



# Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test<sup>1</sup>

This standard is issued under the fixed designation G 77; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers laboratory procedures for determining the resistance of materials to sliding wear. The test utilizes a block-on-ring friction and wear testing machine to rank pairs of materials according to their sliding wear characteristics under various conditions.

1.2 An important attribute of this test is that it is very flexible. Any material that can be fabricated into, or applied to, blocks and rings can be tested. However, the interlaboratory testing has been limited to metals. Thus, the potential materials combinations are endless. In addition, the test can be run with various lubricants, liquids, or gaseous atmospheres, as desired, to simulate service conditions. Rotational speed and load can also be varied to better correspond to service requirements.

1.3 Wear test results are reported as the volume loss in cubic millimetres for both the block and ring. Materials of higher wear resistance will have lower volume loss.

1.4 *This standard does not purport to address the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

- D 2714 Test Method for Calibration and Operation of the Falex Block-on-Ring Friction and Wear Testing Machine<sup>2</sup>
- E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process<sup>3</sup>
- E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods<sup>3</sup>
- E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method<sup>3</sup>
- G 40 Terminology Relating to Wear and Erosion<sup>4</sup>

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee G-2 on Wear and Erosion and is the direct responsibility of Subcommittee G02.40 on Non-Abrasive Wear.

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<sup>2</sup> *Annual Book of ASTM Standards*, Vol 05.02.

<sup>3</sup> *Annual Book of ASTM Standards*, Vol 14.02.

<sup>4</sup> *Annual Book of ASTM Standards*, Vol 03.02.

## 3. Terminology

### 3.1 Definition:

3.1.1 *wear*—damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances.

3.1.2 For additional definitions pertinent to this test method, see Terminology G 40.

## 4. Summary of Test Method

4.1 A test block is loaded against a test ring that rotates at a given speed for a given number of revolutions. Block scar volume is calculated from the block scar width, and ring scar volume is calculated from ring weight loss. The friction force required to keep the block in place is continuously measured during the test with a load cell. These data, combined with normal force data, are converted to coefficient of friction values and reported.

## 5. Significance and Use

5.1 The significance of this test method in any overall measurement program directed toward a service application will depend on the relative match of test conditions to the conditions of the service application.

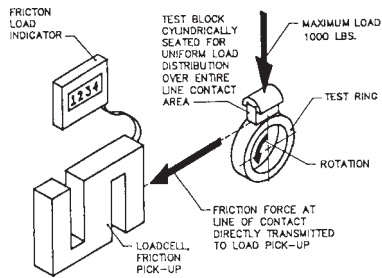
5.2 This test method seeks only to prescribe the general test procedure and method of calculating and reporting data. The choice of test operating parameters is left to the user. A fixed amount of sliding distance must be used because wear is usually non-linear with distance in this test.

## 6. Apparatus and Materials

6.1 *Test Schematic*—A schematic of the block-on-ring wear test geometry is shown in Fig. 1.<sup>5</sup> Acceptable testing machines are shown in Appendix X1.

6.2 *Test Ring*—A typical test ring is shown in Fig. 2. The test ring must have an outer diameter of  $34.99 \pm 0.025$  mm ( $1.377 \pm 0.001$  in.) with an eccentricity between the inner and

<sup>5</sup> Several machines, including the current Falex Model I and the older Dow Corning LFW-1 machines, have been found satisfactory for the purposes of this test. These models may differ in lever arm ratio, load range, speed control (variable or fixed), speed range, and type of friction measuring device. Suitable machines may be purchased from Falex Corporation, 1020 Airpark Dr., Sugar Grove, IL 60554.



**FIG. 1 Test Schematic**

outer surface of no greater than 0.00125 mm (0.0005 in.). For couples where surface condition is not under study, it is recommended that the outer diameter be a ground surface with a roughness of 0.152 to 0.305  $\mu\text{m}$  (6 to 12  $\mu\text{in.}$ ) rms or center line average (CLA), in the direction of motion. However, alternate surface conditions may be evaluated in the test, as desired. It should be kept in mind that surface condition can have an effect on sliding wear results.

6.3 *Test Block*—A test block is shown in Fig. 3. Block width is  $6.35 + 0.000, -0.025$  mm ( $0.250 + 0.000, -0.001$  in.). For couples where surface condition is not a parameter under study, a ground surface with the grinding marks running parallel to the long axis of the block and a roughness of 0.102 to 0.203  $\mu\text{m}$  (4 to 8  $\mu\text{in.}$ ) CLA in the direction of motion is recommended. However, other surface conditions may be evaluated as desired.

6.4 *Analytical Balance*, capable of measuring to the nearest 0.1 mg.

6.5 *Optical device* (or equivalent), with metric or inch-pound unit calibration, is also necessary so that scar width can be measured with a precision of 0.005 mm (0.0002 in.) or equivalent.

## 7. Reagents

- 7.1 *Trichloroethane.*
- 7.2 *Methanol.*

## 8. Preparation and Calibration of Apparatus

8.1 Run the calibration procedure that is in Test Method D 2714 to ensure good mechanical operation of the test equipment.

## 9. Procedure

9.1 Clean the block and ring using a procedure that will remove any scale, oil film, or residue without damaging the surface.

9.1.1 For metals, the following procedure is recommended: clean the block and ring in trichloroethane, ultrasonically, if possible; a methanol rinse may be used to remove any traces of trichloroethane residue. Allow the blocks and rings to dry completely. Handle the block and ring with clean, lint-free cotton gloves from this point on.

9.2 Make surface texture and surface roughness measurements across the width of the block and the ring, as necessary. Note that a surface profile does not completely describe a surface topology. Scanning electron micrographs may be used,

as desired, to augment the description of the wear surfaces. Clean the block and the ring if necessary as in 9.1.

9.3 Demagnetize the metal specimens and ferrous assembly. Weigh the block and ring to the nearest 0.1 mg.

9.4 Measure the block width and ring diameter to the nearest 0.05 mm (0.002 in.).

9.5 Clean the hemispherical block holder, ring shaft, and lubricant reservoir with trichloroethane.<sup>6</sup>

9.6 Put the hemispherical block holder on the block.<sup>6</sup>

9.7 Place the block in position on the machine and, while holding the block in position, place the ring on the shaft and lock the ring in place, using a torque wrench in accordance with the requirements of the specific machine design.<sup>6</sup>

9.8 Center the block on the ring while placing a light manual pressure on the lever arm to bring the block and ring into contact.<sup>6</sup> Be sure the edge of the block is parallel to the edge of the ring and that the mating surfaces are perfectly aligned. This is accomplished by making sure the specimen holder is free during mounting so that the quarter segment can properly seat itself. Release the pressure on the lever arm.

9.9 One may choose either a preloading or a step-loading procedure. Generally, preloading is chosen for variable speed machines, while step-loading is chosen for fixed speed machines in order to avoid an initial high wear transient. The differences in the two procedures are indicated in 9.10-9.22.

9.10 Place the required weights on the load bale and adjust the lever arm in accordance with the requirements of the specific machine design.<sup>6</sup> Then remove the load by raising the weights, if using the preloading procedure, or by removing the weights if using the step-loading procedure.

9.11 If running a lubricated test, clean all components that will come in contact with lubricant; fill the lubricant reservoir with lubricant to 6.4 mm (0.25 in.) above the lower surface of the ring; rotate the ring several times.

9.12 Set the revolution counter to zero.

9.13 Gently lower the weights, applying the required load, if using the preloading procedure.

9.14 If using a variable speed machine, turn on the machine and slowly increase the power to the drive motor until the ring starts to rotate, recording the “static” friction force. Continue to increase the rate of rotation to the desired rate. If using a fixed speed machine, simply turn on the machine.

