An Assessment of the Abrasive Wear Behavior of Ferrous Alloys and Composites Using Small Scale Laboratory Wear Tests

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An Assessment of the Abrasive Wear Behavior of Ferrous Alloys and Composites Using Small Scale Laboratory Wear Tests

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Abstract

Laboratory wear tests are only truly effective when they closely simulate the wear processes experienced by the test piece in the field. Typically, laboratory wear tests only approximate the two- and three-body wear systems of the tribo-environment. The Albany Research Center uses a suite of three laboratory abrasion and impact-abrasion wear tests to rank materials for wear applications. These tests, and the wear mechanisms they approximate, are: (1) dry-sand, rubber-wheel (three-body, low-stress abrasion); (2) pin-on-drum (two-body, high-stress abrasion); and (3) high-speed, impeller-tumbler (impact-abrasion). Subsequently, candidate materials can be ranked according to their performance for each of the wear tests. The abrasion and impact-abrasion test methods will be described, highlighting the predominant wear mechanisms for each test. Data on a wide variety of irons and steels will be presented, with relative ranking of the materials according to the specific wear test.

WEAR IS A MAJOR PROBLEM in excavation, earth moving, mining and minerals processing, and occurs in a wide variety of items, such as bulldozer blades, excavator teeth, rock drill bits, crushers, slushers, ball mills and rod mills, chutes, slurry pumps, and cyclones. The wear of parts, the cost of repair and replacement of these parts, and the associated downtime related to these activities results in significant operational costs. For the most part, large scale wear tests are costly, labor intensive and require a long time to complete. In addition, the environmental variables change over the course of the test, making correlations between tests done at different times of the year or in different locations difficult. In order to overcome these difficulties, laboratory wear tests have flourished.

Although numerous types of laboratory wear testing devices have been built, most are beset by lack of reproducibility or are too application specific to be of general interest. To date, fourteen wear test methods and two wear test practices have been published by the American Society for Testing and Materials (ASTM). The ASTM has published an evaluation of wear testing (1) and a volume describing a wide range of wear test methods (2). In the broad area of abrasion testing, Borik has compared several abrasion tests used to evaluate a variety of abrasion-resistant materials (3).

An ideal wear testing laboratory would have a number of test methods that are small in scale, produce highly reproducible data quickly, and simulate a wide range of field conditions. The test results should be able to predict the wear of a material in actual service. Such tests are difficult to devise because wear processes are dependent on a number of variables that are affected by time and scale. Some of these factors are frictional heating, the work hardening rate of the wear material, the size and nature of the wear debris, the size and nature of abrasive particles, the microstructure of the wear material, and any local and global environmental interactions.

Consequently, hundreds of wear tests have been devised, each an attempt by an investigator to more closely simulate a given wear environment while producing significant wear in a short period of time. There is a need to standardize and minimize the types of laboratory wear tests in order to make inter-laboratory comparisons possible and to reduce the number of tests and types of test specimens required. At the same time, there is a need for the tests to more closely simulate a broader range of field conditions.

Abrasive Wear. High-stress or grinding abrasion occurs when abrasive particles are compressed between two solid surfaces, for example between grinding rods or balls. The high-stress abrasion that occurs in grinding mills takes place over a very small contact region, where the ore particles are caught between the grinding balls or between grinding balls and the mill liner. The high contact pressure produces indentations and scratching of the wearing surfaces, and fractures and pulverizes the abrasive ore particles. Hard minerals such as quartz will indent and scratch martensitic steels having yield strengths of 2100 MPa. High-stress abrasion is sometimes referred to as three-body abrasion, although two-body, high-stress conditions can sometimes exist. High-stress abrasion implies that the abrasive particle is fractured during the wear process. How these small abrasive particles affect the actual removal of material in mineral processing is not well understood. It has been speculated that high-stress grinding abrasion produces wear by a combination of cutting, plastic deformation, surface fracture on a microscopic scale, as well as by tearing, fatigue or spalling on a macroscopic scale.

In ore processing plants, high-stress abrasion produces practically all of the wear on grinding balls and liners in ball mill grinding units. In rod mills where larger chunks of ore are comminuted, wear during the first stage of grinding proceeds by both impact-gouging abrasion and high-stress grinding abrasion. In autogenous grinding mills, charged with ore from 25 cm to 0.2 mm in diameter, both impact-gouging abrasion and grinding abrasion occur.

In high-stress grinding abrasion, the microstructure of the balls and liners influences their wear rate. In unalloyed or low chromium white iron balls, an Fe_3C-type carbide (8 to 10 GPa DPH) structure coexists in a relatively soft ferrite or pearlite (about 1 to 3 GPa) matrix. This results in a composite hardness for the alloy of between 5 and 6 GPa. However, in spite of the relatively high hardness of the composite structure, the balls tend to wear at a rate equivalent to that of the ferrite or pearlite matrix. The abrasive forces that occur during grinding are sufficient to fracture and crumble the carbides, which are poorly supported by the ferrite or pearlite matrix. In a matrix that contains martensite (through alloying or heat treatment), however, the carbides do not fracture as readily, and consequently, better abrasion resistance is obtained.

Low-stress or scratching abrasion occurs when lightly-loaded abrasive particles impinge on and move across the wearing surface, producing cutting and ploughing on a microscopic scale. In aqueous or other liquid environments, corrosion may also contribute to the overall wear rate, in which case erosion-corrosion is the operative wear mechanism. In both cases, low-stress abrasion is the primary mode of wear. The wear rates in terms of metal thickness removed per day are quite low in low-stress abrasion, so a significant portion of the total wear is probably due to the abrasion of a continually reforming oxide film. This may be especially true in the handling of particulates in a wet environment, such as slurries.

