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Development of a two-body wet abrasion test method with attention to the effects of reused abradant

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ABSTRACT

A simple test method has been developed to quantify the response of metals and alloys to two-body wet abrasion. A metallographic polishing machine was modified to create a disk-on-flat sliding test rig. Adhesive-backed SiC grinding papers were used under fixed load and speed to rank the abrasive wear of seven alloy steels, some of which are candidates for drill cones for geothermal drilling. Standardized two-body abrasion tests, like those described in ASTM G132, feed unused abrasive into the contact; however, the current work investigated whether useful rankings could still be obtained with a simpler testing configuration in which specimens repeatedly slide on the same wear path under water-lubricated conditions. Tests using abrasive grit sizes of 120 and 180 resulted in the same relative ranking of the alloys although the coarser grit produced more total wear. Wear decreased when the same abrasive disk was re-used for up to five runs, but the relative rankings of the steels remained the same. This procedure was presented to ASTM Committee G2 on Wear and Erosion as a potential standard test for wet two-body abrasive wear.

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1. Introduction

Wear occurs in many forms. Among them, abrasive wear results in as much as 50% of the material wastage by wear of industrial components [1]. Two-body abrasive wear involves fixed hard particles or protuberances that move tangentially to scratch, plow, cut, gouge, and/or score the opposing surface. Three body-abrasive wear is similar to two-body abrasive wear in some respects, but the abradant is free to tumble, embed, or otherwise move within the interface, producing somewhat different results. The presence of flowing water during abrasion adds another variable that can affect the wear process as well. The current work is focused on wet two-body abrasion.

Reducing the costly effects of abrasive wear damage is important in agriculture, mining, and petroleum exploration. In particular, the wear of the cones in geothermal well drilling results in the loss of hard inserts, and that has been the subject of prior work in this laboratory [2]. Combined impact-abrasion test results showed that under some circumstances, the abrasive component can have a greater effect on material loss than the impact component. Therefore, a relatively simple two-body abrasive wear test was developed to focus on wet abrasion which is commonplace in rock drilling. Since one cannot properly understand the results of a test unless he or she understands the characteristics of the test itself, a series of test variable scoping experiments was conducted before applying the new test to screen candidate materials.

In light of the diversity of abrasive wear's occurrence, different kinds of tests have been developed to measure it. Some use standardized procedures, but others rely on one-of-a-kind apparatus. For example, two ASTM standard test methods have been developed for dry two-body abrasion. These are ASTM G132 [3] and ASTM G174 [4], and the methods differ in several ways. In the former, which describes four possible testing geometries, the holder traverses continuously to supply fresh abrasive to the test specimen. In ASTM G174, the specimen is pressed against a continuous loop of abrasive tape. Both ASTM G132 and G174 are conducted under dry conditions, but many occurrences of two-body abrasive wear (e.g., mining, agriculture, chemical processing, petroleum exploration, geothermal drilling) take place under wet conditions. ASTM G75 [5] and G105 [6] involve wet three-body abrasion, but do not directly address the wet two-body abrasion situation of interest here. Likewise, the rotating ball-on-flat 'micro-abrasion' test has become popular for evaluating thin films and coatings [7], but it does not provide the higher-stress grinding situation of more severe industrial or mining conditions.

The test described here involves a pin-on-disk like configuration in which the sliding specimen remains at the same radial position on the abrasive disk. The device was simpler to construct than a traversing tribometer that supplies fresh abrasive to the

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contact area, but it was important to understand the effects of reusing the same area of the abradant on the method's ability to rank materials. Therefore, the purpose of this paper is to describe the effects of grit size and abrasive paper reuse on the relative rankings of seven steels, three of which are commercial compositions and four of which are experimental compositions that are under evaluation for geothermal drilling applications.