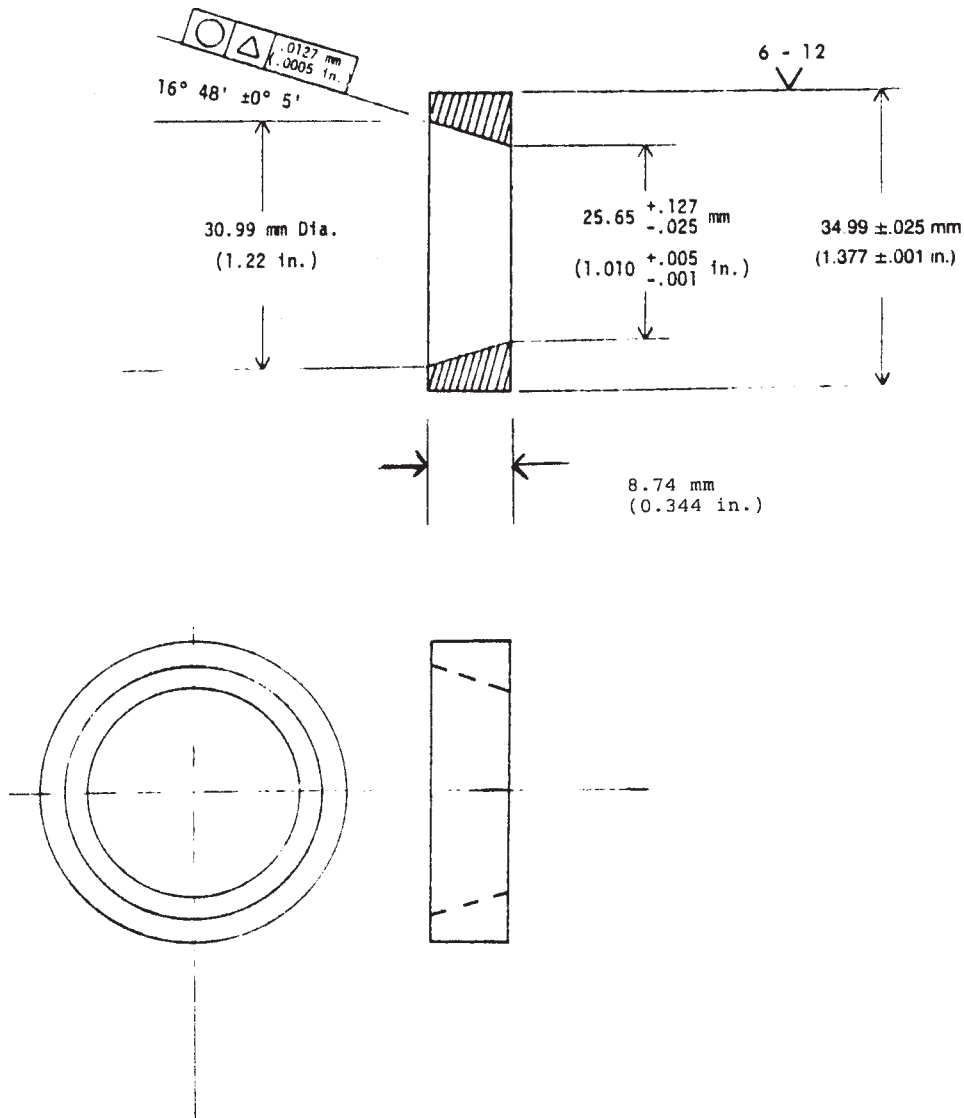
9.15 If using step-loading, start the machine with no weights, then gently add a 133-N (30-lbf) load every 200 rev until the required test load is reached. Adjust the rate of rotation as needed. If the required load is less than 133 N, apply the load in one step.

9.16 During the test, record the friction force, lubricant or block temperature, as required, and, if desired, the vertical displacement of the block.

9.17 Stop the test manually or automatically after the desired number of revolutions.<sup>7</sup>

<sup>6</sup> These instructions are appropriate for the machines shown in Appendix X1. The instructions may be modified, as necessary, by the user to fit the requirements of alternate machine designs.

<sup>7</sup> 5,400 and 10 800 revolutions have been used for metals in interlaboratory test programs.



NOTE 1—The outer diameter and concentricity with the inner diameter are the only critical parameters. The inner diameter is optional depending on machine design. The inside diameter taper shown fits a number of standard machines.

FIG. 2 Test Ring

9.18 A final “static” friction force may be measured with a variable speed machine. Leaving on the full load, wait 3 min ± 10 s, then turn on the machine and slowly increase the power to the drive motor until the ring starts to rotate, recording the “static” final friction force. Then turn off the motor.

9.19 Remove the block and ring, clean, and reweigh to the nearest 0.1 mg. For metals use trichloroethane.

9.20 Make surface roughness measurements and profilometer traces across the width of the block and the ring as desired. A trace along the long axis of the block, through the wear scar, is also useful to verify the scar depth and shape.<sup>8</sup>

9.21 Measure the scar width on the test block in the center and ~1 mm (0.04 in.) away from each edge. These measurements shall be to the nearest 0.1 mm (0.004 in.). Record the average of the three readings. Sometimes oxidation debris or a lip of plastically deformed material will extend over the edge of the wear scar (Fig. 4). When measuring scar width, try to visually ignore this material or measure the scar width in an area where this is not a problem.

9.22 Tapered scars indicate improper block alignment during testing. If the three width measurements on a given scar have a coefficient of variation of greater than 10 %, the test shall be declared invalid.

<sup>8</sup> On some of the old test machines, it is possible for the block to move back and forth slightly, increasing the apparent size of the wear scar. This is generally not a problem on the more rigid Falex machines. If this problem is suspected, a profilometer trace through the wear scar will verify whether or not the scar shape corresponds to the curvature of the ring.

## 10. Calculation

### 10.1 Calculation of Block Scar Volume:

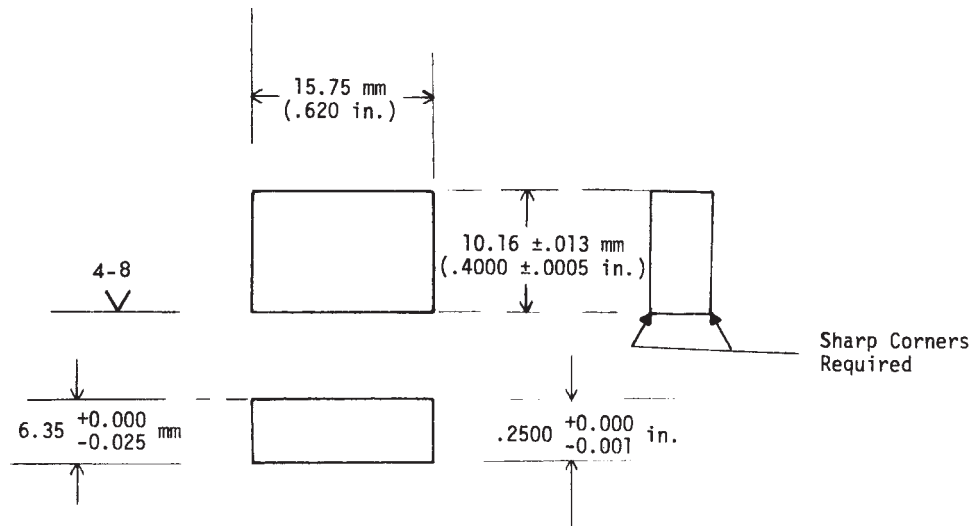
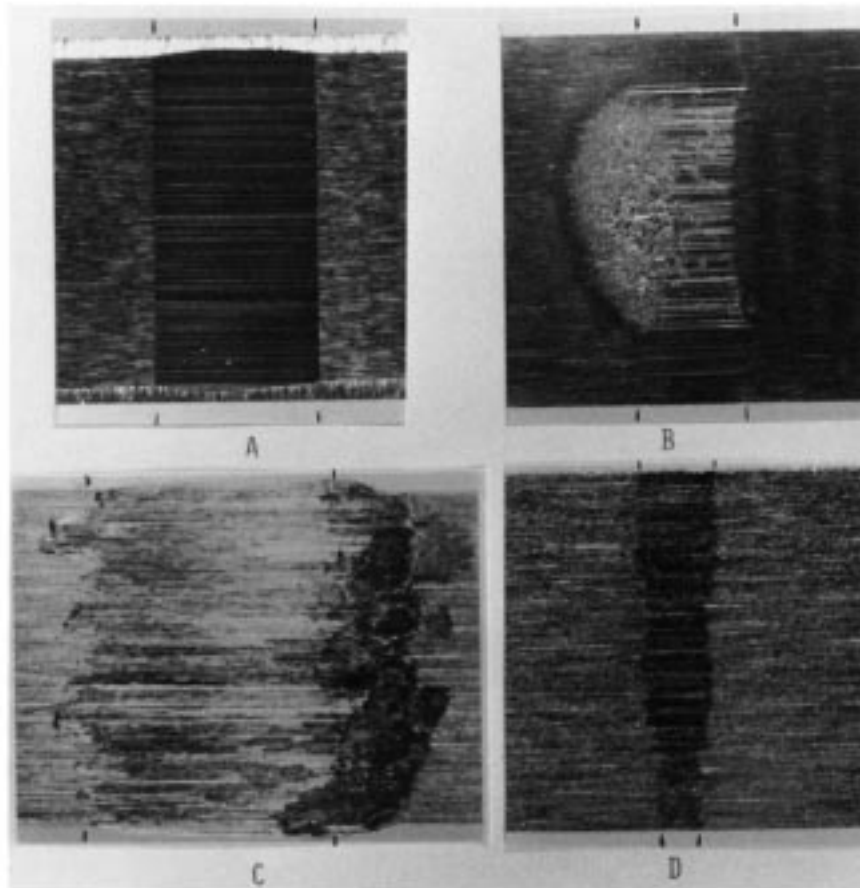