Low-stress scratching abrasion in ore processing machinery occurs primarily in the pumping of sand slurries, in size classifying equipment such as cyclones and gravity classifiers, in chute liners, screens and flotation impellers, and in hydraulic and pneumatic conveying operations. Generally, the impingement angles and particle impact forces are so low that hard and brittle constituents of the microstructure are not fractured by the abrasive forces. Under these circumstances ferrous alloys containing hard carbides provide good to excellent wear resistance. Ceramics and synthetic stone (e.g., fused silicates) are also used for these applications. Molded rubbers and polyurethanes also work well in low stress abrasive conditions, particularly in pump and flotation impellers, linings for cyclone classifiers, and in pipes and screen decks in some screening applications.

Description of Tests and Equipment

Laboratory abrasive wear tests are frequently classified by the type of test equipment used; however, they can be classified in more general terms by the stress level and the geometrical arrangement of the components of the system (4). If the load is sufficient to fracture the abrasive particles, the wear is called high-stress abrasive wear; if the particles do not fracture significantly, it is called low-stress abrasive wear. The distinction between low-stress and high-stress conditions is not sharp. As for geometrical arrangement, if the abrasive particle is in contact with only one other object or held fixed with respect to the other surface, analogous to a tool bit in a lathe, the wear is classified as two-body. If the abrasive particle is loose and free to move between two contacting surfaces, it is referred to as three-body wear. Although the abrasive material is normally harder than the wear object, this is not a necessary condition for classifying the wear as abrasive wear.

Dry-Sand, Rubber-Wheel Wear Test. The dry-sand, rubber-wheel (DSRW) abrasion test apparatus simulates low-stress, three-body abrasive wear (5). This type of wear occurs in the mining industry in linkages, pivot pins, and wire ropes, which suffer slow wear from the sliding and rolling action of abrasive fragments of rock and ore trapped between metal surfaces. Because this type of wear is slow, field trials alone would be too slow for evaluating new materials. The DSRW abrasion test is quick and gives a reasonable correlation with the field tests. Even before the test became an ASTM standard (G65-81) in 1980, it had been used by a number of laboratories for many years. Since becoming an ASTM standard, it has become probably the most popular abrasive wear test in the United States for ranking materials.

DSRW Equipment and Specimen. The basic machine as described in the ASTM standard consists of a rubber-rimmed steel wheel, 228.6 mm in diameter by 12.7 mm wide; a sand hopper connected by a tube to a nozzle that allows 250- to 350-g/min sand flow; a revolution counter that stops the drive motor after a set number of revolutions; and a weighted lever arm that holds the specimen and produces a horizontal force against the wheel where the sand is flowing. The sand is 50- to 70-mesh silica test sand. The hardness of the rubber on the wheel must be durometer A-60±2.

A typical test specimen is a rectangle, 25 by 76 mm, that is 3 to 13 mm thick. The wear surface is ground flat with a surface finish of at least 0.8 μm. The density of the test material must be known in order to calculate the volume of material lost during the course of the test. The relatively simple shape of the test specimen is conducive to specimen preparation. Specimens of pure metals, steels, white cast irons, weld overlays, plastics, and ceramics have been made and tested.

The equipment has two test parameters: sliding distance (i.e., the number of wheel revolutions) and specimen load. The ASTM recognizes four procedures using variations of these two test parameters (5).

From the mass loss and the density of the material, the volume loss is calculated. The test is repeated one or more times. The coefficient of variation between two or more tests for a material must not exceed 7% in order to meet ASTM specifications.

Pin-on-Drum Abrasive Wear Test. The pin-on-drum abrasive wear test involves high-stress, two-body abrasive wear. One end of a cylindrical pin specimen is moved over an abrasive paper, abrading material from the specimen and crushing the fixed abrasive grains. The procedure is believed to simulate wear that occurs during crushing and grinding of ore, processes in which the abrasive particles are crushed, i.e., high-stress abrasive wear.

Considerable pin-abrasive wear testing has been conducted on pin-on-disk equipment, beginning with Robin's machine in 1910 (6). This machine wore a pin sample along a single track on the surface of an abrasive cloth fixed to the flat surface of a disk. Khruschov (7) made a major improvement by making the pin follow a spiral path, like a phonograph, always encountering fresh abrasive. Research using this type of machine, reviewed by Moore (8), helped establish the effect of many parameters, such as abrasive material and size, specimen load, and velocity, on two-body abrasion. Climax Molybdenum Co. developed a pin-on-table machine with several improvements over the pin-on-disk machine (9). Using a converted milling machine, the moving table with abrasive attached provided a constant surface speed. The test specimen was rotated to abrade the pin surface from all directions. Using the operating parameters from the Climax machine, Mutton (10, 11) at the Melbourne Research Laboratories developed a pin-on-drum abrasion machine in which a slowly rotating drum was substituted for the moving table. The pin-on-drum machine at Albany is very similar to the Melbourne machine except for a few minor refinements (12). These latter three machines all can use the same type of abrasive, path length, load, speed of abrasive, and rotational speed of the specimen.

Pin-on-Drum Equipment and Specimen. The equipment consists of a head that rotates the test specimen while traversing the length of a cylindrical surface of a rotating drum covered with abrasive paper. The head has three functions. First, it loads the specimen. Second, it translates the specimen slowly along the drum so that only fresh abrasive is encountered. Third, it rotates the test specimen to produce wear scars in all directions across the end of the specimen. The applied load is normally 66.7 N. The 0.5 m diameter drum is covered with abrasive cloth, either Al_2O_3, SiC, or garnet of the desired size, usually 120 to 150 mesh. The abrasive cloth is obtained in rolls, 61 cm wide, from a commercial source. During operation, the pin traverses 12.7 mm parallel to the axis of the drum while the drum makes one revolution. The wear path is 1.6 m per drum revolution. The drum rotates at 1.7 rpm, giving a surface speed of 2.7 m/min. The pin specimen rotates about a vertical axis at 1.7 rpm. Through a system of gearing, a single motor drives the entire machine, which automatically stops after completing a preset number of drum revolutions. A gear-disengaging mechanism allows repositioning of the specimen at intervals of 6.35 mm along the drum.