2. Test method and materials

A bench-top wet lapping machine that was designed for metallographic specimen polishing was modified to use as a wear tester. As shown in Fig. 1(a) and (b), a fixture was added to clamp a 25.4 mm diameter × 6.4 mm thick disk specimen, in a fixed radial position on the rotating abrasive platen (approximately 67 mm wear track radius). The test is more severe than the loop abrasion test (ASTM G174) because it uses a higher load (5 N) and coarser grit. The use of disks as test specimens enables several tests to be performed on the same specimen simply by rotating the disk into a new position in the clamp. A stream of tap water was supplied by an adjustable arm so that the contact area was continually flooded. The nominal water flow rate from the nozzle was 3.5 ml/s. The short duration of the test, typically 50 s, requires a relatively small quantity of coolant.

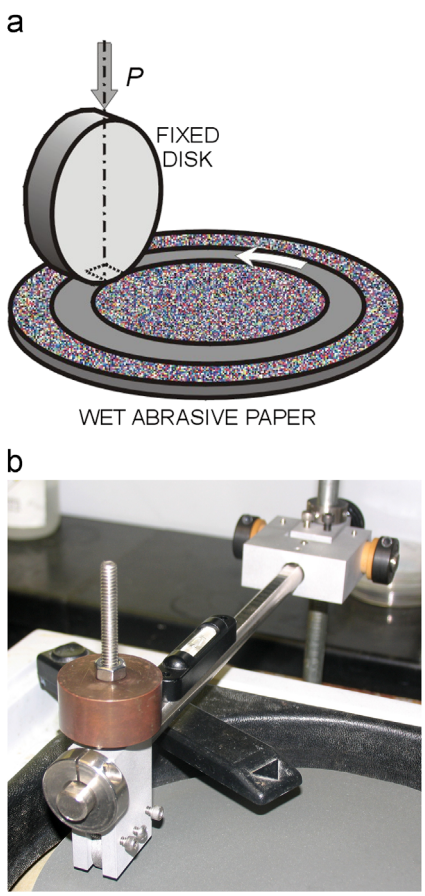

Fig. 1. Disk-on-abrasive test geometry. (a) geometry of contact, (b) physical arrangement.

Two grit sizes of commercial abrasive grinding disks with pressure-sensitive adhesive (PSA) backs were used in these experiments [8]. Initial tests were done with loose sheets of abrasive paper that were held on the platen by a circular frame, but the results proved unsatisfactory due to paper warpage as it got wet. In contrast, the PSA disks remained flat and were used in all tests reported here. Using appropriate weights, the normal force in these experiments was 5.0 N. The surface speed, based on typical wear track diameters from 134–137 mm and a rotation rate of 150 rpm, was 1.05 to 1.08 m/s.

Two methods for measuring wear were initially considered. The first was to measure the width of the flat spot worn on the disk circumference and convert it to wear volume. The second used weight loss (L). If desired, weight loss can be converted to volume V using the density of the alloy (ρ) using:

$$V = L/\rho \tag{1}$$

After comparing results based on both scar width and weight loss methods, weight loss was found to be more repeatable and convenient. It avoided the added steps of making multiple width measurements in a microscope and estimating the actual edge of the wear scar amongst the abrasion marks. A digital analytical balance capable of measuring to the nearest +/−0.2 mg was used to measure specimen weight before and after testing.

If desired, a normalized volumetric wear factor W_{abr} (mm^3/N m) can be calculated using:

$$W_{abr} = (V/Ps) \tag{2}$$

where P=applied load (N), and s=total sliding distance (m). However, it is recognized that by virtue of this geometry the contact pressure on the wear scar decreases as wear occurs, and the wear rate computed from the final mass loss or wear scar dimensions represents an average over time.

Seven ferrous alloys were used in these experiments. Three commercial alloys were used as baseline materials and four were variants of alloy steels processed by various methods and heat treatments. The steels and their measured Rockwell hardness numbers are listed in Table 1. Designations in column two of the table are used in the discussion and in the labeling of plots.

Table 1
Wet abrasion specimen materials.

