THE CHALLENGE OF ACCURATE PREDICTION OF INDUSTRIAL WEAR PERFORMANCE FROM LABORATORY TESTS

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Abstract

Several plant wear trials and several laboratory test methodologies are described and analysed. Each example is evaluated in terms of its success (or lack thereof) in yielding useful quantitative performance data for candidate wear-resistant materials. Field trials are challenging, though if performed with sufficient care and resources they can yield useful quantitative data. To be useful, a laboratory test must satisfy several performance criteria, notably: It should simulate with reasonable fidelity both the macro-mechanics and micro-mechanics of the conditions present in the field; it should be validated against field trials and confirmed to produce accurate quantitative performance predictions for various classes of materials; it should not be excessively sensitive to precise set-up conditions; and it should provide reasonable data productivity and statistical quality. Rather than attempting to break down a complex industrial wear process into its individual component mechanisms and "engineer" each of these mechanisms in the laboratory, fidelity is more likely to be achieved by a mechanically simple device that preserves the natural complexity of the industrial wear process.

In the process of the case studies, commentary is given on two key modes of abrasive wear, namely high normal stress abrasion (HNSA) and low stress sliding abrasion (LSSA). An important lesson from this analysis is the fundamental observation that LSSA does not equate to low wear rates; indeed, the highest wear rates observed industrially are from LSSA, due to the dominance of tangential sliding and high tonnage throughputs. The nature of LSSA is such that materials selection has the capacity to achieve much greater percentage improvements in component service life than is possible in HNSA situations. The proposed new generation of field-validated laboratory tests will provide confidence to invest in the development of superior wear-resistant materials. One promising class of wear-resistant casting alloy is a "double composite" in which niobium-rich carbides provide additional reinforcement to a conventional chromium carbide eutectic cast iron.

Introduction and Aims

Materials Selection for Mining and Minerals Processing Plant

The operators of mining and mineral processing plant face a difficult challenge when selecting the best wear-resistant material for each item of equipment at their site. Experience demonstrates that there is no single material that performs well in every situation. For example, alloys that perform well in slurry pumps are not necessarily the best alloys for ball mill liners or ore chutes. Similarly, alumina-based ceramics might perform reasonably well in some ore chutes, but would not be expected to perform well in ball mills or ground-engaging tools. These differences in the relative performance of candidate wear-resistant materials are due to the different ways in which their microstructures respond to the operative wear modes in these different applications.

Selection of the best or most cost-effective wear-resistant material or product relies upon an understanding of the factors that control the relative performance of the various candidate classes of materials in different wear modes. Moreover, even when armed with such specialist understanding, it is not possible to reliably predict the best material from first principles or general experience alone; appropriate wear tests must be performed utilising the target ore. This is because wear mode is not a simple function of the macro-mechanics of the industry operation, but is strongly influenced by the mineralogy and other properties of the ore.

The requirement for physical tests to be performed raises the need for access to reliable test methodologies. In principle, the gold standard for data generation is a full-scale plant trial or field trial. However, full-scale plant or field trials are expensive, time consuming and carry considerable risk. Moreover, wear rates in the plant can be affected by variable characteristics of the ore stream, and it can take a very long time to collect statistically reliable data. On the other hand, plant operators are justifiably suspicious of the predictions from laboratory tests, which have often been demonstrated to have poor predictive ability.

Aims and Strategies

The objective of the authors' research is to develop new laboratory abrasive wear test methods that are superior to some of the commonly used tests that have been shown to be flawed. Any proposed new laboratory test in this field should satisfy all of the following criteria:

- It should reproduce or simulate, with reasonable fidelity, the actual abrasive wear conditions that are present in the field - notably the ore itself and the contact mechanics;
- It should be validated against empirical trials in the field, and confirmed to produce comparable quantitative relative performance data for different wear-resistant materials;
- It should not be excessively sensitive to precise set-up conditions;
- It should provide reasonable data productivity and statistical quality.

The first criterion above mentions the "ore", that is, the abrasive substance that will be encountered in the plant. Perhaps the most important single requirement for any abrasive wear test is that it must use the same abrasive medium as will be encountered in the target industry operation. It is well established that abrasive wear resistance is not a fundamental material property; it is a system property. This principle is so important, but so often forgotten, that it is worth quoting M.A. Moore [1] on the subject: “In selecting and specifying laboratory wear tests, attention must be paid to the fact that wear performance is systems related, depending not only on materials properties, but also on the characteristics of the abrasive, sliding and loading conditions.” Predictions of industry performance based on laboratory tests using some idealised abrasive substance are very likely to be misleading. This phenomenon will be illustrated in some of the case studies presented in this paper.

Rather than attempting to break down a complex industrial wear process into its individual component mechanisms and “hard-engineer” each of these mechanisms in the laboratory, the first criterion above is more likely to be satisfied by a device that “preserves the natural complexity” of the industrial wear process. The most successful laboratory tests will be those that are mechanically simple at an external macroscopic scale, but are permitted to sustain complex conditions at the internal microscopic scale. This microscopic complexity is what occurs in industrial service, and efforts to simplify it or apply hard controls to the individual component mechanisms are more likely to introduce errors than to achieve useful outcomes.

Controlled experiments can still be carried out in such externally simple, internally complex test devices, by a “subtraction” principle more so than by an “addition” principle. For example, if it is desired to assess the contribution of corrosion mechanisms to an industrial wear environment, the researcher can attempt to “subtract” the corrosion component by a variety of means, such as removing oxygen, removing electrolytes, use of inhibitors, replacing water by inert fluids, use of corrosion-resistant materials, and combinations of these measures. The corrosion component in the natural environment can be assessed by observing the reduction in the total wear rate that occurs when these measures are taken. The interpretation of the results may not be simple, but such experiments are likely to be more illuminating than tests in which the rate of corrosion is measured in some idealised test that bears no resemblance to the service environment.

This paper will present a number of case studies, sourced both from published literature and from the authors’ own work, to illustrate the comparisons between field performance data and the data from various laboratory abrasive wear tests. The ultimate aim is to encourage the wear research community to move from simplistic laboratory tests, which do not reproduce plant conditions and hence cannot predict plant performance, towards a new generation of laboratory or pilot-scale tests that do reproduce plant conditions with reasonable fidelity and can predict plant performance with reasonable accuracy.

Levels of Correlation between Laboratory and Field Performance

In assessing the correlation between laboratory abrasion test data and plant wear data, four levels of correlation fidelity (and hence predictive ability) should be considered, as follows:

1. Rank correlation, or monotonic increasing correlation: If material A wears faster than material B in the laboratory test then the same ranking should be observed in the plant;
2. Linear correlation: A plot of wear rates for various materials in the field or plant versus their wear rates in the laboratory should show an approximately linear form;

3. Quantitative relative correlation, or unit slope correlation: If material A wears for example 60% faster than material B in the laboratory test, then a similar relative wear rate should be observed in the plant. That is, a plot of relative wear rates in the plant versus relative wear rates in the laboratory should show a linear form with a slope of approximately 1;
4. Quantitative absolute correlation - if a material experiences a wear rate in the laboratory test of for example 10 g/MJ then a similar wear rate should be observed in the plant.

Level 1 correlation is clearly inadequate, since it does not provide sufficient information to determine the most cost-effective material to use for a given target application. Swanson [2] described both level 2 correlation (expressed as a "linear correlation between the relative wear rates (or resistances) measured in the laboratory and the field") and level 4 correlation (expressed as "the wear coefficient, K, in the abrasive wear equation, producing similar results in both the field test and the laboratory test"). Swanson did not consider the possibility of a level of correlation intermediate between levels 2 and 4; but in the opinion of the current authors, level 3 correlation should usually be sufficient, since it can determine the most cost-effective material for a given application. Moreover, if the plant wear rate for a benchmark material is available, then a level 3 correlation can even permit prediction of the absolute wear rate for a new material. Full level 4 correlation is only required when attempting to predict operating costs for a plant that is yet to be built.

Case Studies from Literature

<u>Scarcity of Field Performance Data</u>

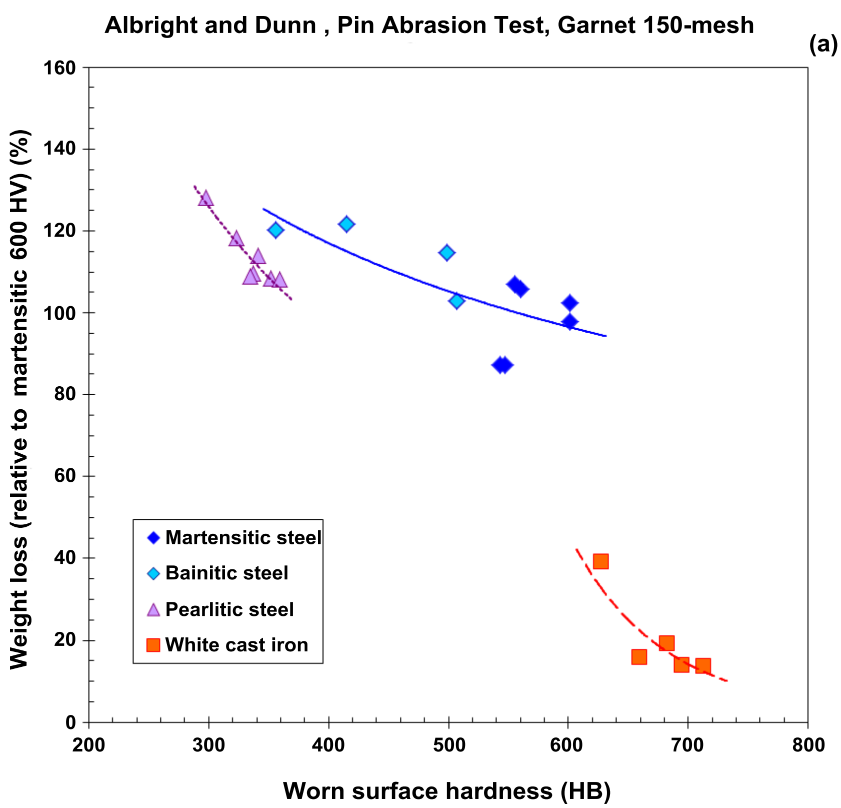
Because plant trials are difficult and expensive to perform, and since confounding variables often render the resulting data questionable, relatively few published studies exist that provide credible plant data. Even more scarce are studies in which credible plant data are correlated with systematic laboratory data for the same or comparable alloys. One of the main aims of the current study is to present some examples of published studies in which this challenging task has been carried out successfully.

<u>Industrial Ball Mill Trial – Albright and Dunn 1983</u>

One of the most detailed and fruitful plant trials that the current authors are aware of was that performed by Albright and Dunn [3]. The plant trial was performed in two nominally identical grate-discharge ball mills, each 2.9 m diameter and 2.4 m long. Each mill was lined with 20 integral-lift shell liners, 1040 mm long and 430 mm wide. The liners had a relatively shallow triple-wave profile, 83 mm thick at the peak and approximately 52 mm at the trough. A total of 40 liners were cast from 22 different alloys and distributed between the two mills. The mills were fed with ore from the Climax Molybdenum mine in Colorado U.S.A., consisting primarily of quartz and granite with a small proportion of MoS_2. The two mills were operated with nominally identical ore feed type and tonnage throughput, until perforation of the least abrasion-resistant liners after approximately 4800 hours operation.

To achieve a useful comparison with the plant data, Albright and Dunn were aware of the need to select a laboratory test that would produce a wear mode matching that of the plant environment. They judged that the grinding mill environment would be characterised by high stress abrasion, as opposed to either low stress abrasion or gouging abrasion. They then stated that "it is widely agreed that the laboratory pin type test provides reasonable insight into the behavior of materials under conditions of high-stress grinding abrasion." This "widely agreed" view will be subjected to critique in the current paper.

Albright and Dunn plotted mill trial mass loss and pin test mass loss, both against liner hardness and against carbon content. After converting the raw mass loss values into a dimensionless relative wear rate (relative to the average wear rate of several martensitic steels with average hardness 600 HV), Gates et al. [4] replotted the data on similar axes, but identified the specific alloy class for each graph point as either pearlitic steel, bainitic steel, martensitic steel or white cast iron. From these plots, Gates et al. pointed out that there was a significant difference between the form of curve produced by the mill trial and that produced by the pin abrasion test. For convenience, these graphs (Figure 2 of the 2007 paper [4]) are reproduced, in slightly modified form, as Figure 1(a) and (b) below. Unlike the 2007 paper, which converted Albright and Dunn's Brinell hardness values to Vickers, the charts here use the original Brinell values. Another difference is that the graphs below use Albright and Dunn's values for the "worn surface" hardness, whereas the 2007 paper used their "shell surface" values. In contrast to what is sometimes found as a result of work-hardening effects, in this case the worn-surface hardness values are mostly somewhat lower than those measured near the original surface, because the advanced wear reveals the softer core of the casting.



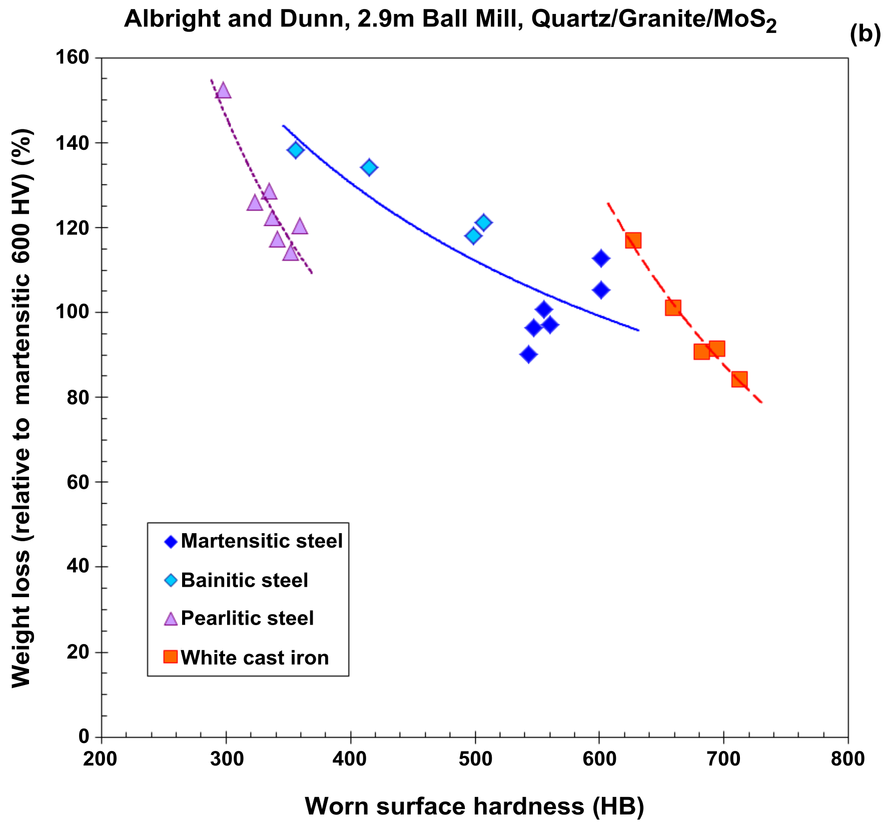


Figure 1. Re-plot of data extracted from Albright and Dunn 1983 [3] (similar to those presented in Figure 2 of Gates et al. 2007 [4]). After identifying the four alloy classes, wear rate relative to martensitic steel of hardness 600 HV is plotted against worn surface hardness.

Explicitly identifying the four alloy classes in the graphs provides a clearer view of the factors controlling wear performance than can be discerned from Albright and Dunn's original graphs. It can be seen, for example, that the pearlitic steels provide better performance (lower wear rates) than their low hardness would have predicted, if one was judging from experience with martensitic, bainitic and tempered martensitic steels.

In the pin abrasion test, as shown in Figure 1(a), the white cast irons show very much lower wear rates than the martensitic steels. The bulk hardness of the white cast irons (average 675 HB) is somewhat higher than that of the martensitic steels (average 568 HB), but the dramatic improvement in wear performance is far greater than can be explained by bulk hardness alone. Gates et al. 2007 [4] argued that the performance advantage is due to the well-documented "particle-reinforced composite effect." The network of very hard chromium-rich M_7C_3 carbides in the white cast iron very effectively protects the matrix and provides abrasion resistance much greater than would be predicted by bulk hardness alone.

However, in the ball mill plant trial, as shown in Figure 1(b), the white cast irons do not show any significant benefit compared to the martensitic steels. Evidently, the carbide network is no longer providing a significant protective effect. It can readily be demonstrated that this loss of the protective effect is due to the introduction of micro-fracture wear mechanisms in the brittle carbides under the conditions of the industrial ball mill.

Many authors have attempted to explain this micro-fracture as being due to the effect of "impact" in the industrial mill. However, Gates and co-workers [4,5] demonstrated that the micro-fracture does not require "impact", being easily shown to occur in small laboratory ball mills operated in sliding mode, hence without significant impact. The authors argued that the micro-fracture is simply characteristic of "high stress abrasion" conditions. They argued that high stress abrasion requires only two conditions to be satisfied:

- A rigid metal counterface that acts to crush the abrasive particles into the wearing surface with significant force;
- An abrasive mineral that has sufficient strength (hardness and fracture toughness) to *transmit* the contact force from the counterface to the wearing surface so as to cause micro-fracture of the reinforcing particles.

The comparison between industrial plant trial behaviour and laboratory abrasion test behaviour can be further elucidated by plotting the wear rates from the two tests directly against each other, rather than by plotting each separately against hardness. Albright and Dunn [3] provided such a direct comparison in Figure 8 of their paper - plotting pin test mass loss against mill trial mass loss. A similar method of presentation has been used in Figure 2 below, plotting dimensionless relative wear rates and again identifying the four alloy classes.

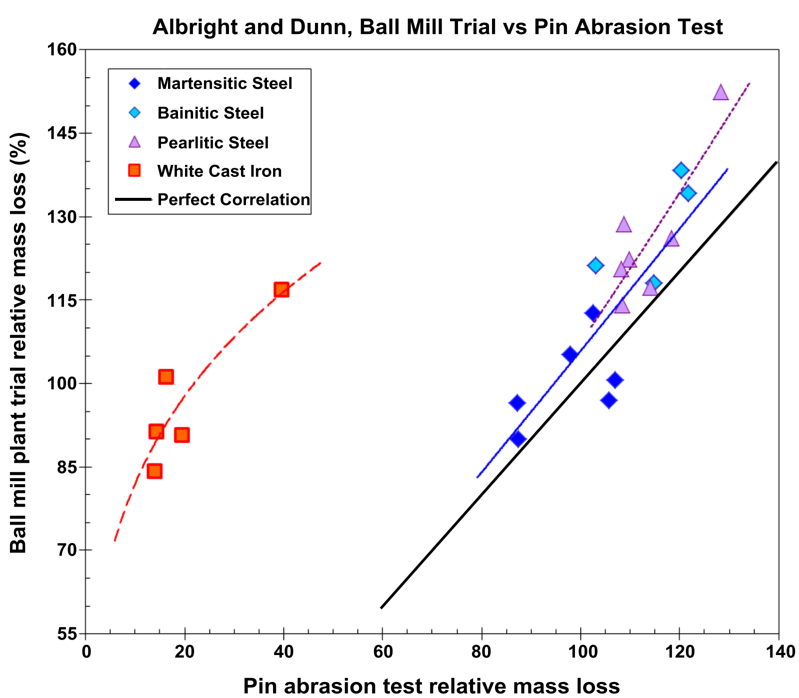


Figure 2. Re-plot of data extracted from Albright and Dunn [3]. Directly compares wear rates from the industrial ball mill trial (grinding quartz and granite) against those for the same alloys in the pin abrasion test (using 150-mesh garnet cloth).