The test specimen consists of a pin 6.35 mm in diameter by 2 to 3 cm long. Specimens are normally prepared by machining in a lathe; hard or brittle metal specimens are cut out by electro-discharge machining and then are finish ground in a lathe. Specimens over a wide range of hardness, including soft magnesium and hardened white cast iron, have been evaluated.

A new test specimen is worn in for approximately four revolutions, or until its entire end displays wear scars, before beginning the test runs. Pin abrasion tests can be run with or without the use of a standard reference specimen. For those tests where a reference specimen is used, the test requires two runs--one on the test specimen and one on reference specimen. The number of drum revolutions is chosen to provide a reasonable amount of wear, that is, about 40 mg loss or whatever is reasonable. For irons and steels ranging in hardness up to about 5.2 GPa (500 BHN), this requires about 6 revolutions (9.6 m sliding distance). Harder materials will require a greater sliding distance. After the test specimen has been run, the reference specimen is run for the same number of drum revolutions with its track exactly between the tracks left by the test specimen. The reference specimen used at Albany is ASTM A514 low alloy steel with a DPH value of 2.6 GPa (269 BHN). Reference specimen wear is used to correct for small variations in the abrasiveness of the abrasive cloth from lot-to-lot and within a given lot.

From the mass loss data for the test specimen, a wear rate can be determined using one of the many equations listed in the literature (13). Typically, these equations represent wear either as the specific wear rate (mm^3/Nm), a dimensionless wear coefficient, or as the volume wear (mm^3/m).

The wear factor makes use of a standard to correct for small differences in the abrasivity of the abrasive cloth. The wear factor for a test specimen using a particular abrasive type under a given load is calculated according to the following relationship:

$$WF = V_x/V_r \qquad (1)$$

where *WF* is the wear factor for a given set of abrasive test conditions (i.e., load, sliding distance, abrasive). The term V_x is the volume of material lost to abrasion for the test specimen for the test conditions used (and it is calculated from the mass loss using the density of the specimen). Alternatively, V_r is the volume lost to abrasion for the reference specimen. Once an abrasion test is completed, the specimens are cleaned ultrasonically in water with detergent to remove any loosely adherent wear debris, rinsed in water, rinsed in alcohol, and air-dried before weighing.

Data gathered from abrasive wear tests are reported in terms of both the volume wear (mm^3/m) and the WF.

Impeller-Tumbler Impact Abrasion Test. Bond (14) developed a laboratory scale test to accurately simulate the wear conditions that exist in the impact crushing of ores (both soft and hard) by impact hammers and blow bars. The rationale for the development of the test apparatus was to be able to predict the wear, and hence the energy consumption, that occurred in the crushing and grinding of ore (15). Bond's equation (i.e., the "Third Theory") found that the energy input required to crush or grind rock is proportional to the square root of the new surface produced. Using his laboratory impact-pulverizing unit facilitated the calculation of the energy requirements needed to reduce a quantity of ore of a given starting size to a quantity of ore of the desired size. A critical factor is knowing the energy input to the driving motor, with due allowance made for frictional losses in the gears and bearings and the energy conversion efficiency of the motor. Once these factors are determined for the laboratory unit, conversion to a full scale unit only requires a knowledge of the energy efficiency of the crushing or grinding unit in the field. For large units, the energy efficiency factor remains fairly constant. In reality abrasive wear in ore processing is complicated by many factors other than energy consumption. However, the Bond approach has been very successful in predicting wear by applying a set of empirical formulas to an abrasion index, as determined in his laboratory wear test machine (15).

The machine used for the test is an impact-pulverizer type in which 1600 grams of screened ore were pulverized by impact with a rapidly rotating paddle made from a standard grade of steel (AISI 4325, hardened to 5.2 GPa (500 HB)). Wear of the paddle was measured in grams (to the nearest tenth of a milligram). This wear constituted the abrasion index (A_i). The energy used in abrading the paddle was also calculated from the screen analysis of the feed and pulverized product, using the Bond work index equation (15,16). From this it is possible to calculate the wear on the paddle in terms of grams per kilowatt-hour. Multiplying the abrasion index by a constant (determined in conjunction with the full scale grinding or crushing machine of interest) gives the wear for an "average" ore in terms of the mass of metal abraded per kilowatt-hour. It is apparent that in using the Bond abrasion index to predict wear in crushing and grinding, the wear equation must be developed for each type of crushing or grinding machine. Bond was able to do this by correlating the reported wear and energy consumption from a large number of crushing and grinding operations with the abrasion index of the respective ores, as determined form his machine.