Alloy	Designation	Processing	Hardness
AISI 1045	1045	25.4 mm diameter bar stock, as-received (non-heat treated)	HRB 93.9 HRC 14.4[a]
AISI 4340	4340	25.4 mm diameter bar stock, as-received (non-heat treated)	HRB 99.5 HRC 23.8
H13 tool steel	H13	25.4 mm diameter bar stock, as-received (non-heat treated)	HRB 85.1 HRC 6.2[a]
Fe–Cr–Mo–W–B–C–Si–Mn–Ni	S-SAM-A	Gas atomized powder, sieved to −325 mesh, hot-isostatic pressed at 1950F for 4 h	HRC 53.7
Fe–Cr–Mo–W–B–C–Si–Mn–Ni	S-SAM-B	Gas atomized powder, sieved to −325 mesh, hot-isostatic pressed at 2125F for 4 h	HRC 49.8
Fe–Cr–Mo–W–B–C–Mn–Si	NC8-A	Gas atomized powder, sieved to −325 mesh, hot-isostatic pressed at 1950F for 4 h	HRC 70.5
Fe–Cr–Mo–W–B–C–Mn–Si	NC8-B	Gas atomized powder, sieved to −325 mesh, hot-isostatic pressed at 2125F for 4 h	HRC 66.6

[a] Values are low on the HRC scale, so they are of questionable validity. Tests were done to facilitate comparison to the harder alloys on the same hardness scale.

3. Results

Specimens of 1045, 4340, and H13 steels were tested three times each using a fresh 180 grit SiC (nominal particle diameter 70 μm) abrasive disk for each experiment. The other four alloys were each tested twice. Weight change (raw) data for each test are displayed in Fig. 2. There was a factor of about nine difference in weight change between the highest and lowest wear amounts, and except for the 1045 and 4340, the test method seemed to discriminate nicely between the wet abrasive wear characteristics of the steels. All four experimental alloys performed better than the baseline steels.

The effects of multiple reuse of the 180 grit paper were studied to compare the most abrasion resistant (NC8 B) and least abrasion resistant (S-SAM A) of the four experimental alloys. That is, the same abrasive sheet was used for five sequential tests, but using a different place on the circumference of the disk for each run. The effects of abrasive reuse are summarized in Fig. 3. Not unexpectedly, the relative ranking of the two alloys was the same regardless of whether fresh or previously used abrasive was the counterface. The ratio of weight loss of the less wear resistant to the more wear resistant material (R) varied from 2.71 to 4.32 as the number of reuses increased. The wear of the less abrasion-resistant alloy decreased more with reused paper than that of the more abrasion-resistant alloy.

In addition to the 180 grit paper, tests were also run to compare paper reuse effects for a coarser grit SiC paper (120 grit, nominal particle diameter 115 μm). The same test conditions as before (P=5 N, v=0.5 m/s, 50 m sliding distance in running water) were used to perform duplicate tests (the first one on new abrasive, and the second one using a new area on the test specimen but with the same abrasive disk). Results for the four experimental steels are shown in Fig. 4. The legend in the figure indicates the grit size and abrasive condition (one test per plotted bar). The relative ranking of the four steels in abrasive wear remains the same regardless of the grit size or number of reuses. However, the effects of abrasive size and condition were least evident for the most abrasion resistant alloy where only the new 120 grit abradant produced noticeably higher wear. Also, there was a greater effect of fresh grit size on the wear of the most wear resistant alloy (NC8-B) than on the less wear resistant (S-SAM-A). Increasing the grit size from 70 to 115 μm increased the wear by a factor of about 1.2 for the S-SAM-A alloy but by a factor of 2.2 for the NC8-B alloy.

