be bolted to the casting of a computer cabinet. In this test, each screw was inserted manually to minimize the chance of cross-threading, then torqued to a specified level, loosened, and removed completely. This sequence was repeated until galling or severe thread damage occurred. Variables evaluated were screw and insert material, molybdenum-disulfide lubricant, cadmium or nickel-plated screws, and thread type. The life-cycle design requirement was 900 cycles. Results of two of these tests can be found in Table 4.

Other examples of prototype tests involve threaded tubular products for deep and gas wells. These connections are prone to galling due to the high torque applied in the makeup operation, that is, near the yield strength of some alloys. Prototype tests were developed to evaluate this condition especially to determine the effectiveness of lubricants or surface treatments. A bolt-nut test apparatus was designed to closely simulate a threaded tubular makeup (Fig. 12) (Ref 23). Lubricants were applied to bolts and nuts according to manufacturer directions, and the makeup torque was applied. The calculated surface stress on the threaded parts and bolt-to-washer mating parts corresponded to metal-to-metal seal parts in actual threads. The makeup speed was slow: 3 rpm. Torque and clamping force were measured. After each makeup and break operation, the threaded parts and bolt-to-washer mating parts were inspected for galling. The lubricant performance was evaluated principally by noting the number of makeup and break cycles until galling was first

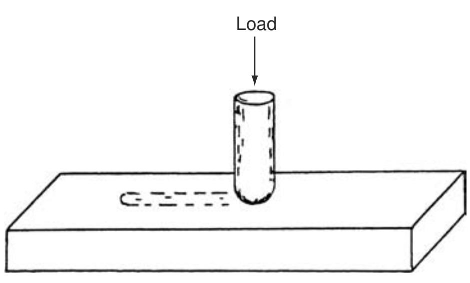


Fig. 10 Pin-on-flat galling test configuration. Source: Ref 21

Table 4 Sample results of two threaded connection galling tests

Test	Screw material	Insert material	Number of cycles to galling of threads
1	17-4 PH stainless steel, $\frac{3}{8}$–24 in., UNF-3A, 41 HRC, nonlubricated	Type 303 stainless steel hole, $\frac{3}{8}$–24 in., UNF-3B, 89 HRB	225
2	17-4 PH stainless steel, H1050, $\frac{3}{8}$–24 in., UNF-3A, 31 HRC, nonlubricated	Nitronic 60 hole, $\frac{3}{8}$–24 in., UNF-3B, 96 HRB	1000

Source: Ref 22

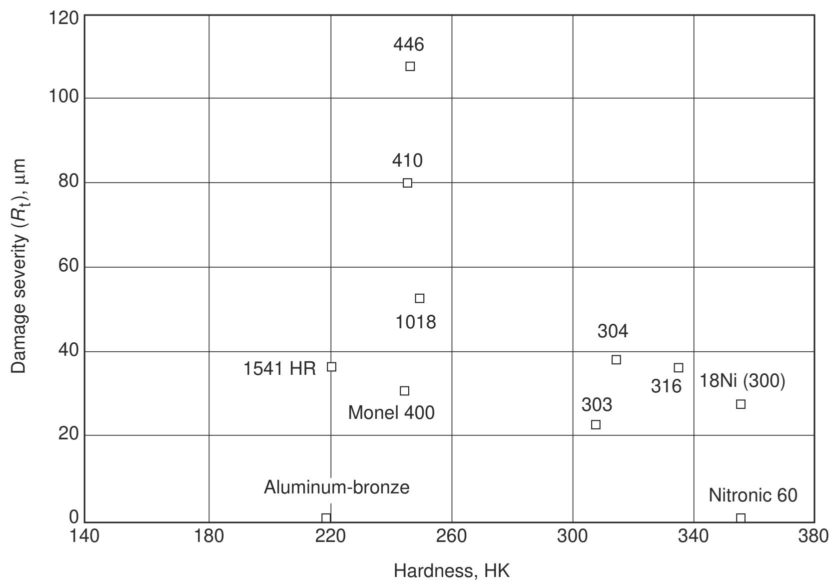


Fig. 11 Damage severity (R_t) as measured by profilometry plotted against hardness for several commercial alloys. Source: Ref 21