Impeller-Tumbler Equipment and Specimen. The impeller-tumbler wear apparatus uses an impeller-in-a-rotating drum arrangement. The central impeller holds the paddles which will subsequently impact the ore media. The impeller and ore reside inside a closed and slowly rotating larger drum. When operating, the drum and the impeller rotate in the same direction. Consequently, the drum, which is rubber lined (to reduce noise and to provide some friction between the drum and the ore), rotates slowly, lifting the ore until it overcomes the frictional forces of the rubber lining and falls into the path of the rapidly rotating impeller paddles. The impeller wear test apparatus at Albany uses three metal paddles as the test specimens instead of one as in the Bond test. These paddles are approximately 25 mm wide by 12.5 mm thick by 75 mm long. During operation the paddles are rotated at 620 rpm, causing them to impact against pieces of a hard abrasive mineral, for example, quartzite or granite or limestone. These impacts cause wear to occur to the paddles from a combination of impact-gouging type events as well as from abrasion. The impeller-tumbler test provides quantitative information on the impact-abrasion wear resistance of the three test specimens through measurements of the mass loss before and after impact-abrasion. Wear test variance is typically less than ten percent for a duplicate set of specimens, although this test does have the potential for greater wear variance than either the dry-sand, rubber-wheel or the pin-on-drum. (Note: Precautions must be exercised when using the impeller-tumbler or any other test apparatus that generates fine wear debris. This test produces a large amount of very fine particulate matter. For example, when working with high silica quartzite, ventilation through the use of a blower-cyclone system, as well as through the use of a respirator or small particle dust mask is required. The silica-rich dust will irritate the mucus membranes in the throat and nasal passages in the short term and can cause silicosis, a form of lung cancer if exposed for longer times.)

The general test procedure for the impeller-tumbler starts with sizing the ore in the range of -1" to +3/4". After this step, 600 grams of ore is measured and the number of particles that make up the charge is counted. Typically, for 600 grams of high silica quartzite, the number of particles range from 38 to 44. The 600 gram charge is then loaded into the impeller and the cover is closed. An empty bag is positioned under a chute which catches any ore debris that escapes the drum and is not vented by the exhaust system (typically the larger pieces). Note that there is a space between the cover and the drum, so that fine ore debris can escape. The drum and impeller are then set into motion. This marks the beginning of the one hour test. The speed of the impeller is adjusted to 620±5 rpm for the first 15 minute interval. After the first 15 minute test interval has elapsed, the test is stopped, the cover is removed and the ore is collected. A fresh 600 gram charge of ore is placed in the drum and the procedure is repeated for a second 15 minute interval. This is done twice more, for a total running time of one hour. The amount of ore passed through the system is 2400 grams. After the four 15 minute tests, the samples are removed, thoroughly cleaned and then hot air dried. They are weighed to determine the mass loss. The specimen is then reversed and a duplicate series of 15 minute tests is run. The results of the two series of tests are averaged and the standard deviation is calculated.

Results and Discussion

Dry-Sand, Rubber-Wheel. For most ferrous materials, testing is performed using a 130 N load for 2,000 revolutions of the rubber wheel (ASTM procedure B), with volume losses ranging from 20 mm^3 to 120 mm^3. The reproducibility of the test is best for volume losses in the range of 20 to 100 mm^3.

Typically, in tests in which less than 20 mm^3 is lost, any small material inhomogeneities are greatly magnified; therefore, a more severe test should be run by using either a greater sliding distance or higher load. Above a 100 mm^3 loss, the groove becomes so deep that it may contact the edge of the rubber wheel and cause erratic results. Therefore, a less severe procedure may be necessary. Using another procedure has a disadvantage in that test results cannot be directly compared among different procedures.

The DSRW test should be used only for ranking of various materials, not for determining the absolute values of wear. For example, a material that wears half as much as another in this test probably will not last twice as long in the field, because the test tends to exaggerate differences. Field factors such as the hardness and particle size of the abrading material will affect the absolute values of wear more than they affect the ranking. Typical wear data are presented in Table I.

From examining the data in Table I, i.e., the volume of material lost as a result of low-stress scratching abrasion, it is clear that the volume wear generally decreases as the hardness of the material increases. However, scratching abrasion is affected by the microstructural morphology of the material being abraded. For example, hard carbides are very effective in lowering the volume wear of a material from pure abrasion. This is reflected in the performance of the Cr white cast iron and the D2 tool steel. Both the Cr white cast iron and the tool steel have a high volume fraction of hard carbides, which aid in protecting the matrix from abrasion by hard particles. Specifically, the reinforcing carbides protect the matrix by limiting the depth and severity of penetration by abrasive particles. They also help protect the matrix by fracturing the abrasive particles as they attempt to scoop the carbides from the matrix. When a material is not protected by a hard second phase, like the AISI 1060 (hardened) steel, it can be abraded at a higher rate than are the carbide reinforced materials. So we see that although the AISI 1060 steel has the highest hardness of all the materials listed in Table I, its volume wear is between 2½ and 3 times greater than the Cr white cast iron or the D2 tool steel.

One criticism of the DSRW test is that the area of contact changes as the test proceeds. That is, as the volume of material removed by abrasion increases, the surface area of contact between the rubber wheel and the DSRW sample increases. Thus, the effective contact area increases continually during the course of the test. This circumstance makes direct comparison of material loss between specimens impossible, especially for those situations where material volume loss is greater than 20 mm^3.

Pin-on-Drum Abrasion Test. This pin-on-drum test apparatus has proven useful in ranking a wide range of materials under the conditions of two-body, high-stress wear. Table II shows typical results for a variety of materials ferrous alloys and composites.

The reproducibility of the test has been very good. In repeating a test immediately, the coefficient of variation for homogeneous, dense samples is typically less than 2%. Results on materials retested after several months time with a different lot of abrasive cloth differed by less than 5% from the earlier results.

As discussed in the previous section, abrasion is affected by the morphology of the microstructure. Once again it is seen that the carbides are very effective in reducing the volume wear of the material as a result of the reinforcing carbides. The Cr white cast iron once again possesses the lowest volume wear with the D2 tool steel next. As before the AISI 1060 steel is worn at a higher rate. However, the relative difference in the wear rate between the three materials is much reduced (although the trend is the same). This reduction in magnitude is due to the change in wear mode, from one of low-stress to one of high-stress. In the high-stress case, the abrasive particles are able to fracture some of the carbides, and as a result, the volume wear increases slightly.