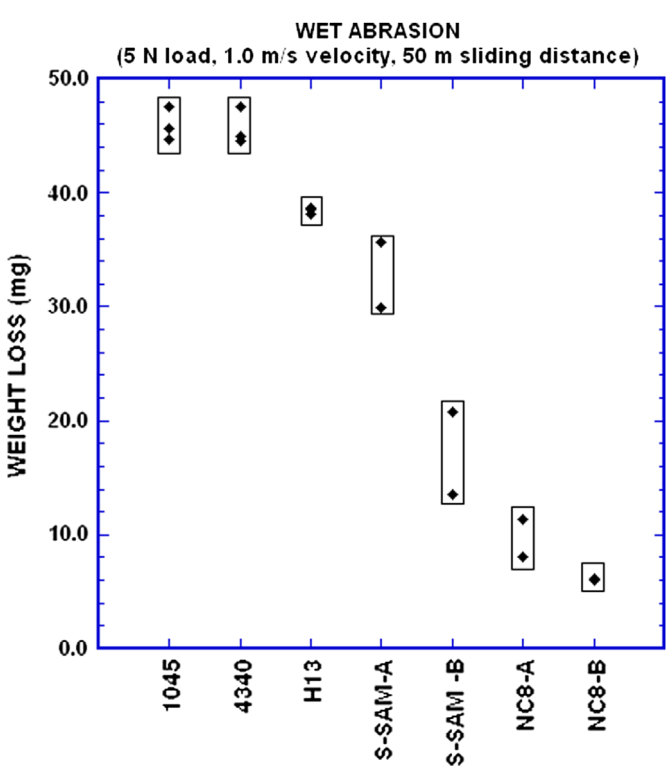

Fig. 2. Weight loss data for wet abrasion of seven steels.

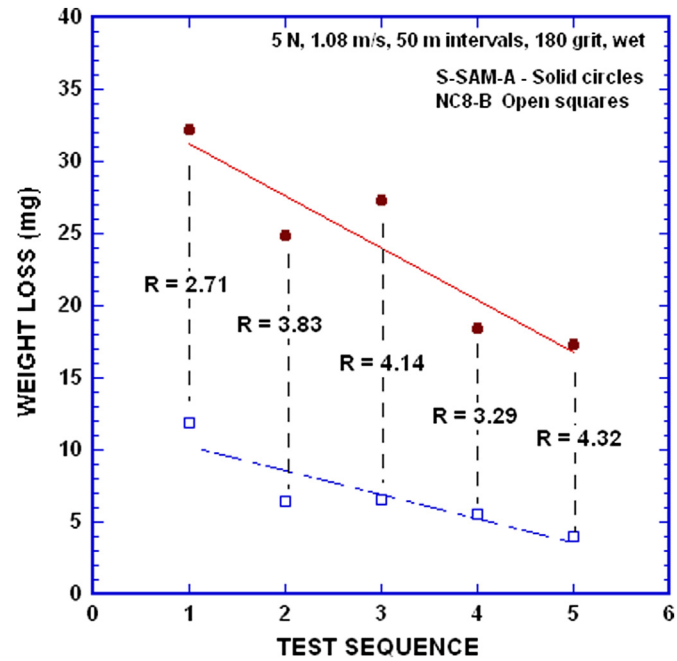

Fig. 3. Effects of reused paper on the relative wear of alloys S-SAM-A and NC8-B.