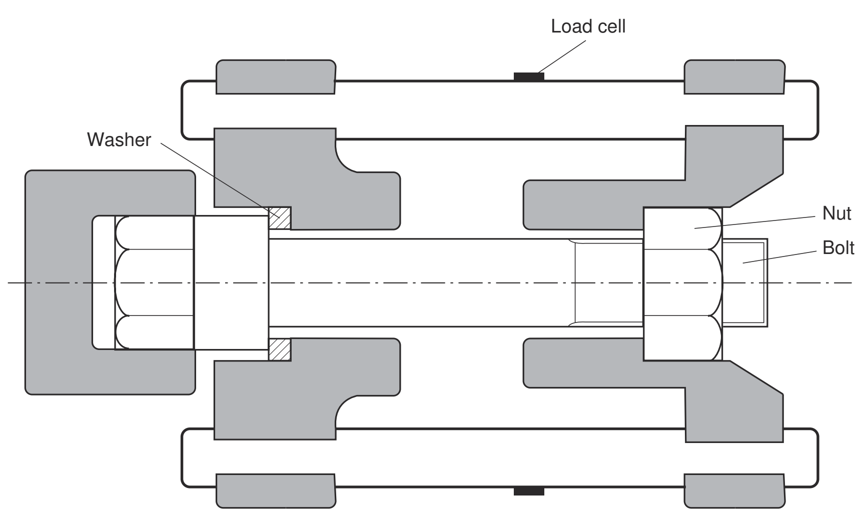


Fig. 12 Bolt-nut galling test apparatus. Source: Ref 23

observed. Also, the variation of torque coefficient was monitored during the test. Typical results are shown in Table 5. Longer test times of 30 days in the fastened state prior to breakout have been evaluated by this method as have higher-temperature test conditions to simulate deep-well service.

Another oil-country threaded tubular test involves thick-walled, high-alloy products such as nonmagnetic drill collars. These 9 m (30 ft) long collars are prone to galling when their threaded box and pin connections are released after being joined with high makeup torques. These connections require an antigalling lubricant or surface treatment, such as ion implantation (Ref 25). To evaluate their effectiveness, make/break galling tests are performed. Full-size connections are machined with threads and lubricant/surface treatments are applied. A large torque machine then "makes" the connection at a specified torque, appropriate for the threaded tubular size, then breaks the connection. The breakout torque is recorded. This procedure is repeated several times (typically 5 to 10 times). Alignment of the box/pin connection is important to prevent galling. After testing, the threads and seal surfaces of the box and pin tubulars are examined for galling. Test results simply report whether or not galling occurred.

Prevention of Galling

Preventing galling damage is a critical part in applications where parts are sliding against each other under high loads and low speeds. It becomes a bigger issue when corrosion-resistant alloys, such as stainless steels, are required under nonlubrication conditions. Despite the best efforts of designers and users, occasions also arise when close clearances result in the contact and rubbing of components in rotating machinery. Of key importance in this case is the prevention of galling, because this can cause seizure and severe damage.

Galling can be resisted in several ways. For applications in which galling is of concern, the following guidelines should be considered:

- Lubricate where possible.
- Keep load, temperature, and speed as low as possible.
- Parts should be dimensionally tight with sufficient clearance.
- Use a surface finish between 0.25 and 1.75 μm (10 and 70 μin.) whenever possible (many stainless parts are electropolished, which can lead to galling and wear).
- Increase contact area, so that there is less stress on parts and less depth of wear.
- Carefully select alloys in unlubricated systems, or where insufficient lubrication may be present. Dissimilar-mated couples with high threshold galling stress values can be chosen or high work-hardening rate austenitic stainless alloys can be selected for improved adhesive and cavitation wear resistance and galling resistance.
- Use surface treatments, such as nitriding, carburizing, and hardface coating, or solid lubricant coatings (i.e., molybdenum disulfide or graphite).

Galling resistance can sometimes be aided by heat treating the opposing parts so that they have a hardness difference of at least 50 HB, which encourages wear of the softer material rather than adhesion and resultant part-to-part material transfer (Ref 26). Another method of discouraging galling is to machine grooves in one or both of the close-clearance components, so that as wear takes place the debris can collect somewhere other than at the close running clearance. This also promotes rapid heat transfer at rubbing interfaces, keeping parts cool and hard. Local surface temperatures can become very high even with grooving, because of the flash-temperature effect, but such temperatures decay in short distances and do not result in galling if surface heat removal is effective (Ref 27). Grooving the surfaces results in a design compromise, however. Although grooving reduces clearance leakage, it also reduces the beneficial shaft support provided by the Lomakin effect (Ref 28).

Finally, the test methods described in this article also provide a basis in the evaluation and prevention of galling. The general comparison of galling potential for different materials can be done by the measurement of the contact stress required for cold welding and subsequent material pullout for a material mated against itself. This is called threshold galling stress. A complete listing of threshold galling data for stainless steels can be found in Ref 12.