If we consider only the steel liner alloys, the correlation between the laboratory test and the plant trial appears to be quite good. Within the 17 steels, rankings are largely preserved between the two tests (within a reasonable statistical scatter), and indeed the correlation appears close to linear. Hence, the pin abrasion test achieves at least “level 2” correlation with the mill trial. Continuing to focus on the steel data, it can be seen that there is a reasonably good match between the quantitative relative wear rates in the two tests. For example, the ratio of the worst-performing steel (pearlitic steel, alloy H) to the equal-best performing steel (martensitic steel, alloy C) is 1.47 in the pin abrasion test and 1.69 in the mill trial. This means that the pin test predicts that the hard martensitic steel will out-perform the soft pearlitic steel by 47%, and in the industrial mill trial the actual benefit is slightly greater, at 69%. Although this is not perfect agreement (the slope of the curve deviates from unity), it is far better than is often achieved by laboratory tests, and might reasonably be judged to achieve “level 3” correlation.

However, if we now turn our attention to the white cast irons, and consider their performance compared to steels of comparable bulk hardness, we can see that the correlation breaks down. The marked difference in behaviour between the two groups can be discerned by comparing the ratio of wear rate of the martensitic steels taken as a group to that of the white cast irons taken as a group. In the pin abrasion test, this ratio is 4.8, but in the mill trial the ratio is only 1.03. Thus, the pin test predicts that white cast irons will give approximately 380% improvement in service life compared to steels, but in the mill trial the white cast irons give negligible improvement. This dramatically demonstrates the inadequacy of the pin abrasion test in predicting plant behaviour. The difference is best understood in terms of a difference in wear mode. In the industrial ball mill environment, with an ore with high quartz content, the wear mode is clearly high stress abrasion, such that particle-reinforced composite alloys provide no significant benefit over homogeneous alloys of comparable bulk hardness. By contrast, the pin abrasion test with garnet abrasive is clearly manifesting a low stress abrasion mode.

This finding is in stark contrast to the widespread view, as articulated by Albright and Dunn, that the pin abrasion test simulates high-stress abrasion. Such a view persisted into later publications, such as those by Hawk, Tylczak and co-workers [6,7] which state that the pin-on-drum test “involves high-stress two-body abrasive wear.” The fallacy of this traditional view of the pin abrasion test has been thoroughly demonstrated by Gates et al. 2007 [4].

A comparison between Figure 1 and Figure 2 reveals that, within the steels, the wear rates in the two test types correlate better with each other than they do with measured hardness. This is an illustration of the fact that wear resistance is not controlled simply by hardness but is significantly affected by the details of the microstructure.

As noted above, if attention is restricted to steels, ie excluding particle-reinforced composites, then the correlation between the pin abrasion test and the ball mill plant trial appears quite good. Indeed, within this restricted set of materials, the test appears to achieve level 3 quantitative relative correlation with a slope very close to 1.

For researchers who have access to the traditional pin abrasion test in one of its forms, it may be tempting to take a view that, so long as comparisons are drawn only between alloys within a given class, the pin test can provide reliable correlation with service performance. Precisely such a concept was suggested by Hawk et al. [6], who wrote "… 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 (such as hardened martensitic steels) will be present, and good/poor performers will stand out." Taken at face value this might be a true statement. However, a laboratory test that is only able to compare materials within a single specific class, and which provides clearly erroneous predictions about other material classes, must be treated with suspicion. At best, such a test should be regarded as having "very limited applicability". In the opinion of the current authors, it is more appropriate to deem the pin test as "unsuitable" for evaluating materials for comminution environments, because it produces a completely different wear mode.

In conclusion, it has been demonstrated that the pin abrasion test does not represent high stress abrasion in any industrially meaningful sense. Consequently, for the prediction of performance in comminution environments, tests should be sought that simulate the industry wear conditions with greater fidelity.

<u>Agricultural Tools - M.A. Moore 1987 and Bialobrzeska 2015</u>

Moore [1] discussed the principles by which a suitable laboratory test might be selected to simulate a given service environment, and hence predict the relative performance of candidate wear-resistant materials. He divided laboratory wear tests into two main categories, according to whether the abrasive particles are loose or fixed. In each of these categories he listed four test types, depending on the contact geometry and nature of the motion (such as circular motion on a rotating flat plate, reciprocating motion on a flat plate, linear motion on a belt, linear motion on the cylindrical surface of the tyre on a rotating wheel, etc.). We regard some of these as so closely equivalent that they do not require separate consideration. In particular, in the case of tests involving the rubbing of the initially flat end of a pin specimen on bonded abrasive cloth, it should be of minimal consequence whether the motion is achieved by circular motion of a flat plate (pin-on-disk test), rotation of a cylinder (pin-on-drum test), or by reciprocation of a flat table (pin-on-plate test). On the other hand, we regard two of Moore's eight listed categories as requiring subdivision, since they have differences that significantly alter their behaviour. These are the loose abrasive tests which Moore described as "Pin-on-Disc or Ring-on-Disc" and as "Rubber (or Steel) Wheel."

In accordance with our understanding of the factors likely to have a significant effect on the relative performance of different wear-resistant materials, we suggest that Moore's eight laboratory test types should be re-grouped into six categories as follows:

- Fixed 1 - Grinding Wheel Abrasion Test, using solid bonded grinding wheel;
- Fixed 2 - Pin Abrasion Test, or more precisely Pin-on-Bonded-Abrasive Test, using bonded abrasive cloth (pin-on-disk, pin-on-drum, pin-on-plate);
- Loose 1 - Pin-on-disk (and potentially pin-on-plate) test converted to an abrasive wear test simply by spreading loose abrasive particles onto the flat surface and assuming that some of the abrasive particles will enter the planar contact zone;

- Loose 2 - Steel Wheel Abrasion Test (and potentially Ring-on-Disk and Four-Ball Micro-abrasion Tests), with either a block specimen held against the rim of a rotating steel wheel or other tapering contact geometries, such that the loose abrasive particles are fairly reliably entrained into the tapering contact zone;
- Loose 3 - Rubber Wheel Abrasion Test, with block specimen held against the rim of a rotating rubber-tyred wheel, such that the loose abrasive particles are reliably entrained into the tapering contact zone;
- Loose 4 - A test described as "Abrasive Tank or Bin", which Moore did not describe in more detail but which is likely to have consisted of rod specimens tracing a circular path through a stationary container of abrasive or, equivalently, stationary rods in a rotating container.

Analysis of example data from tests of the type designated Loose 1 and Loose 2 suggests that tests of this type are seriously problematic, because the wear rate is a strong function of the effectiveness with which the abrasive particles are entrained into the contact zone. Tests of the type Loose 1 are likely to be irretrievably unreliable, because there is no physical reason why the abrasive should be reliably or consistently entrained into the tight planar contact zone. Even in the somewhat better Loose 2 contact geometry, it has been demonstrated that the effectiveness of entrainment and the velocity and mode of particle motion through the contact zone is strongly affected by the relative hardness of the specimen and the counterface. Gore and Gates [8] provided a detailed demonstration of how this "differential friction effect" can lead to highly misleading predictions of the relative performance of alloys. For example, a high speed tool steel with a hardness of 880 HV was measured to have a wear rate comparable to that of aluminium with a hardness of only 80 HV — a result that is unlikely to be reproduced in any field environment.

Tests of the type designated Loose 3 and Loose 4 can be regarded as producing low stress abrasion wear modes, whereas those of type Loose 1 and Loose 2 can be regarded as producing high stress abrasion. For this reason, tests of the type Loose 2, commonly known as the Steel Wheel Abrasion Test (SWAT), are gaining popularity among comminution researchers. However, because of the differential friction effect as discussed above, there are severe reservations about the reliability of predictions from this test. In a paper from the authors from 2007 [4], the Ball Mill Abrasion Test (BMAT) is proven to be a greatly superior laboratory test for the prediction of performance for comminution environments, however, in 1987 Moore was not aware of the BMAT.

Very limited data have been published for tests of the type Fixed 1 or Loose 4. The most commonly used laboratory abrasive wear tests are of types Fixed 2 (Pin Abrasion Test) and Loose 3 (Rubber Wheel Abrasion Test).

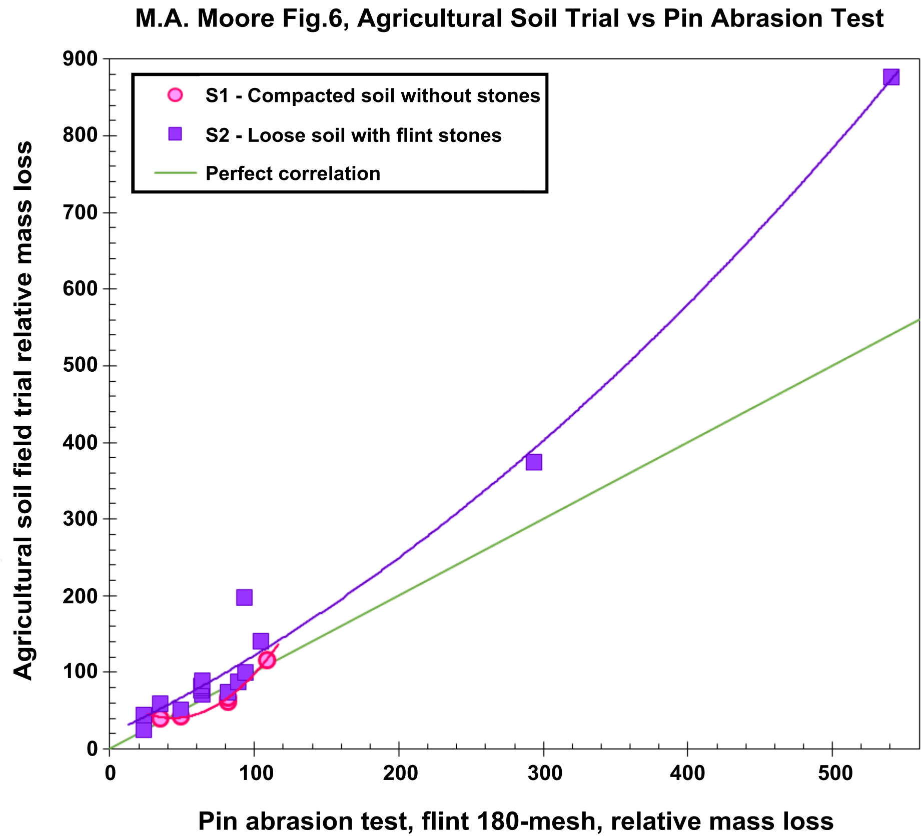
In seeking a laboratory test to simulate the wear of agricultural tools when cultivating stony soils, Moore judged that a test with fixed abrasive was more appropriate than one with loose abrasive. He cited evidence from previous research which had shown that, for typical soil particle size distributions, the wear of agricultural tools tended to be dominated by interactions with stones in the size range 19 to 38 mm. Analysis of load-time history indicated that the most important interactions were not the transient impact events, when a tool first strikes a stone (2 to 250 MPa but less than 1 ms in duration), but rather the more sustained interactions where the tool pushed the stones through the surrounding soil and the stones would thus slide across the tool surface (0.5 to 2.0 MPa but sustained for 0.5 to 5 s duration). Because the stones are somewhat constrained in the soil matrix, Moore reasoned that an appropriate laboratory test would have a stiff counterface with fixed abrasive - to simulate abrasion of the tool either by the stone surface itself or by finer grit particles trapped between the stone and the tool.

Thus, Moore used a test of type Fixed 2, pin-on-disk with bonded flint abrasives in various particle sizes. He compared data from this laboratory test against data from field trials in soils with various stone contents. The relative wear resistance data from Moore's Figures 6 and 7 has been converted to relative wear rate, and the results are presented in Figure 3(a) and (b) below. Over a reasonable range of alloys and soil types, the data show a credible correlation.

This correlation between the pin abrasion test and wear of tools in agricultural field trials should be considered in light of what can be understood about the wear conditions in the field trial. Moore considered that the abrasive asperities on the stones were constrained, and that finer grit particles were "firmly trapped" between the stone and tool surfaces. However, it should not be thought that this represents high stress abrasion in the way that a comminution operation does. Compared to the metallic grinding media in a ball mill, the 19-38 mm stones are relatively light, and their rough surfaces could not be expected to crush the grit particles into the tool surface as strongly as occurs in such a mill. The empirical evidence from data such as Albright and Dunn [3] and other data cited by Gates et al [4] indicates that the Pin Abrasion Test is more representative of low stress abrasion than high stress abrasion, and Moore's agricultural field trials are consistent with this view.

The data presented in Figure 3(a) and (b) achieve at least level 2 (linear) correlation, and could be judged to represent a tolerable level 3 (quantitative relative) correlation. In some regions, the slope of the empirical curve deviates significantly from the ideal value of 1, which must represent differences between the laboratory and field wear modes, but we do not have enough information about the wear-resistant materials or details of the field conditions to permit any more than speculative suggestions regarding the causes of these deviations. It was illustrated by the Albright and Dunn case study that the greatest value is obtained from a field trial when the different classes of wear-resistant materials are clearly identified in the data presentation, and failure to do so risks obscuring important information.

(a)


M.A. Moore Fig.6, Agricultural Soil Trial vs Pin Abrasion Test
S1 - Compacted soil without stones
S2 - Loose soil with flint stones
Perfect correlation
Agricultural soil field trial relative mass loss
Pin abrasion test, flint 180-mesh, relative mass loss
0
100
200
300
400
500
600
700
800
900

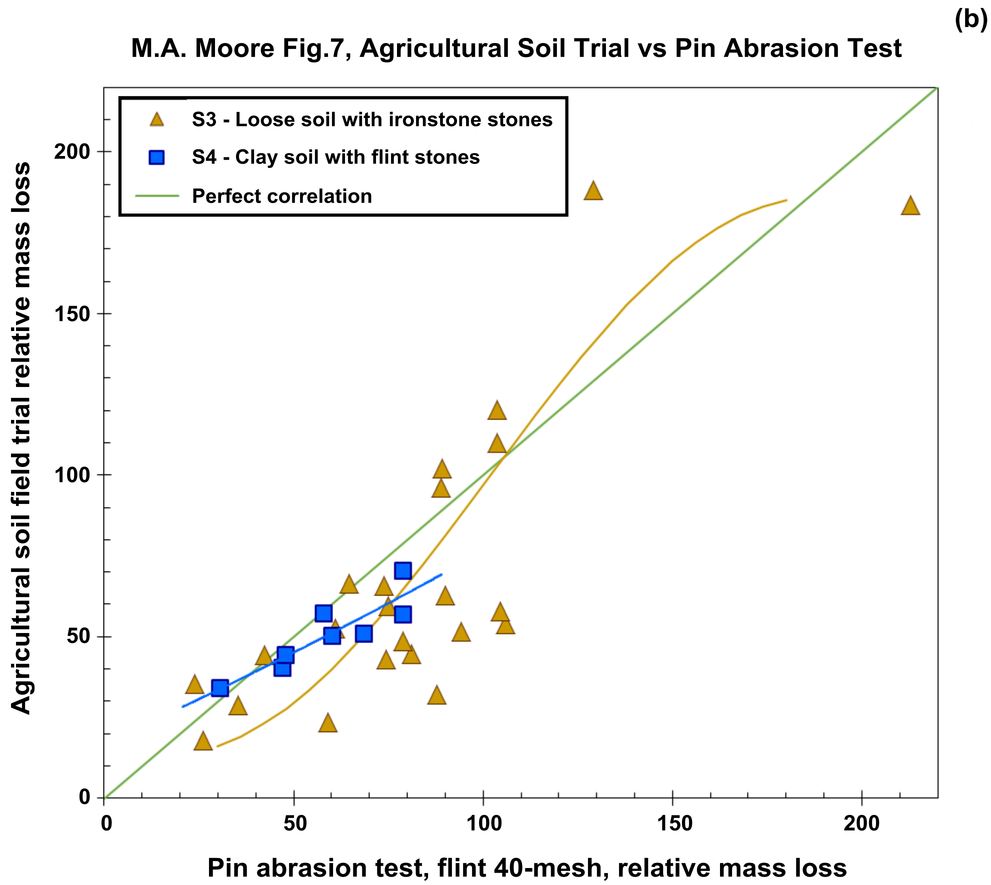


Figure 3. Re-plotted data from Moore 1987 [1] directly comparing wear rates from agricultural field trials against those for the same alloys in the pin abrasion test; (a) using 180-mesh flint, (b) using 40-mesh flint.

Another correlation between laboratory test data and wear measured in an agricultural tool field trial has recently been published by Bialobrzeska and Kostencki [9]. The field trials were performed in cultivated soils largely free of stones. The laboratory tests used the Rubber Wheel Abrasion Test. From the absolute mass loss values presented in their Figure 12, we have calculated relative wear rates and these are presented in Figure 4 below.

On face value Figure 4 could be characterised as showing an adequate level 1 (rank) correlation and perhaps level 2 (linear) correlation, but fall short of a credible level 3 (quantitative relative) correlation because the slope of the empirical curve is much greater than 1. However, it is probably more accurate to observe that the range of wear-resistant materials tested was simply too limited to permit any useful conclusions to be drawn about the quantitative nature of the correlation between laboratory and field performance. All four of the materials used by Bialobrzeska and Kostencki were low-to-medium carbon (0.28-0.37%C) low-alloy steels with hardness in the range 44 to 50 HRC. While such a study might have value for the selection of a specific steel for a given application, it lacks the breadth to be capable of elucidating more widely applicable principles of laboratory-field correlations.

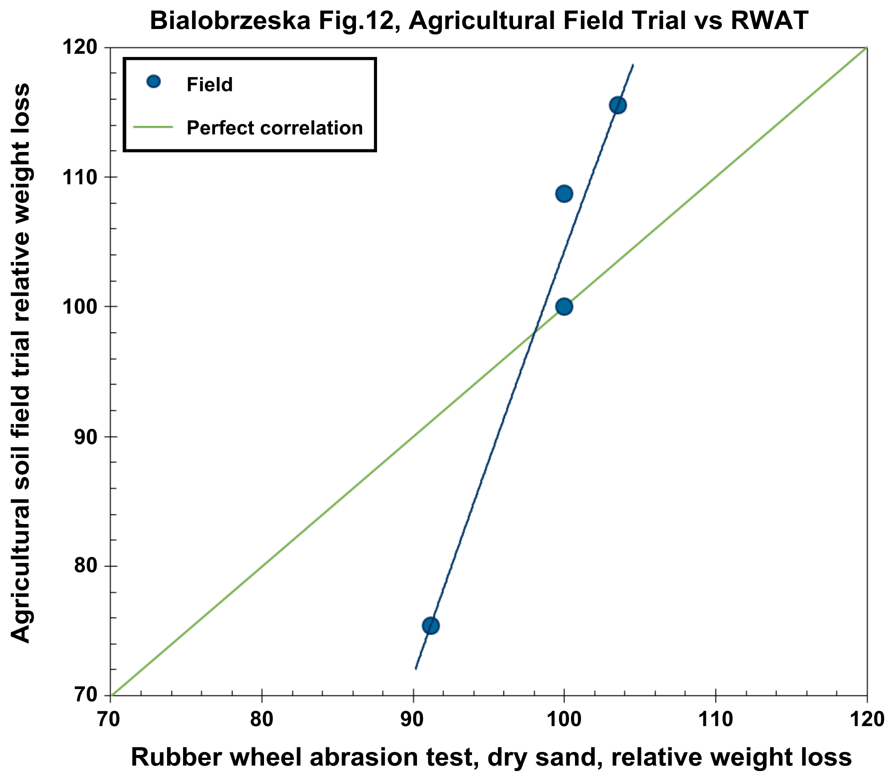


Figure 4. Re-plotted data from Bialobrzeska and Kostencki 2015 [9], directly comparing wear rates from an agricultural field trial against those for the same alloys in the rubber wheel abrasion test.