FIG. 3 Test Block



- A good rectangular scar with straight edges.
- The center of the scar is curved because the block was crowned. Also, debris covers the center left edge of the scar. Ordinarily, the debris should be visually ignored, but in this case scar curvature makes this too difficult. The test should be rerun.
- Severe galling resulted in jagged scar edges and a lip of plastically deformed material along the right side of the scar. The raised lip of material is excluded from the scar measurement. The cross hair should be run to a visual average of the jagged edge, not to the point of a zigzag.
- Tapered scar with jagged edges. This scar is too tapered (coefficient of variation > 10 %); therefore, the test should be rerun.

FIG. 4 Block Scars

**TABLE 1 Block Scar Widths and Volumes for Blocks 6.35-mm Wide Mated Against Rings 34.99 mm in Diameter**

Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )
0.30	0.0008	1.01	0.0312	1.72	0.1541	2.42	0.4295	3.12	0.9212	3.83	1.7062
0.31	0.0009	1.02	0.0321	1.73	0.1568	2.43	0.4348	3.13	0.9301	3.84	1.7196
0.32	0.0010	1.03	0.0331	1.74	0.1595	2.44	0.4402	3.14	0.9391	3.85	1.7331
0.33	0.0011	1.04	0.0340	1.75	0.1623	2.45	0.4456	3.15	0.9481	3.86	1.7467
0.34	0.0012	1.05	0.0350	1.76	0.1651	2.46	0.4511	3.16	0.9572	3.87	1.7603
0.35	0.0013	1.06	0.0360	1.77	0.1679	2.47	0.4567	3.17	0.9663	3.88	1.7740
0.36	0.0014	1.07	0.0371	1.78	0.1708	2.48	0.4622	3.18	0.9755	3.89	1.7878
0.37	0.0015	1.08	0.0381	1.79	0.1737	2.49	0.4679	3.19	0.9847	3.90	1.8017
0.38	0.0017	1.09	0.0392	1.80	0.1766	2.50	0.4735	3.20	0.9940	3.91	1.8156
0.39	0.0018	1.10	0.0403	1.81	0.1796	2.51	0.4792	3.21	1.0034	3.92	1.8296
0.40	0.0019	1.11	0.0414	1.82	0.1826	2.52	0.4850	3.22	1.0128	3.93	1.8437
0.41	0.0021	1.12	0.0425	1.83	0.1856	2.53	0.4908	3.23	1.0223	3.94	1.8578
0.42	0.0022	1.13	0.0437	1.84	0.1887	2.54	0.4966	3.24	1.0318	3.95	1.8720
0.43	0.0024	1.13	0.0448	1.85	0.1917	2.55	0.5025	3.25	1.0414	3.96	1.8863
0.44	0.0026	1.15	0.0460	1.86	0.1949	2.56	0.5085	3.26	1.0511	3.97	1.9007
0.45	0.0028	1.16	0.0472	1.87	0.1980	2.57	0.5145	3.27	1.0608	3.98	1.9151
0.46	0.0029	1.17	0.0485	1.88	0.2012	2.58	0.5205	3.28	1.0706	3.99	1.9296
0.47	0.0031	1.18	0.0497	1.89	0.2045	2.59	0.5266	3.29	1.0804		
0.48	0.0033	1.19	0.0510	1.90	0.2077	2.60	0.5327	3.30	1.0903	4.00	1.9442
0.49	0.0036	1.20	0.0523	1.91	0.2110	2.61	0.5389	3.31	1.1003	4.01	1.9589
0.50	0.0038	1.21	0.0536	1.92	0.2144	2.62	0.5451	3.32	1.1103	4.02	1.9736
0.51	0.0040	1.22	0.0550	1.93	0.2177	2.63	0.5514	3.33	1.1204	4.03	1.9884
0.52	0.0043	1.23	0.0563	1.94	0.2211	2.64	0.5577	3.34	1.1305	4.04	2.0033
0.53	0.0045	1.24	0.0577	1.95	0.2246	2.65	0.5641	3.35	1.1407	4.05	2.0183
0.54	0.0048	1.25	0.0591	1.96	0.2281	2.66	0.5705	3.36	1.1510	4.06	2.0333
0.55	0.0050	1.26	0.0606	1.97	0.2316	2.67	0.5770	3.37	1.1613	4.07	2.0484
0.56	0.0053	1.27	0.0620	1.98	0.235	2.68	0.5835	3.38	1.1717	4.08	2.0636
0.57	0.0056	1.28	0.0635	1.99	0.2387	2.69	0.5900	3.39	1.1822	4.09	2.0788
0.58	0.0059	1.29	0.0650			2.70	0.5967	3.40	1.1927	4.10	2.0941
0.59	0.0062	1.30	0.0665	2.00	0.2423	2.71	0.6033	3.41	1.2033	4.11	2.1095
0.60	0.0065	1.31	0.0681	2.01	0.2460	2.72	0.6100	3.42	1.2139	4.12	2.1250
0.61	0.0069	1.32	0.0696	2.02	0.2497	2.73	0.6168	3.43	1.2246	4.13	2.1406
0.62	0.0072	1.33	0.0712	2.03	0.2534	2.74	0.6236	3.44	1.2353	4.14	2.1562
0.63	0.0076	1.34	0.0728	2.04	0.2572	2.75	0.6305	3.45	1.2462	4.15	2.1719
0.64	0.0079	1.35	0.0745	2.05	0.2610	2.76	0.6374	3.46	1.2571	4.16	2.1877
0.65	0.0083	1.36	0.0761	2.06	0.2648	2.77	0.6443	3.47	1.2680	4.17	2.2036
0.66	0.0087	1.37	0.0778	2.07	0.2687	2.78	0.6513	3.48	1.2790	4.18	2.2195
0.67	0.0091	1.38	0.0796	2.08	0.2726	2.79	0.6584	3.49	1.2901	4.19	2.2355
0.68	0.0095	1.39	0.0813	2.09	0.2765	2.80	0.6655	3.50	1.3013	4.20	2.2516
0.69	0.0099	1.40	0.0831	2.10	0.2805	2.81	0.6727	3.51	1.3125	4.21	2.2678
0.70	0.0104	1.41	0.0849	2.11	0.2846	2.82	0.6799	3.52	1.3238	4.22	2.2840
0.71	0.0108	1.42	0.0867	2.12	0.2886	2.83	0.6872	3.53	1.3351	4.23	2.3003
0.72	0.0113	1.43	0.0885	2.13	0.2927	2.84	0.6945	3.54	1.3465	4.24	2.3167
0.73	0.0118	1.44	0.0904	2.14	0.2969	2.85	0.7019	3.55	1.3580	4.25	2.3332
0.74	0.0123	1.45	0.0923	2.15	0.3011	2.86	0.7093	3.56	1.3695	4.26	2.3498
0.75	0.0128	1.46	0.0942	2.16	0.3053	2.87	0.7168	3.57	1.3811	4.27	2.3664
0.76	0.0133	1.47	0.0962	2.17	0.3096	2.88	0.7243	3.58	1.3928	4.28	2.3831
0.77	0.0138	1.48	0.0981	2.18	0.3139	2.89	0.7319	3.59	1.4045	4.29	2.3999
0.78	0.0144	1.49	0.1001	2.19	0.3182	2.90	0.7395	3.60	1.4163	4.30	2.4168
0.79	0.0149	1.50	0.1022	2.20	0.3226	2.91	0.7472	3.61	1.4281	4.31	2.4338
0.80	0.0155	1.51	0.1042	2.21	0.3270	2.92	0.7549	3.62	1.4401	4.32	2.4508
0.81	0.0161	1.52	0.1063	2.22	0.3315	2.93	0.7627	3.63	1.4521	4.33	2.4679
0.82	0.0167	1.53	0.1084	2.23	0.3360	2.94	0.7706	3.64	1.4641	4.34	2.4851
0.83	0.0173	1.54	0.1106	2.24	0.3405	2.95	0.7785	3.65	1.4762	4.35	2.5024
0.84	0.0179	1.55	0.1127	2.25	0.3451	2.96	0.7864	3.66	1.4884	4.36	2.4197
0.85	0.0186	1.56	0.1149	2.26	0.3497	2.97	0.7944	3.67	1.5007	4.37	2.5371
0.86	0.0192	1.57	0.1172	2.27	0.3544	2.98	0.8025	3.68	1.5130	4.38	2.5547
0.87	0.0199	1.58	0.1194	2.28	0.3691	2.99	0.8106	3.69	1.5254	4.39	2.5723
0.88	0.0206	1.59	0.1217	2.29	0.3638			3.70	1.5379	4.40	2.5899
0.89	0.0213	1.60	0.1240	2.30	0.3686	3.00	0.8188	3.71	1.5504	4.41	2.6077
0.90	0.0221	1.61	0.1264	2.31	0.3735	3.01	0.8270	3.72	1.5630	4.42	2.6255
0.91	0.0228	1.62	0.1287	2.32	0.3783	3.02	0.8353	3.73	1.5757	4.43	2.6434
0.92	0.0236	1.63	0.1311	2.33	0.3833	3.03	0.8437	3.74	1.5884	4.44	2.6614
0.93	0.0243	1.64	0.1336	2.34	0.3882	3.04	0.8520	3.75	1.6012	4.45	2.6795
0.94	0.0251	1.65	0.1360	2.35	0.3932	3.05	0.8605	3.76	1.6141	4.46	2.6977
0.95	0.0259	1.66	0.1385	2.36	0.3983	3.06	0.8690	3.77	1.6270	4.47	2.7159
0.96	0.0268	1.67	0.1410	2.37	0.4034	3.07	0.8776	3.78	1.6401	4.48	2.7343
0.97	0.0276	1.68	0.1436	2.38	0.4085	3.08	0.8862	3.79	1.6531	4.49	2.7527
0.98	0.0285	1.69	0.1462	2.39	0.4137	3.09	0.8948	3.80	1.6663	4.50	2.7712
0.99	0.0294	1.70	0.1488	2.40	0.4189	3.10	0.9036	3.81	1.6795	4.51	2.7897
1.00	0.0303	1.71	0.1514	2.41	0.4242	3.11	0.9124	3.82	1.6928	4.52	2.8084
4.53	2.8272	4.91	3.6032	5.28	4.4849	5.66	5.5303	6.03	6.6946	6.41	8.0512