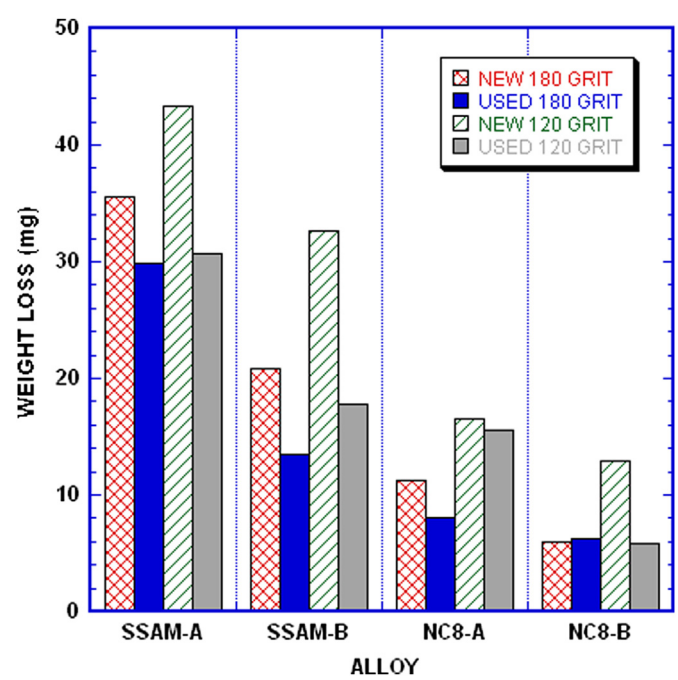

Fig. 4. Effects of reuse on the abrasive wear of four steels.

4. Discussion

Two possibilities were considered to explain the reduced wear rates of the steels with increased paper use. The first possibility

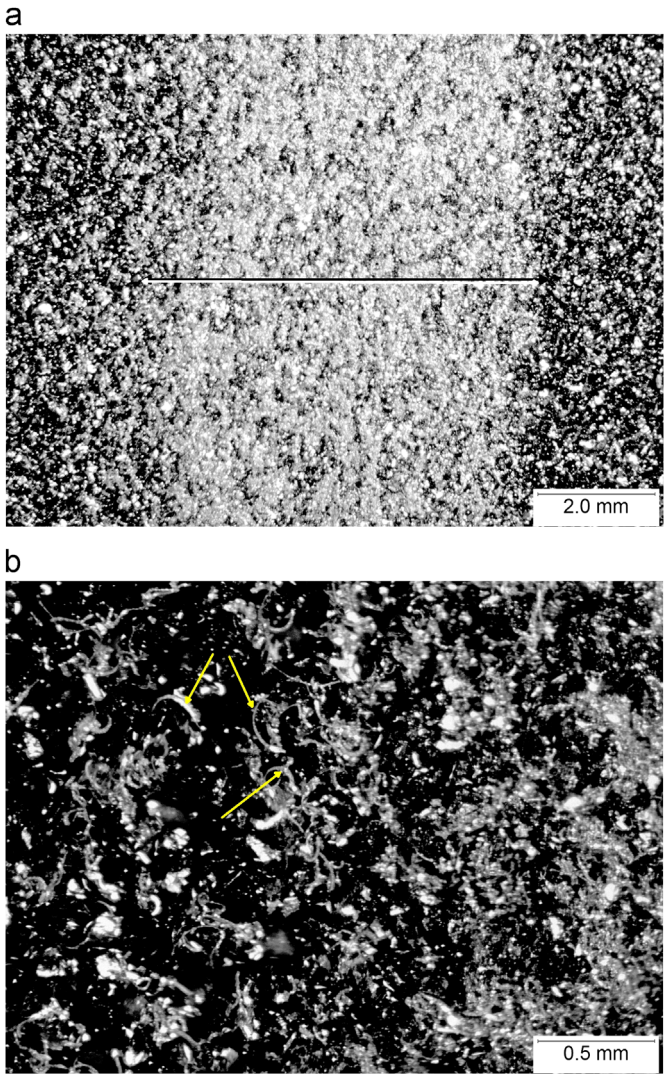

Fig. 5. Wear particles clogging the sliding path after dry abrasion of S-SAM-A steel. (a) Overview of the wear path (contact width is indicated by the arrow), (b) Enlarged view of the edge of the same track showing cutting chips on the left (indicated by arrows) and fine powdery debris on the right. Sliding direction vertical in both cases.

was loading (i.e., filling the space between the grits with debris), and the second was abrasive tip wear. Loading would explain why the more heavily wearing alloy would clog the space between grits faster and thus, its wear rate would drop faster. Likewise, tip blunting, fracture, or grit loss with repeated use would be expected to increase with longer periods of wear testing.