The BMAT – A Better Test for High Stress Abrasion

Past Usage of Laboratory Ball Mills

Laboratory ball mills are widely used to assess the comminution characteristics of ores. Well-known early descriptions of the use of a laboratory ball mill for this purpose were those by Bond and co-workers in the 1930s [10,11]. However, in the 1950s when Bond wanted to measure the abrasiveness of ores, he did not measure the wear of either balls or liners in a laboratory ball mill. Instead, Bond used a completely different apparatus, measuring the wear of a steel paddle driven by a moderately high-speed rotor (paddle tip velocity 7.2 ms^{-1}), striking falling ore particles inside a co-rotating drum [12]. Although it does cause breakage of the ore particles, the paddle-in-drum device lacks any metal counterface to crush the abrasive particles into the wearing surface, and it bears little relationship to a ball mill. Those of Bond's papers that we have reviewed do not explain why he chose the paddle-in-drum device, other than to say that it was adopted "after several other devices had been tried … and rejected for various reasons" [12].

Although it would seem logical to do so, relatively few researchers have used laboratory ball mills to measure the wear resistance of alloys for either grinding media or mill liners. Those who have done so, or who refer to others having done so, include the following:

J.J. Moore and co-workers [13,14] used a ceramic-lined laboratory ball mill, 203 mm in diameter, operated in batch mode. They described their tests as “laboratory marked ball wear tests.” The term “marked ball wear test” (MBWT) is more commonly used in relation to industrial plant trials rather than laboratory tests, but in principle the methodology can be used in any sized mill. Its significance is the fact that the tests are performed with specimens of several different alloys exposed simultaneously [15] - a very useful feature. Moore’s specimens were 26 mm diameter balls in a wide range of alloys - 0.2%C mild steel, 0.9%C low-alloy tempered martensitic steel, 1.1%C martensitic stainless steel, and three different white cast irons. In many of the tests the abrasive used was quartz with up to 10% pyrrhotite, while other tests were performed using a variety of natural ores. The mineral and chemical environments were manipulated in such a way as to permit identification of contributory wear mechanisms, notably corrosion. They stated that a plant trial was also performed in a SAG mill of diameter 8.2 m, but no quantitative data were presented and it is probable that only a single alloy was used.

Iwasaki, J.J. Moore and Lindeke [16] used laboratory and pilot-scale ball mills of diameters between 203 mm and 1067 mm to explore the effect of mill diameter (and also ball diameter) on grinding media wear rates and mineral grinding performance. They used laboratory mills of diameters between 203 and 914 mm operated in batch mode, and pilot-scale mills of diameters between 305 and 1067 mm operated in continuous open-circuit mode. The focus was on the measurement of absolute values of wear rate, for purposes of understanding the scale-up from laboratory to industrial plant. No comparisons were made between the performance of different media alloys.

Chandrasekaran, Natarajan and Kishore [17] used a laboratory ball mill, 200 mm diameter × 200 mm long, operated in batch mode. The specimens were 30 mm diameter forged low-alloy steel balls. Only a single alloy composition was used, but 15 different heat treatments were applied to give a range of microstructures, including pearlite, martensite, tempered martensite, and bainite. Individual alloys were marked using shallow grooves cut by an abrasive wheel. The abrasive was quartzite, and tests were performed dry. Batch test interval duration was two hours, and a total of three such test intervals were used to evaluate performance. Thirumalaisamy and Kishore [18] also used a laboratory ball mill to conduct “marked ball wear test” experiments on the effect of abrasive feed volume on the absolute value of wear rate. They interpreted the resulting data as evidence for a combination of “impact” and “abrasion” wear mechanisms (although this interpretation has been questioned by Gates et al. [4]).

Radziszewski and co-workers [19-21] used a laboratory ball mill as part of their methodology for assessing the rates and component mechanisms of wear in tumbling mills. However, rather than using it as their primary wear testing device, they used it mainly to assess the corrosion component of the total media wear rate. To measure the abrasive wear component, they elected to use a steel wheel abrasion test of the type that had been explored by Gore and Gates [8], based upon the ASTM G65 rubber wheel abrasion test but replacing the rubber-tyred wheel with a solid steel wheel.

Chenje et al. [22] used a laboratory ball mill 450 mm diameter × 450 mm long, operated in batch mode. The specimens were 60 mm diameter cast balls. Three balls each of five different alloys (low-alloy steels and chromium cast irons) were exposed to the test simultaneously. To distinguish between the alloys, each ball was marked using shallow grooves cut by an angle grinder. The abrasive was granite, and tests were performed wet with 65% solids. Batch test interval duration was five hours, and a total of 16 such test intervals were used in order to evaluate the relative performance of the alloys.

Albertin and Sinatora [23] used a 400 mm diameter laboratory ball mill to compare the wear performance of a variety of white cast iron alloys, varying both carbide volume fraction and matrix microstructure. The specimens were 50 mm diameter balls, and the different alloys were exposed simultaneously to the wear environment. Three different abrasives were used — quartz sand, hematite, and a phosphate rock. The tests were conducted in a closed-circuit continuous feed mode for a total of 200 hours exposure. This probably represents the most systematic and industrially-relevant use of the ball mill abrasion test that has been published to date. Albertin and Moraes [24] also used a pilot-scale ball mill to evaluate the performance of 60 mm grinding balls made from various steels and white cast irons when milling coal. The mill was operated in batch mode, but renewing the abrasive every ten hours to a total of 70 hours exposure.

Gates first used a laboratory ball mill for the purposes of abrasive wear testing of alloys in 2001 [25]. Gates and co-workers [4,26-41] have used this apparatus and methodology for a variety of experiments, using mills of various diameters between 300 mm and 1800 mm operated in batch mode. Most of their work has focussed on assessing the factors controlling the relative performance of wear-resistant materials spanning different microstructure classes (as well as numerous specific alloys and heat treatments within a given class). A feature of their work has been critical evaluation of common interpretations about the effect of "impact" in determining the relative performance of different classes of wear-resistant materials.

The recent review by Aldrich [42] is ambiguous in regard to the possible use of laboratory ball mills for measurement of wear rates. Although Aldrich initially lists the marked ball wear test within a section on laboratory testing techniques, the methods described for marking the different media samples are those which, to our knowledge, have been used only for industrial MBWT trials. Moreover, the section refers to placing the test balls into an "operating mill" and retrieving them for mass loss determination "when the mill is down for scheduled maintenance" - comments which presumably have relevance only to industrial mills. Aldrich does not cite any published studies in which MBWTs have been used in the laboratory, but elsewhere cites two papers by Sepulveda [15,43] both of which are concerned explicitly with trials conducted at full scale, not in the laboratory.

Advantages of the BMAT

Previous experience with the ball mill abrasion test indicates that, for the purpose of assessing the performance of wear resistance of materials for comminution environments, it has several advantages over alternative laboratory test devices that have been proposed for this duty. These advantages are:

- There is no difficulty ensuring that the abrasive medium enters and passes through the contact zone between the specimens and counterface bodies - this occurs naturally and indeed inevitably;

- It is able to accommodate essentially any mineral ore or other abrasive medium, in a wide range of particle sizes relevant to industrial service. The measured values of relative wear rates between alloys are not sensitive to the exact abrasive particle size;
- Without the necessity for any complex engineering measures, qualitatively the abrasive particle and counter-body kinematics and contact mechanics in the BMAT naturally match those in an industrial ball mill quite closely;
- Its design facilitates simultaneous exposure of multiple specimens without difficulty - for example, we have frequently performed tests in 500 mm and 600 mm diameter ball mills in which more than 100 individual specimens were tested simultaneously. This contrasts strongly with most standard laboratory tests, which are usually restricted to exposure of between one and three specimens at a time. This feature not only improves productivity but facilitates experimental control and removes the need for careful maintenance of supplies of "standard" consumables;
- As demonstrated by J.J. Moore, the test parameters can readily be manipulated in such a way as to identify and quantify the various component damage mechanisms that contribute to the overall wear rate;
- It is very versatile. A variant on the BMAT, known as the ball mill edge chipping test (BMECT), can also assess the resistance of alloys to small-scale fracture phenomena (chipping at features such as forging laps) - and does so more efficiently than alternative tests such as the Charpy impact test. Another variant, the ball mill impact-fatigue test (BMIFT), can assess the resistance of alloys to impact-fatigue spalling, in much the same way as the dropped ball test (DBT) [44] though at lower energies;
- The apparatus is mechanically simple, robust, and low cost;
- It has been found that the relative wear rates between specimens of different materials have excellent reproducibility, without requiring any arduous controls. With somewhat more careful attention to test conditions, the absolute values of wear rate are also reasonably reproducible within a given batch of abrasive;
- Finally, as will be shown below, if the conditions are set up with sufficient care, the BMAT can achieve level 4 (quantitative absolute) correlation with plant wear rates.

Given these advantages, it becomes difficult to understand why researchers would persist with unrepresentative bench-top abrasive wear tests when attempting to evaluate wear-resistant alloys for comminution operations. We are not suggesting that the BMAT reproduces every aspect of damage mechanisms in large industrial mills; it lacks the ability to reproduce the larger-scale fracture-related consumption mechanisms associated with high impact energies in large industrial mills, hence the BMAT needs to be supplemented by a high energy impact test in those cases. However, for the abrasive and corrosive wear components it is difficult to discern advantages in other more idealised laboratory tests. The quality of the BMAT's predictive ability for industrial ball mill wear rates will be discussed in the case study below.

Like all laboratory tests the BMAT is limited by its size, and questions of scale-up will require further research. However, the above listed advantages indicate that the BMAT is an order of magnitude superior to traditional bench-top laboratory tests. Ultimately, if the intention is to simulate a ball mill, then it is appropriate to use a ball mill.

Level 4 (Absolute) Correlation from Ball Mill Abrasion Test

Newmont Asia Pacific commissioned the authors to develop a methodology by which the absolute values of grinding media consumption rates in an industrial ball mill could be predicted from batch tests in a laboratory ball mill [28,32].

The simplest quantity by which the wear rate of grinding media can be expressed is total mass loss per unit time, in units such as kg/h. Since the primary performance measure of an industrial mill is the rate of production of ore of a desired product particle size distribution, it is industrially more useful to express media wear rate in terms of mass loss per mass of ore ground, in units such as kg/t. Giblett and Seidel [45], however, have found it most useful to express wear rate in terms of mass loss per grinding energy [43,46,47], in units such as kg/kWh or g/MJ. This quantity is sometimes designated the “specific consumption rate”.

To facilitate development of the methodology, Newmont provided us with two key resources:

- Detailed historical data for the rates of consumption of steel grinding media in the ball mills in three of Newmont’s gold ore processing plants, along with detailed milling parameters, such as operating power draw, grinding energy consumed per mass of ore ground, and the measured Bond Work Index values for the ores;
- Supplies of well-characterised ores from each of these sites, sufficient to perform a substantial number of experiments on the effects of laboratory mill setup parameters on test outcomes.

The development of the methodology involved the following steps:

1. Using carefully prepared samples of a well-characterised ore (from Newmont’s Tanami plant), determine the combination of mill setup parameters required to achieve a reliable match between the P80 (80% passing size of the mill product) of the batch mill test and that of the plant mill;
2. Using the known Bond Work Index of the reference ore, assess the effective grinding energy input per mass of ore ground from the measured feed and product particle sizes (F80 and P80);
3. Measure the wear rate for the standard commercial martensitic steel media grade, expressed as specific consumption rate (media mass loss per unit grinding energy input);
4. Measure the specific consumption rate for an alternative (softer) steel media grade;
5. Assess the sensitivity of the measured specific consumption rate values to variations in test parameters, such as test duration and feed F80 (both of which affect the batch product P80 and may cause it to deviate from the plant P80 value);
6. Measure the wear rates produced by two other Newmont ores (KCGM Fimiston and Jundee);
7. Assess the merits of alternative methods of determining the specific energy input for each test (Bond approach versus Levin approach).

The methods and results were presented at the Comminution ’12 conference [32], and a more detailed paper is being prepared for submission for journal publication. Only a brief summary of the methods and outcomes will be presented here. Table I summarises the input parameters used to set up the test.

Table I. Tanami Plant and Laboratory Parameters

Parameter	**Units**	**Plant**	**Laboratory**
Mill diameter	m	5.5	0.30
Mill rotation speed	r/min		52
Ball charge mass	kg		18.1
Ore feed 80% passing size (F80)	mm	10700	3394
Product % passing size (P80)	mm	181	181 (target)
Bond Work Index of ore	$\mu m^{0.5}$.MJ/t	76.9	
Grinding energy per mass of ore ground	MJ/t	49.7	43.9
Batch ore feed mass	kg		2.72
Batch test duration	min		15.1
Grinding energy for standard test	MJ		0.119
Mill power draw	kW	4706	0.132
Mill power constant = energy per revolution	J/r		153

During the first phase of the work, the grinding energy associated with each test was back-calculated from the Bond Work Index and the measured F80 and P80. Since the product P80 is used in the calculation of grinding energy, variations in P80 have the potential to influence the measured value of wear rate expressed as mass loss per grinding energy. In order to explore the sensitivity of the specific consumption rate measurements to variations in P80 either side of the target value, various experiments were conducted in which the product P80 was manipulated via a number of different primary input variables, such as test duration, ore feed volume, ball diameter and mill rotation speed.

Figure 5 presents one of the data sets collected during the research, in which ball charge mass loss and product particle size distribution were measured as a function of test duration, for a constant feed volume of Tanami ore. Naturally, increasing test duration causes an increase in mass loss and a decrease in product particle size. The measured specific consumption rate appears to decrease slightly as a function of increasing test duration. However, it should be noted that the scale is fairly fine, and the value of specific consumption rate is changing by less than 20% for a 90% change in test duration — hence the measurement does not seem overly sensitive to this input parameter.

The sensitivity (or conversely the robustness) of the technique can be most readily assessed by plotting mass loss and specific consumption rate directly against P80. Such a graph is shown in Figure 6 for the same raw data as in Figure 5. Neglecting the single outlier value, it appears that the measured values of specific consumption rate are insensitive to P80 over a range of P80 values from about 120 µm to 230 µm. The main conclusion from the research program was that the methodology was capable of providing reproducible values of specific consumption rate so long as the product P80 from the batch test was within ±50 µm of the plant P80 — a target that is not unreasonably difficult to achieve.

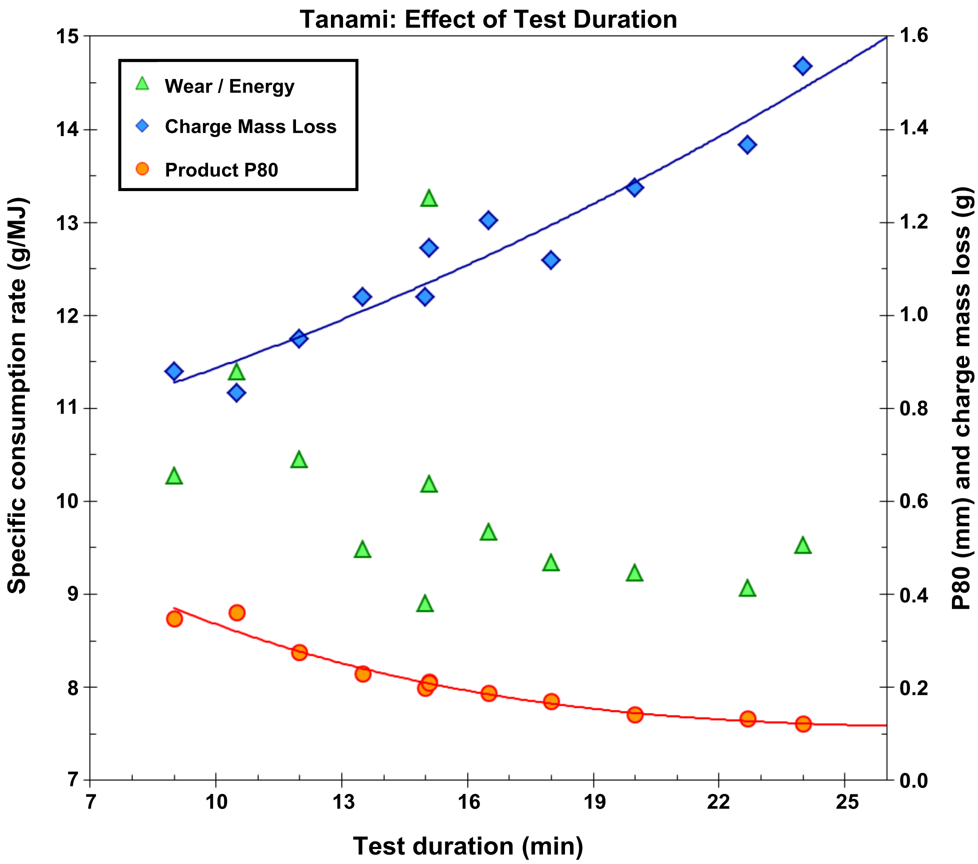


Figure 5. Effect of test duration on 80% passing size of product (secondary axis), charge mass loss (secondary axis), and specific consumption rate (primary axis).

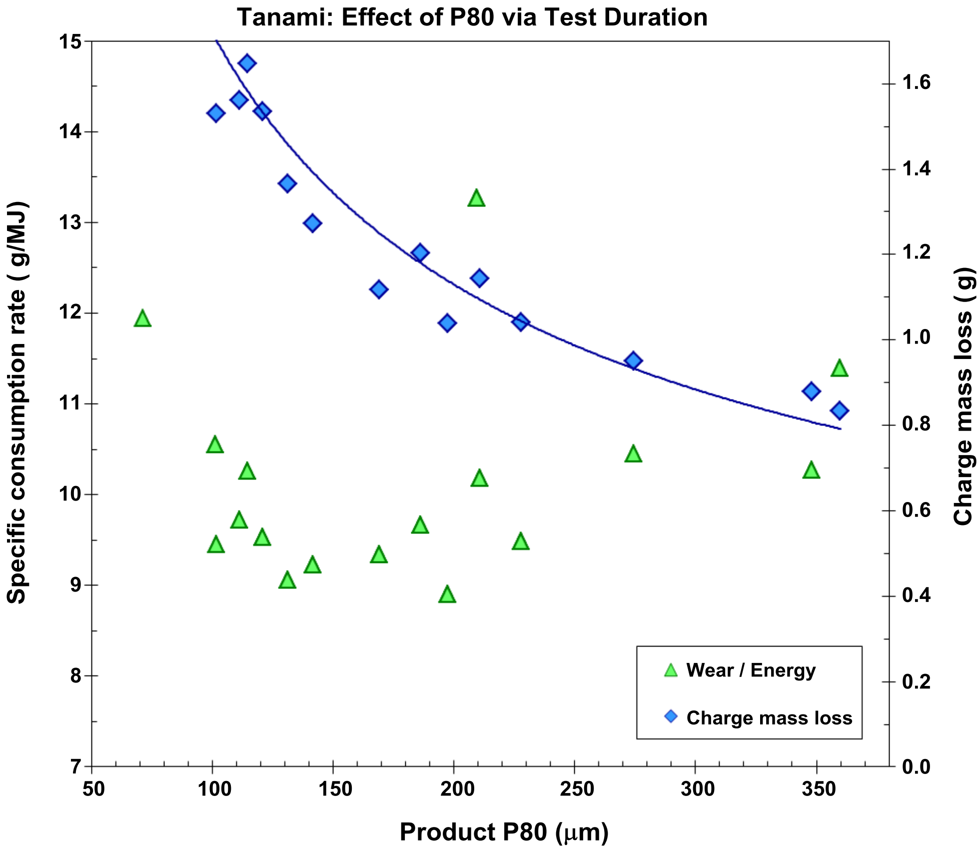


Figure 6. Effect of P80 (varied via test duration) on charge mass loss (secondary axis) and specific consumption rate (primary axis).