Table 5 Bolt-nut test results on the lubrication performance of various lubricants under different test conditions

Lubricant	Test and condition	Makeup and break cycles until galling observed	Torque coefficient(a) at first makeup	Variation of torque coefficient, %
MoS_2-Sb_2O_3-epoxyester film	None	20	73×10^{-3}	+7, –6
		(b)	102	–16
	API grease	(b)	121	+9
		(b)	124	+11
	API grease + sand	9	139	+3, –2
		(b)	125	+18
	API grease + water	24	146	–14
		(b)	125	+5, –6
	API grease + brine	22	149	+7, –7
		(b)	127	+9, –13
Commercial organic resin bonded lubricant containing MoS_2 (MIL-L-23398, 46147, 8937B)	None	9	189	+21
		8	314	–14
	API grease	6	165	–16
		(b)	164	–22
	API grease + sand	14	202	–31
		7.5	175	–14
	API grease + water	22	146	–23
		19	167	–30
	API grease + brine	18	159	–16
		10	159	–21
Commercial paste containing polyalkyleneglycol, lithium soap and MoS_2	None	8	161	+9
	API grease	9	153	–7
		15	152	–11
	API grease + sand	11	160	–10
		7.5	154	–3
	API grease + water	8	124	+10
		7	145	–9
	API grease + brine	8	158	–15
		7.5	140	+11, –1
Electroplated copper film(c)	None	1	310×10^{-3}	...
	API grease	(b)	171	+1, –14
	API grease + sand	10	191	–17
	API grease + water	23	157	+10
	API grease + brine	(b)	158	–17
Heat treated films				
MoS_2-Sb_2O_3-epoxyester film, heat treated at 250 °C (480 °F) × 30 min in air	None	(b)	82	–16
	API grease	(b)	147	+21, –3
	API grease + sand	(b)	135	+10
	API grease + water	(b)	136	+13
	API grease + brine	(b)	140	+7, –3
Commercial organic resin-bonded lubricant containing MoS_2 (MIL-L-23398, 46147, 8937B), heat treated at 250 °C (480 °F) × 30 min in air	None	22	57	+2, –11
	API grease	(b)	125	+5, –12
	API grease + sand	20	127	+32
	API grease + water	(b)	124	+29
	API grease + brine	(b)	120	+26

(a) Torque coefficient (*C*) relates torque (*T*) to bolt tension (*F*) and bolt diameter (*D*) as follows: $T = CDF$. (b) No galling after 25 makeup and break cycles. (c) Copper striking followed by electroplating in $CuSO_4$ bath (15 μm, or 40 μin. thick). API, American Petroleum Institute. Source: Ref 23

Fretting Wear

R.B. Waterhouse, University of Nottingham (United Kingdom)

Fretting refers to a special form of surface wear that occurs from small-amplitude tangential oscillations between two surfaces in contact. The amplitude (or magnitude) of the relative motion in fretting wear is what distinguishes it from other forms of wear during unidirectional and reciprocating sliding contact. In practical cases, fretting wear occurs from extremely small repetitive motion, usually less than 25μm peak-to-peak amplitude.

One immediate consequence of the fretting process in normal atmospheric conditions is the production of oxide debris; hence the terms "fretting wear" and "fretting corrosion" are used for this phenomenon. Surface damage from fretting begins with local adhesion between mating surfaces and progresses when adhered particles are removed from a surface. When adhered particles are removed from the surface, they may react with air or other corrosive environments. Affected surfaces show pits or grooves with surrounding corrosion products.

The movement is usually the result of external vibration, but movement also occurs from cyclic contact stresses (fatigue) between mated parts. This fact gives rise to another and usually more damaging aspect of fretting, namely the early initiation of fatigue cracks. This is termed *fretting fatigue* or *contact fatigue.* Fatigue cracks may also be initiated where the contacting surfaces are under a very heavy normal load or where there is a static tensile stress in one of the surfaces. There are cases where the movement is not simply tangential, but is complicated by the normal force also oscillating to the extent that the surfaces lose contact in each cycle. This leads to a hammering effect, which is termed *impact fatigue.* In this case, the phase relationship between the two motions can be an important factor. Fretting fatigue and the associated methods of testing are described in more detail in the article "Fretting Fatigue" in this Volume.

This section describes the testing and the special problems in the evaluation of fretting wear. For example, one important feature of fretting is that the debris or wear product remains between the surfaces and can play a role in the development of the process. This is particularly true where the surfaces are flat or conforming as in, for example, a hub on an axle. In many experimental investigations, the common type of geometry has been the sphere or cylinder on a flat.