**TABLE 1** *Continued*

Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )
4.54	2.8460	4.92	3.6253	5.29	4.5105	5.67	5.5599	6.04	6.7282	6.42	8.0892
4.55	2.8649	4.93	3.6476	5.30	4.5363	5.68	5.5895	6.05	6.7618	6.43	8.1274
4.56	2.8839	4.94	3.6699	5.31	4.5621	5.69	5.6192	6.06	6.7956	6.44	8.1656
4.57	2.9030	4.95	3.6923	5.32	4.5881	5.70	5.6491	6.07	6.8295	6.45	8.2040
4.58	2.9221	4.96	3.7148	5.33	4.6141	5.71	5.6790	6.08	6.8636	6.46	8.2425
4.59	2.9414	4.97	3.7375	5.34	4.6403	5.72	5.7091	6.09	6.8977	6.47	8.2811
4.60	2.9607	4.98	3.7601	5.35	4.6665	5.73	5.7392	6.10	6.9319	6.48	8.3198
4.61	2.9801	4.99	3.7829	5.36	4.6929	5.74	5.7695	6.11	6.9663	6.49	8.3586
4.62	2.9996			5.37	4.7193	5.75	5.7999	6.12	7.0008	6.50	8.3976
4.63	3.0192	5.00	3.8058	5.38	4.7458	5.76	5.8303	6.13	7.0354	6.51	8.4367
4.64	3.0389	5.01	3.8288	5.39	4.7725	5.77	5.8609	6.14	7.0701	6.52	8.4759
4.65	3.0587	5.02	3.8519	5.40	4.7992	5.78	5.8916	6.15	7.1049	6.53	8.5153
4.66	3.0785	5.03	3.8750	5.41	4.8261	5.79	5.9224	6.16	7.1398	6.54	8.5547
4.67	3.0984	5.04	3.8983	5.42	4.8530	5.80	5.9533	6.17	7.1749	6.55	8.5943
4.68	3.1185	5.05	3.9216	5.43	4.8800	5.81	5.9844	6.18	7.2100	6.56	8.6340
4.69	3.1386	5.06	3.9451	5.44	4.9072	5.82	6.0155	6.19	7.2453	6.57	8.6739
4.70	3.1588	5.07	3.9686	5.45	4.9344	5.83	6.0467	6.20	7.2807	6.58	8.7138
4.71	3.1790	5.08	3.9922	5.46	4.9618	5.84	6.0781	6.21	7.3162	6.59	8.7539
4.72	3.1994	5.09	4.0160	5.47	4.9892	5.85	6.1095	6.22	7.3519	6.60	8.7941
4.73	3.2199	5.10	4.0398	5.48	5.0168	5.86	6.1411	6.23	7.3876	6.61	8.8344
4.74	3.2404	5.11	4.0637	5.49	5.0444	5.87	6.1728	6.24	7.4235	6.62	8.8749
4.75	3.2610	5.12	4.0877	5.50	5.0722	5.88	6.2045	6.25	7.4595	6.63	8.9154
4.76	3.2818	5.13	4.1118	5.51	5.1001	5.89	6.2364	6.26	7.4956	6.64	8.9562
4.77	3.3026	5.14	4.1360	5.52	5.1280	5.90	6.2684	6.27	7.5318	6.65	8.9970
4.78	3.3235	5.15	4.1603	5.53	5.1561	5.91	6.3006	6.28	7.5681	6.66	9.0379
4.79	3.3444	5.16	4.1847	5.54	5.1842	5.92	6.3328	6.29	7.6046	6.67	9.0790
4.80	3.3655	5.17	4.2092	5.55	5.2125	5.93	6.3651	6.30	7.6411	6.68	9.1202
4.81	3.3867	5.18	4.2338	5.56	5.2409	5.94	6.3976	6.31	7.6778	6.69	9.1615
4.82	3.4079	5.19	4.2584	5.57	5.2694	5.95	6.4301	6.32	7.7146	6.70	9.2030
4.83	3.4293	5.20	4.2832	5.58	5.2979	5.96	6.4628	6.33	7.7515	6.71	9.2446
4.84	3.4507	5.21	4.3081	5.59	5.3266	5.97	6.4956	6.34	7.7886	6.72	9.2863
4.85	3.4722	5.22	4.3330	5.60	5.3554	5.98	6.5285	6.35	7.8258	6.73	9.3281
4.86	3.4938	5.23	4.3581	5.61	5.3843	5.99	6.5615	6.36	7.8630	6.74	9.3701
4.87	3.5155	5.24	4.3833	5.62	5.4133			6.37	7.9004	6.75	9.4122
4.88	3.5373	5.25	4.4085	5.63	5.4424	6.00	6.5946	6.38	7.9380	6.76	9.4544
4.89	3.5592	5.26	4.4339	5.64	5.4716	6.01	6.6278	6.39	7.9756		
4.90	3.5811	5.27	4.4593	5.65	5.5009	6.02	6.6611	6.40	8.0134		
4.53	2.8272	4.91	3.6032	5.28	4.4849	5.66	5.5303	6.03	6.6946	6.41	8.0512
4.54	2.8460	4.92	3.6253	5.29	4.5105	5.67	5.5599	6.04	6.7282	6.42	8.0892
4.55	2.8649	4.93	3.6476	5.30	4.5363	5.68	5.5895	6.05	6.7618	6.43	8.1274
4.56	2.8839	4.94	3.6699	5.31	4.5621	5.69	5.6192	6.06	6.7956	6.44	8.1656
4.57	2.9030	4.95	3.6923	5.32	4.5881	5.70	5.6491	6.07	6.8295	6.45	8.2040
4.58	2.9221	4.96	3.7148	5.33	4.6141	5.71	5.6790	6.08	6.8636	6.46	8.2425
4.59	2.9414	4.97	3.7375	5.34	4.6403	5.72	5.7091	6.09	6.8977	6.47	8.2811
4.60	2.9607	4.98	3.7601	5.35	4.6665	5.73	5.7392	6.10	6.9319	6.48	8.3198
4.61	2.9801	4.99	3.7829	5.36	4.6929	5.74	5.7695	6.11	6.9663	6.49	8.3586
4.62	2.9996			5.37	4.7193	5.75	5.7999	6.12	7.0008	6.50	8.3976
4.63	3.0192	5.00	3.8058	5.38	4.7458	5.76	5.8303	6.13	7.0354	6.51	8.4367
4.64	3.0389	5.01	3.8288	5.39	4.7725	5.77	5.8609	6.14	7.0701	6.52	8.4759
4.65	3.0587	5.02	3.8519	5.40	4.7992	5.78	5.8916	6.15	7.1049	6.53	8.5153
4.66	3.0785	5.03	3.8750	5.41	4.8261	5.79	5.9224	6.16	7.1398	6.54	8.5547
4.67	3.0984	5.04	3.8983	5.42	4.8530	5.80	5.9533	6.17	7.1749	6.55	8.5943
4.68	3.1185	5.05	3.9216	5.43	4.8800	5.81	5.9844	6.18	7.2100	6.56	8.6340
4.69	3.1386	5.06	3.9451	5.44	4.9072	5.82	6.0155	6.19	7.2453	6.57	8.6739
4.70	3.1588	5.07	3.9686	5.45	4.9344	5.83	6.0467	6.20	7.2807	6.58	8.7138
4.71	3.1790	5.08	3.9922	5.46	4.9618	5.84	6.0781	6.21	7.3162	6.59	8.7539
4.72	3.1994	5.09	4.0160	5.47	4.9892	5.85	6.1095	6.22	7.3519	6.60	8.7941
4.73	3.2199	5.10	4.0398	5.48	5.0168	5.86	6.1411	6.23	7.3876	6.61	8.8344
4.74	3.2404	5.11	4.0637	5.49	5.0444	5.87	6.1728	6.24	7.4235	6.62	8.8749
4.75	3.2610	5.12	4.0877	5.50	5.0722	5.88	6.2045	6.25	7.4595	6.63	8.9154
4.76	3.2818	5.13	4.1118	5.51	5.1001	5.89	6.2364	6.26	7.4956	6.64	8.9562
4.77	3.3026	5.14	4.1360	5.52	5.1280	5.90	6.2684	6.27	7.5318	6.65	8.9970
4.78	3.3235	5.15	4.1603	5.53	5.1561	5.91	6.3006	6.28	7.5681	6.66	9.0379
4.79	3.3444	5.16	4.1847	5.54	5.1842	5.92	6.3328	6.29	7.6046	6.67	9.0790
4.80	3.3655	5.17	4.2092	5.55	5.2125	5.93	6.3651	6.30	7.6411	6.68	9.1202
4.81	3.3867	5.18	4.2338	5.56	5.2409	5.94	6.3976	6.31	7.6778	6.69	9.1615
4.82	3.4079	5.19	4.2584	5.57	5.2694	5.95	6.4301	6.32	7.7146	6.70	9.2030
4.83	3.4293	5.20	4.2832	5.58	5.2979	5.96	6.4628	6.33	7.7515	6.71	9.2446
4.84	3.4507	5.21	4.3081	5.59	5.3266	5.97	6.4956	6.34	7.7886	6.72	9.2863
4.85	3.4722	5.22	4.3330	5.60	5.3554	5.98	6.5285	6.35	7.8258	6.73	9.3281
4.86	3.4938	5.23	4.3581	5.61	5.3843	5.99	6.5615	6.36	7.8630	6.74	9.3701
4.87	3.5155	5.24	4.3833	5.62	5.4133			6.37	7.9004	6.75	9.4122