Once the methodology was established, it was possible to use the technique to measure the specific consumption rate for the standard grinding media and compare these with the corresponding values from the plant. Table II provides a summary of the primary outcomes of these measurements and comparisons. For the three ores, the table shows a very good match between the specific consumption rate as measured in the laboratory test and that experienced in the plant. For the well-characterised Tanami ore, the error between laboratory prediction and actual plant wear rate is less than 10%. For the two less well characterised ores, the error is no more than 20%.

Table II. Correlation Between BMAT Predictions and Plant Media Consumption Rates

		Plant	Laboratory	Error	Laboratory
			H70 balls		H60 balls
Tanami, The Granites					
Charge mass loss per test	g	N/A	1.26		1.44
Mass loss per mass ore ground	g/kg	0.47	0.46	-2%	0.53
Specific consumption rate	g/MJ	9.2	10.1	9%	12.5
KCGM, Fimiston					
Charge mass loss per test	g	N/A	1.52		
Mass loss per mass ore ground	g/kg	0.19	0.56	192%	
Specific consumption rate	g/MJ	8.3	10.0	20%	
Jundee					
Charge mass loss per test	g	N/A	1.82		
Mass loss per mass ore ground	g/kg	0.30	0.67	122%	
Specific consumption rate	g/MJ	8.0	9.0	13%	

The significance of these findings should not be underestimated. What has been developed is a laboratory test methodology that provides full level 4 correlation with plant wear rates. It can predict, within about 20%, the absolute values of wear rate in the plant; and can do so directly from first principles, without any empirical "calibration" factors.

It might be noticed in Table II that, for all three plants, the laboratory test slightly over-predicts the plant wear rate. This suggests that, despite its small size, the laboratory mill is successfully reproducing the important consumption mechanisms that occur in the much larger industrial ball mills. This indicates that "impact" or fracture-related consumption mechanisms are not significant in any of these three industrial mills.

Conceivably the slight over-prediction of consumption rate by the laboratory mill could be due to an excessive contribution from corrosion in the small batch mill - a possibility raised by Dodd and Dunn [48]. However, this small difference could also be influenced by a variety of other factors which might differ between laboratory and plant, such as, for example, the possibility of differences in abrasion resistance between the actual media being used in the plant and the batch of small-diameter media that was used for the laboratory tests. Such details can be explored in further research, but should not be permitted to divert our attention from the primary significance of these findings - which is that we have achieved level 4 correlation in a simple laboratory test apparatus.

Finally, it may be noted that when wear rate is expressed as mass loss per mass of ore ground, the laboratory test is much less successful in predicting plant wear rate. The prediction appears good for the Tanami ore, but poor for the KCGM and Jundee ores. Clearly, it is mass loss per grinding energy (specific consumption rate) which should be the focus of attention in further work.

The Importance of Low Stress Sliding Abrasion

Understanding the Difference between High Stress Abrasion and Low Stress Abrasion

Several different approaches to classifying abrasive wear have been suggested [49], and occasionally these conflict with each other [50]. The primary purpose of a wear classification scheme must be to guide mitigation measures (and if a proposed classification scheme cannot be demonstrated to provide useful guidance of this type then it is reasonable to question its value).

Such an explicit purpose for wear classification is offered in recognition of the fact that measures which may be successful in reducing the rate of wear in one wear mode, might actually increase the rate of wear in another wear mode. The most commonly cited example of this is when increasing hardness, rather than achieving the desired reduction in wear rate through reduction of indentation depth, instead precipitates a more damaging wear mechanism - from micro-ploughing to micro-cutting, or from micro-cutting to micro-fracture. Such a phenomenon can be understood in terms of the Archard wear equation in its form applicable to abrasive wear:

$$W = k_1.k_2.F.v / H \tag{1}$$

where:

- W is the wear rate, expressed as volume of material removed (and hence volume of debris created) per unit time;
- k_1 is a dimensionless geometric constant indicating the sharpness of the abrasive particles - whereby, for a given value of contact force, a sharper particle (larger value of k_1) penetrates deeper into the material and creates an indentation with a larger cross-sectional area in planes perpendicular to the surface of the indented material;
- k_2 is the ratio of the volume of material removed to the volume of the groove - bearing in mind that, in a ductile material, a groove can be created by a "micro-ploughing" mechanism in which material is merely displaced laterally, rather than by a "micro-cutting" mechanism in which material is directly removed from the surface as primary debris;
- F is the normal contact force;
- v is the tangential sliding velocity;
- H is the hardness of the material being worn (expressed in units of contact force per projected area of indentation).

In abrasive wear occurring by a pure micro-cutting mechanism, the value of the coefficient k_2 should equal or approach 1, while in wear dominated by micro-ploughing mechanisms, k_2 is very much smaller than 1, (eg. perhaps 0.01). Hence, for a given value of indentation depth, micro-cutting is a much more damaging mechanism than micro-ploughing. In addition, if micro-fracture wear mechanisms occur, cracking and release of fragments from outside of the primary wear groove can result in a value of k_2 greater than 1, hence this is extremely damaging.

Excessive increases in the hardness of the material can decrease ductility and toughness and precipitate these detrimental transitions in wear mechanism. If this occurs, it is possible for the increase in hardness to cause an increase in wear rate instead of the intended decrease. Even if complete ranking reversals do not occur, these detrimental transitions in wear mechanism can readily degrade the quantitative benefit achievable from a harder material and may thus reverse the cost-benefit balance.

A change in material hardness is not the only parameter that can influence wear coefficients. It has already been noted that more angular abrasive particles can lead to greater penetration depth for a given contact force, hence increasing the magnitude of the coefficient k_1 in the Archard equation. Sharp cutting edges may also promote more damaging wear mechanisms, thereby increasing the coefficient k_2.

The possibility (indeed the frequent observation) of such reversals of cost-benefit balance is the reason why the distinction between high stress abrasion and low stress abrasion is of such great practical importance. We regard this as the most important single distinction to be made in any classification scheme governing sub-divisions of abrasive wear.

Among those authors who propose classification schemes involving a distinction between high stress abrasion (HSA) and low stress abrasion (LSA), most place the emphasis on contact stress in relation to fracture of the abrasive particles. It is usually proposed that the dividing line between HSA and LSA is determined by whether or not the abrasive particles fracture. Fracture of the abrasive particles generates fresh sharp cutting edges which, as described above, can lead to increases in both coefficients k_1 and k_2 in the Archard equation.

However, if particle fracture was sufficient to define HSA, then crushing of a soft, weak mineral such as talc would be regarded as HSA. This would clearly not be a useful conclusion to draw from a classification scheme. Gates et al. [4] demonstrated that particle fracture alone is not sufficient to create the kind of HSA conditions that lead to high wear rates in general and poor performance from particle-reinforced composite materials in particular. For these damaging conditions to arise, it is also necessary to satisfy two conditions: firstly that there must be a rigid counterface which pushes the abrasive particles into the wearing surface with significant force; and secondly that the abrasive mineral particles must be strong enough to transmit the forces from the counterface to the wearing surface and its microstructural elements. Thus, rather than "fracture" of the abrasive particles, almost conversely it is probably the "strength" of the abrasive mineral that is the strongest determinant of HSA conditions [29].

<u>The Economics of Low Stress Abrasion – Misleading Nomenclature</u>

Almost everything that is written about high stress abrasion versus low stress abrasion would tend to suggest that in HSA the wear rates are high and in LSA the wear rates are low. The nomenclature itself almost inevitably suggests this. If this inference were accurate, then economically it might be appropriate to invest resources primarily in HSA and to largely ignore LSA.

However, experience tells us that the highest industrial wear rates are in situations which we judge to be low stress abrasion - in live ore transfer chutes. "Live" transfer chutes are those in which rock-box designs are not employed and hence the ore flows through the transfer station in a continuous stream, creating near-continuous sliding against the liners rather than the tumbling action that occurs in a rock-boxed chute. A practical example has been seen in the inspection, by the authors, of an iron ore chute (in 2000 at BHP Iron Ore's Finucane Island ore handling plant in Port Hedland, Australia) in which NiHard 4 white cast iron blocks, 75 mm in thickness, were wearing out within two weeks. Another example was a live chute passing copper-gold ore in Papua New Guinea in which 100 mm NiHard block liners were wearing out in as little as four days.

The empirical evidence available in the Port Hedland installation [51] indicated that the wear mode was low stress abrasion. For example, there was no evidence to suggest that the high wear rates in the NiHard castings were due to micro-fracture wear mechanisms in the brittle carbides, promoted by "impact" or other conditions in the chute. Rather, the evidence indicated that the high wear rates in the live chute were simply a function of the continuous sliding abrasive action and the high tonnage throughputs, exacerbated by some sub-optimal installation design features.

Improved Nomenclature

Ball mills and other comminution equipment in the mining industry commonly show the characteristic features of HSA, but wear rates approaching those described above for LSA in ore chutes have never been encountered by the authors. The reason that HSA does not typically produce such high wear rates is readily understood in terms of the $F \times v$ term in the Archard wear equation. The contact force F may be high, but the total wear rate may be quite low if the sliding velocity v is low.

This very simple observation serves to alert us to the fact that contact force is only one of the two input parameters that characterise the distinction between HSA and LSA. The accepted nomenclature for the two wear modes might encourage an emphasis on the F term and a neglect of the v term, but this can be misleading. It is suggested that the tribology community should consider a move to two-part descriptors, such as to remind the user that sliding velocity is at least as important as contact force.

In the past there was a practice in some circles (notably in the U.S. mining industry) to denote the HSA wear mode as "high stress grinding abrasion", or simply "grinding abrasion" [49,52]. The latter was suggested in reference to a type of industrial operation within which this wear mode frequently occurs, namely mineral grinding (comminution). In practice, nomenclature involving the words "grinding abrasion" has fallen out of favour. This might be in recognition of the ambiguity [50] of the word "grinding", which in addition to mineral comminution can also refer to machine workshop operations using bonded grinding wheels. When using grinding wheels, the sliding velocities are high and contact forces are low — the opposite of true HSA. There is an obvious risk that early-career researchers might assume that a grinding wheel would make a good laboratory test to simulate "grinding abrasion", and indeed such tests have been used [1]. It is preferable that the accepted nomenclature should not encourage such misconceptions.

The following two-part descriptors are recommended:

- "Low stress sliding abrasion" (LSSA) - emphasising the dominance of tangential sliding. This designation has considerable merit, since it conveys the limited ability to damage the microstructure and yet also conveys the sliding that can lead to high wear rates;
- "High normal stress abrasion" (HNSA) - emphasising the dominance of normal contact forces over tangential motion. Various alternative candidate designations that have been considered are discussed below.

For HNSA, alternative designations that have been considered or might be considered include high stress grinding abrasion (HSGA), high stress crushing abrasion or high stress comminution abrasion (HSCA). Although it might seem to have the virtue of elegant simplicity, the abbreviated term "crushing abrasion" is not recommended. It is questionable whether the empirical evidence supports the notion that jaw crushers produce a HSA wear mode. Currently, the wear mode in jaw crushers is denoted "gouging abrasion", and ill-defined as this term might be, it will probably suffice pending further research. Instead of either "grinding" or "crushing", the word "comminution" might better indicate the conditions involved in the wear mode currently being denoted HSA. If used in the two-part descriptor "high stress comminution abrasion," it would probably convey most of the important aspects of this wear mode with minimal ambiguity. All of these designations retain the phrase "high stress" which can serve to focus attention on the need for a rigid counterface to achieve this characteristic wear mode. Choice of an ideal descriptor is worthy of ongoing attention from the tribology community, but the term high normal stress abrasion appears to have the most merit of those considered to date.

The most important lesson from the above discussion is the fundamental observation that low stress abrasion does not equate to low wear rates; indeed, the highest wear rates that are observed industrially are caused by low stress sliding abrasion. Irrespective of the nomenclature chosen, it is clear that, economically, LSA has just as much claim for allocation of resources as HSA does. Improved nomenclature is needed in order to convey this fact, and the new terms HNSA and LSSA will be used hereafter.

Materials Selection for Low Stress Sliding Abrasion

The nature of LSSA is such that materials selection has the capacity to achieve much greater improvements in component service life than is possible in HNSA. Gates et al. [4] showed that in HNSA the curve of wear rate versus hardness is very flat, and that most particle-reinforced composite alloys provide minimal benefit compared to homogenous alloys of comparable bulk hardness. Consequently, only relatively small incremental improvements in service life are achievable though the use of harder or "better" wear-resistant materials in such conditions. By contrast, in LSSA, the wear rate versus hardness curve is much steeper, and particle-reinforced composite alloys provide major benefits compared to homogeneous alloys.

Figure 10 shows the data from a plant trial conducted in the upper "hood" section of the iron ore chute mentioned above. This was one of two trials conducted in the Port Hedland ore transfer chute. These trials will be described in more detail below, but a clear outcome was to provide field confirmation of the concept stated in the above paragraph - that in LSSA environments, materials selection has the capacity to achieve major improvements in service life.

<u>High Wear Rates from LSSA – Iron Ore Chute</u>

The duty of an ore transfer chute is to "catch" a stream of ore discharged from the head pulley of one conveyer belt, re-direct it and load it evenly onto a second conveyer belt travelling in a different direction. It must achieve this task automatically and passively, without any human or mechanical intervention, using only momentum and gravity. Importantly, it must carry out this duty without interruption to the operation.

Two things which can create interruptions to production are changing out worn liners, and clearing blockages. Liner wear in chutes can often be very effectively managed by use of "rock-boxing" designs, in which a series of ledges trap some of the rock and fines. This minimises wear by two quite distinct mechanisms:

- For a significant proportion of the time that the ore stream is passing across the liner surfaces, it does not contact the metal but instead contacts the layer of trapped rock and fines. Effectively, the ore itself acts as a zero-cost, continuously self-renewing wear-resistant coating;
- The ledges alter the nature of the motion of the ore stream - from a unidirectional sliding motion to a tumbling motion.

In Australia's Pilbara region iron ore operations, the ore becomes highly cohesive when damp. The disadvantage of rock-boxing designs is that the tumbling action encourages formation of blockages. In the wet season, in some transfer stations it was reported that large proportions of the week were consumed by clearing blockages with high-pressure hoses.

To address this problem, in 1999 BHP Iron Ore engaged Tasman Warajay Pty Ltd to provide a non-blocking "Controlled Flow" (live) chute for the CN40/CN42 transfer point at Finucane Island - shown in Figure 7. This transfer point handled the majority of the mid-size (lump, 6 to 40 mm) product of the plant, plus adhering fines (6 mm), and included a substantial recirculating load. At that time it carried an estimated average 1800 tonnes per hour, and plans were underway to increase production to 2000 tonnes per hour. If such a transfer point experiences a blockage, plant production stops. The value of lost ore production due to unplanned stoppages was at that time estimated at AU$210,000 per hour.

Figure 7. CN40/CN42 transfer station at BHP Iron Ore's Finucane Island operation in 2000, with Tasman Warajay "Controlled Flow" chute.

The live chute performed to specification in terms of its non-blocking characteristics, with blockage events falling to a small fraction of the number previously experienced. However, the chute became subject to significant down-time for replacement of wear liners. In the highest wear areas, any given liner plate needed to be changed out every 1 to 2 weeks. By comparison, traditional chutes at the site with extensive rock-boxing required relatively little maintenance, with typically three months between charge-outs of the fastest-wearing components. In essence, the blockage problem had been solved but a wear problem had been introduced. The current author, Gates, was engaged to investigate the reasons for the rapid wear and to recommend solutions [51].

From the viewpoint of plant production and overall profitability, in principle, wear should be a less serious problem than blockages, because the liner change-outs can be performed during scheduled maintenance periods, whereas blockages occur randomly, stopping production. The reported estimate of $3,000 per week in maintenance costs might seem insignificant compared with $210,000 per hour of lost production. Nevertheless, the high maintenance requirement was a problem to the company's maintenance department at Finucane Island. Moreover, to enable the planned increase in productivity to 2,000 tonnes per hour, it was clearly necessary that maintenance shutdown intervals be longer than one week. At most sites it would be desired that maintenance shutdowns occur no more frequently than every three months, but at Finucane Island at that time it was conceded that four week intervals would be acceptable.

To achieve this goal it was necessary to find ways to increase component service life by a factor of four or more. Available information suggested that, if the operative wear mode was low stress sliding abrasion, then such an increase should be feasible. The goals for the project were as follows:

- Extend the period between liner change-outs to at least four weeks;
- Make the change-outs easier and quicker to perform;
- Accomplish the above objectives without re-introduction of blockages;
- Provide guidelines for the best liner products to use in different positions within the chute;
- Provide the information necessary for manufacturers of live chutes to successfully deploy this technology (previously highly successful in general bulk solids handling duty) in hard-rock mining operations.

The evidence collected from site, and subsequent laboratory investigations, enabled clear identification of the reasons for the high wear rates and maintenance burden experienced in the live chute by comparison with traditional chutes at the site. The reasons, and some resulting recommendations, are summarised below.

Problem 1, Lack of Rock-Boxing: Rock-boxing is remarkably effective in reducing metal wear, not only because it promotes impingement of incoming ore onto rock rather than onto metal, but also because it causes ore particles to tumble rather than slide across the metal. By removing the rock-boxing, wear rates will inevitably be higher. Recommendation: It is not practical to re-introduce rock-boxing to the subject chutes because this would destroy the controlled-flow and non-blocking characteristics. Instead, other solutions must be found to control wear rates to acceptable levels.

Problem 2, Monolithic Linings: Use of large-area monolithic linings, such as rolled and fabricated weld-overlay plate, leads to high maintenance costs, despite the fact that chromium carbide overlay plate itself offers good abrasion resistance. This is because perforation at a single point of high abrasion intensity requires replacement of the entire sheet. This represents an unacceptable maintenance burden, both because of the high cost of the replacement sheets and because of the time-consuming nature of the required on-site work. Recommendation: Segmented liners are recommended since they are faster to replace; but attention must be paid to avoiding preferential wear at joints and bolt recesses (see below).

Problem 3, Impingement Points: The point where a free-falling ore stream first impinges on the liner is a site of high wear. The site and laboratory investigations determined that this high wear was not caused by introduction of dynamic stress-wave micro-fracture wear mechanisms (as originally suspected), but simply because the deceleration vector provides a source of significant normal contact force F in conjunction with the substantial sliding velocity v. Recommendation: In view of the identified wear mode, it was viable to address the problem by use of available abrasion-resistant materials, such as high-alloy white cast irons with high volume fractions of chromium carbides.