The phenomenon of loading was readily observed in a dry abrasion test that was conducted using the alloy S-SAM-A against 180 grit paper for 250 m sliding distance with the same load and speed as for wet tests. Examination of the worn abrasive paper after testing, when it was still applied to the platten, showed particle accumulation between the abrasive grains (see Fig. 5(a)). On the wear path, the debris was fine, loose, and powdery. Adjacent to the track, however, tiny cutting chips were observed (see Fig. 5(b) in which the edge of the wear track divides the image approximately in half vertically). The steel debris that remained on the wear path was powdered by repeated contact, but that which fell to the side retained its cutting chip shape. In contrast to the dry abrasion test, optical microscopy of used papers from wet abrasive tests failed to show any evidence of residual debris accumulation, even for the steels that wore most. Apparently, flowing water swept away any wear debris before it could accumulate. Consequently, the observed reduction in wear rates with multiple use, illustrated in Fig. 3, could not be explained in terms of paper loading.

Since paper loading could not be verified as the reason for the observed decrease in steel wear rate with numbers of tests, grit wear became a more likely explanation. Optical microscopy of the sliding path on paper used in wet abrasion tests failed to reveal any changes in the morphology of the abrasive points, but a paper by Mulhearn and Samuels [9] on the abrasion of steel by SiC papers reported that: "for any grade of paper, the number of contacting particles increases with increased use, the proportionate increase being larger the coarser the grade of paper." One could interpret that observation in several ways. First, fracture of abrasive grits tips can produce more and more cutting edges. Second, the surface being abraded could roughen to the point where more intermeshing with the paper occurs and thus the specimen contacts more grits. In pin-on-disk type experiments with up to 400 repeated passes over the same paper (c.f. the current experiments ranged from 125–600 passes), Mulhearn and Samuels also found, in agreement with current results, that the wear rate from a steel specimen decreased with increasing numbers of passes. Additional research in that area, such as conducting experiments in which the shapes of individual grit particles or regions on the sliding path could be tracked, or investigating the effects of various lots or makes of abrasive paper, was beyond the scope of this work. The nature of the specimen wear process, due to third-body production, abradant condition, and grit wear, could potentially change over time, and the authors have therefore set a test duration of 50 m for comparative purposes. That length was generally sufficient to differentiate between steels and noticeably wear the abrasive paper.

Initial results using this simple test method based on a modified polishing machine as a tool for ranking relative abrasion resistance are encouraging; however, further research is needed to establish the method's sensitivity to various applied variables. These include not only normal force and speed, but also the effects of abrasives of similar grit size but from different manufacturers [10], investigating the wear of the abradant cutting edges in more detail, characterizing the effects of cutting point wear, and investigating any changes in the wear processes of the test pieces themselves with increasing sliding distance. Pursuing such fundamental tribology issues would establish a firmer basis on which to interpret the present test results and establish data repeatability, particularly if the test were a candidate for standardization.

While the focus in this paper was on test methodology, it was nevertheless interesting to note the unexpected trend between hardness and abrasive wear of the most and least wear-resistant of the four experimental alloy steels tested, regardless of whether tests were done with new or once-used abrasive. Fig. 6 shows that the heat treatment that resulted in a slightly higher hardness within each alloy composition also produced more wear of that alloy. However, for two alloys that differed significantly in hardness, the harder the alloy, the lower was its abrasive wear rate, as might be expected. Therefore, when improving a given alloy's resistance to abrasive wear, hardness alone should not be used as the sole governing parameter. Changes in microstructure and fracture toughness of the alloy resulting from the two processing treatments were apparently as important as final hardness in regard to abrasion resistance.