TABLE 1 Continued

Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Block Scar Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )	Width (mm)	Volume (mm <sup>3</sup> )
4.88	3.5373	5.25	4.4085	5.63	5.4424	6.00	6.5946	6.38	7.9380	6.76	9.4544
4.89	3.5592	5.26	4.4339	5.64	5.4716	6.01	6.6278	6.39	7.9756		
4.90	3.5811	5.27	4.4593	5.65	5.5009	6.02	6.6611	6.40	8.0134		

10.1.1 Block scar volume may be derived from block scar width by using Table 1 (applicable only when ring diameter is  $34.99 \pm 0.025$  mm ( $1.377 \pm 0.001$  in.) and scar length (block width) is  $6.35 + 0.000, -0.025$  mm ( $0.250 + 0.000, -0.001$  in.)).

10.1.2 The preferred method of calculating block scar volume is by using the formula shown in Fig. 5. This formula may be programmed on a calculator or computer.

10.1.3 Block scar volume is not calculated generally from block mass loss because block mass is subject to effects of materials transfer, generation of oxide films, or penetration of the material by the lubricant. Keeping in mind the above factors, block mass loss may be interpreted semiquantitatively in a comparative evaluation of various material couples. If the block scar cannot be accurately measured following 9.21 and the guidance in Fig. 4, a scar volume should not be calculated, but a notation made of the problem; for example, material transfer, plastic deformation, etc.

10.2 Calculate coefficient of friction values from friction force values as follows:

$$f = F/W \tag{1}$$

where:

- $f$  = coefficient of friction
- $F$  = measured friction force, N (lbf), and
- $W$  = normal force, N (lbf).

10.3 Calculate ring volume loss as follows:

$$\text{volume loss} = \frac{\text{ring mass loss}}{\text{ring density}} \tag{2}$$

NOTE 1—If the ring gains mass during the test, the volume loss is reported as zero with a notation that weight gain occurred. Mass loss is effected by material transfer from one component to another, by generation of oxide films, or by infiltration into porous material by the lubricant, or combinations thereof. If material transfer to the ring is obvious, then a ring scar volume should not be calculated from the weight loss measurement, but a notation should be made that material transfer occurred.

### 11. Report

11.1 Report any unusual event or an overload shutoff of the machine (on some machines it is possible to have an automatic shutoff at a preset frictional load). If the machine malfunctions or a test block has a tapered scar, the data shall not be used, and the test shall be rerun.

11.2 Report the following:

11.2.1 Test Parameters:

11.2.1.1 Block material and hardness (whenever applicable),

11.2.1.2 Ring material and hardness (whenever applicable),

11.2.1.3 Ring and block initial and final surface roughness,

11.2.1.4 Ring rpm,

11.2.1.5 Lubricant,

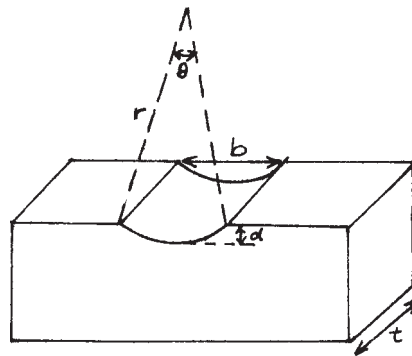
11.2.1.6 Test load,

11.2.1.7 Test distance (see 14.1), and

11.2.1.8 Number of duplicates run for each test condition.

11.2.2 Results—report the average and the coefficient of variation (the coefficient of variation is the standard deviation divided by the average; it is expressed as a percent).

11.2.2.1 Block scar width, mm,



- $t$  = block width, mm
- $r$  = radius of ring, mm
- $D$  =  $2r$  = diameter of ring, mm
- $b$  = average scar width, mm
- $\theta$  = sector angle in radians
- $d$  = scar depth, mm

$$\begin{aligned} \text{Scar Width} &= b = D \sin \frac{\theta}{2} \\ \text{Scar volume} &= \frac{D^2 t}{8} (\theta - \sin \theta) \end{aligned}$$

$$\text{where } \theta = 2 \sin^{-1} \frac{b}{D}$$

$$\text{ImC Scar Volume} = \frac{D^2 t}{8} \left[ 2 \sin^{-1} \frac{b}{D} - \sin \left( 2 \sin^{-1} \frac{b}{D} \right) \right]$$

FIG. 5 Block Scar Volume Based on the Width of the Scar

11.2.2.2 Block scar volume, mm<sup>3</sup>, calculated from scar width,

11.2.2.3 Ring weight loss, mg,

11.2.2.4 Ring scar volume, mm<sup>3</sup>,<sup>9</sup> and

11.2.2.5 Final dynamic coefficient of friction.

11.2.3 *Reporting Optional:*

11.2.3.1 Block weight loss, mg,

11.2.3.2 Ring heat treatment,

11.2.3.3 Block heat treatment,

11.2.3.4 Lubricant composition, and

11.2.3.5 Coefficient of friction (initial static and dynamic friction and final dynamic friction).

## 12. Precision and Bias

12.1 The precision and bias of the measurements obtained with this test procedure will depend upon strict adherence to the stated test procedure.