Problem 4, Open Bolt Recesses: The primary reason for the poor outcomes of early attempts to use segmented liners was that these liners were weakened by open bolt recesses exposed to the ore flow. The preferential wear of the liner below each of these bolt recesses was obvious to the eye, and can be discerned in Figure 9 and Figure 11(a). The preferential wear persisted to a significant extent even when the bolt recesses were filled with hardened 4140 steel square-headed bolts, again shown in Figure 11(a). Recommendations: Either fill the bolt recesses with a material at least as wear-resistant as the liner block itself; or change the liner design to one with integral backing studs, avoiding through-bolting.

Problem 5, Sub-optimal Wear-resistant Alloys: NiHard 4 is an adequate but not outstanding wear-resistant alloy. NiHard castings (known on site as “billets”) may seem to have the advantage of lower cost than products such as Duaplate, but in view of down-time issues this saving in unit cost is probably false economy. Moreover, the benefit from the greater thickness of these “billets” is negated if the method of fastening means that they must be discarded after less than half of their thickness is used. Recommendation (a): Composite products such as Domite, Duablock and Duaplate use a mild steel backing plate to reinforce the abrasion-resistant alloy. This protects against gross brittle fracture, thus permitting the use of harder (potentially more brittle) alloys, with high volume fractions of chromium carbides, than would be feasible in a simple casting. Recommendation (b): Where thick through-bolted castings appear more favourable, in addition to addressing the problem of open bolt recesses as above, it is important to use alloys which simultaneously maximise abrasion resistance while maintaining adequate fracture toughness. Better performance than NiHard is offered by high-Cr-Mo white cast irons with tailored compositions and heat treatments. There is also scope for future alloy development for cast block products that will achieve even higher abrasion resistance — at least comparable with that of weld-overlay plates and without the inherent weakness introduced by relief-check cracking in the weld deposit.

<u>Plant Wear Trial in Iron Ore Chute</u>

The above recommendations were accepted by BHP Iron Ore and Tasman Warajay, leading to immediate commencement of plant trials to verify and optimise the proposed solutions.

As a temporary solution to the perforation of the original rolled Duaplate (a relatively thin chromium carbide weld overlay plate) in the upper “hood” section of the chute, cast NiHard 4 plates had been retrofitted over the remains of the original continuous lining. In the hood, liner change-outs are more difficult than in the spoon, due to accessibility problems. Heavy block liner castings would create occupational health and safety (OHS) concerns, and moreover their greater thickness may have created a geometric problem, given that they were being bolted over an existing liner.

In ore transfer chutes, the intensity of conditions varies sharply in both longitudinal and lateral directions, as can be discerned from the deeply worn recesses (associated with the freefall impingement zone) visible in Figure 9. Moreover, the location of the most intense wear zone has been observed to move with time - compare Figure 9(a) with Figure 9(b). Therefore, in order to compare candidate materials using a simultaneous exposure trial, it is necessary to use a type of planar array wear test design [7].

The two rows of retrofitted NiHard 4 plates that were in place at the time of the site inspection are shown in Figure 8. The NiHard plates had dimensions $445 \times 145 \times 32$ mm, and weighed approximately 15 kg. Such large plates are not ideal for a planar array wear test under these conditions, but at the time it was not feasible to manufacture an insert containing a larger number of smaller coupons. Given that a pattern of bolt holes already existed to suit the NiHard plates, it was recommended that this geometry be retained.

To improve the wear life, Duaplate segments of thickness 17 on 12 mm were selected and cut to the dimensions of the NiHard plates, with studs welded to the backing plate. It was predicted that the Duaplate would perform better than the NiHard 4, because of its high volume fraction of very hard chromium-rich carbides. The useful thickness of abrasion-resistant alloy in the two cases was comparable, since the NiHard plates can only be allowed to wear some 19 mm (in the vicinity of the bolt) before failure of the bolt becomes a danger.

Figure 8. Retrofitted NiHard 4 cast liner segments bolted to the original continuous lining in the upper "hood" section of a live chute in Port Hedland, Australia. The added plates were not sufficient to span the whole of the impingement zone at the entrance to the hood.

(a)

(b)

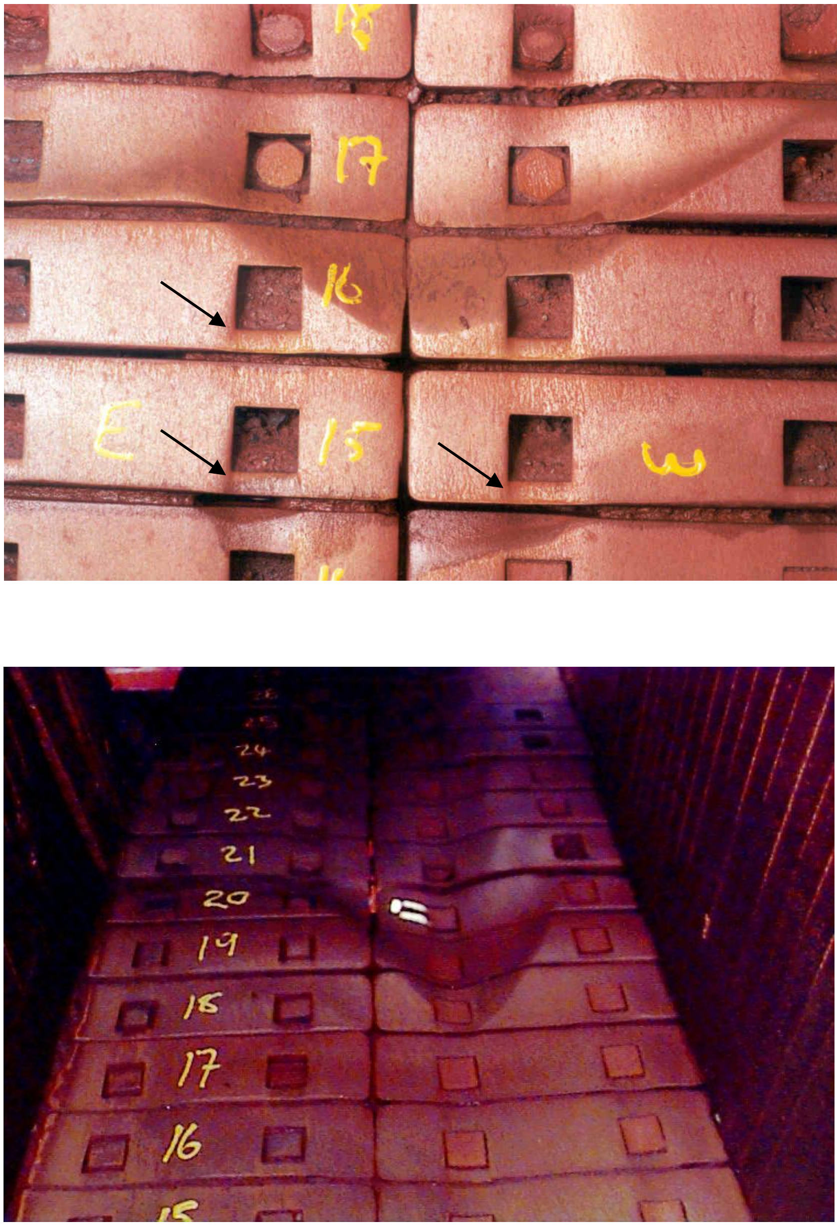


Figure 9. Cast liner blocks in the lower "spoon" section of the live chute; photographs taken at different times in 2000. Wear intensity varies strongly both longitudinally and laterally. Moreover, the point of maximum wear was seen to shift from week to week — compare location of high-wear zone in (a) with that in (b). In addition to intense wear at the freefall impingement point, preferential wear can also be discerned below (downstream from) the open bolt recesses.

The trial used a chequer-pattern of alternating liner plates in the two alloy products. No photograph was taken of the actual trial installation. Both installation and monitoring (weighing) were performed by a local fabrication contractor (Euan Bucknall of Total Machining & Fabrication). As can be seen in Figure 10, the trial was successful in yielding quantitative information from which the relative performance of the two liner products could be assessed. The following features can be observed from Figure 10:

- The absolute values of wear rates were reasonably consistent between the two trial periods, and this is true for both materials;
- For the NiHard, the highest wear rate clearly occurs at row 7. However, for the Duaplate this does not appear to be a particularly high wear area. Given that these data come from simultaneous exposure of the two materials, this difference is somewhat surprising. The difference may be due to the two materials responding differently to ore impingement angle;
- Other than one outlier point at row 5 in the second exposure period, the data show the Duaplate to be clearly superior to the NiHard, in most locations offering between 3 and 5 times longer service life;
- However, the quantitative relative performance of the two materials varies strongly as a function of longitudinal position. It may be that high impingement angles near the entrance to the hood lead to less favourable performance from the Duaplate — either by encouraging micro-fracture of the brittle carbides, or by attacking the exposed edges of the relief-check cracks in the weld overlay. Unfortunately, it was not possible for us to inspect the installation or the used samples so as to directly assess such mechanisms.

Motivated by the outcomes of this trial, more Duaplate segments were ordered. In mid-December 2000, it was reported that the life of a given Duaplate liner in the high-wear areas was 10 to 12 weeks, compared with an average of three weeks with the NiHard 4. This 3- to 4-fold improvement confirmed the predictions from the trial wear-rate data.

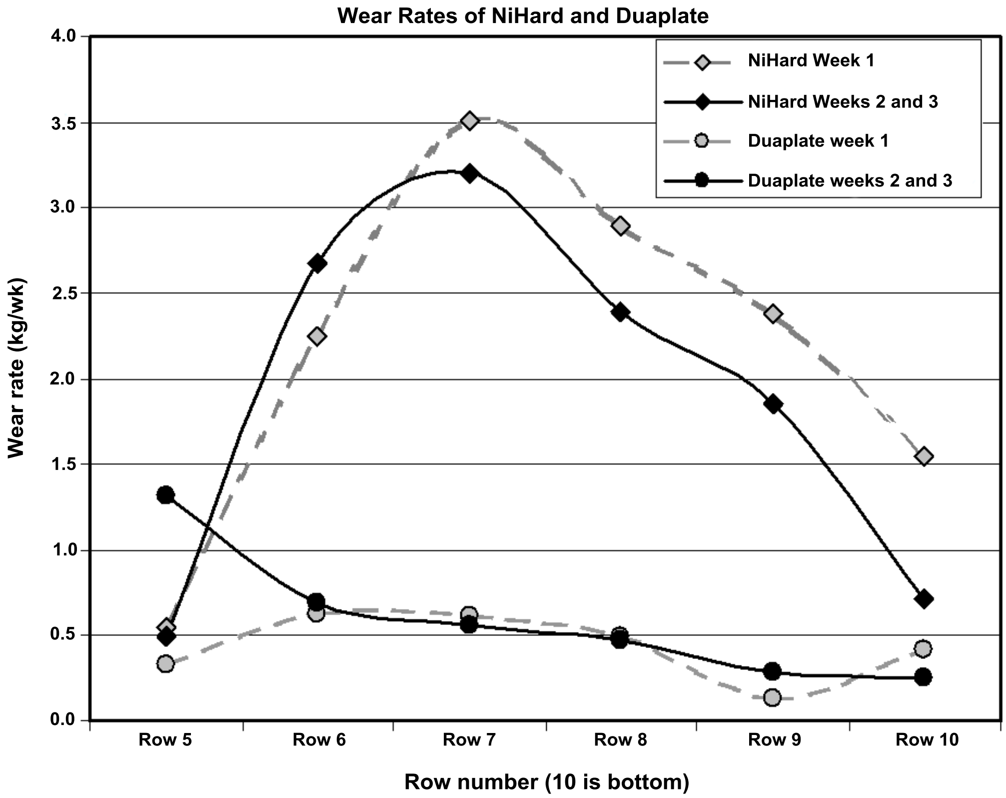


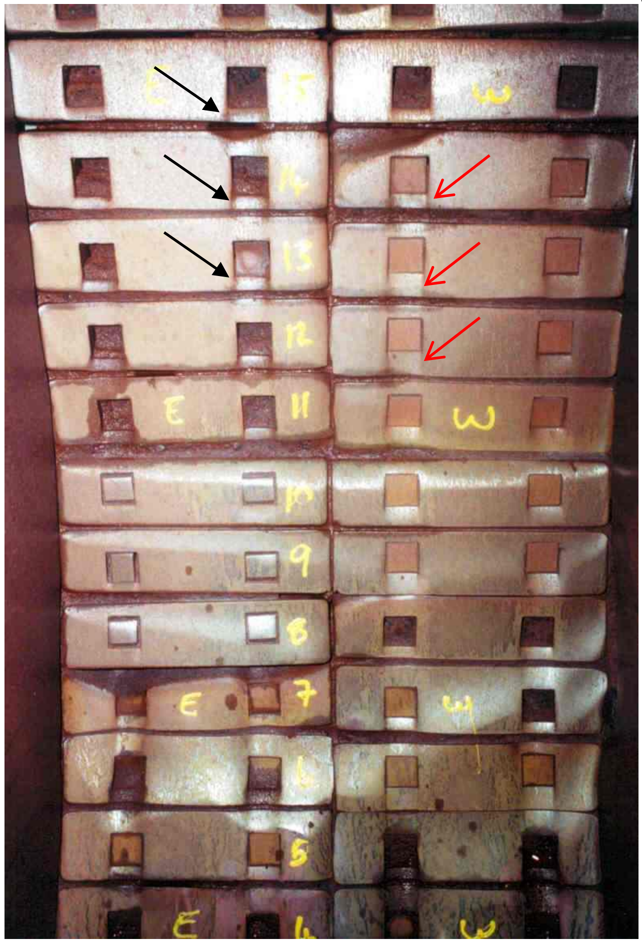
Figure 10. Wear rate measurements from plant trial in hood section of live chute passing iron ore at 1,800 tonnes per hour. Trial used planar array design with plate segments in two alloy products - cast NiHard 4 and Duaplate weld overlay.

The outcomes of this trial confirm and highlight the potential for improving equipment service life in LSSA environments, by the appropriate selection of wear-resistant products and by intelligent installation design. The importance of the latter point is highlighted by Figure 11, which shows the lower "spoon" section of the live chute at Port Hedland. The photographs show:

- The damaging effect of open bolt recesses with conventional hex-head bolts. The higher impingement angle at the downstream edge of the recess leads to high local wear rates, eventually leading to strong channelling of ore flow, creating a line of intense wear;
- The modest improvement obtained simply by use of high square-headed bolts made from hardened 4140 steel;
- The greater improvement obtained by use of Domite (brazed high Cr-Mo white cast iron) bolt caps.

The first Domite-capped bolts were installed in the week prior to the author's site visit. As shown in Figure 11(b), the higher abrasion-resistance of the Domite resulted in it standing slightly proud of the NiHard, even after only one week of service. The Domite plugs were very successful in preventing preferential wear at the bolt recesses. The only preferential wear occurred where the narrow Domite piece was oriented axially so that did not fill the full width of the bolt recess - see middle-left bolt cap in Figure 11(b).

(a)



(b)

Figure 11. The lower “spoon” section of the live chute at Port Hedland. Shows the damaging effect of open bolt recesses ((a), black solid-headed arrows), the modest improvement obtained from hardened 4140 steel bolt caps ((a), red open-headed arrows), and the greater improvement obtained by use of white cast iron bolt caps (b).

A data-collection exercise was instigated in an attempt to quantify the increase in liner life attributable to use of the Domite-capped bolts by comparison with simple 4140 steel square-headed bolts. A total of six NiHard “billet” castings - three with 4140 bolts and three with Domite-capped bolts - were weighed on a weekly basis.

The results of this trial were ambiguous. Although in the majority of cases it appeared that the billets with Domite-capped bolts suffered less wear, there were anomalies due to the fact that the wear intensity in the spoon varies strongly with position, not only down the length of the spoon but also from east to west across the spoon. The protocol used for this trial had been designed to minimise the labour involved in removing, weighing and replacing billets each week, but in practice this protocol was a failure. A different protocol, involving larger numbers of billets installed in a chequer pattern, and weighed less frequently, was proposed for any future data-collection exercises, but was not implemented at that time.

Despite the failure to quantify the increase in billet life, direct observation of wear patterns made it clear that the Domite-capped bolts were a success. On the strength of these trials, BHP Iron Ore decided to order a large batch of Domite-capped bolts for use throughout the spoon. In mid-December 2000 the maintenance contractors reported that the wear in the spoon was under a good level of control:

- With open bolt recesses, the billet life at the positions of highest wear intensity had been only 1–2 weeks;
- With 4140 square-headed bolts this increased to 3–4 weeks;
- With Domite plugs it was reported that the life of any given billet was 10–12 weeks.

This satisfied the target four-fold increase in liner life, and extended the necessary maintenance intervals (for this section of the chute) to an acceptable level.

Seeking a Better Test for Low Stress Sliding Abrasion

Existing Tests for Low Stress Sliding Abrasion

For the reasons described above, low stress sliding abrasion is a highly fruitful area for research and development.

Opportunities to conduct field trials, such as those described in this paper, are rare. Even when opportunities do occur, the resulting statistics are often quite poor. Consequently, there is a powerful need for laboratory tests capable of providing reliable predictions of the relative service lives of candidate wear-resistant products.

The most commonly used laboratory test for low stress sliding abrasion is the rubber wheel abrasion test (RWAT). The RWAT does not appear to suffer from problems of the magnitude of those that beset the pin abrasion test (whereby the PAT produces a wear mode markedly different from that which it is purported to represent). Indeed, the RWAT has some significant benefits, since it unquestionably produces low stress sliding abrasion yet creates usefully high wear rates, thus yielding a reasonably high rate of data production. However, it has four features which give cause for concern:

- Unless one is investigating the wear performance of pavements subject to abrasion by grit under the influence of rubber-soled shoes and vehicle tyres, then most industrial wear environments do not involve a rubber counterface. Admittedly, we do not have any definitive information to indicate that the rubber wheel introduces anomalies into the data, but in principle it seems unwise to introduce a feature which so clearly deviates from industrial conditions;
- At a practical level, the RWAT introduces significant limitations into the types of abrasive materials that are able to be used. It has repeatedly been demonstrated that mineral properties and particle shapes can significantly affect the relative performance of candidate wear-resistant materials; hence, it is of considerable concern that the RWAT is almost always operated with an idealised quartz sand abrasive;
- Because the ASTM G65 rubber wheel abrasion test only exposes one specimen at a time, it is critically important to maintain invariant conditions from test to test, year to year and laboratory to laboratory. This is challenging and somewhat expensive to achieve. Moreover, it can be very time-consuming to generate a statistically credible data set for a large number of candidate wear-resistant materials. In our laboratory, drawing upon our experience with the BMAT, we have a strong preference for tests that simultaneously expose large numbers of specimens. Simultaneous exposure removes the need for idealised "standard" abrasives, and confers the freedom to use the actual abrasives from any given end user's site operations;
- There are some laboratory wear performance predictions from the RWAT that, as described below, appear questionable as to their quantitative (level 3) accuracy.

In 2002, the authors performed abrasive wear tests on competing commercial wear plate products used in underground ore chutes at BHP Billiton Cannington mine [53]. Three of the products were quenched-and-tempered martensitic steels and one was a chromium carbide weld overlay product (AS/NZS 2576 class 2360).

