# APPENDIXS

# APPENDIX A

Table A1 Size distribution of fillers.

| Size (scale log; μm) | WC-Cr-Ni cored wire (%) | WC-Cr-Fe cored wire (%) | W-Cr-Fe nanocomposite cored wire (%) |
|---|---|---|---|
| 0.0582 | 0.00049 | 0.0001 | 0.00217 |
| 0.0679 | 0.00168 | 0.00039 | 0.00559 |
| 0.0791 | 0.00438 | 0.00106 | 0.01052 |
| 0.0921 | 0.00957 | 0.00237 | 0.01701 |
| 0.1073 | 0.01829 | 0.00456 | 0.02498 |
| 0.1250 | 0.0314 | 0.0078 | 0.03415 |
| 0.1456 | 0.04942 | 0.01218 | 0.04414 |
| 0.1697 | 0.07247 | 0.01768 | 0.05451 |
| 0.1977 | 0.1002 | 0.02417 | 0.06482 |
| 0.2303 | 0.13191 | 0.03139 | 0.07462 |
| 0.2683 | 0.16654 | 0.03902 | 0.08356 |
| 0.3125 | 0.20282 | 0.04667 | 0.09135 |
| 0.3641 | 0.23935 | 0.05392 | 0.09787 |
| 0.4242 | 0.27481 | 0.0604 | 0.10328 |
| 0.4941 | 0.30822 | 0.06586 | 0.10811 |
| 0.5757 | 0.33926 | 0.07028 | 0.11352 |
| 0.6707 | 0.36877 | 0.07408 | 0.12151 |
| 0.7813 | 0.39906 | 0.07821 | 0.13501 |
| 0.9103 | 0.44894 | 0.09115 | 0.17607 |
| 1.0604 | 0.50291 | 0.10673 | 0.22294 |
| 1.2354 | 0.56494 | 0.12825 | 0.28144 |
| 1.4393 | 0.63663 | 0.15912 | 0.35553 |
| 1.6767 | 0.71602 | 0.20274 | 0.44656 |
| 1.9534 | 0.79549 | 0.26233 | 0.55204 |
| 2.2757 | 0.86263 | 0.34119 | 0.6661 |
| 2.6512 | 0.90731 | 0.44313 | 0.78197 |
| 3.0887 | 0.9267 | 0.57111 | 0.89405 |
| 3.5983 | 0.93052 | 0.72853 | 1.00398 |
| 4.1920 | 0.94326 | 0.9224 | 1.12493 |
| 4.8837 | 0.99241 | 1.16181 | 1.2752 |
| 5.6895 | 1.09946 | 1.45232 | 1.46915 |
| 6.6283 | 1.26811 | 1.77909 | 1.70048 |
| 7.7219 | 1.49283 | 2.1147 | 1.95208 |
| 8.9960 | 1.77692 | 2.45244 | 2.22156 |

Table A1 (continuous) Size distribution of fillers.

| Size (scale log; μm) | WC-Cr-Ni cored wire (%) | WC-Cr-Fe cored wire (%) | W-Cr-Fe nanocomposite cored wire (%) |
|---|---|---|---|
| 10.4804 | 2.12047 | 2.79687 | 2.50798 |
| 12.2096 | 2.50421 | 3.13088 | 2.78568 |
| 14.2242 | 2.93474 | 3.48527 | 3.06737 |
| 16.5712 | 3.40052 | 3.86512 | 3.3457 |
| 19.3055 | 3.89961 | 4.28464 | 3.63027 |
| 22.4909 | 4.43153 | 4.74377 | 3.93209 |
| 26.2019 | 4.99293 | 5.22038 | 4.25995 |
| 30.5252 | 5.56356 | 5.66285 | 4.60824 |
| 35.5618 | 6.1073 | 5.99857 | 4.95379 |
| 41.4295 | 6.58283 | 6.14521 | 5.25878 |
| 48.2654 | 6.94437 | 6.02358 | 5.46588 |
| 56.2292 | 7.18986 | 5.62077 | 5.5373 |
| 65.5070 | 6.69991 | 4.98736 | 5.46355 |
| 76.3157 | 5.78699 | 4.22965 | 5.2756 |
| 88.9077 | 4.63978 | 3.3821 | 4.80158 |
| 103.5775 | 3.49255 | 2.8112 | 4.29912 |
| 120.6678 | 2.48978 | 2.53154 | 3.79512 |
| 140.5780 | 1.68412 | 2.44227 | 3.26733 |
| 163.7733 | 0.87845 | 2.40929 | 2.69882 |
| 190.7959 | 0.07278 | 2.30431 | 2.09279 |
| 222.2773 | 0 | 2.00602 | 1.48677 |
| 258.9530 | 0 | 1.47786 | 0.88075 |
| 301.6802 | 0 | 0.80373 | 0.27473 |
| 351.4575 | 0 | 0.1296 | 0 |
| 409.4479 | 0 | 0 | 0 |
| 477.0068 | 0 | 0 | 0 |
| 555.7130 | 0 | 0 | 0 |
| 647.4056 | 0 | 0 | 0 |
| 754.2275 | 0 | 0 | 0 |
| 878.6750 | 0 | 0 | 0 |

Table A2 Size distribution in-flight particles.

| Size (scale log; µm) | WC-Cr-Ni cored wire (%) | WC-Cr-Fe cored wire (%) | W-Cr-Fe nanocomposite cored wire (%) |
|---|---|---|---|
| 0.0582 | 0 | 0 | 0 |
| 0.0679 | 0 | 0 | 0 |
| 0.0791 | 0 | 0 | 0 |
| 0.0921 | 0 | 0 | 0 |
| 0.1073 | 0 | 0 | 0 |
| 0.1250 | 0 | 0 | 0 |
| 0.1456 | 0 | 0 | 0 |
| 0.1697 | 0 | 0 | 0 |
| 0.1977 | 0 | 0 | 0 |
| 0.2303 | 0 | 0 | 0 |
| 0.2683 | 0 | 0 | 0 |
| 0.3125 | 0 | 0 | 0 |
| 0.3641 | 0 | 0 | 0 |
| 0.4242 | 0 | 0 | 0 |
| 0.4941 | 0 | 0 | 0 |
| 0.5757 | 0 | 0.0307 | 0 |
| 0.6707 | 0 | 0.03214 | 0 |
| 0.7813 | 0 | 0.03724 | 0 |
| 0.9103 | 0.0352 | 0.0601 | 0.10007 |
| 1.0604 | 0.08827 | 0.08574 | 0.11344 |
| 1.2354 | 0.17697 | 0.1186 | 0.13651 |
| 1.4393 | 0.31937 | 0.16349 | 0.17526 |
| 1.6767 | 0.53349 | 0.22269 | 0.23015 |
| 1.9534 | 0.83178 | 0.2949 | 0.29543 |
| 2.2757 | 1.22269 | 0.38249 | 0.37348 |
| 2.6512 | 1.70388 | 0.49222 | 0.467 |
| 3.0887 | 2.25222 | 0.63294 | 0.57025 |
| 3.5983 | 2.85444 | 0.83067 | 0.69827 |
| 4.1920 | 3.51082 | 1.12359 | 0.86605 |
| 4.8837 | 4.23559 | 1.56736 | 1.10759 |
| 5.6895 | 5.0365 | 2.22292 | 1.46149 |
| 6.6283 | 5.87703 | 3.11979 | 1.94881 |
| 7.7219 | 6.66753 | 4.23351 | 2.57495 |
| 8.9960 | 7.34021 | 5.51025 | 3.34873 |
| 0.4804 | 7.8647 | 6.85747 | 4.26611 |

Table A2 (continuous)Size distribution in-flight particles.

| | | | |
|---|---|---|---|
| 12.2096 | 8.12156 | 8.04435 | 5.24583 |
| 14.2242 | 8.16738 | 8.92845 | 6.23328 |
| Size (scale log; μm) | WC-Cr-Ni cored wire (%) | WC-Cr-Fe cored wire (%) | W-Cr-Fe nanocomposite cored wire (%) |
| 16.5712 | 8.03578 | 9.33366 | 7.10155 |
| 19.3055 | 7.10877 | 9.22445 | 7.75063 |
| 22.4909 | 5.89994 | 8.68236 | 8.13069 |
| 26.2019 | 4.58816 | 7.86851 | 8.26796 |
| 30.5252 | 3.33706 | 6.46539 | 8.25164 |
| 35.5618 | 2.25729 | 5.11152 | 7.53948 |
| 41.4295 | 1.39689 | 3.81537 | 6.53262 |
| 48.2654 | 0.53648 | 2.58962 | 5.30546 |
| 56.2292 | 0 | 1.45584 | 3.9826 |
| 65.5070 | 0 | 0.46167 | 2.71559 |
| 76.3157 | 0 | 0 | 1.65429 |
| 88.9077 | 0 | 0 | 0.91103 |
| 103.5775 | 0 | 0 | 0.50071 |
| 120.6678 | 0 | 0 | 0.33464 |
| 140.5780 | 0 | 0 | 0.28282 |
| 163.7733 | 0 | 0 | 0.24354 |
| 190.7959 | 0 | 0 | 0.1752 |
| 222.2773 | 0 | 0 | 0.10685 |
| 258.9530 | 0 | 0 | 0 |
| 301.6802 | 0 | 0 | 0 |
| 351.4575 | 0 | 0 | 0 |
| 409.4479 | 0 | 0 | 0 |
| 477.0068 | 0 | 0 | 0 |
| 555.7130 | 0 | 0 | 0 |
| 647.4056 | 0 | 0 | 0 |
| 754.2275 | 0 | 0 | 0 |
| 878.6750 | 0 | 0 | 0 |

Table A3 Perimeter, area, D.S. and splat size of WC-Cr-Ni splats.

| No. | Perimeter (μm) | Area ($\mu m^2$) | D.S. | Splat size (μm) |
|---|---|---|---|---|
| 1 | 563.99 | 11334 | 2.23 | 120.16 |
| 2 | 629.77 | 11499 | 2.75 | 121.03 |
| 3 | 197.06 | 2054 | 1.51 | 51.15 |
| 4 | 126.5 | 882 | 1.44 | 33.52 |
| 5 | 328.64 | 3818 | 2.25 | 69.74 |
| 6 | 108.32 | 652 | 1.43 | 28.82 |
| 7 | 283.7 | 4355 | 1.47 | 74.48 |
| 8 | 210.06 | 2325 | 1.51 | 54.42 |
| 9 | 436.06 | 6806 | 2.22 | 93.11 |
| 10 | 134.18 | 1089 | 1.32 | 37.25 |
| 11 | 127.34 | 1078 | 1.20 | 37.06 |
| 12 | 178.85 | 1630 | 1.56 | 45.57 |
| 13 | 104.79 | 839 | 1.04 | 32.69 |
| 14 | 228.3 | 2070 | 2.00 | 51.35 |
| 15 | 133.37 | 839 | 1.69 | 32.69 |
| 16 | 249.02 | 3070 | 1.61 | 62.54 |
| 17 | 231.83 | 2215 | 1.93 | 53.12 |
| 18 | 81.18 | 415 | 1.26 | 22.99 |
| 19 | 88.83 | 449 | 1.40 | 23.92 |
| 20 | 83.3 | 414 | 1.33 | 22.96 |
| 21 | 535.3 | 7841 | 2.91 | 99.94 |
| 22 | 563.8 | 7007 | 3.61 | 94.48 |
| 23 | 167.5 | 1190 | 1.88 | 38.93 |
| 24 | 1712.1 | 44145 | 5.29 | 237.14 |
| 25 | 444.4 | 5006 | 3.14 | 79.86 |
| 26 | 211.1 | 2181 | 1.63 | 52.71 |
| 27 | 120.6 | 571 | 2.03 | 26.97 |
| 28 | 568.6 | 9423 | 2.73 | 109.56 |
| 29 | 188.7 | 1531 | 1.85 | 44.16 |
| 30 | 124 | 659 | 1.86 | 28.97 |
| 31 | 181.4 | 1750 | 1.50 | 47.22 |
| 32 | 86 | 460 | 1.28 | 24.21 |
| 33 | 85.3 | 480 | 1.21 | 24.73 |
| 34 | 80.7 | 384 | 1.35 | 22.12 |
| 35 | 63.3 | 211 | 1.51 | 16.39 |
| 36 | 285.4 | 3170 | 2.05 | 63.55 |
| 37 | 118.6 | 650 | 1.72 | 28.78 |

Table A3 (continuous) Perimeter, area, D.S. and splat size of WC-Cr-Ni splats.

| | | | | |
|---|---|---|---|---|
| 38 | 115.3 | 410 | 2.58 | 22.85 |
| 39 | 59.2 | 268 | 1.04 | 18.48 |
| 40 | 822.38 | 22840 | 2.36 | 170.57 |
| 41 | 481.48 | 7474 | 2.47 | 97.58 |
| 42 | 224.01 | 1558 | 2.56 | 44.55 |
| 43 | 111.38 | 750 | 1.32 | 30.91 |
| 44 | 269.5 | 2662 | 2.17 | 58.23 |
| 45 | 148.15 | 822 | 2.13 | 32.36 |
| 46 | 181.01 | 959 | 2.72 | 34.95 |
| 47 | 309.64 | 3405 | 2.24 | 65.86 |
| 48 | 121 | 587 | 1.99 | 27.35 |
| 49 | 189.49 | 1807 | 1.58 | 47.98 |
| 50 | 132.8 | 1155 | 1.22 | 38.36 |
| 51 | 212.07 | 1402 | 2.55 | 42.26 |
| 52 | 150.45 | 1263 | 1.43 | 40.11 |
| 53 | 327.98 | 5469 | 1.57 | 83.47 |
| 54 | 829.43 | 15772 | 3.47 | 141.75 |
| 55 | 587.68 | 9344 | 2.94 | 109.10 |
| 56 | 93.74 | 548 | 1.28 | 26.42 |
| 57 | 258.09 | 2401 | 2.21 | 55.30 |
| 58 | 97.53 | 565 | 1.34 | 26.83 |
| 59 | 209.57 | 2827 | 1.24 | 60.01 |
| 60 | 635.92 | 15819 | 2.04 | 141.96 |
| 61 | 329.74 | 5749 | 1.51 | 85.58 |
| 62 | 158.61 | 1107 | 1.81 | 37.55 |
| 63 | 240.42 | 3398 | 1.35 | 65.79 |
| 64 | 240.01 | 1893 | 2.42 | 49.11 |
| 65 | 278.77 | 4171 | 1.48 | 72.89 |
| 66 | 195.25 | 1646 | 1.84 | 45.79 |
| 67 | 157.71 | 1074 | 1.84 | 36.99 |
| 68 | 98.24 | 531 | 1.45 | 26.01 |
| 69 | 326.81 | 4627 | 1.84 | 76.77 |
| 70 | 1556.7 | 57216 | 3.37 | 269.98 |
| 71 | 452.5 | 8188 | 1.99 | 102.13 |
| 72 | 392.3 | 5161 | 2.37 | 81.08 |
| 73 | 313.5 | 5490 | 1.43 | 83.63 |
| 74 | 331.6 | 5196 | 1.68 | 81.36 |
| 75 | 219.6 | 2207 | 1.74 | 53.02 |
| | | **Average** | **1.93** | **70.95** |
| | | **SD** | **0.70** | **47.29** |