12.2 The consistency of agreement in repeated tests on the same material will depend upon material homogeneity, machine and material interaction, and close observation of the test by a competent machine operator.

12.3 Tables X2.3 and X2.4 show representative coefficients of variation which were obtained in the interlaboratory tests with metals.

12.3.1 The variation on block scar width (lubricated tests) is in line with the variations specified in the calibration Test Method D 2714.

12.3.2 Because the block scar volume calculation involves essentially a cubing of the scar width measurement, the coefficient of variation for block scar volume is substantially higher than that for block scar width.

12.3.3 Because dry tests are so sensitive to initial surface condition, such as adsorbed films, and to ambient conditions, for instance humidity, the coefficients of variation tend to run higher in dry as opposed to lubricated tests.

12.3.4 If a material couple is run in this test under conditions which are borderline for galling, significantly higher coefficients of variation for block scar width and volume may occur. In this case, it is suggested that the materials be run under less severe conditions; for example, at lower load.

12.3.5 Conversely, coefficients of variation may run higher in tests where very little wear occurs if one approaches the limits of measurement precision. In this case, it is recommended that more severe conditions, for instance higher load or longer running time, be used.

12.3.6 In order to achieve a high confidence level in evaluating test results, it is desirable to run a large number of replicate tests. However, this can be quite expensive. One must, therefore, determine an acceptable sample size, balancing cost against allowable sampling error and taking into account the coefficient of variation of the test procedure. Because the coefficients of variation run rather high in the block-on-ring test, a minimum of three duplicate tests is

required for meaningful test results. Even with three duplicates the sampling error is *greater than* the coefficient of variation of the test for the data obtained in the interlaboratory tests. A sample size of four results in a sampling error that is equal to the coefficient of variation of the test. Sampling error may be reduced by further increasing sample size. The relationship in Practice E 122 between sample size (*n*), sampling error (*e*), and test coefficient of variation (*v*) is expressed by the following formula:

$$n = (1.96v/e)^2 \quad (3)$$

12.3.7 The following are the average values and 95 % confidence limits for round robin three for metals. For an H-60 block and a S-10 ring, dry, the average value of the wear volume on the block is 0.65 mm<sup>3</sup> for a 5400 rev (197 rpm) and 134 N test; the 95 % confidence limit within a laboratory is 0.47 mm<sup>3</sup>; and the 95 % confidence limit between laboratories is 0.67 mm<sup>3</sup>. The average value of the wear scar width is 2.76 mm; the 95 % confidence limit within a laboratory is 0.076 mm; and the 95 % confidence limit between laboratories is 0.47 mm. The average value of the wear volume on the block with mineral oil lubrication is 0.047 mm<sup>3</sup> for a 10 800 rev (197 rpm) and 803 N test; the 95 % confidence limit within a laboratory is 0.020 mm<sup>3</sup>; and the 95 % confidence limit between laboratories is 0.57 mm<sup>3</sup>. The average value of the wear scar width is 1.09 mm; the 95 % confidence limit with a laboratory is 0.098 mm; and the 95 % confidence limit between laboratories is 0.27 mm. The average value of the wear volume on the block without lubrication is 0.71 mm<sup>3</sup> for a 5 400 rev (72 rpm) and 134 N test; the 95 % confidence limit within a laboratory is 0.74 mm<sup>3</sup>; and the 95 % confidence limit between laboratories is 0.83 mm<sup>3</sup>. The average value of the wear scar width is 2.83 mm; the 95 % confidence limit with a laboratory is 1.02 mm; and the 95 % confidence limit between laboratories is 1.12 mm.

12.4 *Bias*—This test method has no bias since the values determined are specific to this test.

## 13. Typical Test Values (from Interlaboratory Test Experience)

13.1 Typical test results are listed in Appendix X2. For metals these comprise interlaboratory tests two and three by the Alpha Wear Task Group of Committee G-2. Obviously, the range of materials run in the interlaboratory tests was quite limited. Coefficients of variation may be different for other classes of materials.

## 14. Discussion

14.1 Wear is usually *not* linear with sliding distance in this test. Therefore, test results may only be compared for tests run for the same number of revolutions.

14.2 Because there is initial line contact between the block and the ring, initial Hertzian stresses tend to run quite high in this test. The formula for calculating the maximum Hertzian stress for elastic materials is:

$$\sigma = 0.798 \sqrt{tD \left[ \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]} \quad (4)$$

<sup>9</sup> When reporting results, ring scar volumes should only be reported if all duplicate rings lost weight and the average weight loss exceeds 1 mg. Otherwise, ring scar volume should be reported as "too small to accurately measure; ring weight loss did not exceed 1 mg."



for nonself-mating wear tests, and:

$$\sigma = 0.564 \sqrt{\frac{WE_1}{tD(1 - \nu_1^2)}} \quad (5)$$

for self-mating wear tests or for materials with same elastic constants,

where:

$\sigma$  = maximum compressive stress, MPa (psi),

- $W$  = normal load, N (lbf),
- $t$  = block width, mm (in.),
- $D$  = ring diameter, mm (in.),
- $\nu_1$  = Poisson's ratio of block,
- $\nu_2$  = Poisson's ratio of ring,
- $E_1$  = elastic modulus of block, MPa (psi), and
- $E_2$  = elastic modulus of ring, MPa (psi).

**15. Keywords**

15.1 block-on-ring; metal; sliding; wear; wear test

**APPENDIXES**

**(Nonmandatory Information)**

**X1. DESCRIPTION OF THE FALEX MODEL 1 FRICTION AND WEAR TESTING MACHINE**

X1.1 A stationary rectangular test block is pressed with a predetermined load, maximum 5783 N (1300 lbf), against a rotating ring (Fig. X1.1). The load is accurately maintained throughout the test. Bearing pressures (maximum Hertz pressures) in the line contact area between the rectangular specimen and the rotating ring may range up to 1376 MPa (199 096 psi). The maximum Hertzian stress calculated is for initial contact and for steel on steel only ( $E_1 = E_2 = 2.07 \times 10^5$  MPa ( $30 \times 10^6$  psi) and  $\nu_1 = \nu_2 = 0.3$ ).

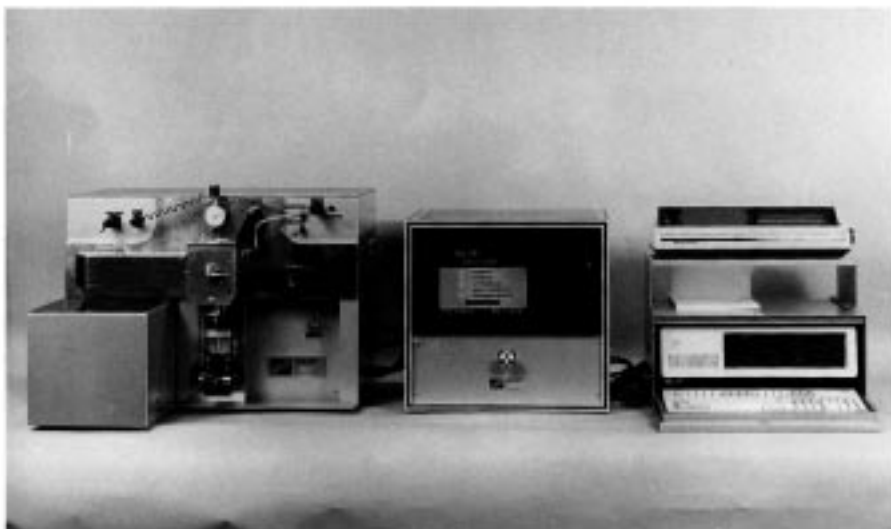
X1.2 Resulting friction is indicated throughout the test by a digital friction force indicator with cutoff. A digital cycle counter and cutoff reads out the number of revolutions of the test specimen. One criterion in the test is when friction reaches a preselected maximum. For this purpose a friction cutoff can be set and the machine will automatically shut off upon reaching it.

X1.3 In a substitute method, a thermocouple is embedded in the specimen and a temperature controller/indicator termi-

nates the test when the temperature of the test block reaches a previously set value.