There are some other slight changes in the rankings of the materials when the abrasive wear mode is changed to one of high-stress. Although hardness is a good first indicator of how a material will perform in a tribological setting, it does not unambiguously define wear performance. Other factors like fracture toughness and work-hardening ability of the matrix also play a part in establishing the overall performance. Unfortunately this area of research has been overlooked, and it is not possible to pinpoint the exact reason why the 304 SS steel performs almost as well as the AISI 4340 (hardened) steel.

In addition to ranking materials, the pin-on-drum abrasive wear test is very effective at discerning volume wear and wear mechanisms for a wide range of metals, alloys, composites, ceramics, and polymers. The surface area remains constant during the test and consequently different materials can

Table I. Typical dry-sand, rubber-wheel wear test results.

Alloy and Designation	Hardness (BHN)	Volume Loss	
		Procedure A	Procedure B
304 SS	153	408.0	170.8
ASTM A514	269	------	134.1
AISI 4340	515	------	74.0
D2 Tool Steel	608	45.3	14.6
Cr White Cast Iron	698	31.5	12.7
AISI 1060 (Hardened)	716	------	32.1

Table II. Typical pin-on-drum wear test data for ferrous alloys and composites (66.7 N load, 6.35 mm diameter pin).

Alloy and Designation	Hardness (BHN)	Wear Loss	
		WF	(mm^3/m)
304 SS	153	0.73	0.86
ASTM A514	269	0.98	1.11
AISI 4340	515	0.73	0.95
D2 Tool Steel	608	0.42	0.49
Cr White Cast Iron	698	0.27	0.31
AISI 1060 (Hardened)	716	0.50	0.56

Table III. Typical Impeller-Tumbler Wear Data for Ferrous Alloys

Alloy and Designation	Hardness (BHN)	Volume Loss (mm^3/hr)
304 SS	153	104.7
ASTM A514	269	94.7
AISI 4340	515	89.7
D2 Tool Steel	608	69.5
Cr White Cast Iron	698	67.1
AISI 1060 (Hardened)	716	63.9

be compared directly.

Impeller-Tumbler Impact Wear Test. Typical impeller-tumbler wear results are found in Table III. For the ferrous alloys tested, the volumes loss decreases as the hardness of the alloy increases. The impeller-in-drum produces an environment that has aspects of both impact and abrasion. The tests are relatively easy to perform, taking approximately three hours to run a duplicate set of samples. In the Albany set-up, three materials are run at a time. Results are fairly reproducible, especially when the materials are homogeneous and have uniform through section hardness.

It is interesting the impeller-in-drum wear test ranks the materials exactly according to their hardness (i.e., for those materials listed in Table III). It should not be construed that this is always the case. Typically, for monolithic materials, the impact-abrasive wear test ranks materials of a general class (e.g., all martensitic alloys) pretty much according to their hardness. However, if Cr white irons (with different heat treatments) or other types of ferrous alloys and composites are added, the picture becomes less clear. (See Figure 2(c).) It has been noticed that composite materials, or materials with a hard second phase, do not in general perform as well in this environment as they do in one of pure abrasion, be it low-stress or high-stress.

As was discussed in the previous section, the interrelationship between a material's mechanical properties and its wear behavior is not precisely known. Thus, it is hard to say why some low hardness materials perform well in this test compared to high hardness materials. We have performed Vickers hardness tests on the impacted and abraded surfaces that result from this test for materials run for four hours. For a 304 SS, the hardness increased from 205 VHN at the start of the test to a value of 470 VHN at its conclusion (130% increase). Alternatively, the hardness for a 4340 steel increased only about 2% under the same conditions (i.e., from 540 to 550 VHN, although the scatter in the tested sample was high). So it is clear that the structure of the near surface region changes greatly and this affects the subsequent wear behavior of the material. It is also clear that the mechanical properties of the material being tested are also important in understanding just how that material will perform in a particular tribological environment.

Correlation of Wear Data

A number of ferrous alloys and composites were run in the laboratory to determine their wear behavior using the dry-sand, rubber-wheel, the pin-on-drum and the impeller-tumbler wear tests. These materials can be divided into the following five groups: austenitic stainless steels, miscellaneous hardened (i.e., martensitic) steels and white cast irons, powder metallurgy (P/M) tool steels, AISI 4340-type steels (i.e., slightly different chemistries and different heat treatments), and P/M TiC reinforced ferrous composites. In addition, the Brinell hardness of each of the materials was determined as an ancillary mechanical property with which to make correlations.

Figure 1 consists of two graphs for commercially available wear resistant steels used for wear applications in the mining and minerals processing industries. Their particular composition is unimportant, however, they have all been hardened to between 3.8 and 5.4 GPa (360 and 520 BHN). The microstructures are roughly equivalent in nature, with the matrix consisting primarily of martensitic bainitic structure with possibly some retained austenite. In both graphs, (a) for the plot of volume loss from abrasion using the dry-sand, rubber-wheel and (b) for the plot of volume loss per meter of travel on the abrasive paper, a linear relationship with hardness can be used to describe the data. In both cases the volume loss decreases with increasing hardness.

In Figure 1(a), the relationship between DSRW wear and hardness can be described by the empirical relationship:

$$\Delta V_{DSRW} = 239 - 0.35\ \text{BHN}$$

The r^2 value for this data set is 0.93, which implies a fairly strong correlation between DSRW wear and hardness. For the case of pin abrasion, a linear fit of the data yield an empirical relationship of the form:

$$\Delta V_{pin} = 1.75 - 0.002\ \text{BHN}$$

In this case, the r^2 value is only 0.58, a good indication of the scatter in the data which implies little correlation between pin volume wear and hardness. In Figure 1 the 95% confidence interval is shown as dotted lines on the respective graphs. In Figure 1(a) all data points but three lie within this interval. In Figure 1(b) six data points fall outside this interval.