Table A4 Perimeter, area, D.S. and splat size of WC-Cr-Fe splats.

| Feature Name | Perimeter | Area | D.S. | Splat size |
|---|---|---|---|---|
| 1 | 865.23 | 15242 | 3.91 | 139.34 |
| 2 | 212.95 | 1863 | 1.94 | 48.72 |
| 3 | 87.16 | 376 | 1.61 | 21.89 |
| 4 | 76.6 | 402 | 1.16 | 22.63 |
| 5 | 380.2 | 4736 | 2.43 | 77.67 |
| 6 | 209.63 | 1929 | 1.81 | 49.57 |
| 7 | 674.3 | 13728 | 2.64 | 132.24 |
| 8 | 380.16 | 3625 | 3.17 | 67.95 |
| 9 | 250.5 | 2420 | 2.06 | 55.52 |
| 10 | 350.32 | 4568 | 2.14 | 76.28 |
| 11 | 236.08 | 2421 | 1.83 | 55.53 |
| 12 | 149.7 | 832 | 2.14 | 32.56 |
| 13 | 306.03 | 2731 | 2.73 | 58.98 |
| 14 | 427.64 | 4149 | 3.51 | 72.70 |
| 15 | 424.77 | 7753.8 | 1.85 | 99.39 |
| 16 | 998 | 16951 | 4.68 | 146.95 |
| 17 | 689.42 | 14804 | 2.56 | 137.33 |
| 18 | 436.01 | 7313.3 | 2.07 | 96.52 |
| 19 | 87.16 | 376 | 1.61 | 21.89 |
| 20 | 76.6 | 402 | 1.16 | 22.63 |
| 21 | 380.2 | 4736 | 2.43 | 77.67 |
| 22 | 209.63 | 1929 | 1.81 | 49.57 |
| 23 | 674.3 | 13728 | 2.64 | 132.24 |
| 24 | 380.16 | 3625 | 3.17 | 67.95 |
| 25 | 250.5 | 2420 | 2.06 | 55.52 |
| 26 | 87.16 | 376 | 1.61 | 21.89 |
| 27 | 76.6 | 402 | 1.16 | 22.63 |
| 28 | 380.2 | 4736 | 2.43 | 77.67 |
| 29 | 209.63 | 1929 | 1.81 | 49.57 |
| 30 | 674.3 | 13728 | 2.64 | 132.24 |
| 31 | 380.16 | 3625 | 3.17 | 67.95 |
| 32 | 250.5 | 2420 | 2.06 | 55.52 |
| 33 | 350.32 | 4568 | 2.14 | 76.28 |
| 34 | 236.08 | 2421 | 1.83 | 55.53 |
| 35 | 149.7 | 832 | 2.14 | 32.56 |
| 36 | 306.03 | 2731 | 2.73 | 58.98 |
| 37 | 427.64 | 4149 | 3.51 | 72.70 |
| 38 | 424.77 | 7753.8 | 1.85 | 99.39 |
| 39 | 998 | 16951 | 4.68 | 146.95 |
| 40 | 689.42 | 14804 | 2.56 | 137.33 |

Table A4 (continuous) Perimeter, area, D.S. and splat size of WC-Cr-Fe splats.

| | | | | |
|---|---|---|---|---|
| 41 | 436.01 | 7313.3 | 2.07 | 96.52 |
| 42 | 87.16 | 376 | 1.61 | 21.89 |
| 43 | 76.6 | 402 | 1.16 | 22.63 |
| 44 | 380.2 | 4736 | 2.43 | 77.67 |
| 45 | 209.63 | 1929 | 1.81 | 49.57 |
| 46 | 674.3 | 13728 | 2.64 | 132.24 |
| 47 | 380.16 | 3625 | 3.17 | 67.95 |
| 48 | 350.32 | 4568 | 2.14 | 76.28 |
| 49 | 236.08 | 2421 | 1.83 | 55.53 |
| 50 | 149.7 | 832 | 2.14 | 32.56 |
| 51 | 306.03 | 2731 | 2.73 | 58.98 |
| 52 | 427.64 | 4149 | 3.51 | 72.70 |
| 53 | 87.16 | 376 | 1.61 | 21.89 |
| 54 | 76.6 | 402 | 1.16 | 22.63 |
| 55 | 380.2 | 4736 | 2.43 | 77.67 |
| 56 | 209.63 | 1929 | 1.81 | 49.57 |
| 57 | 674.3 | 13728 | 2.64 | 132.24 |
| 58 | 380.16 | 3625 | 3.17 | 67.95 |
| 59 | 250.5 | 2420 | 2.06 | 55.52 |
| 60 | 350.32 | 4568 | 2.14 | 76.28 |
| 61 | 236.08 | 2421 | 1.83 | 55.53 |
| 62 | 149.7 | 832 | 2.14 | 32.56 |
| 63 | 306.03 | 2731 | 2.73 | 58.98 |
| 64 | 427.64 | 4149 | 3.51 | 72.70 |
| 65 | 424.77 | 7753.8 | 1.85 | 99.39 |
| 66 | 998 | 16951 | 4.68 | 146.95 |
| 67 | 689.42 | 14804 | 2.56 | 137.33 |
| 68 | 436.01 | 7313.3 | 2.07 | 96.52 |
| 69 | 87.16 | 376 | 1.61 | 21.89 |
| 70 | 76.6 | 402 | 1.16 | 22.63 |
| 71 | 380.2 | 4736 | 2.43 | 77.67 |
| 72 | 209.63 | 1929 | 1.81 | 49.57 |
| 73 | 674.3 | 13728 | 2.64 | 132.24 |
| 74 | 380.16 | 3625 | 3.17 | 67.95 |
| 75 | 180.72 | 1409 | 1.85 | 42.37 |
| | | **Average** | **2.50** | **69.75** |
| | | **SD** | **0.74** | **34.36** |

Table A5 Perimeter, area, D.S. and splat size of W-Cr-Fe nanocomposite splats.

| Feature Name | Perimeter | Area | D.S. | Splat size |
|---|---|---|---|---|
| 1 | 319.7 | 3002 | 2.7 | 61.8 |
| 2 | 788.4 | 11270 | 4.4 | 119.8 |
| 3 | 324.5 | 4472 | 1.9 | 75.5 |
| 4 | 904.6 | 13832 | 4.7 | 132.7 |
| 5 | 703.9 | 8174 | 4.8 | 102.0 |
| 6 | 623.3 | 16411 | 1.9 | 144.6 |
| 7 | 377.8 | 4692 | 2.4 | 77.3 |
| 8 | 1712.7 | 39536 | 5.9 | 224.4 |
| 9 | 1163.1 | 20804 | 5.2 | 162.8 |
| 10 | 448.5 | 3685 | 4.3 | 68.5 |
| 11 | 539.5 | 5262 | 4.4 | 81.9 |
| 12 | 668.3 | 8528 | 4.2 | 104.2 |
| 13 | 654.3 | 9253 | 3.7 | 108.6 |
| 14 | 344.4 | 4456 | 2.1 | 75.3 |
| 15 | 220 | 1779 | 2.2 | 47.6 |
| 16 | 619.8 | 7677 | 4.0 | 98.9 |
| 17 | 864.3 | 19947 | 3.0 | 159.4 |
| 18 | 642.7 | 10523 | 3.1 | 115.8 |
| 19 | 1449.8 | 35762 | 4.7 | 213.4 |
| 20 | 531.9 | 6370 | 3.5 | 90.1 |
| 21 | 550.4 | 4023 | 6.0 | 71.6 |
| 22 | 803.2 | 19358 | 2.7 | 157.0 |
| 23 | 1057.9 | 22910 | 3.9 | 170.8 |
| 24 | 489.3 | 6033 | 3.2 | 87.7 |
| 25 | 1712.7 | 39536 | 5.9 | 224.4 |
| 26 | 1163.1 | 20804 | 5.2 | 162.8 |
| 27 | 448.5 | 3685 | 4.3 | 68.5 |
| 28 | 539.5 | 5262 | 4.4 | 81.9 |
| 29 | 668.3 | 8528 | 4.2 | 104.2 |
| 30 | 654.3 | 9253 | 3.7 | 108.6 |
| 31 | 344.4 | 4456 | 2.1 | 75.3 |
| 32 | 220 | 1779 | 2.2 | 47.6 |
| 33 | 619.8 | 7677 | 4.0 | 98.9 |
| 34 | 864.3 | 19947 | 3.0 | 159.4 |
| 35 | 642.7 | 10523 | 3.1 | 115.8 |
| 36 | 1449.8 | 35762 | 4.7 | 213.4 |
| 37 | 531.9 | 6370 | 3.5 | 90.1 |
| 38 | 550.4 | 4023 | 6.0 | 71.6 |
| 39 | 803.2 | 19358 | 2.7 | 157.0 |
| 40 | 1057.9 | 22910 | 3.9 | 170.8 |
| 41 | 489.3 | 6033 | 3.2 | 87.7 |
| 42 | 1100.9 | 20169 | 4.8 | 160.3 |

Table A5 (continuous) Perimeter, area, D.S. and splat size of W-Cr-Fe nanocomposite splats.

| | | | | |
|---|---|---|---|---|
| 43 | 1163.1 | 20804 | 5.2 | 162.8 |
| 44 | 448.5 | 3685 | 4.3 | 68.5 |
| 45 | 539.5 | 5262 | 4.4 | 81.9 |
| 46 | 668.3 | 8528 | 4.2 | 104.2 |
| 47 | 654.3 | 9253 | 3.7 | 108.6 |
| 48 | 344.4 | 4456 | 2.1 | 75.3 |
| 49 | 220 | 1779 | 2.2 | 47.6 |
| 50 | 619.8 | 7677 | 4.0 | 98.9 |
| 51 | 864.3 | 19947 | 3.0 | 159.4 |
| 52 | 642.7 | 10523 | 3.1 | 115.8 |
| 53 | 1449.8 | 35762 | 4.7 | 213.4 |
| 54 | 531.9 | 6370 | 3.5 | 90.1 |
| 55 | 550.4 | 4023 | 6.0 | 71.6 |
| 56 | 803.2 | 19358 | 2.7 | 157.0 |
| 57 | 1057.9 | 22910 | 3.9 | 170.8 |
| 58 | 851 | 12675 | 4.5 | 127.1 |
| 59 | 326.5 | 4131 | 2.1 | 72.5 |
| 60 | 276.3 | 3664 | 1.7 | 68.3 |
| 61 | 868.3 | 10810 | 5.6 | 117.3 |
| 62 | 285.5 | 2548 | 2.5 | 57.0 |
| 63 | 298 | 3002 | 2.4 | 61.8 |
| 64 | 509.6 | 9341 | 2.2 | 109.1 |
| 65 | 774.4 | 8141 | 5.9 | 101.8 |
| 66 | 560.1 | 5934 | 4.2 | 86.9 |
| 67 | 372.4 | 3757 | 2.9 | 69.2 |
| 68 | 132.6 | 929 | 1.5 | 34.4 |
| 69 | 387.3 | 2322 | 5.1 | 54.4 |
| 70 | 266.8 | 1800 | 3.1 | 47.9 |
| 71 | 1057.9 | 22910 | 3.9 | 170.8 |
| 72 | 851 | 12675 | 4.5 | 127.1 |
| 73 | 326.5 | 4131 | 2.1 | 72.5 |
| 74 | 592.7 | 5437 | 5.1 | 83.2 |
| 75 | 340.3 | 2316 | 4.0 | 54.3 |
| | | **Average** | **3.31** | **100.438** |
| | | **SD** | **1.3** | **44.9** |
| | | | | |

Table A6 Roughness (µm) of coatings.

| Coatings | WC-Cr-Ni | WC-Cr-Fe | W-Cr-Fe nanocomposite |
|---|---|---|---|
| 1 | 15 | 14.6 | 14.2 |
| 2 | 14.8 | 14.8 | 14.2 |
| 3 | 15.8 | 14.60 | 12.6 |
| 4 | 18.2 | 15.80 | 11.4 |
| 5 | 15 | 15.6 | 14.4 |
| 6 | 17.60 | 16.2 | 13.4 |
| 7 | 13.60 | 17.4 | 14.6 |
| 8 | 17.6 | 19.1 | 13.2 |
| 9 | 16.8 | 16.5 | 15.4 |
| 10 | 13.2 | 18.5 | 13.4 |
| **Average** | **15.76** | **16.31** | **13.68** |
| **SD** | **1.74** | **1.59** | **1.14** |

Table A7 Porosity (%) of WC-Cr-Ni coating.

| Coatings | WC-Cr-Ni | WC-Cr-Fe | W-Cr-Fe nanocomp. |
|---|---|---|---|
| 1 | 8.194 | 9.515 | 7.07 |
| 2 | 5.87 | 7.512 | 5.02 |
| 3 | 10.714 | 7.821 | 2.817 |
| 4 | 6.734 | 12.298 | 3.6 |
| 5 | 6.271 | 8.07 | 3.812 |
| 6 | 8.291 | 7.512 | 5.02 |
| 7 | 8.588 | 7.821 | 2.817 |
| 8 | 8.106 | 12.298 | 3.6 |
| 9 | 8.329 | 8.07 | 3.812 |
| 10 | 8.543 | 10.727 | 6.538 |
| **Average** | **8** | **9.2** | **4.8** |
| **SD** | **0.9** | **1.6** | **1.7** |