On the assumption that the chutes would involve low stress sliding abrasion, the rubber wheel abrasion test was selected. In recognition of the importance of the mineral type, the RWAT tests were performed both with quartz sand and with screened Cannington mine ore fines. The results are summarised in Table III.

Table III. Rubber Wheel Abrasion Test Data for Cannington Mine

Abrasive Mineral:		Sand			Cannington Ore		
Plate	**Hardness**	**Weight Loss** (mg)		**Life**	**Weight Loss (mg)**		**Life***
Material	**(HV)**	**Mean**	**Std Dev**	**(%)**	**Mean**	**Std Dev**	**(%)**
Q+T Plate 1	442	35	2	100%	343	9	100%
Q+T Plate 2	399-419	38	5	91%	397	19	86%
Q+T Plate 3	387	71	7	49%	506	11	68%
2360 Overlay	872	29	7	122%	8.8	1.3	3900%

* "Life" = relative wear resistance compared to (quenched and tempered) Q+T Plate 1. This only translates into relative service life if equal thicknesses of material are being compared.

The performance rankings of the four materials are the same in the two abrasive materials, with projected service life rankings, as follows: 2360 overlay > Q+T plate 1 > Q+T plate 2 > Q+T plate 3. These performance rankings match the measured hardness rankings (noting that the hardness readings were taken from the specimen face on which the wear tests were performed).

However, the two abrasives produced markedly different absolute values of wear rate in the RWAT. In the three martensitic steels, the wear rate in Cannington ore was some seven to ten times higher than for the same material tested in sand. For the hardfaced plate the opposite situation applies, with the wear rate in sand being some three times higher than that in Cannington ore. Such contrary behaviour is remarkable and requires explanation.

The two characteristics of an abrasive that are likely to affect the absolute wear rates in this way are the particle size and the particle angularity. In LSSA, coarser particles, and more angular (sharper) particles, both generally increase wear rates. The Cannington ore contains a proportion of coarser particles (up to 850 μm), and is certainly more angular than the quartz sand. However, it should not be assumed that the Cannington ore is inherently more abrasive than sand, since as already noted, on the hardfaced plate it produces lower wear rates than the sand does.

This contrary behaviour can be understood in terms of the interaction between the abrasive minerals in the ore and the hard particles in the weld overlay. Clearly, the minerals in the Cannington ore are not hard enough or strong enough to damage the chromium carbides in the hardfaced plate. This will remain true whether the particles are angular or rounded, large or small. Therefore, although the angularity of the Cannington ore makes it highly aggressive to martensitic steels, it does not render it particularly aggressive to the hardfaced plate. This is sufficient to explain the observed behaviour.

For the three martensitic steel plate materials, the relative wear resistances measured in the Cannington ore tests are not greatly different from those measured in the sand tests. The only significant difference is that the disadvantage of using the softer Q+T plate 3 compared to the two harder steels appears greater in sand than it does in Cannington ore.

In both abrasives, the hardfaced plate performs better than any of the martensitic steel plate materials. This confirms that with both abrasives the wear mode is LSSA, whereby the particle-reinforced composite alloy performs significantly better than the homogeneous steel. However, the difference is much greater in Cannington ore than in sand. In sand, the benefit of using the hardfaced plate appears modest, whereas in Cannington ore the measured increase in wear resistance is huge. Evidently, the nature of the Cannington ore creates a more extreme differential in performance between the two alloy classes.

These laboratory test results suggest that in Cannington ore the clad plate offers very much higher service life. In practice, the increase in service life may not be as great as the factor of ~39 suggested by the bottom-right cell in Table III. One factor in this respect is that the weld deposit does not constitute the full plate thickness of the clad plate, and even the total thickness may be less than that of the martensitic steel plate. Any raw performance ratio indicated by the wear test must be multiplied by the ratio of the usable thickness of hardfacing deposit to the usable thickness of martensitic steel plate.

More importantly for the current discussion is the question of whether it can be guaranteed that the wear mode in the rubber wheel abrasion test is identical to that in the intended field application. Will the clad plate really offer 39 times better wear performance (per thickness) in service? This is the type of question for which wear researchers should be diligently seeking answers.

Inner-circumference Sliding Bed Abrasion Test

In an attempt to address the above-described disadvantages of the rubber wheel abrasion test, the authors have expended considerable effort designing, constructing, trialling and sometimes abandoning new designs of laboratory test devices for low stress sliding abrasion. The new laboratory test for LSSA, denoted the "inner-circumference sliding bed abrasion test" (IC-SBAT), is the result of this process.

The criteria for developing a new design of laboratory test for LSSA included the following:

- First and foremost, it must be capable of accommodating the actual abrasive substance that is present in the field operation. This is not negotiable, since the mineral is the strongest single factor controlling relative performance of candidate wear-resistant materials;
- Secondly, it must reproduce with reasonable fidelity both the macro-mechanics and the micro-mechanics of abrasive-to-metal contact that are present in the field;
- It should avoid artificial devices such as rubber counterfaces or bonded abrasive products. Since these devices are not present in the field, they make it less likely that the laboratory test would be capable of reproducing the contact mechanics conditions of the industrial operation;
- The laboratory test should enable simultaneous exposure of multiple specimens. This provides the opportunity for one or more internal reference materials to be included in every test, which eliminates the traditional problem of the need to maintain strictly invariant abrasion intensity from test to test. It also improves data productivity and statistical quality;
- Finally, its design should seek to avoid the common situation in which specimen wear is dominated by leading-edge effects.

The last of these criteria warrants discussion. An example of an existing test which successfully avoids this problem is the rubber wheel abrasion test. The contact geometry is such that the wear scar is entirely contained within the flat face of the specimen and there are no significant leading-edge effects. By contrast, in most slurry-pot devices the measured specimen mass loss is strongly influenced by what occurs at exposed edges upon which the abrasive particles impinge. This may or may not be a fair representation of what occurs in service; but in such devices there is a concern that the measured wear rates may be unduly sensitive to the precise details of specimen preparation or installation, leading to the potential for erroneous results.

The “inner-circumference” design of the IC-SBAT is aimed at avoiding leading edge effects. The basic design is illustrated in Figure 12. The abrasive bed is driven past the stationary specimen array by paddles. Currently, the device has two specimen rings accommodating 22 specimens each, but there is capacity to increase to a larger number of rings. The wear intensity is not identical between the rings, but this can be accounted for by use of reference specimens.

The inner-circumference specimen array has the consequence that the leading edge of one specimen is protected by the trailing edge of the upstream specimen. Even if installation does not achieve complete protection, the sharp leading edges are somewhat recessed, out of the main flow stream. Consequently, the wear is concentrated on the flats of the specimens, so it becomes possible to assess the rate of thickness loss. The specimens shown in Figure 13(a) have been subjected to an IC-SBAT test and show no tendency for preferential wear on leading edges.

The device is very versatile, accommodating a wide variety of abrasive types, operation modes and speeds. Figure 12(b) shows the IC-SBAT loaded with 20 mm gravel for a sliding-bed abrasion test, while Figure 14 shows the device being operated in slurry erosion or wet particle erosion mode (IC-WPET). Figure 15 shows specimens after a relatively long-term (60 hour) test in IC-WPET mode. In the polyurethane specimen, Figure 15(b), there is preferential wear at the impingement zone, but this is located some 2 mm behind the leading edge. Impingement angle is of course very important in erosive wear, and we are currently working on design modifications that will allow the impingement angle to be manipulated.

(a)

(b)

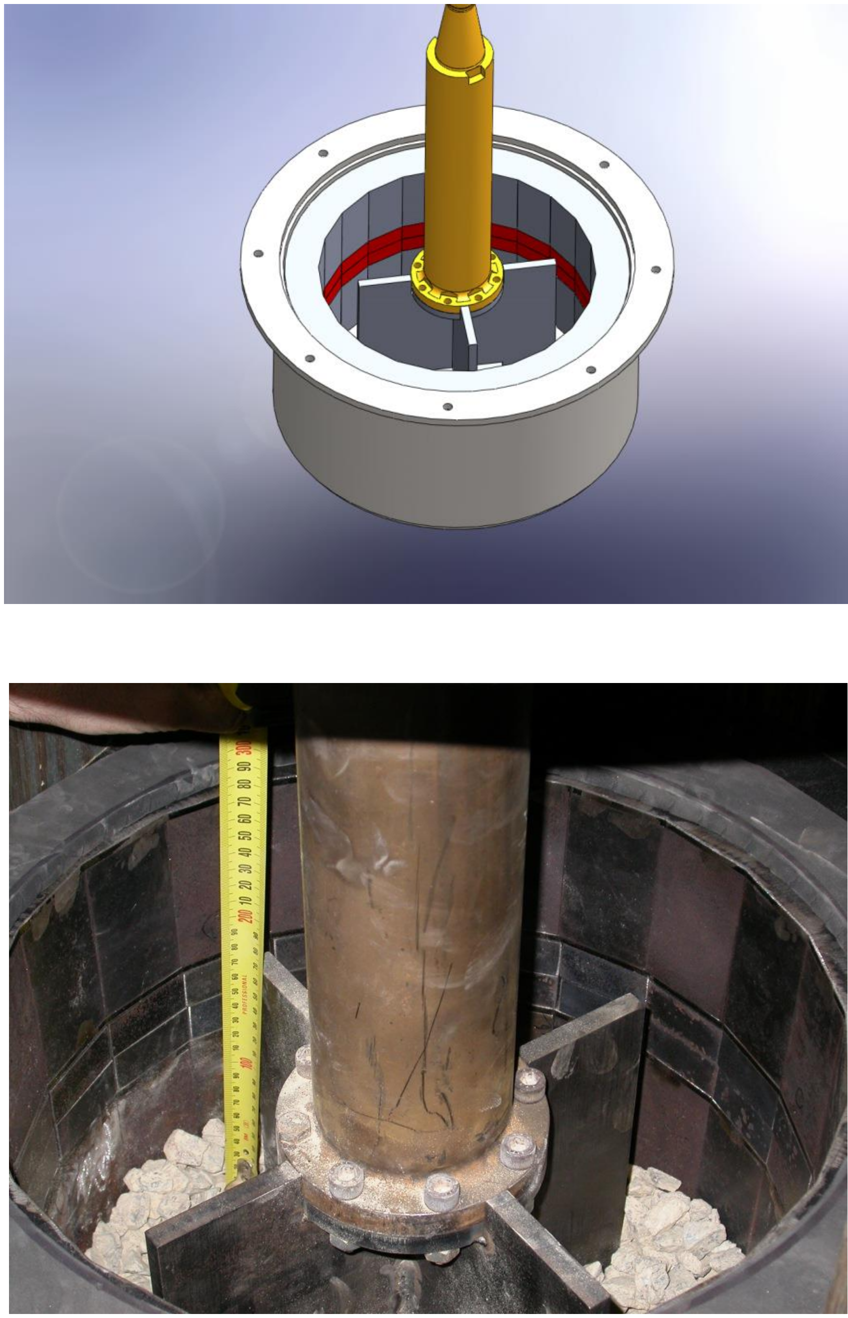


Figure 12. Key design features of the IC-SBAT (inner-circumference sliding bed abrasion test); (a) Design drawing, (b) Constructed device ready for a test with 20 mm gravel.

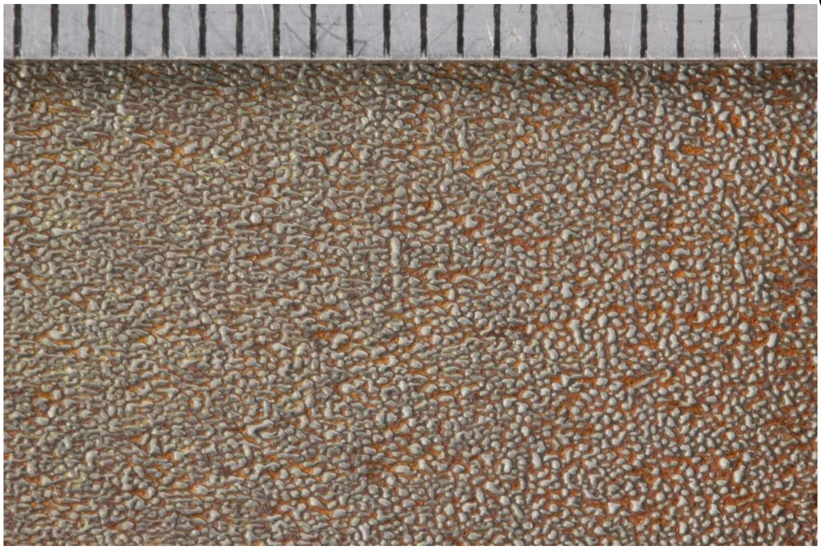
(a)

(b)

Figure 13. Different specimen sets installed in the IC-SBAT; (a) Mild steel specimens used for commissioning trials, (b) Polymeric wear-resistant materials, including polyurethanes and ultra-high molecular weight polyethylene, installed for a consultancy project.

Figure 14. Operation of the IC-SBAT device in wet particle erosion mode (IC-WPET).

(a)



(b)

Figure 15. Worn specimens after testing in the IC-SBAT device when operated in wet particle erosion mode (IC-WPET); (a) Stippled surface of mild steel specimen, due to erosion-corrosion (scale millimetres), (b) Polyurethane specimen showing impingement zone behind the leading edge (specimen 55×25 mm, particle flow from left to right).

Plant Trial Comparison for IC-SBAT

To date one plant trial has been performed in an attempt to correlate the IC-SBAT data with industrial wear rate data. The trial was in an Aran pug mill mixer at Karreman quarry in Brisbane, Australia. The trial was detailed and sustained, involving simultaneous exposure of six different white cast iron alloys, with at least ten paddle specimens of each alloy. The trial was run for 20 weeks, with approximately 100,000 tonnes of production throughput in each of the two parallel legs of the twin pug-mill mixing station.

Of the six paddle types compared, two were commercial paddles - one supplied by the original equipment supplier and one after-market replacement component. The other four paddle types were cast in a Brisbane foundry to our alloy specifications, aimed at achieving a wide variety of microstructure types within the generic high-Cr-Mo white cast iron alloy class. Figure 16 shows the CAD model for the experimental paddle castings and Figure 17 shows some of the resulting castings along with the commercial paddles.

The compositions of the six alloys are shown in Table IV. Alloy F contains the strong carbide formers niobium, vanadium and titanium, with a stoichiometric balance of surplus carbon above what would be required in the host white cast iron alloy. In the induction furnace, 2.4% niobium was added, but at that time (2010) there was no access to vacuum melting facilities. Oxidation led to loss of approximately two-thirds of both the niobium and the titanium that had been added.

Figure 18 shows two views of the pug mill, firstly during installation of the paddles and secondly during the course of the trial. Figure 19 shows two of the worn paddles. Many of the paddles were more extensively worn than these, but these were chosen for scanning electron microscope (SEM) examination as representing the stage of wear likely to dominate the life of the component.

The relative abrasive wear performance of the six alloys was measured in two laboratory tests, the RWAT and the IC-SBAT, for comparison with the pug mill trial results. In the RWAT the usual quartz sand was used, but the IC-SBAT used greywacke gravel from the quarry where the trial was conducted. The quantitative results are shown in Table V.

Scanning electron microscope images of the worn surfaces from the pug mill trial and from the IC-SBAT, at comparable magnifications and imaging conditions, are shown in Figure 20 and Figure 21. Figure 20 shows secondary electron images, emphasising the topography of the worn surface. The wear scars from the IC-SBAT and the pug mill environment are very similar. The abrasive particle motion appears to be predominantly sliding, but with some embedding. In both the pug mill and the IC-SBAT, the wear grooves are only semi-continuous. By contrast, in the RWAT the grooves were completely continuous and straight.

Figure 21 shows backscattered electron images, which provide atomic number contrast. These images enable assessment of the way in which the abrasive particles interact with the M_7C_3 reinforcing particles. Shown here is alloy B, the after-market paddles, which performed relatively poorly, apparently because the matrix was undesirably soft. There was only a small amount of cracking of the carbides, such that the wear mode appears to be predominantly low stress sliding abrasion. However, in this alloy and under these conditions the carbides are not providing very strong protection of the matrix.

The rank order of alloy performance is much the same in the two laboratory tests as in the plant trial. However, the quantitative RWAT results were poor at differentiating between the reference alloy (the OEM paddle A) and the three inferior alloys. The IC-SBAT provided a better match, but on these inferior alloys the pug mill was the most severe of the three tests.

In all three tests, alloy F, containing carbides of niobium, vanadium and titanium, provided the best wear resistance of the six alloys. The worn surface of this alloy is shown in Figure 22. It can be seen that the niobium-rich carbides stand proud - significantly more so than the chromium carbides do. Despite the relatively low volume fraction of these niobium-rich carbides, they are evidently having a protective effect for the host alloy around them. The complex alloy appears to be functioning as a kind of "double-composite", with two different reinforcing phases. If the volume fraction of NbC particles was increased, it would seem probable that they would provide even more effective protection to the host alloy.

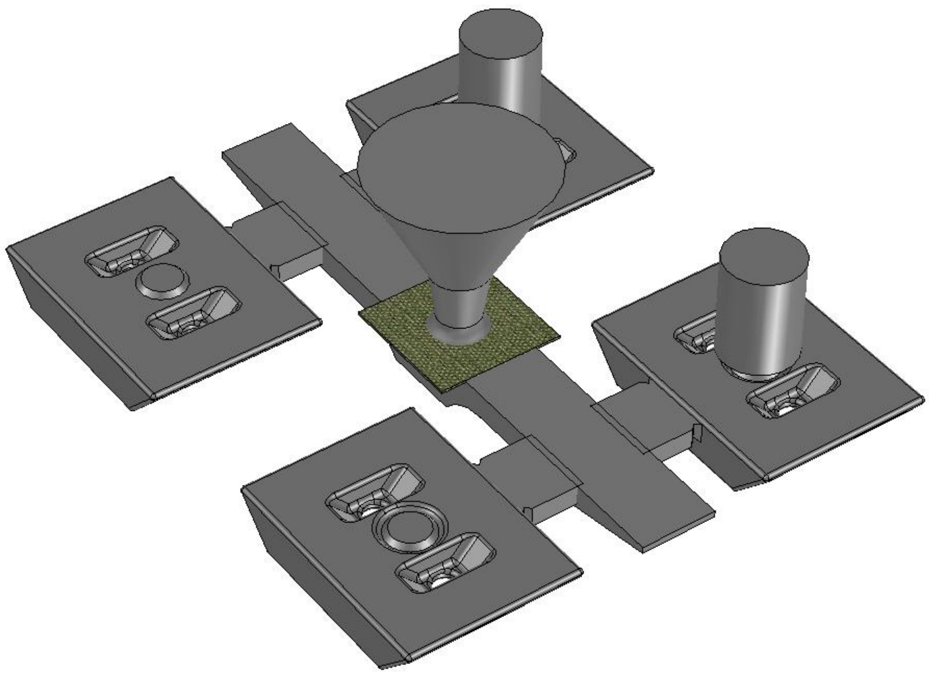


Figure 16. CAD model for the paddle castings that were manufactured in various white cast iron alloys for purposes of the pug mill trial.

Figure 17. Paddles ready for installation in the pug mill trial. Paddles A were the OEM paddles, B the after-market paddles, D and F were alloys cast for the purposes of the trial.

(a)

(b)

Figure 18. One leg of the pug mill; (a) during installation of the paddles and (b) at an inspection conducted during the course of the trial.