X1.4 The test shaft of the machine is supported by two roller bearings, and the mandrel end of the shaft protrudes through the front panel of the machine where the test specimens are mounted. The test block, that is held stationary against the revolving ring, is restrained from horizontal movement by a unique type of holder. The design of this block holder allows the test block to align itself automatically in a manner prescribed by ASTM specifications for compression-loaded specimens. This maintains uniform loading throughout the area of contact between the specimens regardless of the force existing between them.

X1.5 The normal force between the test specimens is produced by hanging dead weights on the lower end of a compound lever system which is designed in such a way as to allow the full value of the friction force to be transmitted to the frictional load pickup device.



**FIG. X1.1 New Falex Machine**

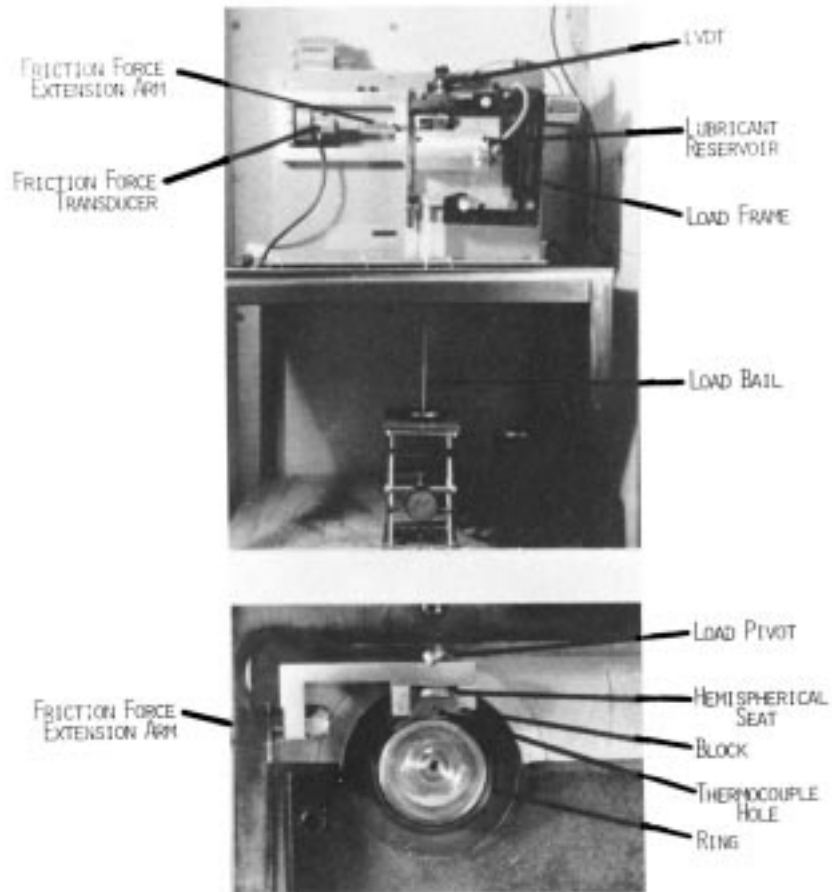


FIG. X1.2 Older Dow Corning Model

X1.6 Speed ranges with variable speed control are available from 12 to 7411 rpm. Specimens can be tested up to a maximum of 260°C (500°F). With optional equipment, the test chamber can be pressurized to 1.03 MPa (150 psi), run in special atmospheres, or run in vacuum.

X1.7 The machine can easily be modified, with optional equipment, to run Timken-type tests. The machine can also run a cylinder on cylinder using the standard Falex test ring and a 10.16 mm (0.400-in.) diameter test cylinder.

X1.8 A separate electric control cabinet is furnished with the machine, and it contains continuous readout instruments for each of the variables as well as the machine controls. An automatic timer or cycle counter and cutoff, or both, can also be provided in this cabinet. Output from any or all of the indicating instruments can easily be set up with recorders for complete data records.

## X2. INTERLABORATORY TEST RESULTS

X2.1 Interlaboratory tests two and three with metals were run using S-10 rings and H-30 and H-60 blocks from Falex Corp. The S-10 rings are steel type 4620 of surface hardness 58 to 63 HRC. The H-30 blocks are 01 tool steel of hardness 30 HRC. The H-60 blocks are 01 tool steel of hardness 60 HRC. See Tables X2.1-X2.4.

X2.1.1 The mineral oil used in the lubricated tests is USP heavy mineral oil, Saybolt 340 to 350 viscosity. This may be purchased at any drugstore.

X2.2 *Statistical Symbols*—Additional symbols can be found in Practice E 177.

**TABLE X2.1 Summary of the Test Results Obtained from Interlaboratory Test Number 2**

NOTE 1—The test conditions used are listed in Table X2.3 in order.

Laboratory	Averages ( $\bar{x}$ )				Deviation from Average ( $d$ )				Standard Deviation ( $S$ )			
	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction
A	4.350	2.490	<sup>A</sup>	0.120	0.1733	0.2633	...	-0.0100	0.087	0.1992	...	0.0100
C	4.300	2.410	<sup>A</sup>	0.170	0.1233	0.1833	...	0.0300	0.219	0.3856	...	0.0060
D	3.880	1.780	<sup>A</sup>	0.130	-0.2967	-0.4467	...	-0.0100	0.210	0.2848	...	0.0210
B	unable to run this load											
Col. Avg. ( $\bar{x}$ )	4.177	2.227	...	0.140	( $S\bar{x}$ ) 0.258	0.389	...	0.023	(Sr) 0.182	0.300	...	0.014
A	2.790	0.658	<sup>A</sup>	0.090	0.6875	0.3388	...	0.0900	0.114	0.0790	...	0.0099
B	1.860	0.196	<sup>A</sup>	0.090	-0.2425	-0.1233	...	-0.0267	0.279	0.0823	...	0.0333
C	2.120	0.289	<sup>A</sup>	0.140	0.0175	-0.0303	...	0.0233	0.318	0.1301	...	0.0073
D	1.640	0.134	<sup>A</sup>	0.120	-0.4625	-0.1853	...	0.0033	0.230	0.0563	...	0.0000
Col. Avg. ( $\bar{x}$ )	2.103	0.319	...	0.117	( $S\bar{x}$ ) 0.499	0.235	...	0.025	(Sr) 0.247	0.091	...	0.018
A	0.990	0.030	<sup>A</sup>	0.090	-0.0933	-0.0110	...	0.0900	0.078	0.0075	...	0.0000
C	0.990	0.030	<sup>A</sup>	0.130	-0.0933	-0.0110	...	0.0200	0.000	0.0000	...	0.0056
D	1.270	0.063	<sup>A</sup>	0.110	0.1867	0.0220	...	0.0000	0.076	0.0113	...	0.0167
B	unable to run this load											
Col. Avg. ( $\bar{x}$ )	1.083	0.041	...	0.110	( $S\bar{x}$ ) 0.162	0.019	...	0.065	(Sr) 0.063	0.008	...	0.010
A	1.040	0.034	<sup>A</sup>	0.110	0.0300	0.0025	...	...	0.038	0.0041	...	0.0060
B	0.970	0.028	<sup>A</sup>	0.080	-0.0400	-0.0035	...	-0.0100	0.006	0.0005	...	0.0112
C	1.040	0.034	<sup>A</sup>	0.070	0.0300	0.0025	...	-0.0200	0.050	0.0048	...	0.0056
D	0.990	0.030	<sup>A</sup>	0.120	-0.0200	-0.0015	...	0.0300	0.042	0.0036	...	0.0149
Col. Avg. ( $\bar{x}$ )	1.010	0.032	...	0.090	( $S\bar{x}$ ) 0.036	0.003	...	0.026	(Sr) 0.038	0.004	...	0.010
A	1.140	0.045	<sup>A</sup>	0.080	-0.0075	-0.0010	...	...	0.114	0.0171	...	0.0000
B	1.170	0.049	<sup>A</sup>	0.070	0.0225	0.0030	...	-0.0223	0.021	0.0025	...	0.0055
C	1.140	0.045	<sup>A</sup>	0.120	-0.0075	-0.0010	...	0.0277	0.058	0.0072	...	0.0060
D	1.140	0.045	<sup>A</sup>	0.087	-0.0075	-0.0010	...	-0.0053	0.125	0.0149	...	0.0148
Col. Avg. ( $\bar{x}$ )	1.148	0.046	...	0.092	( $S\bar{x}$ ) 0.015	0.002	...	0.025	(Sr) 0.090	0.012	...	0.008

<sup>A</sup>Average weight loss was not greater than 1 mg.