Table A8 Hardness ($HV_{300g}$) of coatings.

| Coatings | WC-Cr-Ni | WC-Cr-Fe | W-Cr-Fe nanocomposite |
|---|---|---|---|
| 1 | 1381 | 1074 | 1295 |
| 2 | 1368 | 1035 | 1174 |
| 3 | 1259 | 948 | 1164 |
| 4 | 1164 | 941 | 1164 |
| 5 | 1134 | 847 | 1144 |
| 6 | 1087 | 810 | 1106 |
| 7 | 1061 | 805 | 1088 |
| 8 | 1010 | 805 | 1087 |
| 9 | 994 | 760 | 1074 |
| 10 | 956 | 755 | 1052 |
| 11 | 934 | 687 | 1035 |
| 12 | 853 | 687 | 1019 |
| 13 | 822 | 639 | 1019 |
| 14 | 794 | 635 | 995 |
| 15 | 705 | 608 | 994 |
| **Average** | **1034.80** | **802.40** | **1094.00** |
| **SD** | **202.63** | **144.80** | **82.82** |

Table A9 Sliding wear test of coatings.

| Coatings | Width track (μm) | | | | Average. | Volume loss($mm^3$) |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | |
| WC-Cr-Ni 4mm | 322.1 | 360.2 | 365.4 | 381.1 | 357.20 | 0.0305 |
| 6mm | 313.1 | 323.7 | 332.4 | 334.3 | 325.88 | 0.0345 |
| 8mm | 240.1 | 298.3 | 287.1 | 292.4 | 279.48 | 0.0352 |
| | | | | | **Average** | **0.0334** |
| | | | | | **SD** | **0.000** |
| WC-Cr-Fe 4mm | 407.7 | 409.5 | 365.4 | 381 | 1563.60 | 0.0397 |
| 6mm | 410.6 | 455.4 | 469.1 | 450.1 | 1785.20 | 0.0886 |
| 8mm | 426.2 | 452.1 | 365.2 | 369 | 1612.50 | 0.0871 |
| | | | | | **Average** | **0.718** |
| | | | | | **SD** | **0.006** |
| W-Cr-Fe nanocomp 4mm | 407.7 | 409.5 | 365.4 | 381 | 1563.60 | 0.0607 |
| 6mm | 410.6 | 421.4 | 450.1 | 450.1 | 1732.20 | 0.0456 |
| 8mm | 376.2 | 452.1 | 365.2 | 369 | 1562.50 | 0.0761 |
| | | | | | **Average** | **0.0610** |
| | | | | | **SD** | **0.006** |

Table A10 Coating weight loss (g) of abrasive wear test.

| Coatings | | Distance m. | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 300 | 450 | 600 | 750 |
| WC-Cr-Ni | 1 | 50.6178 | 50.5093 | 50.4585 | 50.4078 | 50.359 |
| | 2 | 49.8471 | 49.7419 | 49.6943 | 49.6462 | 49.598 |
| | 3 | 49.9602 | 49.8544 | 49.8012 | 49.7475 | 49.6978 |
| WC-Cr-Fe | 1 | 48.8625 | 48.7627 | 48.7132 | 48.6641 | 48.613 |
| | 2 | 49.2362 | 49.1353 | 49.0848 | 49.0347 | 48.9824 |
| | 3 | 38.9206 | 38.8181 | 38.7665 | 38.7134 | 38.6639 |
| W-Cr-Fe nanocomp. | 1 | 48.2474 | 48.1593 | 48.1181 | 48.0773 | 48.0361 |
| | 2 | na | 48.5184 | 48.4752 | 48.4306 | 48.3872 |
| | 3 | 48.9669 | 48.8787 | 48.8357 | 48.7918 | 48.7507 |

Table A10 (continue) Coating weight loss (g) of abrasive wear test.

| Coatings | | Distance m. | | | | |
|---|---|---|---|---|---|---|
| | | 900 | 1050 | 1200 | 1350 | 1500 |
| WC-Cr-Ni | 1 | 50.3104 | 50.2635 | 50.2166 | 50.1716 | 50.1273 |
| | 2 | 49.5501 | 49.5000 | 49.4537 | 49.4064 | 49.3603 |
| | 3 | 49.6497 | 49.6025 | 49.5552 | 49.5111 | 49.4647 |
| WC-Cr-Fe | 1 | 48.5644 | 48.5164 | 48.4689 | 48.4218 | 48.3766 |
| | 2 | 48.9311 | 48.8822 | 48.8334 | 48.784 | 48.7383 |
| | 3 | 38.614 | 38.5649 | 38.5161 | 38.4682 | 38.4176 |
| W-Cr-Fe nanocomp. | 1 | 47.992 | 47.9501 | 47.906 | 47.8641 | 47.8261 |
| | 2 | 48.345 | 48.3032 | 48.2589 | 48.2181 | 48.1777 |
| | 3 | 48.7093 | 48.6685 | 48.6279 | 48.5881 | 48.5481 |

Table A11 Roughness of WC-Cr-Ni pump plunger coating.

| No | Roughness (μm) | | | | |
|---|---|---|---|---|---|
| 1 | 0.66 | 0.5 | 0.76 | 0.7 | 0.42 |
| 2 | 0.88 | 0.58 | 0.74 | 0.72 | 0.4 |
| 3 | 0.72 | 0.66 | 0.8 | 0.94 | 0.42 |
| 4 | 0.82 | 0.46 | 1.04 | 0.54 | 0.38 |
| 5 | 0.96 | 0.54 | 1.08 | 0.48 | 0.42 |
| 6 | 0.8 | 0.62 | 0.68 | 0.6 | 0.34 |
| 7 | 1.1 | 0.56 | 0.96 | 0.56 | 0.32 |
| 8 | 1.09 | 0.78 | 0.72 | 0.92 | 0.32 |
| | | | | **Average** | **0.75** |
| | | | | **SD** | **0.1** |

Table A12 Roughness of WC-Cr-Fe pump plunger coating.

| No | Roughness (μm) | | | | |
|---|---|---|---|---|---|
| 1 | 0.94 | 0.58 | 0.76 | 0.8 | 0.5 |
| 2 | 0.86 | 0.62 | 0.72 | 0.62 | 0.36 |
| 3 | 0.88 | 0.52 | 0.86 | 1.12 | 0.46 |
| 4 | 1.42 | 0.84 | 0.54 | 0.7 | 0.58 |
| 5 | 1.12 | 0.84 | 0.64 | 0.52 | 0.48 |
| 6 | 0.62 | 0.72 | 0.74 | 0.78 | 0.56 |
| 7 | 0.96 | 0.66 | 0.98 | 0.88 | 0.48 |
| 8 | 1.92 | 0.6 | 0.78 | 0.64 | 0.5 |
| | | | | **Average** | **0.82** |
| | | | | **SD** | **0.2** |

Table A13 Roughness of W-Cr-Fe nanocomposite pump plunger coating.

| No | Roughness (μm) | | | | |
|---|---|---|---|---|---|
| 1 | 1 | 5 | 10 | 15 | 16.5 |
| 2 | 0.74 | 0.62 | 0.42 | 0.48 | 0.46 |
| 3 | 0.46 | 0.6 | 0.4 | 0.86 | 0.54 |
| 4 | 0.86 | 0.82 | 0.38 | 0.48 | 0.46 |
| 5 | 0.78 | 0.68 | 0.42 | 0.54 | 0.44 |
| 6 | 0.58 | 0.5 | 0.36 | 0.46 | 0.42 |
| 7 | 0.78 | 0.82 | 0.34 | 0.82 | 0.44 |
| 8 | 0.66 | 0.4 | 0.54 | 0.56 | 0.46 |
| | | | | **Average** | **0.58** |
| | | | | **SD** | **0.1** |

Table A14 Decreasing diameter (mm) of pump plunger test under simulate condition.

| | WC-Cr-Ni coating | | | WC-Cr-Fe coating | | | W-Cr-Fe nanocomposite coating | | |
|---|---|---|---|---|---|---|---|---|---|
| | Original | Used | Decrease | Original | Used | Decrease | Original | Used | Decrease |
| 1 | 69.866 | 69.865 | 0.001 | 69.867 | 69.842 | 0.025 | 69.879 | 69.873 | 0.006 |
| 2 | 69.866 | 69.865 | 0.001 | 69.870 | 69.869 | 0.001 | 69.880 | 69.879 | 0.001 |
| 3 | 69.866 | 69.864 | 0.002 | 69.869 | 69.870 | n/a | 69.882 | 69.881 | 0.001 |
| 4 | 69.866 | 69.865 | 0.001 | 69.871 | 69.870 | 0.001 | 69.883 | 69.884 | n/a |
| 5 | 69.865 | 69.864 | 0.001 | 69.871 | 69.870 | 0.001 | 69.885 | 69.884 | 0.001 |
| 6 | 69.865 | 69.865 | 0 | 69.871 | 69.871 | 0 | 69.886 | 69.885 | 0.001 |
| 7 | 69.864 | 69.864 | 0 | 69.871 | 69.871 | 0 | 69.887 | 69.887 | 0 |
| 8 | 69.865 | 69.866 | n/a | 69.872 | 69.871 | 0.001 | 69.888 | 69.888 | 0 |
| 9 | 69.865 | 69.864 | 0.001 | 69.872 | 69.872 | 0 | 69.889 | 69.888 | 0.001 |
| 10 | 69.865 | 69.864 | 0.001 | 69.872 | 69.872 | 0 | 69.889 | 69.889 | 0 |
| 11 | 69.865 | 69.865 | 0 | 69.873 | 69.871 | 0.002 | 69.891 | 69.890 | 0.001 |
| 12 | 69.865 | 69.865 | 0 | 69.872 | 69.871 | 0.001 | 69.891 | 69.891 | 0 |
| 13 | 69.865 | 69.864 | 0.001 | 69.872 | 69.870 | 0.002 | 69.891 | 69.891 | 0 |
| 14 | 69.865 | 69.865 | 0 | 69.872 | 69.870 | 0.002 | 69.893 | 69.890 | 0.003 |
| 15 | 69.864 | 69.865 | n/a | 69.872 | 69.870 | 0.002 | 69.892 | 69.891 | 0.001 |
| **Avg.** | | | ***n/a** | | | **0.00271** | | | **0.00114** |
| **SD** | | | ***n/a** | | | **0.0008** | | | **0.0009** |

* lower than detection limit of CMM

# APPENDIX B

Designation: G 65 – 91

## Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus[1]

This standard is issued under the fixed designation G 65; 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 (ϵ) 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 metallic materials to scratching abrasion by means of the Dry Sand/Rubber Wheel Test. It is the intent of this test method to produce data that will reproducibly rank materials in their resistance to scratching abrasion under a specified set of conditions.

1.2 Abrasion test results are reported as volume loss in cubic millimetres for the particular test procedure specified. Materials of higher abrasion resistance will have a lower volume loss.

NOTE 1—In order to attain uniformity among laboratories, it is the intent of this test method to require that volume loss due to abrasion be reported only in the metric system as cubic millimetres. 1 $mm^3 = 6.102 \times 10^{-5}$ $in^3$.

1.3 This test method covers four recommended procedures which are appropriate for specific degrees of wear resistance or thicknesses of the test material.

1.3.1 *Procedure A*—This is a relatively severe test which will rank metallic materials on a wide volume loss scale from low to extreme abrasion resistance. It is particularly useful in ranking materials of medium to extreme abrasion resistance.

1.3.2 *Procedure B*—A short-term variation of Procedure A. It may be used for highly abrasive resistant materials but is particularly useful in the ranking of medium- and low-abrasive resistant materials. Procedure B should be used when the volume-loss values developed by Procedure A exceeds 100 $mm^3$.

1.3.3 *Procedure C*—A short-term variation of Procedure A for use on thin coatings.

1.3.4 *Procedure D*—This is a lighter load variation of Procedure A which is particularly useful in ranking materials of low abrasion resistance. It is also used in ranking materials of a specific generic type or materials which would be very close in the volume loss rates as developed by Procedure A.

1.4 *This standard does not purport to address the safety problems 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 2240 Test Method for Rubber Property—Durometer Hardness[2]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[3]

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[4]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[5]

G 40 Terminology Relating to Wear and Erosion[6]

2.2 *American Foundrymen's Society Standards:*

AFS Foundry Sand Handbook, 7th Edition[7]

### 3. Terminology

3.1 *Definition—abrasive wear*—wear due to hard particles or hard protuberances forced against and moving along a solid surface (Terminology G 40).

NOTE 2—This definition covers several different wear modes or mechanisms that fall under the abrasive wear category. These modes may degrade a surface by scratching, cutting, deformation, or gouging (**1** and **6**).[8]

### 4. Summary of Test Method

4.1 The Dry Sand/Rubber Wheel Abrasion test (Fig. 1) involves the abrading of a standard test specimen with a grit of controlled size and composition. The abrasive is introduced between the test specimen and a rotating wheel with a chlorobutyl rubber tire or rim of a specified hardness. This test specimen is pressed against the rotating wheel at a specified force by means of a lever arm while a controlled flow of grit abrades the test surface. The rotation of the wheel is such that its contact face moves in the direction of the sand flow. Note that the pivot axis of the lever arm lies within a plane which is approximately tangent to the rubber wheel surface, and normal to the horizontal diameter along which the load is applied. The test duration and force applied by the lever arm is varied as noted in Procedure A through D. Specimens are weighed before and after the test and the loss in mass recorded. It is necessary to convert the mass loss to volume loss in cubic millimetres, due to the wide differences in the density of materials. Abrasion is reported as volume loss per specified procedure.

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[1] This test method is under the jurisdiction of ASTM Committee G-2 on Wear and Erosion and is the direct responsibility of Subcommittee G02.30 on Abrasive Wear.

Current edition approved Feb. 22, 1991. Published May 1991. Originally published as G 65 – 80. Last previous edition G 65 – 85.

[2] *Annual Book of ASTM Standards,* Vols 08.02 and 09.01.