Table IV. Alloy Compositions of Commercial and Experimental Paddles in Pug Mill Trial

Code	Description	C (mass%)	Cr (mass%)	Mo (mass%)	Nb+V +Ti (mass%)	CVF_1† (vol%)	Ratio CrE_1/C†	Hardness (HV)
E	Stable austenite	4.15	27.5	0.00	—	51	6.5	550
B	After-market paddles	3.45	29.6	0.06	—	43	8.4	522
D	Reduced-CVF	1.87	13.8	2.60	—	16	7.8	797
A	OEM paddles	3.38	27.2	0.00	—	41	7.8	666
C	17Cr-3Mo	3.02	18.0	2.88	—	32	6.3	852
F	17Cr-3Mo + Nb,V,Ti	3.59	16.7	3.13	2.7‡	34*	5.7*	897

† Carbide volume fraction CVF normally calculated from Maratray's [54] formula, % carbides = 12.33(% C) + 0.55(% Cr) – 15.2. However here, both CVF_1 and ratio CrE_1/C are based upon a "chromium equivalent" $CrE_1 = Cr + [(Mo–1.25)\times 52.0/95.9]$, where 1.25% was the average Mo content in the systematic series of 42 alloys used by Maratray and Usseglio-Nanot [55] to determine their empirical formula.

‡ Strong carbide former concentrations were planned to be 2.4%Nb, 1.3%V, 1.2%Ti, but air melting resulted in oxidation losses which reduced the levels to 0.85%Nb, 1.33%V, 0.47%Ti.

* In alloy F, the listed C, Cr and Mo compositions are as-analysed bulk levels, but the values of CVF_1 and CrE_1/C are the estimated values for the "host" alloy, after stoichiometric carbon removed from solution by Nb, V, Ti.

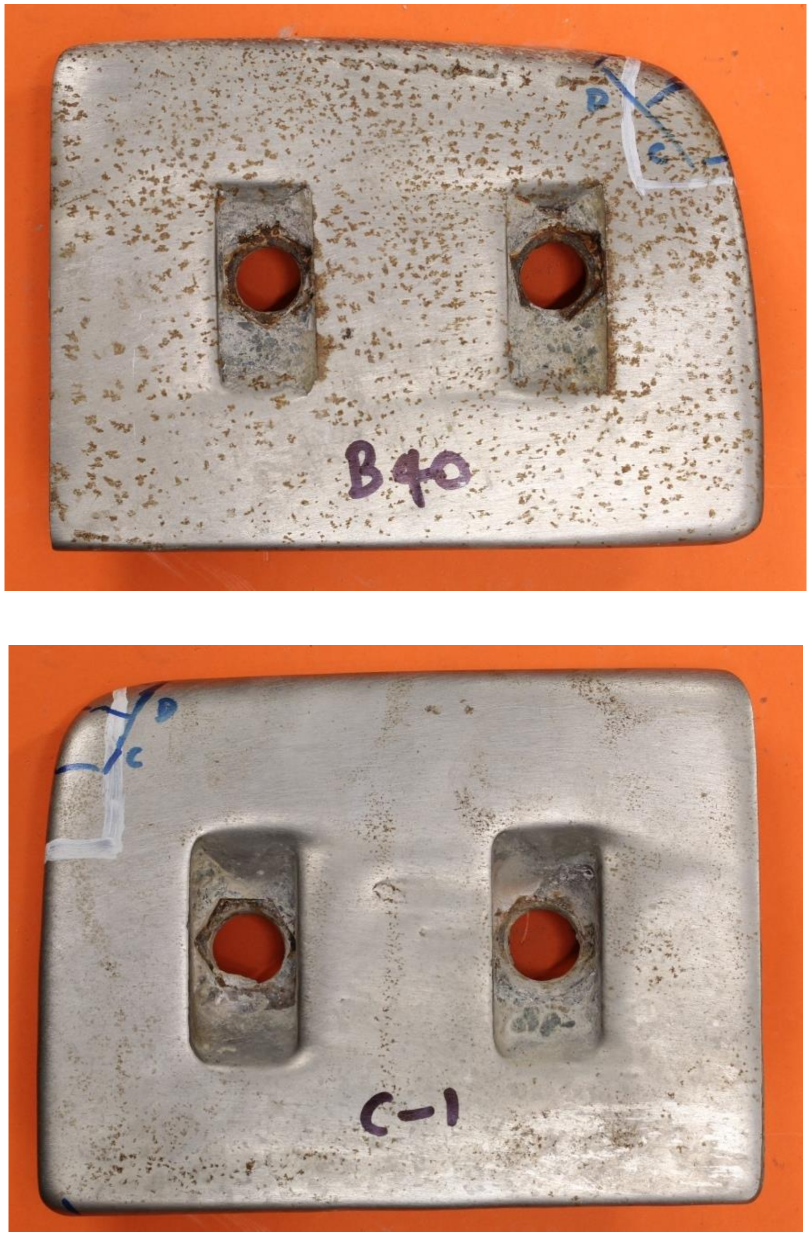
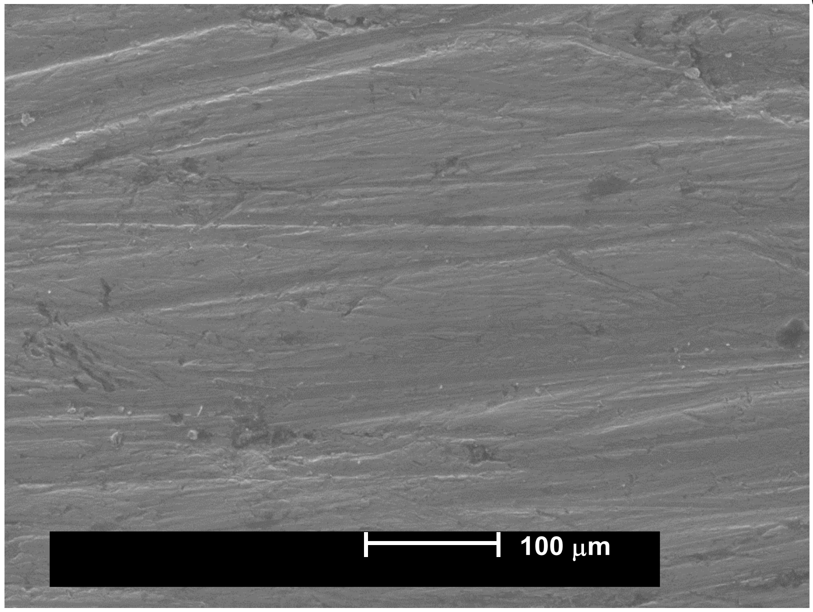
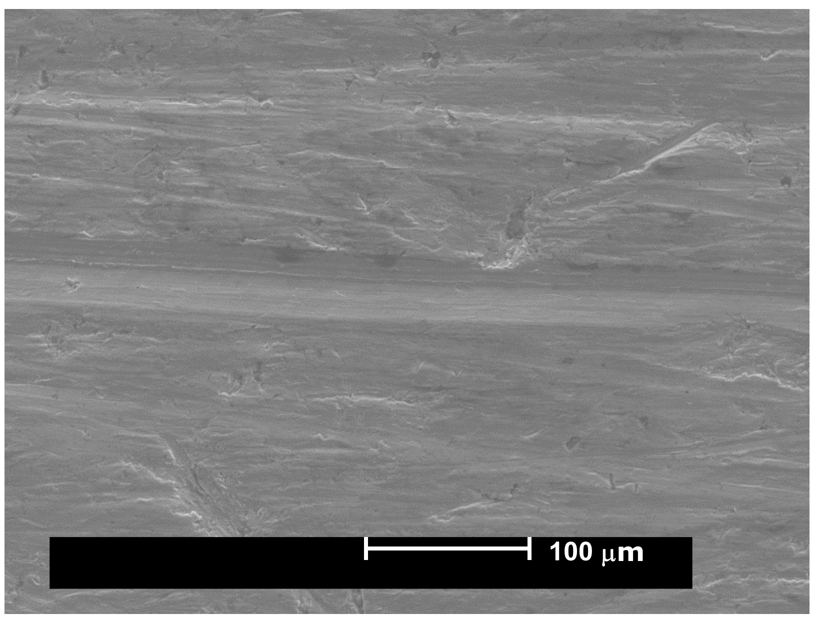


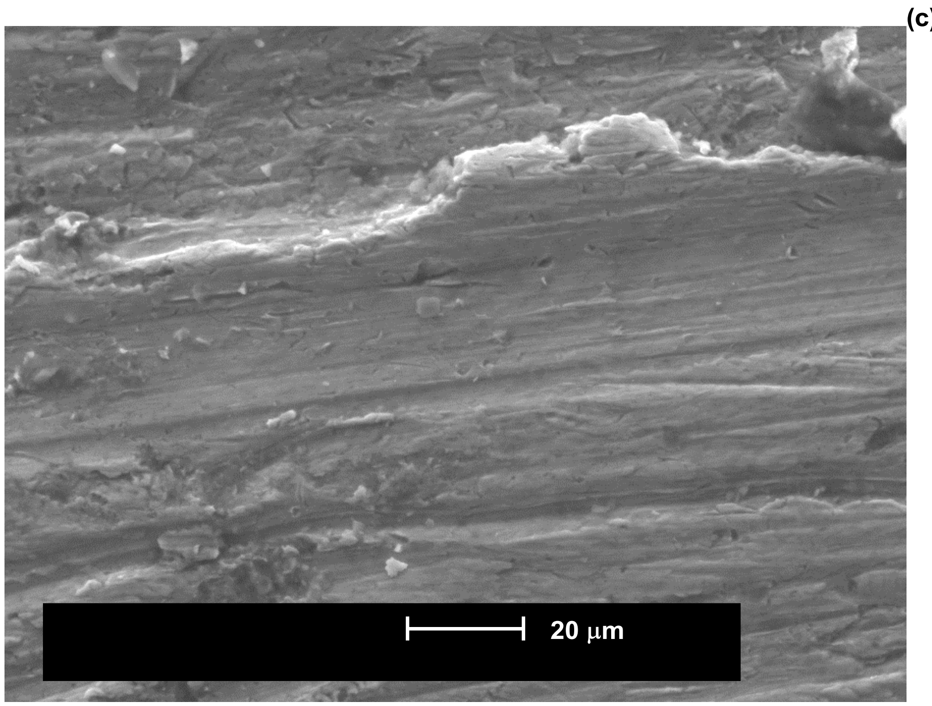
Figure 19. Worn paddles recovered after the pug mill trial, marked for cutting of samples for SEM examination of worn surfaces.

(a)



(b)





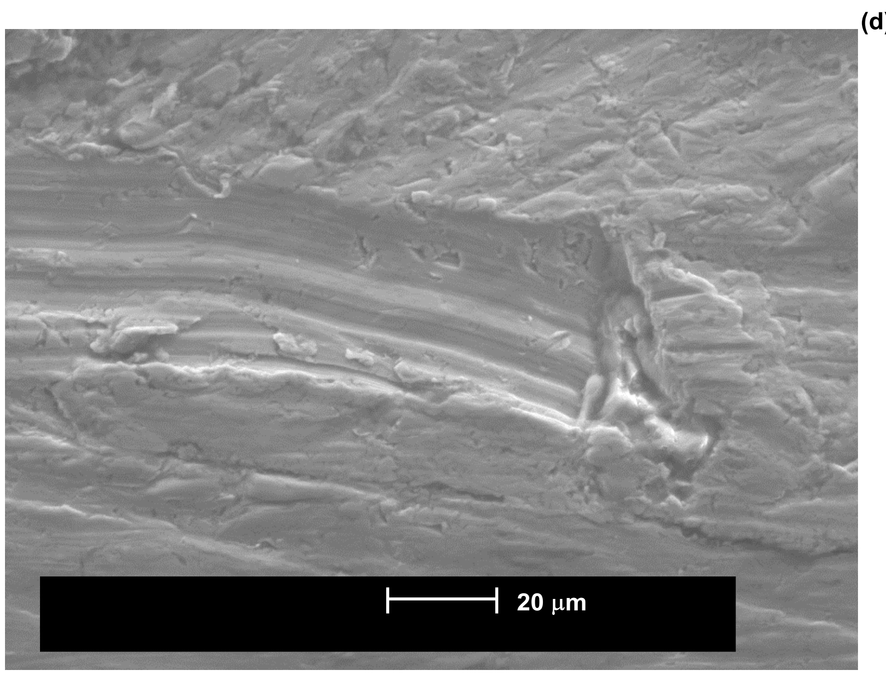
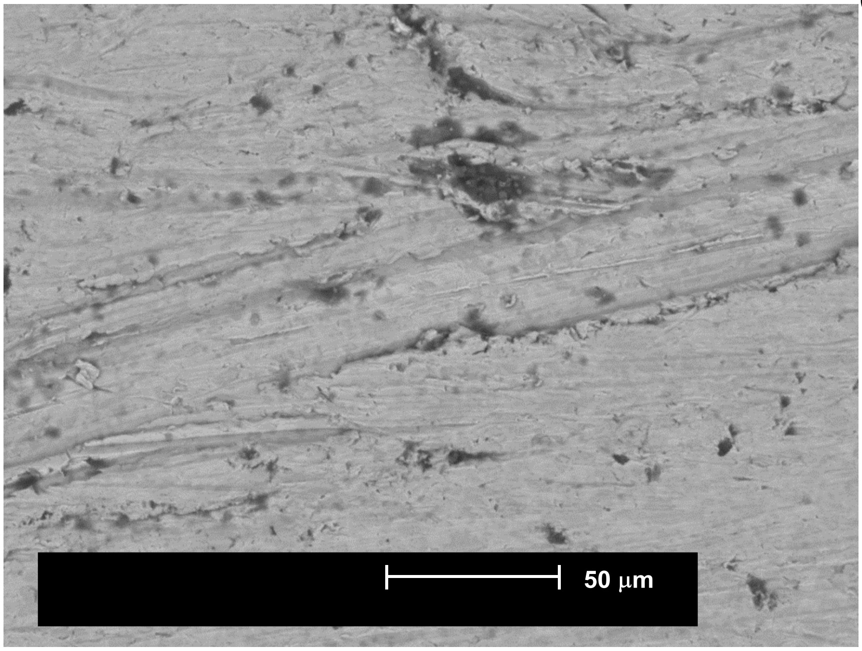
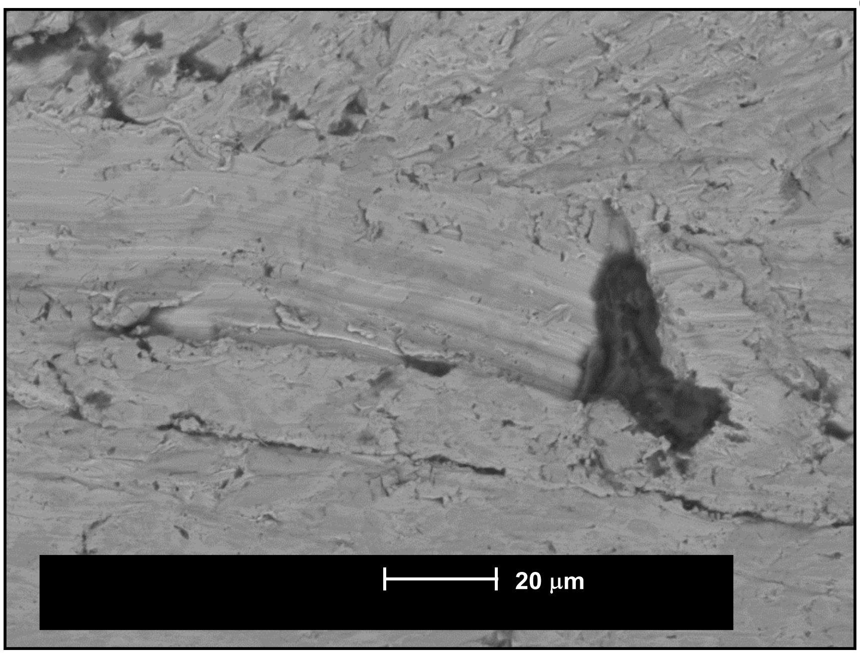


Figure 20. SEM secondary electron images comparing the worn surface characteristics from the pug mill trial with those from the IC-SBAT with the same greywacke abrasive;
(a) Pug mill worn surface at low-medium magnification, (b) IC-SBAT worn surface at low-medium magnification, (c) Pug mill at medium-high magnification, (d) IC-SBAT at medium-high magnification.

(a)



(b)



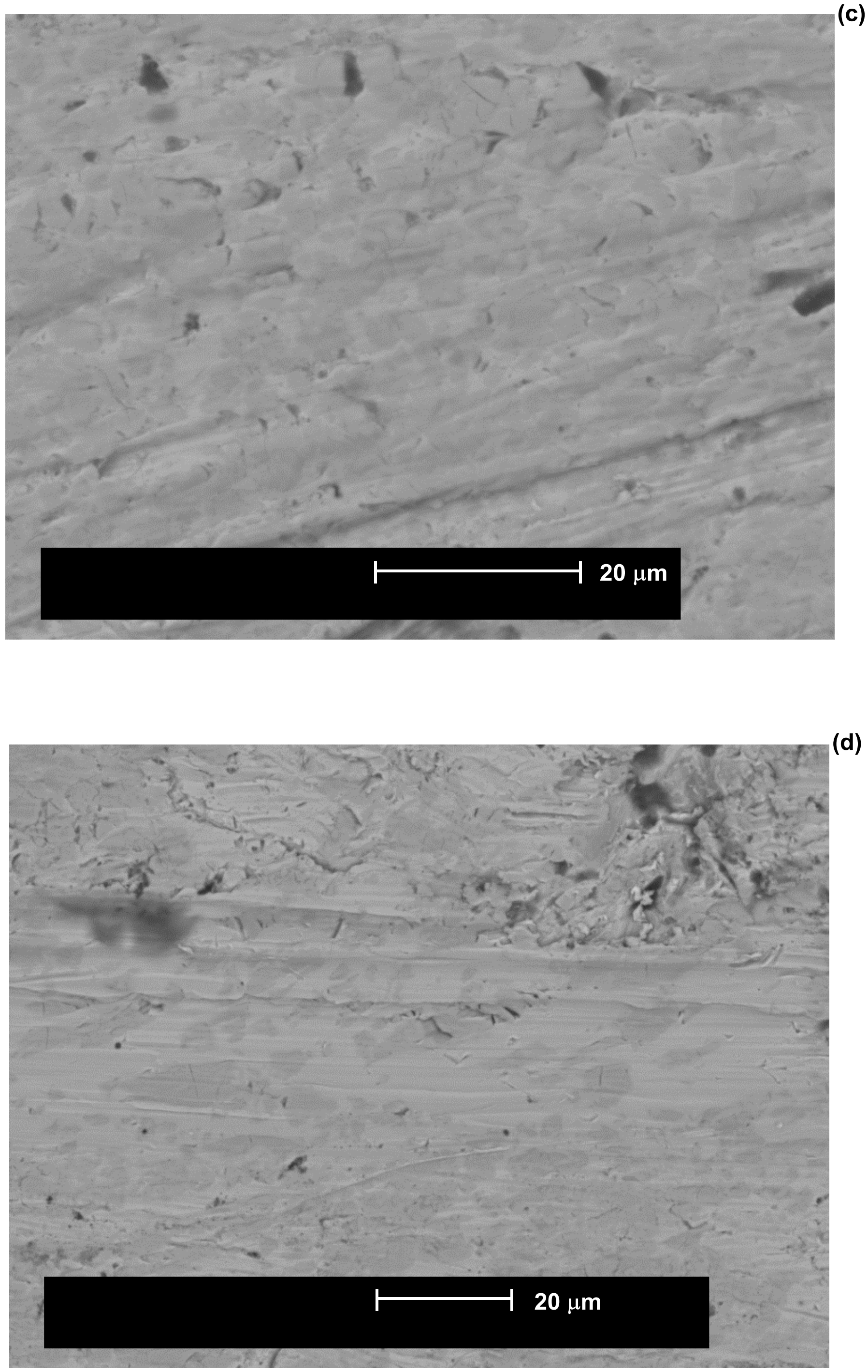
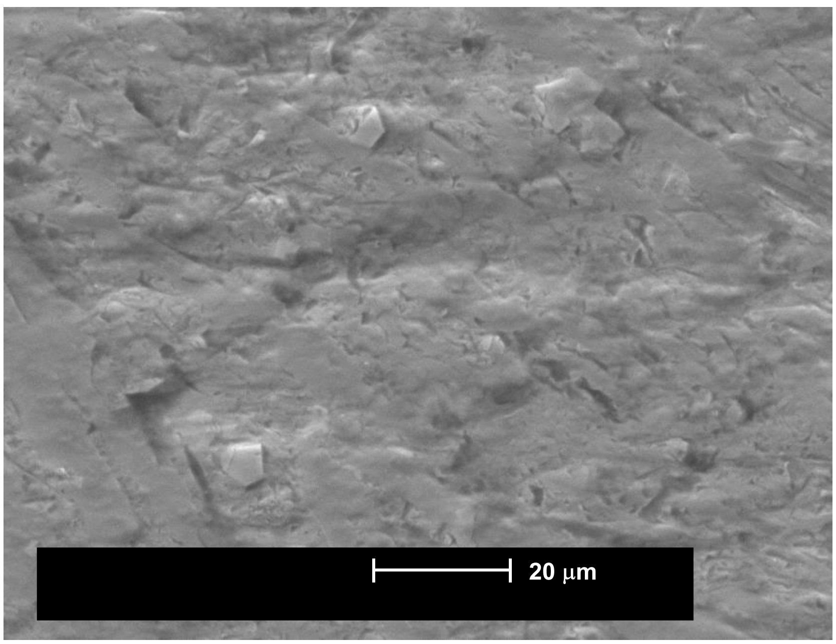


Figure 21. SEM backscattered electron images; (a), (b) Pug mill and IC-SBAT worn surfaces at medium-high magnification, (c), (d) Pug mill and IC-SBAT worn surfaces at high magnification.