Another problem in investigating fretting wear in the laboratory has been devising systems to produce controlled movement of extremely small amplitude and the ability to measure and monitor that amplitude in the very area of the contact. It follows, of course, that the amount of wear debris produced is also very small, which creates problems where quantitative measurements are required. This section describes how these problems have been overcome by investigators in the past.

Fretting Mechanism

In general, fretting occurs between two tight-fitting surfaces that are subjected to a cyclic, relative motion of extremely small amplitude. Although certain aspects of the mechanism of fretting are still not thoroughly understood, the fretting process is generally divided into the following three parts: initial conditions of surface adhesion, oscillation accompanied by the generation of debris, and fatigue and/or wear in the region of contact.

Fretting wear occurs from repeated shear stresses that are generated by friction during small amplitude oscillatory motion or slip between two surfaces pressed together in intimate contact. In fretting, the term *slip* is used to denote small amplitude surface displacements, in contrast to *sliding,* which denotes macroscopic displacements. In many cases, slip only occurs over part of the contacting surfaces and is therefore referred to as partial slip. Fretting damage has been detected at amplitudes of less than 1 μm (Ref 29). As the amplitude is increased, the process resembles unidirectional or reciprocating sliding wear. The upper limit has been suggested as 75 μm (Ref 30), and Fig. 13 shows the volume of wear damage as a function of slip amplitude.

The severity of fretting damage is influenced by several factors including:

- *Contact Load.* As long as fretting amplitude is not reduced, fretting wear will increase linearly with increasing load.
- *Amplitude.* There appears to be no measurable amplitude below which fretting does not occur. However, if the contact conditions are such that deflection is only elastic, it is not likely that fretting damage will occur. Fretting wear loss increases with amplitude. The effect of amplitude can be linear, or there can be a threshold amplitude above which a rapid increase in wear occurs (Ref 30). The transition is not well established and probably depends on the geometry of the contact.
- *Frequency.* When fretting is measured in volume of material removed per unit sliding distance, there does not appear to be a frequency effect.
- *Number of Cycles.* An incubation period occurs during which fretting wear is negligible. After the incubation period, a steady-state wear rate is observed, and a more general surface roughening occurs as fretting continues.
- *Relative Humidity.* For materials that rust in air, fretting wear is higher in dry air than in saturated air.
- *Temperature.* The effect of elevated temperature on fretting depends on the oxidation characteristics of the material.

The effects of these factors are discussed in more detail in Ref 30 and 31. The article "Fretting Fatigue" in this Volume also provides additional details on the effects of these test variables. The main focus of this section is on fretting test rigs and wear measurements.

Fretting Rigs

Experimental rigs for investigating fretting wear are either driven mechanically or by an electromagnetic vibrator. Figure 14 shows a mechanical rig driven by an electric motor with eccentric loading device. Other methods of producing small amplitude have been the use of rotating out-of-balance weights, but control here is much more difficult.

A key factor in test rigs is the type of contact, because the ease with which debris can escape from the contact region influences the fretting process itself. For example, the escape of debris in the crossed-cylinder arrangement (Fig. 15) is greatly influenced by the direction of motion (Ref 32). The arrangement shown in Fig. 15(b) allows the debris to escape by being pushed out by the axial movement of the upper cylinder, leading to more frequent metal-to-metal contact and a higher wear rate than the arrangement shown in Fig. 15(a).

The original machine designed by Tomlinson (Fig. 16) comprised a long horizontal lever connected to an annular specimen in contact with a horizontal flat specimen with the load applied by a vertical rod through the center of the specimen

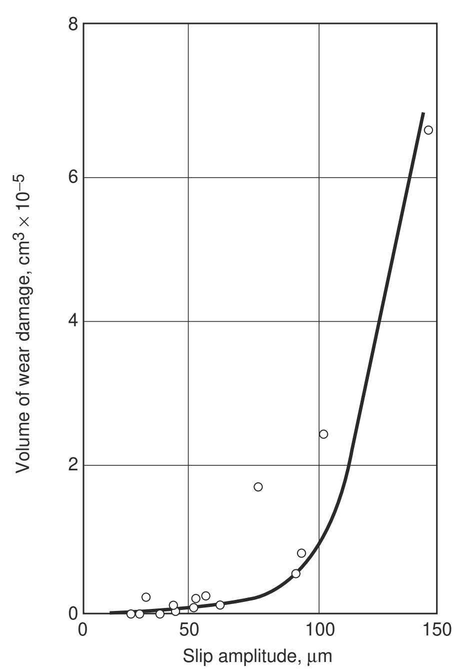


Fig. 13 Effect of slip amplitude on fretting damage of mild steel. Source: Ref 30