[3] *Annual Book of ASTM Standards,* Vols 04.01, 04.02, 04.06, 04.07, 05.05, and 14.02.

[4] *Annual Book of ASTM Standards,* Vol 14.02.

[5] *Annual Book of ASTM Standards,* Vols 04.01, 04.02, 14.02, and 15.01.

[6] *Annual Book of ASTM Standards,* Vol 03.02.

[7] Available from American Foundrymen's Society, Golf and Wolf Roads, Des Plaines, IL 60016.

[8] The boldface numbers in parentheses refer to the list of references at the end of this practice.

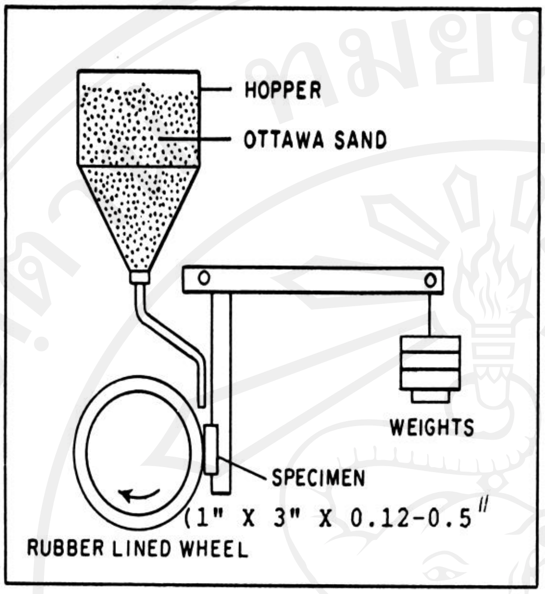



**FIG. 1 Schematic Diagram of Test Apparatus**

## 5. Significance and Use (1 through 7)

5.1 The severity of abrasive wear in any system will depend upon the abrasive particle size, shape, and hardness, the magnitude of the stress imposed by the particle, and the frequency of contact of the abrasive particle. In this practice these conditions are standardized to develop a uniform condition of wear which has been referred to as scratching abrasion (**1** and **2**). The value of the practice lies in predicting the relative ranking of various materials of construction in an abrasive environment. Since the practice does not attempt to duplicate all of the process conditions (abrasive size, shape, pressure, impact, or corrosive elements), it should not be used to predict the exact resistance of a given material in a specific environment. Its value lies in predicting the ranking of materials in a similar relative order of merit as would occur in an abrasive environment. Volume loss data obtained from test materials whose lives are unknown in a specific abrasive environment may, however, be compared with test data obtained from a material whose life is known in the same environment. The comparison will provide a general indication of the worth of the unknown materials if abrasion is the predominant factor causing deterioration of the materials.

## 6. Apparatus and Material[9]

6.1 Figure 2 shows a typical design and Figs. 3 and 4 are photographs of the test apparatus which may be constructed from readily available materials. Also, see Ref (**2**). Several elements are of critical importance to ensure uniformity in test results among laboratories. These are the type of rubber used on the wheel, the type of abrasive and the shape, positioning and the size opening of the sand nozzle, and a suitable lever arm system to apply the required force.

6.2 *Rubber Wheel*—The wheel shown in Fig. 5 shall consist of a steel disk with an outer layer of chlorobutyl rubber molded to its periphery. Uncured rubber shall be bonded to the rim and fully cured in a steel mold. The optimum hardness of the cured rubber is Durometer A-60. A range from A 58 to 62 is acceptable. At least four hardness readings shall be taken on the rubber approximately 90° apart around the periphery of the wheel using a Shore A Durometer tester in accordance with Test Method D 2240. The gage readings shall be taken after a dwell time of 5 s. The recommended composition of the rubber and a qualified molding source is noted in Table 1. (See 9.9 for preparation and care of the rubber wheel before and after use and see Figs. 2 and 5.)

6.3 *Abrasive*—The type of abrasive shall be a rounded quartz grain sand as typified by AFS 50/70 Test Sand (Fig. 7) furnished by the qualified source.[10] The moisture content shall not exceed 0.5 weight %. Sand that has been subjected to dampness or to continued high relative humidity may take on moisture, which will affect test results. Moisture content may be determined by measuring the weight loss after heating a sample to approximately 120°C (250°F) for 1 h minimum. If test sand contains moisture in excess of 0.5 % it shall be dried by heating to 100°C (212°F) for 1 h minimum and the moisture test repeated. In high-humidity areas sand may be effectively stored in constant temperature and humidity rooms or in an enclosed steel storage bin equipped with a 100-W electric bulb. Welding electrode drying ovens, available from welding equipment suppliers are also suitable. Multiple use of the sand may affect test results and is not recommended. AFS 50–70 Test Sand is controlled by the qualified source to the following size range using U.S. Sieves (Specification E 11).

| U.S. Sieve Size | Sieve Opening | % Retained on Sieve |
|---|---|---|
| 40 | 425 µm (0.0165 in.) | none |
| 50 | 300 µm (0.0117 in.) | 5 max |
| 70 | 212 µm (0.0083 in.) | 95 min |
| 100 | 150 µm (0.0059 in.) | none passing |

6.4 *Sand Nozzle*—Figure 6 shows the fabricated nozzle design which was developed to produce an accurate sand flow rate and proper shape of sand curtain for test procedures. The nozzle may be of any convenient length that will allow for connection to the sand hopper using plastic tubing. In new nozzles, the rate of sand flow is adjusted by grinding the orifice of the nozzle to increase the width of the opening to develop a sand flow rate of 300 to 400 g/min. During use, the nozzle opening must be positioned as close to the junction of the test specimen and the rubber wheel as the design will allow. (See Fig. 8.)

6.4.1 Any convenient material of construction that is available as welded or seamless pipe may be used for the construction of the fabricated nozzle. Stainless steel is preferred because of its corrosion resistance and ease of welding. Copper and steel are also used successfully.

6.4.2 *Formed Nozzle*—Nozzles formed from tubing may be used only when they duplicate the size and shape (rectangular orifice and taper), and the sand flow characteristics

[9] Original users of this test method fabricated their own apparatus. Commercially available machines are available from the following manufacturers of abrasion testing equipment: Falex Corp., 2055 Comprehensive Dr., Aurora, IL 60505 and Fisher Foundry Systems Co., 407 Hadley St., P.O. Box 40, Holly, MI 48442.

[10] Available from Ottawa Silica Co., P.O. Box 577, Ottawa, IL 61350.

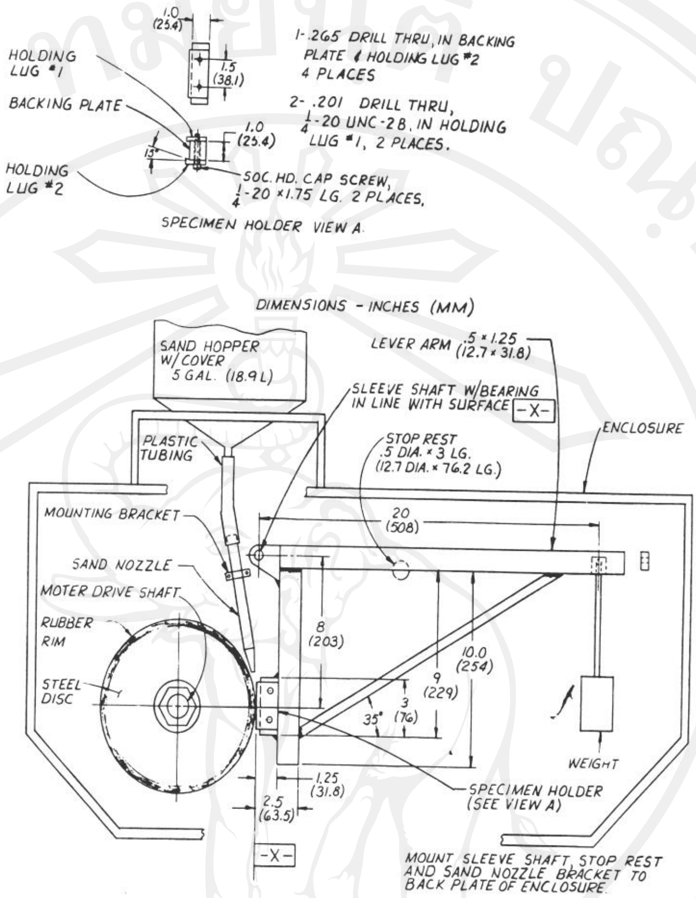



FIG. 2 Dry Sand/Rubber Wheel Abrasion Test Apparatus

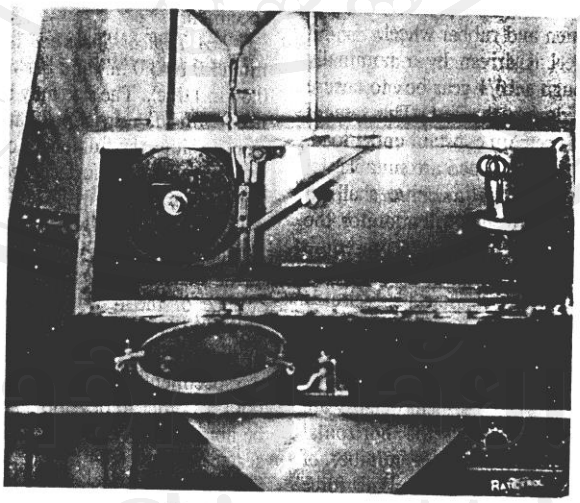


FIG. 3 Wheel and Lever Arm

(flow rate and streamlined flow) of the fabricated nozzle. (See Figs. 6 and 9.)

6.4.3 *Sand Flow*—The nozzle must produce a sand flow rate of 300 to 400 g/min (0.66 to 0.88 lb/min).

6.4.4 *Sand Curtain*—Figure 9 shows the proper streamlined flow and the narrow shape of the sand curtain as it exits

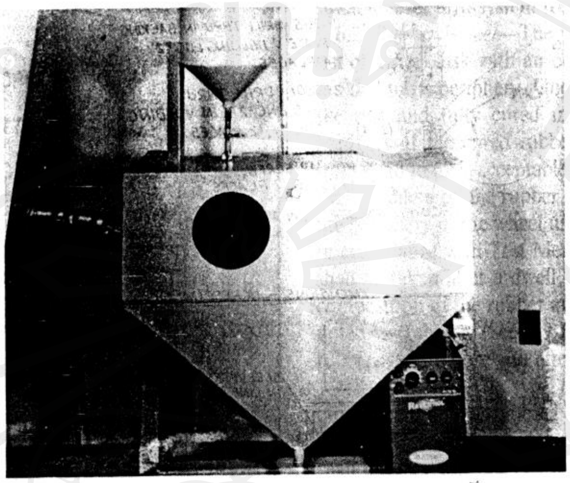


FIG. 4 Enclosure Frame

**TABLE 1 Formula for Chlorobutyl Rubber[A]**

NOTE—Specific gravity of mix: 1.15. Pressure cure: 20 min at 160°C (320°F).

| Materials | Proportions by Weight |
|---|---|
| Chlorobutyl No. HT 10-66 (Enjay Chem.) | 100 |
| Agerite Staylite-S | 1 |
| HAF black | 60 |
| Circolight oil | 5 |
| Stearic acid | 1 |
| Zinc oxide | 5 |
| Ledate | 2 |

[A] Available from Woodlawn Rubber Co., 6130 Interstate Circle, Cincinnati, OH 05242.

from the sand nozzle. A turbulent sand flow as depicted in Fig. 10 will tend to produce low and inconsistent test results. It is intended that the sand flows in a streamlined manner and passes between the specimen and rubber wheel.

6.5 *Motor Drive*—The wheel is driven by a nominally 0.7-kW (1-hp) d-c motor through a 10/1 gear box to ensure that full torque is delivered during the test. The rate of revolution (200 ± 10 rpm) must remain constant under load. Other drives producing 200 rpm under load are suitable.

6.6 *Wheel Revolution Counter*—The machine shall be equipped with a revolution counter that will monitor the number of wheel revolutions as specified in the procedure (Section 9). It is recommended that the incremental counter have the ability to shut off the machine after a preselected number of wheel revolutions or increments up to 12 000 revolutions is attained.

6.7 *Specimen Holder and Lever Arm*—The specimen holder is attached to the lever arm to which weights are added, so that a force is applied along the horizontal diametral line of the wheel. An appropriate number of weights must be available to apply the appropriate force (Table 2) between the test specimen and the wheel. The actual weight required should not be calculated, but rather should be determined by direct measurement by noting the load required to pull the specimen holder away from the wheel. A convenient weight system is a can filled with sand (see Fig. 2).

6.8 *Analytical Balance*—The balance used to measure the loss in mass of the test specimen shall have a sensitivity of 0.001 g. Procedure C requires a sensitivity of 0.0001 g.

6.9 *Enclosure, Frame, and Abrasive Hopper*—Figures 3 and 4 are photographs of a typical test apparatus. The size and shape of the support elements, enclosure, and hopper may be varied according to the user's needs.

## 7. Specimen Preparation and Sampling

7.1 *Materials*—It is the intent of this test method to allow for the abrasion testing of any material form, including wrought metals, castings, forgings, gas or electric weld overlays, plasma spray deposits, powder metals, metallizing, electroplates, cer- mets, ceramics etc. The type of material will, to some extent, determine the overall size of the test specimen.

7.2 *A Typical Specimen* is a rectangular shape 25 by 76 mm (1.0 by 3.0 in.) and between 3.2 and 12.7 mm (0.12 and 0.50 in.) thick. The size may be varied according to the user's need with the restriction that the length and width be sufficient to show the full length of the wear scar as developed by the test. The test surface should be flat within 0.125 mm (0.005 in.) maximum.

7.3 *Wrought, Cast, and Forged Metal*—Specimens may be machined to size directly from the raw material.

7.4 *Electric or Gas Weld Deposits* are applied to one flat surface of the test piece. Double-weld passes are recommended to prevent weld dilution by the base metal. The heat of welding may distort the test specimen. When this occurs, the specimen may be mechanically straightened or ground or both. In order to develop a suitable wear scar, the surface to be abraded must be ground flat to produce a smooth, level surface at least 63.4 mm (2.50 in.) long and 19.1 mm (0.75 in.) for the test. (See 7.5.) Note that the welder technique, heat input of welds, and the flame adjustment of gas welds will have an effect on the abrasion resistance of a weld deposit.