In Figure 2, there are three graphs of volume loss versus Brinell hardness, where a wide range of ferrous alloys and composites have been tested. In these instances, the materials tested consisted of austenitic stainless steels, powder metallurgy tool steels, powder metallurgy TiC reinforced composites, and various other steels and cast irons. (The key to the alloys and composites are found on the plots.) In Figure 2 (a) and (b), the same trend is observed as occurred in Figure 1. Generally speaking, there was a decrease in the volume of material lost due to abrasion as the hardness of the alloy or composite increased. The major difference between the data in Figure 1 and 2 is that there is more scatter in the results in Figure 2. This occurs primarily as a result of the variety of alloys and composites tested, where some of them have hard carbide reinforcement. This is especially noticeable in Figure 2(a), the data for the dry-sand, rubber-wheel where at the higher hardnesses (>6.9 GPa or 650 BHN), there is little change in volume loss with increasing hardness. In fact the DSRW data in Figure 2(a) is seen to follow two diverse trends, one for the monolithic alloys of low-medium to high hardness (~600 BHN), and one for the P/M TiC reinforced composites and tool steels (>600 BHN). For the latter materials, there is little change in

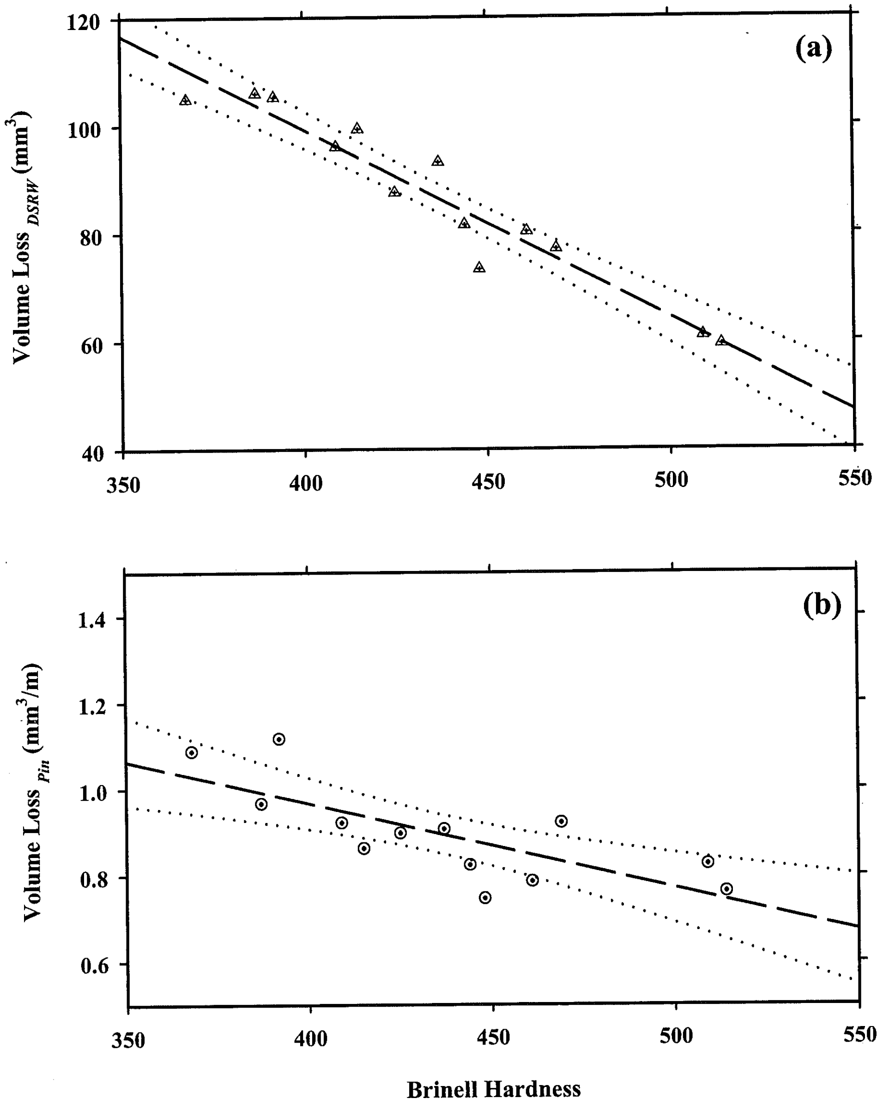

Fig. 1 - Plots of volume of material lost to abrasion as a function of Brinell hardness for a series of martensitic wear resistant alloys: (a) for tests run on the dry-sand, rubber-wheel and (b) for tests run on the pin-on-drum.

volume wear with change in hardness.

For the pin data, there is only one general trend, i.e., a decrease in volume wear with increasing hardness. As was observed in Figure 1(b), there is significant scatter in the data, but in general there is no significant deviation in this general trend.

Figure 2(c) shows the results of the impeller wear test. In this case the data is more widely scattered than in the previous two graphs, and no trend with hardness is apparent. For the monolithic materials the trend between volume wear and hardness is essentially flat (although in a real sense volume wear decreases with increasing hardness, just not as quickly as for the DSRW and pin abrasion wear tests). However, anomalous response in the wear behavior can be noted at the higher hardnesses. Instead of all the data in the plot falling on one curve, several trends are now apparent. For example, the powder metallurgy materials with reinforcing carbides show internally consistent behavioral trends quite different from each other and from the more homogeneous martensitic and austenitic steels and cast irons. Indeed, the powder metallurgy materials with high volume fractions of carbides exhibit volume losses equal to or greater than materials several hundred BHNs lower. This is indicated in the figure by lines showing the volume wear-hardness relationship for these materials. It is clear that the slope is much steeper in each instance than for the monolithic alloys. This anomalous behavior is an indication that the carbides are generally less effective in reducing the wear in an environment that includes impact events in addition to abrasion.