Table V. Wear Data from Pug Mill Trial and Comparative Laboratory Tests

Code	**CVF_1†**	**Ratio**	**Hardness**	**Relative Wear Life**		
	(vol%)	**CrE_1/C†**	**(HV)**	**RWAT**	**IC-SBAT**	**Pug Mill**
E	51	6.5	550	95	78	50
B	43	8.4	522	97	81	63
D	16	7.8	797	106	78	63
A	41	7.8	666	100	100	100
C	32	6.3	852	135	167	110
F	34*	5.7*	897	185	185	123

† See footnote † in Table IV.
* See footnote * in Table IV.



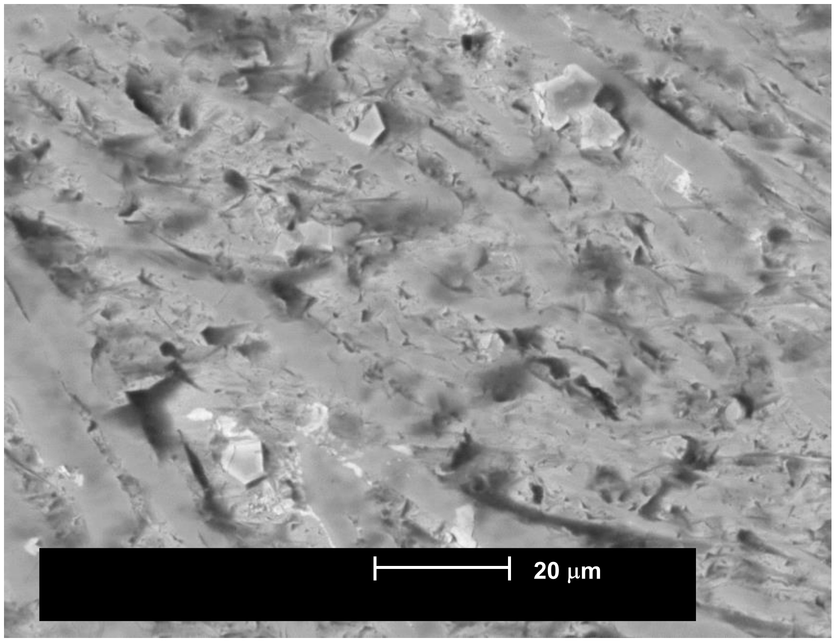


Figure 22. SEM images showing the worn surface of the NbVTi-bearing alloy F in the IC-SBAT with greywacke. The Nb-rich carbides stand proud of the matrix, and evidently provide a measure of protection to the host alloy despite their low volume fraction.

Summary of Field Trial Outcomes

Table VI provides a summary of plant trials that have been conducted, supplemented by a particularly fruitful study from the literature as reviewed in this paper. The right-hand columns show the levels of success that can be attributed to each trial, in terms of: whether quantitative performance data were successfully obtained; whether field-laboratory correlations were obtained; and whether the experimental wear-resistant material (if any) performed favourably.

It is commonly reported that a majority of the wear trials undertaken never yield quantitative data, because of lack of control or other practical problems. In light of this, it is remarkable that six out of seven trials conducted by the authors were successful in providing quantitative data.

The second success measure, that of field-to-laboratory correlation, can be regarded as the “holy grail” of tribological studies. The Newmont trial was especially remarkable in this respect, demonstrating that the laboratory ball mill abrasion test can achieve full level 4 correlation with plant wear data.

Table VI. Summary of Some Plant Trial Outcomes

Site	Equipment	Alloys	QD†	FLC†	EMF †
(Climax [3])	Ball mill liners	Pearlitic steel, Martensitic steel, Various WCIs	(✓)	(✓)	–
Mount Isa Mines	Rod mill lifter bar	Pearlitic steel, Reduced-CVF WCI	✓	×	✓
Mount Isa Mines	SAG mill liner/lifters	Pearlitic steel, transformation-toughened WCI	×	×	×
Alcoa Pinjarra	SAG mill liner/lifters	Pearlitic steel, Martensitic steel	✓	✓	×
BHP Port Hedland	Transfer chute	NiHard 4, High-Cr-Mo WCI, Duaplate	✓	×	✓
Moranbah North	Tailings pipes	Mild steel, HDPE, experimental polymer	✓	×	×
Karreman Quarry	Pug mill paddles	6 different WCIs	✓	✓	✓
Newmont Tanami	Ball mill balls	Martensitic steel (absolute wear rates)	✓	✓✓	–

† QD = Quantitative data obtained; FLC = field-laboratory correlation obtained; EMF = Experimental wear-resistant material performed favourably.

Conclusions

This paper has analysed the challenges that are faced in predicting the field performance of wear-resistant materials. Attempts to predict long-term performance can be based either upon laboratory wear tests or on quantitative field trials, but both approaches require considerable care and critical analysis before they are likely to yield reliable predictions.

Four levels of correlation between laboratory and field data can be identified, namely 1) rank, 2) linear, 3) quantitative relative and 4) quantitative absolute correlation. To make rational economic decisions regarding materials selection, equipment operators require access to predictive data exhibiting at least level 3 correlation.

Site personnel are often sceptical about laboratory test data, and this paper has provided examples demonstrating that such reservations are well justified. Sometimes, in an effort to isolate and control individual aspects of the wear environment, laboratory tests become so idealised that they no longer represent industrial conditions in any substantive sense, and their predictions may be more misleading than useful. An alternative strategy is proposed whereby mechanically simple laboratory test machines are permitted to preserve the natural complexity of the industrial environment. In such machines, the dominant wear mechanisms can be discerned indirectly by means of experiments in which key input parameters are systematically varied.

The paper has described two laboratory wear tests developed using this alternative strategy: the ball mill abrasion test (BMAT) for high stress abrasion as occurs in comminution environments; and the inner-circumference sliding bed abrasion test (IC-SBAT) for low stress sliding abrasion as occurs in ore chutes. The BMAT has been shown to be greatly superior to the “standard” pin abrasion test (PAT) that is often suggested (incorrectly) to simulate high stress abrasion. The BMAT easily achieves level 3 correlation, and with additional care can achieve level 4 correlation. The newly developed IC-SBAT shows promise for achieving level 3 correlation.

If performed with sufficient care and resources, field trials can yield useful quantitative data. However, to be sustainable in the longer term, research and development for wear-resistant materials requires access to laboratory tests that are intelligently designed and thoroughly validated against field performance. Armed with such tests, we will be in a position to evaluate a much wider range of candidate materials than could reasonably be evaluated in the field.

References

1. M.A. Moore, “Laboratory Simulation Testing for Service Abrasive Wear Environments,” *Wear of Materials 1987* (New York, NY: American Society of Mechanical Engineers, 1987), 673-687.

2. P.A. Swanson, “Comparison of Laboratory Abrasion Tests and Field Tests of Materials Used in Tillage Equipment,” *Tribology: Wear Test Selection for Design and Application*, ASTM STP 1199, ed. A.W. Ruff and R.G. Bayer (Philadelphia, PA: American Society for Testing and Materials, 1993), 80-99.

3. D.L. Albright and D.J. Dunn, “Wear Behaviour of Iron and Steel Castings for the Mining Industry,” *Journal of Metals*, 35 (11) (1983), 23-29.

4. J.D. Gates, et al., “The Meaning of High Stress Abrasion and its Application in White Cast Irons,” *Wear*, 263 (2007), 6-35.

5. G.J. Gore and J.D. Gates, “‘Impact-Abrasion’: Has its Time Come … and Gone?,” *Materials Australia*, 32 (Jul/Aug 2000), 13-15.
‘

6. J.A. Hawk et al., “Laboratory Abrasive Wear Tests: Investigation of Test Methods and Alloy Correlation,” *Wear*, 225-229 (1999), 1031-1042.

7. J.H. Tylczak, J.A. Hawk and R.D. Wilson, “A Comparison of Laboratory Abrasion and Field Wear Results,” *Wear*, 225-229 (1999), 1059-1069.

8. G.J. Gore and J.D. Gates, “Effect of Hardness on Three Very Different Forms of Wear,” *Wear*, 203-204 (1997), 544-563.

9. B. Bialobrzeska and P. Kostencki, “Abrasive Wear Characteristics of Selected Low-alloy Boron Steels as Measured in Both Field Experiments and Laboratory Tests,” *Wear*, 328-329 (2015), 149-159.

10. W.L. Maxson, F. Cadena and F.C. Bond, “Grindability of Various Ores,” *Transactions American Institute of Mining and Metallurgical Engineers*, 112 (1933), 130-146.

11. F.C. Bond and W.L. Maxson, “Grindability and Grinding Characteristics of Ores,” American Institute of Mining and Metallurgical Engineers Technical Publication No. 888, 1938 (*Transactions American Institute of Mining and Metallurgical Engineers*, 134 (1939), 296).

12. F.C. Bond, “Metal Wear in Crushing and Grinding,” *Chemical Engineering Progress*, 60 (2) (1964), 90-93.

13. A.K. Gangopadhyay and J.J. Moore, “The Role of Abrasion and Corrosion in Grinding Media Wear,” *Wear*, 104 (1985), 49-64.

14. J.J. Moore, R. Perez, A. Gangopadhyay et al., “Factors Affecting Wear in Tumbling Mills: Influence of Composition and Microstructure,” *International Journal of Mineral Processing*, 22 (1988), 313-343.

15. J.E. Sepúlveda, “Methodologies for the Evaluation of Grinding Media Consumption Rates at Full Plant Scale,” *Minerals Engineering*, 17 (2004), 1269-1279.

16. I. Iwasaki, J.J. Moore and L.A. Lindeke, “Effect of Ball Mill Size on Media Wear,” *Minerals and Metallurgical Processing*, 4 (2) (1987), 160-168.

17. T. Chandrasekaran, K.A. Natarajan and Kishore, “Influence of Microstructure on the Wear of Grinding Media,” *Wear*, 147 (1991), 267-274.

18. C. Thirumalaisamy and Kishore, “Estimation of Abrasive and Impact Components of Overall Wear,” *Materials Australia*, 32 (July/August 2000), 19-20.

19. P. Radziszewski, “Developing an Experimental Procedure for Charge Media Wear Prediction,” *Minerals Engineering*, 13 (2000), 949-961.

20. P. Radziszewski, “Exploring Total Media Wear,” *Minerals Engineering*, 15 (2002), 1073-1087.

21. P. Radziszewski et al., “Tumbling Mill Steel Media Abrasion Wear Test Development,” *Minerals Engineering*, 18 (2005) 333-341.

22. T.W. Chenje, D.J. Simbi and E. Navara, “Relationship Between Microstructure, Hardness, Impact Toughness and Wear Performance of Selected Grinding Media for Mineral Ore Milling Operations,” *Materials and Design*, 25 (2004), 11-18.

23. E. Albertin and A. Sinatora, “Effect of Carbide Fraction and Matrix Microstructure on the Wear of Cast Iron Balls Tested in a Laboratory Ball Mill,” *Wear*, 250 (2001), 492-501.

24. E. Albertin and S. deMoraes, “Maximizing Wear Resistance of Balls for Grinding of Coal,” *Wear*, 263 (2007), 43-47.

25. J.D. Gates, “Abrasion in a Vertical Roller Mill” (Report #40325 for Queensland Cement Limited, UQ Materials Performance, Oct 2001), 1-29.

26. Z. Hildebrand, “A New High-Stress Abrasion Testing Method” (B.Eng. thesis, The University of Queensland, Nov 2002).

27. J.D. Gates, “Alloy Development and Optimisation of Abrasion-Resistant White Cast Irons – Final Report on 2006-2007 R&D Project” (Report #40912 for Bradken, CAST Cooperative Research Centre, Mar 2008), 1-90.

28. J.D. Gates, “Grinding Media Wear Testing for Continuous Improvement Program – Phase 01” (Report #41133+41218 for Newmont Asia Pacific and Comsteel Grinding Media, CAST Cooperative Research Centre, May 2008), 1-11.

29. J.D. Gates et al., “Effect of Abrasive Mineral on Alloy Performance in the Ball Mill Abrasion Test,” *Wear*, 265 (2008), 865-870.

30. A. Comino, “Effect of ‘Impact’ on the Performance of White Cast Irons Relative to Low-alloy Steels in Grinding Mills” (B.Eng. thesis, The University of Queensland, Oct 2009).

31. C. Blyth, “Effect of Impingement Angles on the Performance of White Cast Irons Relative to Low-alloy Steels in Grinding Mills” (B.Eng. thesis, The University of Queensland, Oct 2010).

32. J.D. Gates, “Grinding Media Wear Testing – Phase 02” (Report #41293 for Newmont Asia Pacific, CAST Cooperative Research Centre, Jul 2011), 1-46.

33. J.D. Gates, A.L. Giblett and R. Dunne, “Prediction of Plant Ball Mill Media Wear Rates from Laboratory Ball Mill Test Data” (Paper presented at Comminution ’12, Cape Town, South Africa, Apr 2012).

34. L. Keen, “Effect of Tempering on Abrasion and Chipping of White Irons” (B.Eng. thesis, The University of Queensland, Oct 2012).

35. A.A. AbdulKadir, “The Ball Mill Edge Chipping Test (BMECT) for Evaluating Fracture Toughness of White Cast Irons” (B.Eng. thesis, The University of Queensland, Oct 2013).

36. I.T. Cheong, “Exploring the Ball Mill Impact-fatigue Test (BMIFT)” (B.Eng. thesis, The University of Queensland, Oct 2013).

37. P.J. Bennet and J.D. Gates, “Mill Media Research Phase 04 – Effect of Corrosion on Wear Performance of Cast Chrome-Iron vs Forged Low-Alloy Steel Media” (Report #41562-04 for Newmont Mining Corporation, AMPAM, Feb 2014), 1-48.

38. J.D. Gates, “Wear Performance of Grinding Media using BMAT with Kittilä (Finland) Ore” (Report #41942 for Metso Process Technology & Innovation, UQ Materials Performance, Jul 2014), 1-20.

39. J.D. Gates, “Wear Performance of Grinding Media in Cananea Ore and Preparations for Cananea Plant Trial” (Report #42011 for Metso Process Technology & Innovation, UQ Materials Performance, Sept 2014), 1-49.

40. B. Hadaway, “Understanding the Performance Characteristics of Commercial Grinding Media” (B.Eng. thesis, The University of Queensland, Oct 2014).

41. M. Goode, “Understanding the Relationship between Corrosion and Abrasion Consumption Mechanisms in Grinding Mills” (B.Eng. thesis, The University of Queensland, Oct 2014).

42. C. Aldrich, “Consumption of Steel Grinding Media in Mills – A Review,” *Minerals Engineering*, 49 (2013), 77-91.

43. J. Sepulveda, B. DeAraugo and L. Wardell-Johnson, “Comparative Evaluation of Grinding Media Consumption Rates at Full Plant Scale” (Paper presented at SAG 2006, Vancouver, B.C., Canada, 2006), 1-18.

44. R. Blickensderfer and J.H. Tylczak, “A Large-scale Impact Spalling Test,” *Wear*, 84 (1983), 361-371.

45. A. Giblett and J. Seidel, “Measuring, Predicting and Managing Grinding Media Wear” (Paper presented at SAG 2011, Vancouver, B.C., Canada, Sep 2011), 1-12.

46. J. Levin, “Observations on the Bond Standard Grindability Test, and a Proposal for a Standard Grindability Test for Fine Materials,” *Journal of the South African Institute of Mining and Metallurgy*, 89 (1) (1989), 13-20.

47. M.C. Fuerstenau and K.N. Han, *Principles of Mineral Processing*, (Littleton, CO: Society for Mining Metallurgy and Exploration, 2003), 85.

48. J. Dodd et al., “Relative Importance of Abrasion and Corrosion in Metal Loss in Ball Milling,” *Minerals and Metallurgical Processing*, 2 (4) (1985), 212-216.

49. J.D. Gates and G.J. Gore, “Wear of Metals: Philosophies and Practicalities,” *Materials Forum*, 19 (1995), 53-89.

50. J.D. Gates, “Two-body and Three-body Abrasion: A Critical Discussion,” *Wear*, 214 (1998), 139-146.

51. J.D. Gates, “Wear Liners for Iron Ore Chutes – Final Report” (Report #40274 for Tasman Warajay Pty Ltd, UQ Materials Performance, Dec 2000), 1-10.

52. H.S. Avery, “The Measurement of Wear Resistance,” *Wear*, 4 (1961), 427-449.

53. J.D. Gates, “Wear Tests on Bisalloy 500 and Other Wear Plate” (Report #40557 for BHP Billiton Cannington Mine, UQ Materials Performance, Sep 2002), 1-16.

54. F. Maratray, “Choice of Appropriate Compositions for Chromium-Molybdenum White Irons,” *Transactions of the American Foundrymen’s Society*, 79 (1971), 121-124

55. F. Maratray and R. Usseglio-Nanot, *Atlas – Transformation Characteristics of Chromium and Chromium-Molybdenum White Irons*, (Paris, France: Climax Molybdenum S.A., 1970), 16