7.5 *Finish*—Test specimens should be smooth, flat, and free of scale. Surface defects such as porosity and roughness may bias the test results, and such specimens should be avoided unless the surface itself is under investigation. Typical

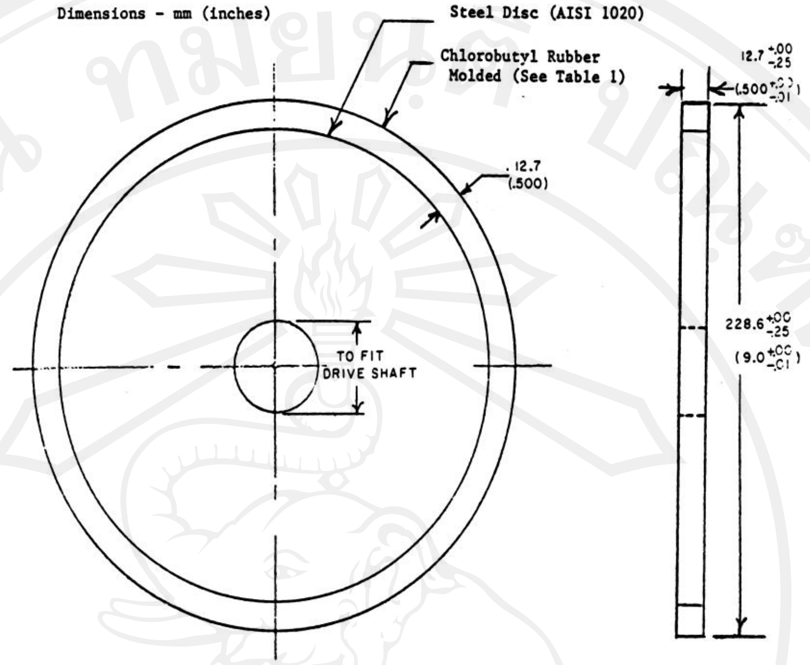



FIG. 5 Rubber Wheel

suitable surfaces are mill-rolled surfaces such as are present on cold-rolled steel, electroplated and similar deposits, ground surfaces, and finely machined or milled surfaces. A ground surface finish of approximately 0.8 μm (32 μin.) or less is acceptable. The type of surface or surface preparation shall be stated in the data sheet.

**8. Test Parameters**

8.1 Table 2 indicates the force applied against the test specimen and the number of wheel revolutions for test Procedures A through D.

8.2 *Sand Flow*—The rate of sand flow shall be 300 to 400 g/min (0.66 to 0.88 lb/min).

8.3 *Time*—The time of the test will be about 30 min for Procedures A and D, 10 min for Procedure B, and 30 s for Procedure C, depending upon the actual wheel speed. In all cases the number of wheel revolutions and not the time shall be the controlling parameter.

8.4 *Lineal Abrasion*—Table 2 shows the lineal distance of scratching abrasion developed using a 228.6-mm (9-in.) diameter wheel rotating for the specified number of revolutions. As the rubber wheel reduces in diameter the number of wheel revolutions shall be adjusted to equal the sliding distance of a new wheel (Table 2) or the reduced abrasion rate shall be taken into account by adjusting the volume loss produced by the worn wheel to the normalized volume loss of a new wheel. (See 10.2.)

**9. Procedure**

9.1 *Cleaning*—Immediately prior to weighing, clean the specimen with a solvent or cleaner and dry. Take care to remove all dirt or foreign matter or both from the specimen. Dry materials with open grains (some powder metals or ceramics) to remove all traces of the cleaning solvent, which may have been entrapped in the material. Steel specimens having residual magnetism should be demagnetized or not used.

9.2 Weigh the specimen to the nearest 0.001 g (0.0001 g for Procedure C).

9.3 Seat the specimen securely in the holder and add the proper weights to the lever arm to develop the proper force pressing the specimen against the wheel. This may be measured accurately by means of a spring scale which is hooked around the specimen and pulled back to lift the specimen away from the wheel. A wedge should be placed under the lever arm so that the specimen is held away from the wheel prior to start of test. (See Fig. 2.)

9.4 Set the revolution counter to the prescribed number of wheel revolutions.

9.5 *Sand Flow and Sand Curtain*—The rate of sand flow through the nozzles shall be between 300 g (0.66 lb)/min and 400 g (0.88 lb)/min. Do not start the wheel rotation until the proper uniform curtain of sand has been established (see Fig. 9 and Note 3).

9.5.1 The dwell time between tests shall be the time required for the temperature of the rubber wheel to return to room temperature. For Procedure B the dwell time shall be at least 30 min.

9.6 Start the wheel rotation and immediately lower the lever arm carefully to allow the specimen to contact the wheel.

9.7 When the test has run the desired number of wheel revolutions, lift the specimen away from the wheel and stop the sand flow and wheel rotation. The sand flow rate should

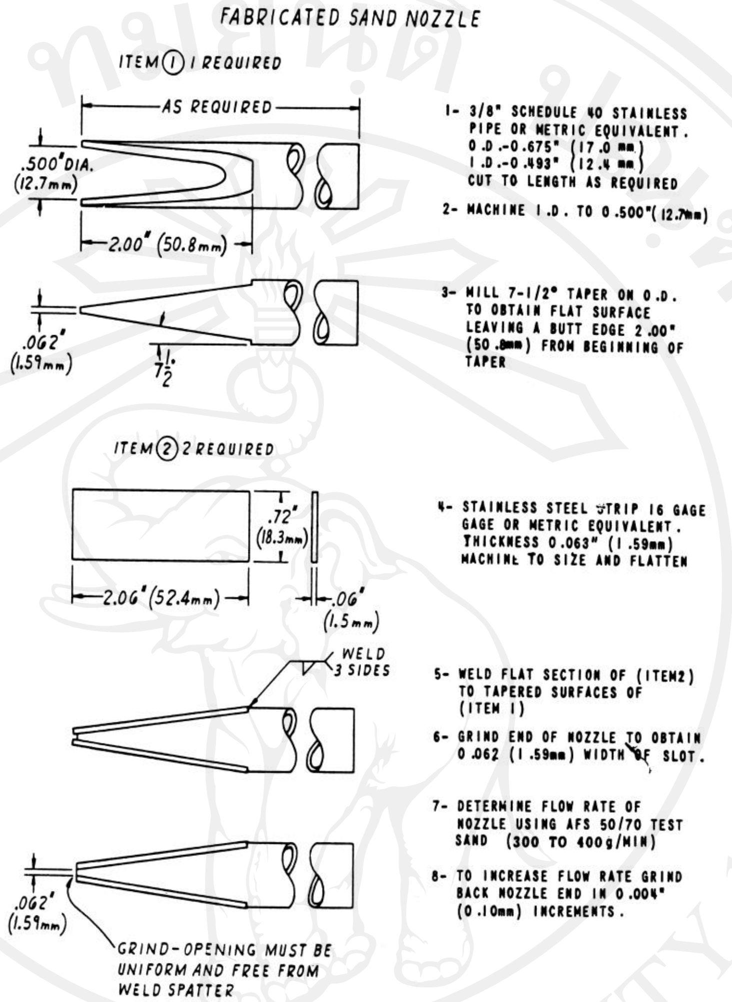



**FIG. 6 Sand Nozzle**

be measured before and after a test, unless a consistent flow rate has been established.

9.8 Remove the specimen and reweigh to the nearest 0.001 g (0.0001 g for Procedure C).

9.8.1 *Wear Scar*—Observe the wear scar and compare it to the photographs of uniform and nonuniform wear scars in Fig. 11. A nonuniform pattern indicates improper alignment of the rubber rim to the test specimen or an unevenly worn rubber wheel. This condition may reduce the accuracy of the test.

9.9 *Preparation and Care of Rubber Wheels*—Dress the periphery of all new rubber wheels and make concentric to the bore of the steel disk upon which the rubber is mounted. The concentricity of the rim shall be within 0.05 mm (0.002 in.) total indicator reading on the diameter. Follow the same dressing procedure on used wheels that develop grooves or that wear unevenly so as to develop trapezoidal or uneven wear scars on the test specimen (Fig. 11). The intent is to produce a uniform surface that will run tangent to the test specimen without causing vibration or hopping of the lever arm. The wear scars shall be rectangular in shape and of uniform depth at any section across the width. The rubber wheel may be used until the diameter wears to 215.9 mm (8.50 in.). New rubber rims may be mounted on steel disks by the qualified source (6.2).

9.10 *Wheel Dressing Procedure*—The preferred dressing procedure for the periphery of the rubber rim is to mount a diamond-cut file[11] in place of the specimen in the holder and run the machine with load until the wheel is clean. Another dressing procedure for the periphery of the rubber rim is to mount the wheel on a lathe, and machine the surface with a tool bit especially ground for rubber applications. Grind a carbide or high-speed steel tool bit to very deep rake angles (Fig. 12). Feed the tool across the rubber surface in the opposite direc- tion from that normally used for machining steel. This allows the angular surface of the tool bit to shear away thin layers of rubber without

[11] Available from the Falex Corp., 2055 Comprehensive Drive, Aurora, IL 60501.

FIG. 7 25X Magnification AFS 50/70 Test Sand Ottawa Silica Co.

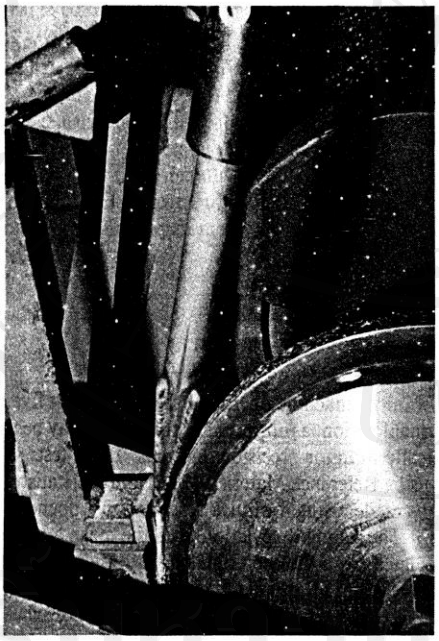


FIG. 8 Position of Sand Nozzle

tearing or forming grooves in the rubber as would occur when using the pointed edges of the tool. The recommended machining parameters are: *Feed*—25 mm/min (1.0 in./min); *Speed*—200 rpm; *Depth of Cut*—0.254 mm (0.010 in.) to 0.762 mm (0.030 in.). The dressed wheel should be first used on a soft carbon steel test specimen (AISI 1020 or equivalent) using Procedure A. This results in a smooth, uniform non-sticky surface. An alternative dressing method involves the use of a high-speed grinder on the tool post of a lathe. Take great care since grinding often tends to overheat and smear the rubber, leaving a sticky surface. Such a surface will pick up and hold sand particles during testing. If the grinding method is used, not more than 0.05 mm (0.002 in.) may be ground from the surface at one time so as to prevent overheating.

## 10. Calculating and Reporting Results

10.1 The abrasion test results should be reported as volume loss in cubic millimetres in accordance with the specified procedure used in the test. For example, ___mm³ per ASTM___ Procedure ___. While mass loss results may be used internally in test laboratories to compare materials of equivalent densities, it is essential that all users of this test procedure report their results uniformly as volume loss in publications or reports so that there is no confusion caused by variations in density. Convert mass loss to volume loss as follows:

$$\text{Volume loss, mm}^3 = \frac{\text{mass loss (g)}}{\text{density (g/cm}^3)} \times 1000$$

10.2 *Adjusting the Volume Loss*—As the rubber wheel decreases in diameter the amount of scratching abrasion developed in a given practice will be reduced accordingly. The actual volume loss produced by these slightly smaller wheels will, therefore, be inaccurate. The "adjusted volume loss" value takes this into account and indicates the actual abrasion rate that would be produced by a 228.6-mm (9.00-in.) diameter wheel. Calculate the adjusted volume loss (AVL) as follows:

$$\text{AVL} = \text{measured volume loss} \times \frac{\text{228.6 mm (9.00 in.)}}{\text{wheel diameter after use}}$$

10.3 *Reporting Test Results*—All significant test parameters and test data as noted in Tables 2 and 3 shall be reported. Any variation from the recommended procedure must be noted in the comments. The report shall include a statement of the current precision and accuracy of the test apparatus as qualified by the testing of Reference Materials (11.6). The volume loss data developed by the initial qualification tests (11.4) or the volume loss data developed by the periodic re-qualification tests (11.4.3) should be listed on the data sheet (Table 3).

## 11. Precision and Bias

11.1 The precision and bias of the measurements obtained with this test method will depend upon strict adherence to the stated test parameters and maintenance of the proper sand flow rate and sand curtain throughout the duration of the test.