Figure 3 presents three graphs which depict the correlations between the various laboratory wear tests. In

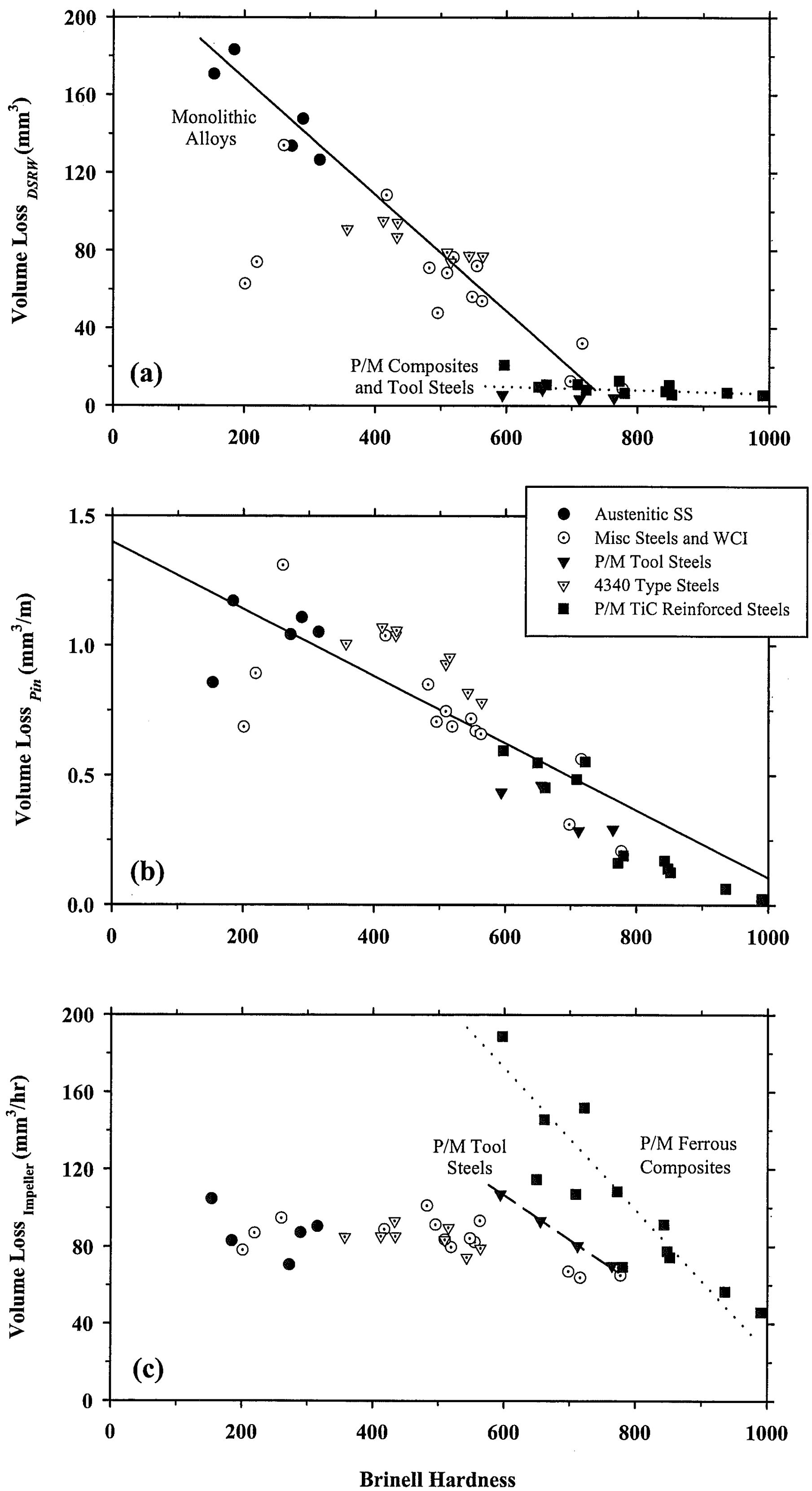

Fig. 2 - Plots of volume of material lost to abrasion and impact-abrasion as a function of Brinell hardness for various steels, irons and P/M ferrous tool steels and composites: (a) for tests run on the dry-sand, rubber-wheel, (b) for tests run on the pin-on-drum, and (c) for tests run on the impeller-in-drum.