**TABLE X2.2 Summary of the Test Results Obtained from Interlaboratory Test Number 3**

NOTE 1—The test conditions used are listed in Table X2.4 in order.

Laboratory	Averages ( $\bar{x}$ )				Deviation from Average ( $d$ )				Standard Deviation ( $S$ )			
	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction	Block Scar Width (mm)	Block Scar Volume (mm <sup>3</sup> )	Ring Scar Volume (mm <sup>3</sup> )	Final Dynamic Friction
A	3.070	0.860	0.345	...	0.2375	0.1527	-0.1200	...	0.070	0.0378	0.107	...
B	2.570	0.515	0.771	0.598	-0.2625	-0.1923	0.3060	0.0287	0.334	0.1957	0.551	0.0138
C	3.020	0.877	0.468	0.670	0.1875	0.1697	0.0030	0.1007	0.453	0.4034	0.2059	0.0576
D	2.670	0.577	0.276	0.440	-0.1625	-0.1303	-0.1890	-0.1293	0.454	0.2827	0.207	0.2376
Col. Avg. ( $\bar{x}$ )	2.833	0.707	0.465	0.569	( $S\bar{x}$ ) 0.250	0.188	0.219	0.118	(Sr) 0.363	0.266	0.316	0.141
A	1.140	0.072	<sup>A</sup>	...	0.0475	0.0252	...	...	0.015	0.0069	...	...
B	1.050	0.035	<sup>A</sup>	0.071	-0.0425	-0.0117	...	-0.0033	0.002	0.0085	...	0.0006
C	0.990	0.029	<sup>A</sup>	0.080	-0.1025	-0.0178	...	0.0057	0.050	0.0044	...	0.0100
D	1.190	0.051	<sup>A</sup>	0.072	0.0975	0.0042	...	-0.0023	0.048	0.0061	...	0.0252
Col. Avg. ( $\bar{x}$ )	1.093	0.047	...	0.074	( $S\bar{x}$ ) 0.090	0.019	...	0.005	(Sr) 0.035	0.007	...	0.016
A	3.050	0.881	0.323	...	0.2950	0.2280	-0.1000	...	0.043	0.0608	0.033	...
B	2.870	0.717	0.151	0.588	0.1150	0.0640	-0.2720	0.0320	0.184	0.1362	0.128	0.0006
C	2.440	0.443	0.855	0.590	-0.3150	-0.2100	0.4320	0.0340	0.222	0.1285	0.142	0.0100
D	2.660	0.571	0.363	0.490	-0.0950	-0.0820	-0.0600	-0.0660	0.452	0.2741	0.217	0.0252
Col. Avg. ( $\bar{x}$ )	2.755	0.653	0.423	0.556	( $S\bar{x}$ ) 0.264	0.189	0.302	0.057	(Sr) 0.269	0.169	0.146	0.016

<sup>A</sup>Average weight loss was not greater than 1 mg.

**TABLE X2.3 Statistical Analyses of the Test Results from Interlaboratory Two**

Test Material & Conditions	Measured Parameters	$\bar{x}$	$S_r$	$S_R$	$V_r$ (%)
<b>Interlaboratory Test #2</b>					
H-30 block versus S-10 ring, $r/min = 197$ revolutions = 5400 load = 2006 N (450 lb) lubricant = mineral oil	block scar width (mm)	4.177	0.182	0.298	4.4
	block scar volume (mm <sup>3</sup> )	2.227	0.300	0.460	13.5
	ring scar volume (mm <sup>3</sup> )				
	final dynamic friction	0.140	0.014	0.026	9.9
<b>Interlaboratory Test #2</b>					
H-30 block versus S-10 ring, $r/min = 197$ revolutions = 5400 load = 803 N (180 lb) lubricant = mineral oil	block scar width (mm)	2.102	0.247	0.543	11.8
	block scar volume (mm <sup>3</sup> )	0.319	0.091	0.246	28.5
	ring scar volume				
	final dynamic friction	0.117	0.018	0.018	15.2
<b>Interlaboratory Test #2</b>					
H-60 block versus S-10 ring, $r/min = 197$ revolutions = 5400 load = 2006 N (450 lb) lubricant = mineral oil	block scar width (mm)	1.083	0.063	0.170	5.8
	block scar volume (mm <sup>3</sup> )	0.041	0.008	0.020	19.1
	ring scar volume (mm <sup>3</sup> )				
	final dynamic friction	0.110	0.101	0.066	9.2
<b>Interlaboratory Test #2</b>					
H-60 block versus S-10 ring, $r/min = 197$ revolutions = 5400 load = 803 N (180 lb) lubricant = mineral oil	block scar width (mm)	1.01	0.038	0.048	3.8
	block scar volume (mm <sup>3</sup> )	0.032	0.004	0.004	11.6
	ring scar volume (mm <sup>3</sup> )				
	final dynamic friction	0.092	0.010	0.010	11.3
<b>Interlaboratory Test #2</b>					
H-60 block versus S-10 ring, $r/min = 197$ revolution = 10 800 load = 803 N (180 lb) lubricant = mineral oil	block scar width (mm)	1.148	0.09	0.09	7.8
	block scar volume (mm <sup>3</sup> )	0.046	0.012	0.012	25.9
	ring scar volume (mm <sup>3</sup> )				
	final dynamic friction	0.092	0.008	0.027	9.1

**TABLE X2.4 Statistical Analyses of the Test Results from Interlaboratory Number Three**

Test Material & Conditions	Measured Parameters	$\bar{x}$	$S_r$	$S_R$	$V_r$ (%)
<b>Interlaboratory #3</b>					
H-60 block versus S-10 ring, $r/min = 72$ revolutions = 5400 load = 134 N (30 lb) lubricant = dry	block scar width (mm)	2.833	0.363	0.401	12.8
	block scar volume (mm <sup>3</sup> )	0.707	0.266	0.297	37.6
	ring scar volume (mm <sup>3</sup> )	0.465	0.316	0.350	68.0
	final dynamic friction	0.569	0.141	0.170	24.9
<b>Interlaboratory #3</b>					
H-60 block versus S-10 ring, $r/min = 197$ revolutions = 10 800 load = 803 N (180 lb) lubricant = mineral oil	block scar width (mm)	2.755	0.027	0.228	1.0
	block scar volume (mm <sup>3</sup> )	0.653	0.169	0.239	25.9
	ring scar volume (mm <sup>3</sup> )	0.423	0.146	0.328	34.5
	final dynamic friction	0.556	0.016	0.059	2.9
<b>Interlaboratory #3</b>					
H-60 block versus S-10 ring, $r/min = 197$ revolutions = 5400 load = 134 N (30 lb) lubricant = dry	block scar width (mm)	1.093	0.035	0.095	3.2
	block scar volume (mm <sup>3</sup> )	0.047	0.007	0.202	14.9
	ring scar volume (mm <sup>3</sup> )	0.423	0.217	0.35	51.3
	final dynamic friction	0.074	0.016	0.160	21.6

$p$  number of laboratories  
 $n$  number of replicates  
 $x_j$  an individual test result  
 $\bar{x}_j$  average of a cell<sup>10</sup>  
 $\bar{x}$  the average of cell averages for a material  
 $d_j$  deviation of a cell =  $\bar{x}_j - \bar{x}$   
 $S_j$  standard deviation of a cell  
 $S_{\bar{x}}$  standard deviation of cell averages  
 $S_r$  repeatability standard deviation  
 $S_R$  reproducibility standard deviation

$V_r$  estimated relative standard deviation or coefficient of variation within a laboratory for the parameter measured (repeatability) =  $100(S_r/\bar{x})$  %  
 $V_R$  estimated relative standard deviation or coefficient of variation between laboratories for the parameter measured (reproducibility) =  $100(S_R/\bar{x})$  %

<sup>10</sup> A cell is defined as the set of replicate test results for a particular parameter or variable, as measured in a single laboratory for a single material.

X2.3 *Statistical Relationships*—Additional statistical relationships can be found in Practice E 691.

$$S^2 = \sum_1^n (x_j - \bar{x}_j)^2 / (n - 1) \quad (\text{X2.1})$$

$$S_{\bar{x}}^2 = \sum_1^p d_j^2 / (p - 1)$$

$$S_r^2 = \sum_1^p S_j^2 / p$$

$$S_R^2 = S_{\bar{x}}^2 + S_r^2 (n - 1) / n$$

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