11.2 The degree 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.

11.3 Normal variations in the abrasive, rubber wheel characteristics, and procedure will tend to reduce the accuracy of the test method as compared to the accuracy of such material property tests as hardness or density. Properly conducted tests will, however, maintain a 5 % or less

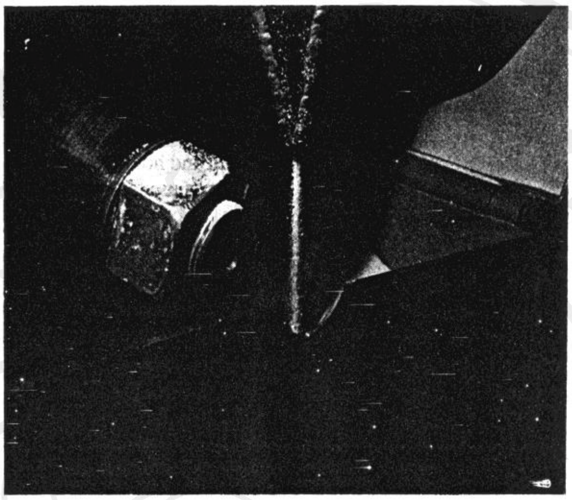


FIG. 9 Sand Flow—Streamlined

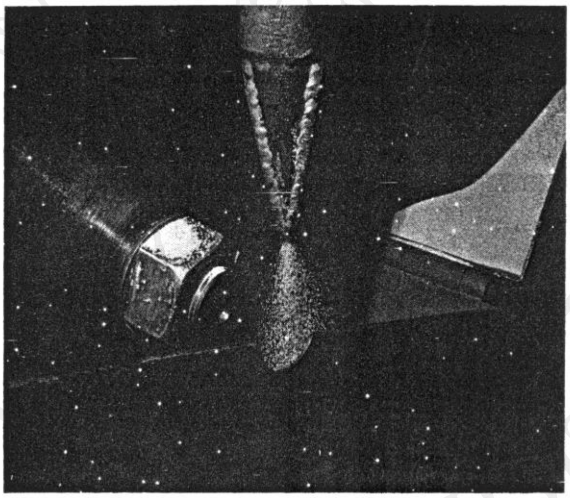


FIG. 10 Sand Flow—Turbulence

TABLE 2 Test Parameters

| Specified Procedure | Force Against Specimen[A] N (lb) | Wheel Revolutions | Lineal Abrasion[B] m | (ft) |
|---|---|---|---|---|
| A | 130 (30) | 6000 | 4309 | (14 138) |
| B | 130 (30) | 2000 | 1436 | (4 711) |
| C | 130 (30) | 100 | 71.8 | (236) |
| D | 45 (10.1) | 6000 | 4309 | (14 138) |

[A] Force tolerance is ±3 %.
[B] See 8.4.
N = Newton (SI metric term for force)
1 lbf = 4.44822 N
1 Kgf = 9.806650 N

coefficient of variation of volume loss values which will characterize the abrasive resistance of materials (see Appendix X1).

11.4 *Initial Machine Operation and Qualification*—The number of tests to establish precision and bias of the apparatus for initial machine operation shall be at least five. After initial qualification, a minimum of three tests may be used to periodically monitor precision and bias. These tests shall be made, using Reference Materials (11.6) and the statistical calculations made, using formulas described in Appendix X1.4.

11.4.1 The standard deviation from the mean average shall be calculated from the accumulated test results and reduced to the coefficient of variation in accordance with Appendix X1. The coefficient of variation shall not exceed 7 % in materials of the 20 to 60-mm$^3$, volume loss range. If this value is exceeded, the machine operation shall be considered out of control and steps taken to eliminate erratic results.

11.4.2 In any test series all data must be considered in the calculation including outliers (data exceeding the obvious range). For example, an exceedingly high or low volume loss must not be disregarded except in the case of observed faulty machine operation.

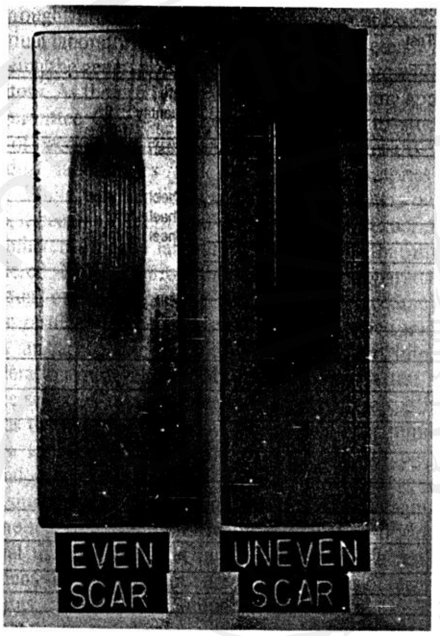



**FIG. 11 Typical Wear Scars Uneven and Nonuniform Wear Scars Indicate Improper Alignment or Wear of Rubber Wheel**

11.4.3 *Re-Qualification of Apparatus*—After the test apparatus has been initially qualified, it is required that one or more standard reference materials be periodically tested to ensure the accuracy of the data generated by the apparatus. This is particularly necessary when new test operators are involved or when the apparatus is not used on a regular basis. Re-qualification is also required for interlaboratory testing and for the qualification of materials as specified in customer and vendor contracts.

11.5 While two or more laboratories may develop test data that is within the acceptable coefficient of variation for their own individual test apparatus, their actual averages may be relatively far apart. The selection of sample size and the method for establishing the significance of the difference in averages shall be agreed upon between laboratories and shall be based on established statistical methods in Practices E 122, E 177, and STP 15D.[12]

11.6 *Reference Materials*—Reference materials[13] may be used for periodic monitoring of the test apparatus and procedures in individual laboratories.

11.6.1 While any of the four test procedures (Table 2) may be used on reference materials, it is recommended that Procedure A be used for the more abrasion-resistant materials such as AISI D-2 Tool Steel. When Procedure A volume loss values exceed 100 $mm^3$ in materials such as annealed low-carbon steel, greater accuracy in material ranking can be obtained by using Procedures B or D.

11.6.2 *Two Types of Reference Materials:*

11.6.2.1 *AISI D-2 Tool Steel (Nonfree Machining Type)*—This is Reference Material No. 1 for Procedure A.[14]

(*a*) Harden 1010°C (1850°F)—25 min at temperature.

(*b*) Air cool to room temperature.

(*c*) Temper at 205°C (400°F)—1 h at temperature.

(*d*) Air Cool Hardness 59–60 HRC.

(*e*) Procedure A, qualifying volume loss range—36 ± 3 $mm^3$.

11.6.2.2 *AISI H-13 Tool Steel*—This is Reference Material No. 2 for Procedure B.[15]

[12] *Manual on Presentation of Data and Control Chart Analysis, ASTM STP 15D*, Am. Soc. Testing Mats., 1976.

[13] Contact the Office of Standard Reference Materials, National Bureau of Standards, Washington, DC 20234, or ASTM Headquarters.

[14] For information on D-2 Tool Steel, Standard Reference Material No. 1857, contact the Office of Standard Reference Materials, Bill Chemistry Bldg., National Bureau of Standards, Washington, DC 20234.

[15] For information on H-13 Tool Steel contact ASTM Headquarters, Subcommittee G02.30.

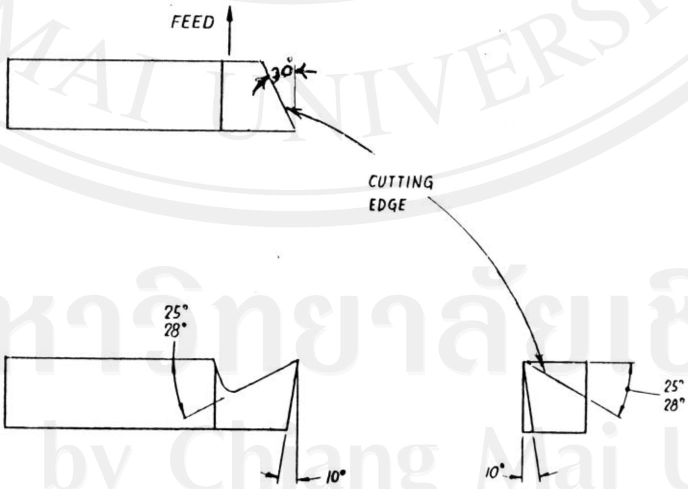



**FIG. 12 Typical Wheel Dressing Tool**

TABLE 3 Data Sheet

Dry Sand/Rubber Wheel Test
ASTM G-65 Procedure ____

Qualification of Apparatus (11.4): Date ____
Reference Materials ____ Quantity ____
Adjusted Volume Loss (avg) ____ mm³ Coefficient of Variation ____ %

Test Data

Material Description: ____ Wheel diameter: ____
Heat Treatment: ____ Wheel width: ____
Hardness: ____ Wheel hardness: ____
Surface Preparation ____

| | | | | | | |
|---|---|---|---|---|---|---|
| Test No. | | | | | | |
| Test load | | | | | | |
| Wheel revolutions | | | | | | |
| Sand flow, g/min | | | | | | |
| Initial mass, g | | | | | | |
| Final mass, g | | | | | | |
| Mass loss, g | | | | | | |
| Density, $g/cm^3$ [A] | | | | | | |
| Volume loss, $mm^3$ (mass loss/density) × 1000 | | | | | | |
| Adjusted volume loss, $mm^3$ | | | | | | |

Comments: ____

Company Name ____ Tested by ____ Date ____

[A] Density of materials may be obtained from *ASM Metals Handbook*, Vol 1, 8th ed. or suppliers of materials.

(*a*) Harden 1010/1024°C (1850/1875°F) in neutral salt bath 25 min at temperature.

(*b*) Air cool to room temperature.

(*c*) Double temper at 593°C (1100°F) for 2 h and 2 h. Air cool between tempers. Hardness 47–48 HRC.

(*d*) Procedure B, qualifying volume loss range—56.5 ± 4 $mm^3$.

11.6.3 Volume loss values for reference materials are developed in round-robin testing by the Abrasive Wear Task Group of ASTM Subcommittee G02.30.[16] (See Appendix X1.6 for typical volume loss values of other materials.) It is the intent of Subcommittee G02.30 to develop several reference materials for abrasive wear testing.

[16] Supporting data available from ASTM Headquarters. Request RR: G2-1004.

## REFERENCES


**(1)** Avery, H. S., "The Nature of Abrasive Wear," *SAE Preprint 750822*, Society of Automotive Engineers, Warrendale, PA, 1975.

**(2)** Tucker, R. C., and Miller, A. E., *Low Stress Abrasive and Adhesive Wear Testing, ASTM STP 615*, Philadelphia, PA, 1975, pp. 68–90.

**(3)** Avery, H. S., "The Measurement of Wear Resistance," *Wear*, Vol 4, No. 6, November/December 1961, pp. 427–449.

**(4)** "Report of Iron and Steel Technical Committee," *Abrasive Wear*, J965, Society of Automotive Engineers, 1966.

**(5)** Borik, F., "Rubber Wheel Abrasion Test," *SAE Preprint 700687*, Society of Automotive Engineers, 1970.

**(6)** Avery, H. S., "Classification and Precision of Abrasion Tests," *Source Book on Wear Control Technology*, American Society for Metals, Metals Park, OH, 1978.

**(7)** Haworth, R. D., Jr., "The Abrasion Resistance of Metals," *Transactions American Society for Metals*, Vol 41, 1949, pp. 819–854.


## APPENDIX

**(Nonmandatory Information)**

## X1. SOME STATISTICAL CONSIDERATIONS IN ABRASION TESTING

### X1.1 Background

X1.1.1 The Dry Sand/Rubber and Wheel Abrasion Test as developed and described by Haworth, Avery, and others **(1)** through **(7)** has been in various stages of evolution and use over the last two or more decades. A number of variations of this test procedure have been used by several research and industrial laboratories in the United States who were faced with the problem of evaluating hard surfacing alloys, castings, and wrought products for their resistance to abrasive wear. Individual laboratories set their own test parameters with the goal being the generation of reproducible test data within the laboratory. As the need for standardization became apparent, Subcommittee G02.30 formed a task group to study the effect of each test parameter on the overall results within individual laboratories and among all laboratories as a group. While standardization of test parameters was attained, it became evident that the variability or experimental error inherent in each laboratory was a factor that must be considered. Not only must the test method, apparatus, and individual operator generate correct results (accuracy) but the test results must be consistently reproducible (precision) within an acceptable narrow range. Another important consideration in developing accurate and precise test results was the selection of adequate sample size. More specifically this was the need for laboratories to agree on the number of times a test should be repeated on a given homogeneous material in order to obtain a meaningful average result. While single test results and simple arithmetic averaging may in some few cases be useful in individual laboratories, it is essential that statistical techniques and multiple testing of specimens be utilized for the qualification of each test apparatus, and for the comparison of materials. Further information on statistical methods may be found in Recommended Practice E 122, STP 15D, and in the references.

**X1.2 Statistical Equations**

X1.2.1 Several equations for the calculation of optimum sample size, standard deviation, and coefficient of variation are used in the statistical analysis of data. To ensure uniformity among laboratories using the Dry Sand/Rubber Wheel Test, the standard deviation and coefficient of variation of results produced from a series of tests shall be calculated by the following equations:

$$s = \text{standard deviation (small sample size, 2 to 10)} = R/d_2 \quad (1)$$

$$s = \text{standard deviation (any sample size)} = \sqrt{\Sigma(x - \bar{x})^2/n - 1} \quad (2)$$

$$V = \text{\% coefficient of variation} = (s/\bar{x}) \times 100 \quad (3)$$

$$n = \text{sample size (95 \% confidence level)} = (1.96\ V/e)^2 \quad (4)$$

where:

$s$ = standard deviation from the mean,
$V$ = variability of the test procedure, %,
$x$ = value of each test result (volume loss in $mm^3$),
$\bar{x}$ = mean or arithmetic average for $n$ tests,
$\Sigma x$ = sum total of all test values,
$n$ = number of tests or observations,
$e$ = allowable sampling error, %,
$R$ = difference between the highest and lowest test value, and
$d_2$ = deviation factor, which varies with sample size (see Table X1.1).

**TABLE X1.1 Factors for Estimating Standard Deviation from the Range on the Basis of Sample Size**

| Sample Size ($n$) | $d_2$ | $1/d_2$ |
|---|---|---|
| 2 | 1.128 | 0.8865 |
| 3 | 1.693 | 0.5907 |
| 4 | 2.059 | 0.4857 |
| 5 | 2.326 | 0.4299 |
| 6 | 2.534 | 0.3946 |
| 7 | 2.704 | 0.3698 |
| 8 | 2.847 | 0.3512 |
| 9 | 2.970 | 0.3367 |
| 10 | 3.078 | 0.3249 |

**X1.3 Use of Statistical Methods**

X1.3.1 In evaluating the precision and accuracy of any test procedure, new users must deal with the concepts of mean averages, standard deviation from the mean, variability of test results, range of results, allowable sampling error, and particularly the effect of sample size. While it is obvious that a large number of tests on the same material is desirable and will yield a high confidence level in evaluating test results, many abrasion test evaluations are made on a small number of samples. This is due to the fact that in much abrasion work, large number of test specimens are just not available. In addition to this a new user is concerned with evaluating the accuracy of his first few (2 or 3) test results during the initial test campaign which certainly should not inspire much confidence because of the small number of tests. However, even with this admittedly small sample size the user may calculate the variability of results, which may give a general indication of precision of the apparatus and test method (see X1.4). As more data are accumulated from the same homogeneous material and new data are accumulated from different materials, the accumulated variability values may be averaged to provide a better estimate of the precision of the apparatus and procedure.