5. Summary and conclusions

A simple two-body, wet abrasion test apparatus was constructed using a metallographic lapping machine. Unlike two-body abrasion

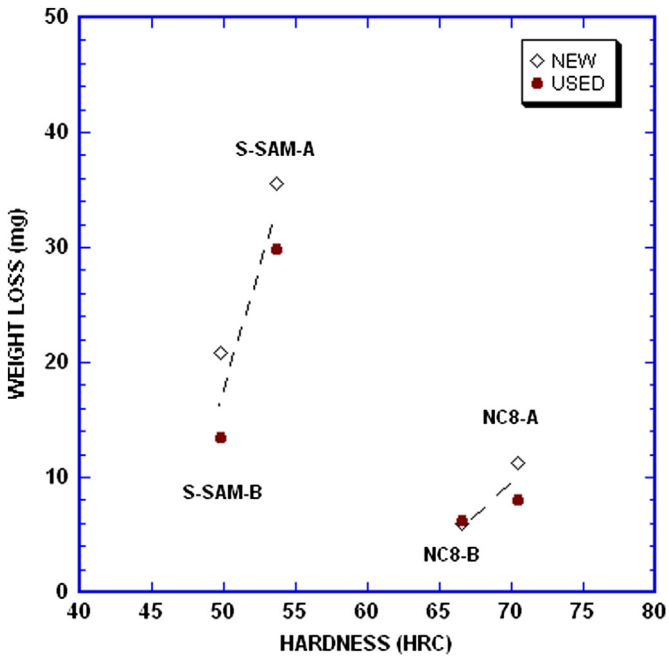

Fig. 6. Effects of hardness and 180 grit abrasive paper reuse on wet abrasion weight loss.

tests in which a fresh abradant is supplied to the contact, this method continues to slide the test piece over the same path. To determine if that configuration would affect the ability of the test to rank a series of materials, seven different steels were tested using two grades of abrasive paper, and in both fresh and previously used conditions. The following conclusions were obtained:

1) The relative ranking of four steels in two-body wet abrasive wear was independent of whether 180 or 120 grit fresh abrasive paper was used, although the quantity of wear was higher with coarser grit as expected.
2) While the quantity of wear decreased with abradant reuse, the relative ranking of four experimental alloys remained the same when testing was done on abrasive paper that had been reused on the same material.
3) Five subsequent tests using the same 180 grit paper, each test using a new area of the slider specimen, resulted in decreasing specimen weight loss with the number of reuses. Comparing a relatively high and low abrasion-resistant alloy, the less wear-resistant alloy was more affected by abradant reuse than the more wear-resistant alloy. The causes for that trend could not be explained in terms of paper loading with debris, and it is proposed, based on earlier published work, that changing grit morphology was the cause. This remains to be verified.
4) The two-body wet abrasive wear test described here is straightforward to implement using readily available equipment and abrasive products. The test-to-test variability, based on two or three tests per material, was sufficiently small to rank the relative wet abrasive wear rates of seven different grades of steel. That relative ranking was insensitive to the grit size (within the range of 120–180 grit). There would appear to be no advantage in running longer tests, with the possible exception of achieving better discrimination between the most wear-resistant alloys in which the weight loss was less than about 10 mg.
5) While not specifically addressed here, the test method has a potential to be used with standard reference specimen materials to determine the relative loss in abrasion efficiency of various abrasive papers, textiles, and other adhesively fixable surfaces. It may also be considered as an alternative to the other types of abrasion tests, such as the rotary wear test that described in ASTM G195 [11].
6) Thermal treatments of individual alloys that slightly increased their hardness (HRC) actually reduced their wear resistance. However, when comparing one alloy class to another, the harder of the two alloy classes experienced less wet abrasive wear.

As a result of the work described here, this test method was presented to ASTM Subcommittee G02.30 (Abrasive Wear) for consideration as a new standard test method during its 2012 spring meeting. The test has the advantage of low cost, the use of simple specimens and fixtures, and short testing times. It also does not require the kind of specialized mechanical assemblies that are needed to conduct tests in which fresh abrasive is continuously provided to the sliding contact, as for example in ASTM G132 [3].

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