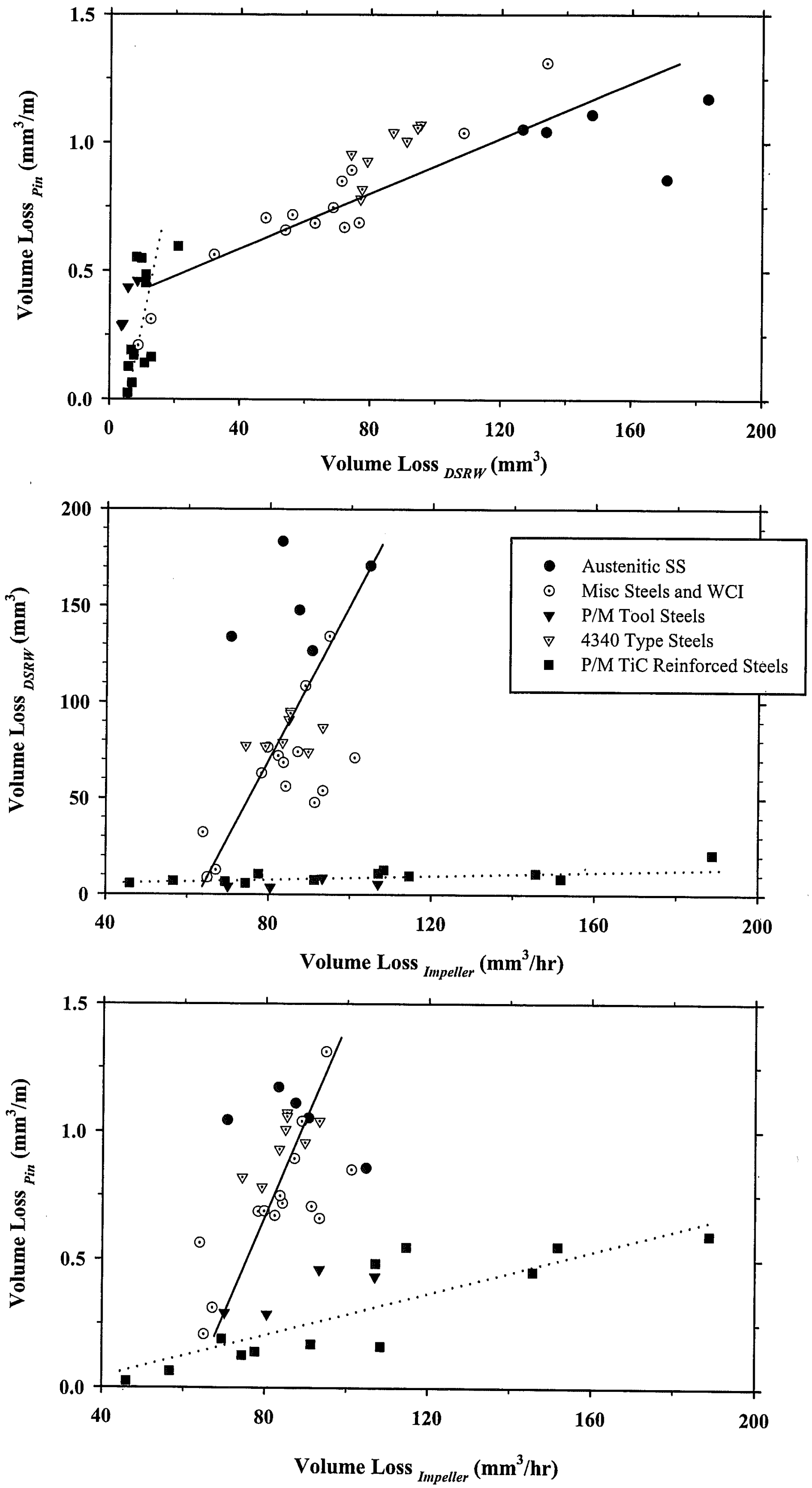

Fig. 3 - Plots of correlations of material lost to wear for (a) pin-on-drum versus dry-sand, rubber-wheel, (b) dry-sand, rubber-wheel versus impeller-in-drum, and (c) pin-on-drum versus impeller-in-drum.

Figure 3(a), for example, the relationship between volume loss due to pin abrasion and that from the dry-sand, rubber-wheel is depicted. Although there is a good deal of scatter, a relationship between the two purely abrasive wear tests is apparent. As was noted earlier in the graphs of volume wear versus hardness, two distinct regions stand out. In the low wear region of the graph, the carbide reinforced materials are much more effective in a low-stress wear environment, showing little change in DSRW volume wear. Conversely, these materials do not perform as well in the high-stress wear environment, as indicated by the almost vertical slope of the curve through the data. This is not too surprising because in the high-stress case, the abrasive can fracture and/or pluck out the reinforcing carbides. This is not a viable material removal mechanism in the low-stress case. Thus, the rate of material removal will be higher for the pin abrasion test.

In the high wear region, there is more of a "one-to-one" correlation between the wear from the DSRW and the wear from pin abrasion. This is not surprising either, because these materials performed in roughly the same way in the graphs of volume wear versus hardness.

When the data from the impeller-tumbler wear test is graphed against that of either the pin abrasion or the dry-sand, rubber-wheel test, the anomalous behavior of the powder metallurgy composites once again stands out compared to the other data. In both cases, data from the martensitic and austenitic steels and cast irons form one trend, while the data from the powder metallurgy materials follow another trend. For the steels and cast irons, large relative changes in volume loss from pin abrasion and dry-sand, rubber-wheel abrasion result in modest changes in the loss of material from impact-abrasion. On the other hand, for the PM alloys and composites, the reverse is true. In this case, small changes in purely abrasive processes can correspond to rather large changes in the impact-abrasion behavior. Consequently, it is apparent that the PM materials should not uniformly be used in impact or high-stress conditions without careful testing to see if the carbides remain intact as a result of grinding abrasion and/or impact.

Summary and Conclusions

A suite of laboratory wear tests has been described for testing ferrous alloys and composites. These laboratory tests simulate the various forms of abrasion and impact-abrasion, and offer a reliable and quick way to screen materials for anomalous wear behavior.

When using these or any other laboratory wear tests, the wear classifications of the "real" tribological environment need to be carefully assessed to see if more that one of them is operating. This will provide a rational way to select which of the laboratory wear tests that should be used in evaluating the wear behavior.

Finally, given the high degree of scatter in wear data, a functional relationship between data from different wear tests may not emerge. However, trends within classes of alloys will be present, and good/poor performers will stand out.

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