**X1.4 Small Sample Size (2 to 10)**

X1.4.1 In statistical analysis the estimated standard deviations of large sample sizes (over 10) are derived from the square root of the mean square of deviations from the average. A typical user of this test procedure will more likely start out with less than 10 test results. In these cases the standard deviation ($s$) is more efficiently derived from the range ($R$) of the sample observation than from the root mean square. For such samples the standard deviation is obtained by multiplying the range of available observations (the difference between the highest and the lowest numerical value) by a deviation factor (Eq 1) that varies with the sample size. Once the standard deviation is obtained, the percent coefficient of variation is attained by dividing the standard deviation by the average test value $\bar{x}$ and multiplying by 100. The deviation factor is obtained from Table X1.1.

X1.4.2 *Example 1*—This example shows a typical analysis for standard deviation and coefficient of variation of three abrasion tests (Procedure A) made upon hardened tool steel. These data as well as subsequent data shown in other examples are taken from actual round-robin test data obtained in the early stages of the standardization of the test procedure.

Number of tests ($n$) = 3
Volume loss data ($x$) = 44.6 $mm^3$, 39.9 $mm^3$, 32.6 $mm^3$
Average of volume loss ($\bar{x}$) = 39.03
Range of test = 12.0

$$\text{Standard deviation } (S) = R/d_2 = 12/1.693 = 7.09 \quad (1)$$

$$\text{Coefficient of variation } (v) = (s/\bar{x}) \times 100 = (7.09/39.03) \times 100 = 18.17 \quad (3)$$

Note that the 18.17 % variation is well above the acceptable 7 % maximum as indicated in 11.3.1 of the standard. It is obvious that this particular test apparatus or procedure was

TABLE X1.2 Minimum Acceptable Sample Size (n) for 95 % Confidence

| v | Allowable Sampling Error (e) 1 % | 2 % | 3 % | 4 % | 5 % | 6 % | 7 % | 8 % | 10 % |
|---|---|---|---|---|---|---|---|---|---|
| Coefficient of Variation, % | | | | | | | | | |
| 1 | 4 | 1 | ... | ... | ... | ... | ... | ... | ... |
| 2 | 16 | 4 | 2 | 1 | ... | ... | ... | ... | ... |
| 3 | 35 | 9 | 4 | 3 | 2 | 1 | ... | ... | ... |
| 4 | 62 | 16 | 7 | 4 | 3 | 2 | 2 | ... | ... |
| 5 | 96 | 24 | 11 | 6 | 4 | 3 | 2 | 2 | 1 |
| 6 | ... | 35 | 16 | 9 | 6 | 4 | 3 | 2 | 2 |
| 7 | ... | 47 | 21 | 12 | 8 | 6 | 4 | 3 | 2 |
| 8 | ... | 62 | 28 | 16 | 10 | 7 | 5 | 4 | 3 |
| 9 | ... | 78 | 35 | 20 | 13 | 9 | 7 | 5 | 4 |
| 10 | ... | 96 | 43 | 24 | 16 | 11 | 8 | 6 | 4 |

TABLE X1.3 Volume Loss Range

| Material | Standard Values Practice A, mm³ | Practice B, mm³ | Practice D, mm³ |
|---|---|---|---|
| 1. AISI tool steel D-2 reference material No. 1[A] | 36 ± 3 | ... | ... |
| 2. AISI tool steel H-13 reference material No. 2[A] | ... | 56.5 ± 4 | ... |
| | Non-Standard Values | | |
| a. 316 stainless bar annealed RB-80 | 260 ± 20 | ... | 78 ± 8 |
| b. AISI 1090 plate-normalized 900°C (1600°F) air-cooled 24-26 HRC | 80 ± 8 | ... | 29 ± 4 |
| c. 17-4PH stainless-aged 500°C (925°F)-4 h at temperature, air-cooled-43 HRC | 225 ± 20 | ... | 66 ± 5 |
| d. Stellite 1016 hard surfacing overlay-57-58 HRC applied by oxyacetylene welding process (3S flame) | 21 ± 4 | ... | ... |
| e. Sintered tungsten carbide (Kennametal K-714, Valenite 2889) | 1.5 ± 1 | ... | ... |

[A] See 11.6.2 for heat treat.

out of control. The cause was found to be inconsistent sand flow rates which were corrected in subsequent tests.

## X1.5 Large Sample Size (10 or over)

X1.5.1 *Example 2*—This example shows the analysis for the coefficient of variation of ten abrasion tests (Procedure A) made upon hardened D-2 tool steel. The standard deviation was calculated from Eq 1 and the test data were set down in the following format:

| Test Number | $x$ | $x - \bar{x}$ | $(x - \bar{x})^2$ |
|---|---|---|---|
| 1 | 40.8 | 1.74 | 7.5076 |
| 2 | 36.9 | −1.16 | 1.3455 |
| 3 | 38.5 | 0.44 | 0.1936 |
| 4 | 39.4 | 1.34 | 1.7956 |
| 5 | 38.2 | 0.14 | 0.0196 |
| 6 | 36.4 | −1.66 | 2.7556 |
| 7 | 41.3 | 3.24 | 10.4976 |
| 8 | 35.8 | −2.26 | 5.1076 |
| 9 | 36.9 | −1.15 | 1.3456 |
| 10 | 36.4 | −1.66 | 2.7556 |
| | $\bar{x} = 38.06$ | | $33.3239 = (x - \bar{x})^2$ |

$$s = \sqrt{\Sigma(x - \bar{x})^2/n - 1} = 33.3239/9 = 1.924 \qquad (2)$$
$$V = (s/\bar{x}) \times 100 = (1.92/38.06) \times 100 = 5.06\ \%$$

In this particular test series the 5.06 % coefficient of variation indicated the test procedure was under satisfactory control. Subsequent modification of the sand nozzle to develop more uniform sand flow resulted in even greater precision.

X1.5.2 *Example 3*—In still another test series one apparatus developed very precise results with a coefficient of variation of 4.3 %, which is well within the acceptable value. This indicated that the apparatus was producing consistent results. The volume loss values, however, were not accurate and were significantly below the volume loss limits for hardened D-2 tool steel as shown in Table X1.3 of the test method ($34 \pm 3$ mm$^3$). The cause was found to be in the design of the sand nozzle and was corrected by fabricating a nozzle with accurate dimensions and streamlined sand flow.

## X1.6 Estimated Sample Size and Allowable Sampling Error

X1.6.1 As indicated previously the availability of multiple test specimens in abrasion testing is sometimes limited. When this occurs the user must have some criterion upon which to judge the minimum acceptable sample size for meaningful results. Recommended Practice E 122 describes the choice of sample size to estimate the average quality of a lot or process. The following equation takes into account the allowable sampling error and the inherent variability or experimental error of the test method (coefficient of variation).

$$n = (1.96\ v/e)^2 \qquad (4)$$

Table X1.2 is based upon this equation. It indicates a 5 % probability that the difference between the sample estimate of the mean value $\bar{x}$, and that obtainable from averaging all values from a very high number of tests, will exceed the allowable sampling error ($e$). This corresponds to a 95 % confidence level which is an appropriate criterion for abrasion tests. For example, if the coefficient of variation of the test apparatus as determined by multiple testing is 7 %, the minimum sample size would be 8 in order to obtain a 5 % allowable sampling error. Note, however, that if the test results for the 8 samples do not generate a coefficient of variation of 7 % or less the test is not valid and corrective action must be taken.

## X1.7 Typical Volume Loss Values

X1.7.1 Procedure A of the Dry Sand/Rubber Wheel Test will produce volume losses in metallic materials ranging from 0.25 to 250 mm$^3$. The more abrasion-resistant materials will develop the least volume loss. Table X1.3 shows typical volume loss ranges that may be expected in the metals listed. They are offered as guidelines only and not as purchasing specifications or as standard reference specimens. Any material specifications involving this test method must be by agreement between the seller and the purchaser. When volume losses exceed 100 $mm^3$, greater accuracy in material ranking is obtained by using Procedure D (see Table 2). Procedure A should be used for the more abrasion-resistant materials.

Designation: G 99 – 90[ε1]

# Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus[1]

This standard is issued under the fixed designation G 99; 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 (ε) indicates an editorial change since the last revision or reapproval.

ε1 NOTE—Figure 1(a) was added editorially in November 1990.

## 1. Scope

1.1 This test method describes a laboratory procedure for determining the wear of materials during sliding using a pin-on-disk apparatus. Materials are tested in pairs under nominally non-abrasive conditions. The principal areas of experimental attention in using this type of apparatus to measure wear are described. The coefficient of friction may also be determined.

1.2 The values stated in SI units are to be regarded as standard.

1.3 *This standard does not purport to address the safety problems 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:*

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[2]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[2]

E 178 Practice for Dealing with Outlying Observations[2]

G 40 Terminology Relating to Wear and Erosion[3]

## 3. Summary of Test Method

3.1 For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk center. In either case, the sliding path is a circle on the disk surface. The plane of the disk may be oriented either horizontally or vertically.

NOTE 1—Wear results may differ for different orientations.

3.1.1 The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. Other loading methods have been used, such as, hydraulic or pneumatic

NOTE 2—Wear results may differ for different loading methods.

3.2 Wear results are reported as volume loss in cubic millimetres for the pin and the disk separately. When two different materials are tested, it is recommended that each material be tested in both the pin and disk positions.

3.3 The amount of wear is determined by measuring appropriate linear dimensions of both specimens before and after the test, or by weighing both specimens before and after the test. If linear measures of wear are used, the length change or shape change of the pin, and the depth or shape change of the disk wear track (in millimetres) are determined by any suitable metrological technique, such as electronic distance gaging or stylus profiling. Linear measures of wear are converted to wear volume (in cubic millimetres) by using appropriate geometric relations. Linear measures of wear are used frequently in practice since mass loss is often too small to measure precisely. If loss of mass is measured, the mass loss value is converted to volume loss (in cubic millimetres) using an appropriate value for the specimen density.

3.4 Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed. One set of test conditions that was used in an interlaboratory measurement series is given in Tables 1 and 2 as a guide. Other test conditions may be selected depending on the purpose of the test.

3.5 Wear results may in some cases be reported as plots of wear volume versus sliding distance using different specimens for different distances. Such plots may display non-linear relationships between wear volume and distance over certain portions of the total sliding distance, and linear relationships over other portions. Causes for such differing relationships include initial "break-in" processes, transitions between regions of different dominant wear mechanisms, etc. The extent of such non-linear periods depends on the details of the test system, materials, and test conditions.

3.6 It is not recommended that continuous wear depth data obtained from position-sensing gages be used because of the complicated effects of wear debris and transfer films present in the contact gap, and interferences from thermal expansion or contraction.

## 4. Significance and Use

4.1 The amount of wear in any system will, in general, depend upon the number of system factors such as the applied load, machine characteristics, sliding speed, sliding distance, the environment, and the material properties. The value of any wear test method lies in predicting the relative ranking of material combinations. Since the pin-on-disk test method does not attempt to duplicate all the conditions that

[1] 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.

Current edition approved April 27, 1990. Published June 1990.

[2] *Annual Book of ASTM Standards*, Vol 14.02.

[3] *Annual Book of ASTM Standards*, Vol 03.02.

TABLE 1 Characteristics of the Interlaboratory Wear Test Specimens

NOTE—See Note 4 in 10.3 for information.

| | Composition (weight %) | Microstructure | Hardness (HV 10) | Roughness[A] | |
|---|---|---|---|---|---|
| | | | | $R_z$ (mean) (µm) | $R_a$ (mean) (µm) |
| Steel ball (100 Cr6) (AISI 52 100)[B] Diameter 10 mm | 1.35 to 1.65 Cr<br>0.95 to 1.10 C<br>0.15 to 0.35 Si<br>0.25 to 0.45 Mn | martensitic with minor carbides and austenite | 838 ± 21 | 0.100 | 0.010 |
| Steel disc (100 Cr6) (AISI 52 100)[C] Diameter 40 mm | <0.030 P<br><0.030 S | martensitic with minor carbides and austenite | 852 ± 14 | 0.952 | 0.113 |
| Alumina ball[D] | 95 % $Al_2O_3$ (with additives of $TiO_2$, | equi-granular alpha alumina with very minor secondary | 1610 ± 101 (HV 0.2) | 1.369 | 0.123 |
| Alumina disc[D] | MgO and ZnO) | phases | 1599 ± 144 (HV 0.2) | 0.968 | 0.041 |

[A] Measured by stylus profilometry. $R_z$ is maximum peak-to-valley roughness. $R_a$ is arithmetic average roughness.
[B] Standard ball-bearing balls (SKF).
[C] Standard spacers for thrust bearings (INA).
[D] Manufactured by C.I.C.E.S.A.

TABLE 2 Results of the Interlaboratory Tests[A]

NOTE 1— See Note 4 in 10.3.
NOTE 2— Numbers in parentheses refer to all data received in the tests. In accordance with Practice E 178, outlier data values were identified in some cases and discarded, resulting in the numbers without parentheses. The differences are seen to be small.
NOTE 3—Values preceded by ± are one standard deviation.
NOTE 4—Between eleven and twenty laboratories provided these data.
NOTE 5—Calculated quantities (for example, wear volume) are given as mean values only.
NOTE 6—Values labeled "NM" were found to be smaller than the reproducible limit of measurement.

| Results (ball) (disk) | Specimen Pairs | | | |
|---|---|---|---|---|
| | Steel-steel | Alumina-steel | Steel-alumina | Alumina-alumina |
| Ball wear scar diameter (mm) | 2.11 ± 0.27<br>(2.11 ± 0.27) | NM | 2.08 ± 0.35<br>(2.03 ± 0.41) | 0.3 ± 0.06<br>(0.3 ± 0.06) |
| Ball wear volume ($10^{-3}$ $mm^3$) | 198<br>(198) | ... | 186<br>(169) | 0.08<br>(0.08) |
| Number of values | 102<br>(102) | ... | 60<br>(64) | 56<br>(59) |
| Disk wear scar width (mm) | NM | 0.64 ± 0.12<br>(0.64 ± 0.12) | NM | NM |
| Disk wear volume ($10^{-3}$ $mm^3$) | ... | 480<br>(480) | ... | ... |
| Number of values | ... | 60<br>(60) | ... | ... |
| Friction coefficient | 0.60 ± 0.11 | 0.76 ± 0.14 | 0.60 ± 0.12 | 0.41 ± 0.08 |
| Number of values | 109 | 75 | 64 | 76 |

[A] Test conditions: $F = 10$ $N$; $v = 0.1$ $ms^{-1}$, $T = 23°C$; relative humidity range 12 to 78 %; laboratory air; sliding distance 1000 m; materials: steel = AISI 52 100; and alumina = $\alpha$-$Al_2O_3$.

may be experienced in service (for example; lubrication, load, pressure, contact geometry, removal of wear debris, and presence of corrosive environment), there is no ensurance that the test will predict the wear rate of a given material under conditions differing from those in the test.

## 5. Apparatus

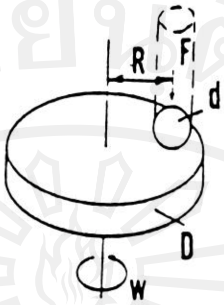
5.1 *General Description*—Figure 1 shows a schematic drawing of a typical pin-on-disk wear test system, and photographs of two differently designed apparatuses.[4] One type of typical system consists of a driven spindle and chuck for holding the revolving disk, a lever-arm device to hold the pin, and attachments to allow the pin specimen to be forced against the revolving disk specimen with a controlled load. Another type of system loads a pin revolving about the disk center against a stationary disk. In any case the wear track on the disk is a circle, involving multiple wear passes on the same track. The system may have a friction force measuring system, for example, a load cell, that allows the coefficient of friction to be determined.

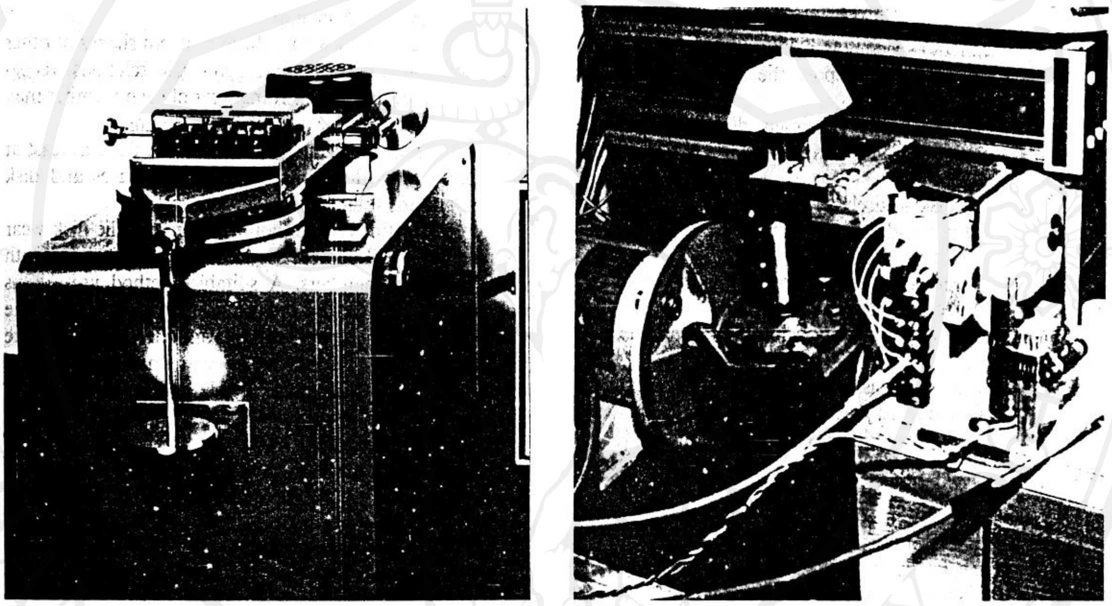
5.2 *Motor Drive*—A variable speed motor, capable of maintaining constant speed (±1 % of rated full load motor speed) under load is required. The motor should be mounted in such a manner that its vibration does not affect the test. Rotating speeds are typically in the range 0.3 to 3 rad/s (60 to 600 r/min).

5.3 *Revolution Counter*—The machine shall be equipped with a revolution counter or its equivalent that will record the number of disk revolutions, and preferably have the ability to shut off the machine after a pre-selected number of revolutions.

5.4 *Pin Specimen Holder and Lever Arm*—In one typical system, the stationary specimen holder is attached to a lever arm that has a pivot. Adding weights, as one option of loading, produces a test force proportional to the mass of the

[4] A number of other reported designs for pin-on-disk systems are given in "A Catalog of Friction and Wear Devices," American Society of Lubrication Engineers (1973). A commercially built machine is available from Falex Corporation, 2055 Comprehensive Drive, Aurora, IL 60505.



NOTE—*F* is the normal force on the pin, *d* is the pin or ball diameter, *D* is the disk diameter, *R* is the wear track radius, and *w* is the rotation velocity of the disk.

**FIG. 1 (*a*) Schematic of pin-on-disk wear test system. (*b*) Photographs of two different designs.**

weights applied. Ideally, the pivot of the arm should be located in the plane of the wearing contact to avoid extraneous loading forces due to the sliding friction. The pin holder and arm must be of substantial construction to reduce vibrational motion during the test.

5.5 *Wear Measuring Systems*—Instruments to obtain linear measures of wear should have a sensitivity of 2.5 μm or better. Any balance used to measure the mass loss of the test specimen shall have a sensitivity of 0.1 mg or better; in low wear situations greater sensitivity may be needed.

## 6. Test Specimens and Sample Preparation

6.1 *Materials*—This test method may be applied to a variety of materials. The only requirement is that specimens having the specified dimensions can be prepared and that they will withstand the stresses imposed during the test without failure or excessive flexure. The materials being tested shall be described by dimensions, surface finish, material type, form, composition, microstructure, processing treatments, and indentation hardness (if appropriate).

6.2 *Test Specimens*—The typical pin specimen is cylindrical or spherical in shape. Typical cylindrical or spherical pin specimen diameters range from 2 to 10 mm. The typical disk specimen diameters range from 30 to 100 mm and have a thickness in the range of 2 to 10 mm. Specimen dimensions used in an interlaboratory test with pin-on-disk systems are given in Table 1.

6.3 *Surface Finish*—A ground surface roughness of 0.8 μm (32 μin.) arithmetic average or less is usually recommended.

NOTE 3—Rough surfaces make wear scar measurement difficult.

6.3.1 Care must be taken in surface preparation to avoid subsurface damage that alters the material significantly. Special surface preparation may be appropriate for some test programs. State the type of surface and surface preparation in the report.

## 7. Test Parameters

7.1 *Load*—Values of the force in Newtons at the wearing contact.

7.2 *Speed*—The relative sliding speed between the contacting surfaces in metres per second.

7.3 *Distance*—The accumulated sliding distance in meters.

7.4 *Temperature*—The temperature of one or both specimens at locations close to the wearing contact.

7.5 *Atmosphere*—The atmosphere (laboratory air, relative humidity, argon, lubricant, etc.) surrounding the wearing contact.

## 8. Procedure

8.1 Immediately prior to testing, and prior to measuring or weighing, clean and dry the specimens. Take care to remove all dirt and foreign matter from the specimens. Use non-chlorinated, non-film-forming cleaning agents and solvents. Dry materials with open grains to remove all traces of the cleaning fluids that may be entrapped in the material. Steel (ferromagnetic) specimens having residual magnetism should be demagnetized. Report the methods used for cleaning.

8.2 Measure appropriate specimen dimensions to the nearest 2.5 μm or weigh the specimens to the nearest 0.0001 g.

8.3 Insert the disk securely in the holding device so that the disk is fixed perpendicular (±1°) to the axis of the resolution.

8.4 Insert the pin specimen securely in its holder and, if necessary, adjust so that the specimen is perpendicular (±1°) to the disk surface when in contact, in order to maintain the necessary contact conditions.

8.5 Add the proper mass to the system lever or bale to develop the selected force pressing the pin against the disk.

8.6 Start the motor and adjust the speed to the desired value while holding the pin specimen out of contact with the disk. Stop the motor.

8.7 Set the revolution counter (or equivalent) to the desired number of revolutions.

8.8 Begin the test with the specimens in contact under load. The test is stopped when the desired number of revolutions is achieved. Tests should not be interrupted or restarted.

8.9 Remove the specimens and clean off any loose wear debris. Note the existence of features on or near the wear scar such as: protrusions, displaced metal, discoloration, microcracking, or spotting.

8.10 Remeasure the specimen dimensions to the nearest 2.5 μm or reweigh the specimens to the nearest 0.0001 g, as appropriate.

8.11 Repeat the test with additional specimens to obtain sufficient data for statistically significant results.

## 9. Calculation and Reporting

9.1 The wear measurements should be reported as the volume loss in cubic millimetres for the pin and disk, separately.

9.1.1 Use the following equations for calculating volume losses when the pin has initially a spherical end shape of radius *R* and the disk is initially flat, under the conditions that only one of the two members wears significantly:

$$\text{pin (spherical end) volume loss, mm}^3 = \frac{\pi\,(\text{wear scar diameter, mm})^4}{64\,(\text{sphere radius, mm})} \quad (1)$$

assuming that there is *no significant disk wear.* This is an approximate geometric relation that is correct to 1 % for (wear scar diameter/sphere radius) < 0.3, and is correct to 5 % for (wear scar diameter/sphere radius) < 0.7. The exact equation is given in Appendix 1.

$$\text{disk volume loss, mm}^3 = \frac{\pi\,(\text{wear track radius, mm})(\text{track width, mm})^3}{6\,(\text{sphere radius, mm})} \quad (2)$$

assuming that there is *no significant pin wear.* This is an approximate geometric relation that is correct to 1 % for (wear track width/sphere radius) < 0.3, and is correct to 5 % for (wear track width/sphere radius) < 0.8. The exact equation is given in Appendix X1.

9.1.2 Calculation of wear volumes for pin shapes of other geometries use the appropriate geometric relations, recognizing that assumptions regarding wear of each member may be required to justify the assumed final geometry.

9.1.3 Wear scar measurements should be done at least at two representative locations on the pin surfaces and disk surfaces, and the final results averaged.

9.1.4 In situations where both the pin and the disk wear significantly, it will be necessary to measure the wear depth profile on both members. A suitable method uses stylus profiling. Profiling is the only approach to determine the exact final shape of the wear surfaces and thereby to calculate the volume of material lost due to wear. In the case of disk wear, the average wear track profile can be integrated to obtain the track cross-section area, and multiplied by the average track length to obtain disk wear volume. In the case of pin wear, the wear scar profile can be measured in two orthogonal directions, the profile results averaged, and used in a figure-of-revolution calculated for pin wear volume.

9.1.5 While mass loss results may be used internally in laboratories to compare materials of equivalent densities, this test method reports wear as volume loss so that there is no confusion caused by variations in density. Take care to use and report the best available density value for the materials tested when calculating volume loss from measured mass loss.

9.1.6 Use the following equation for conversion of mass loss to volume loss.

$$\text{volume loss, mm}^3 = \frac{\text{mass loss, g}}{\text{density, g/cm}^3} \times 1000. \quad (3)$$

9.2 If the materials being tested exhibit considerable transfer between specimens without loss from the system, volume loss may not adequately reflect the actual amount or severity of wear. In these cases, this test method for reporting wear should not be used.

9.3 Friction coefficient (defined in Terminology G 40) should be reported when available. Describe the conditions associated with the friction measurements, for example, initial, steady-state, etc.

9.4 Adequate specification of the materials tested is important. As a minimum, the report should specify material type, form, processing treatments, surface finish, and specimen preparation procedures. If appropriate, indentation hardness should be reported.

## 10. Precision and Bias[5]

10.1 The precision and bias of the measurements obtained with this test method will depend upon the test parameters chosen.

10.2 The reproducibility of repeated tests on the same material will depend upon material homogeneity, machine and material interaction, and careful adherence to the specified procedure by the machine operator.

10.3 Normal variations in the procedure will tend to reduce the accuracy of the test method as compared to the accuracy of such material property tests as hardness, density, or thermal expansion rate. Properly conducted tests should, however, maintain a within-laboratory coefficient of variation of 20 % or less for wear loss values. Table 2 contains wear data obtained from interlaboratory tests (see Note 4). Those tests have been acceptable within-laboratory variation, and further, a between-laboratory coefficient of variation of 40 %.

[5] Additional data are available at ASTM Headquarters.

NOTE 4—The interlaboratory data given in Tables 1 and 2 resulted through the cooperation of thirty one institutions in seven countries with the help of national representatives within the Versailles Advanced Materials and Standards (VAMAS) working party on wear test methods.

10.4 In any test series, all data must be considered in the calculation, including outliers (data exceeding the obvious range); they are treated according to Recommended Practice E 178.

10.5 While two or more laboratories may develop test data that is within the acceptable coefficient of variation for their own individual test apparatus, the actual data of each laboratory may be relatively far apart. The selection of sample size and the test method for establishing the significance of the difference in averages shall be agreed upon between laboratories and shall be based on established statistical methods of Recommended Practice E 122, Practice E 177, and STP 15D.[6]

[6] Manual on Quality Control of Materials, ASTM STP 15D, Am. Soc. Testing Mats., 1951.

## APPENDIX

### (Nonmandatory Information)

### X1. EQUATIONS

X1.1 Exact equations for determining wear volume loss are as follows for:

X1.1.1 A spherical ended pin:

$$\text{pin volume loss} = (\pi h/6)[3d^2/4 + h^2]$$

where:

$h = r - [r^2 - d^2/4]^{1/2}$

$d$ = wear scar diameter, and

$r$ = pin end radius.

*Assuming no significant disk wear.*

X1.1.2 A disk:

$$\text{disk volume loss} = 2\pi R\,[r^2 \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{1/2}]$$

where:

$R$ = wear track radius, and

$d$ = wear track width.

*Assuming no significant pin wear.*

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**International conference (proceeding)**

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