Method Article

Ball mill abrasion test (BMAT): Method development and statistical evaluations

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ABSTRACT

High-stress abrasive wear is a major material consumption process in mining and ore beneficiation industries. The common laboratory high-stress abrasion apparatuses suffer from lack of capability of closely simulating the service conditions of grinding media and mill liners, being the main consumables in these sectors. The ball mill abrasion test (BMAT) is a versatile abrasive wear tester that facilitates reliable modelling of kinematics and contact mechanics of the industrial mills. Unlike ‘standard’ test devices, natural rocks of any type and/or blend with desired particles size distributions can be charged into the BMAT for tests under various ranges of liquids, grinding media and durations. It is simple to design, low-cost to manufacture, reliable to evaluate alloys performance and reproducible to rank abrasion-resistant materials. In this work, BMAT’s two operation modes, BMAT-T (tumbling mode) and BMAT-C (cassette mode) are introduced. The performed comprehensive analysis on the method development, statistical assessment and further procedures refinement showed that:

- In the BMAT-T, 20-hour tests using the planned operational parameters and normalisation method result in statistically reliable and reproducible outcomes.
- In the BMAT-C, four 20-hr intervals, different operational parameters and specific specimen distribution pattern are needed to obtain high quality measurements.
- The maximum observed relative standard deviation in the all statistical and alloy-performance evaluation campaigns was 6.6% — an excellent quality dimension for an abrasion test.

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Introduction

The ball mill abrasion test (BMAT) is an industrially-relevant multipurpose wear test method that enables tribologists and abrasion scientists to study the abrasive wear behaviour of materials for various service applications, particularly for grinding balls and mill liners, under conditions and contact mechanics very similar to the industrial ball mills. Although the BMAT is capable to be operated under low-stress conditions, it is commonly utilised to simulate the abrasive wear conditions under high-stress abrasion contacts.

Due to the relative novelty of this test and its significant potential to be widely employed as a reliable predictor of wear performance in high-stress abrasion environments, this communication focuses on testing procedure developments, statistical data quality evaluation and then procedure refinement. In the following sections, two modes of the BMAT, tumbling mode (BMAT-T) and liner mode (BMAT-C), will be introduced. The important testing parameters to plan reproducible test campaigns will be fully explained. The requirements for the materials and abrasive minerals used in these tests will be given along with the methods for normalisation of the raw weight loss data. In order to assess reliability and reproducibility of the developed methodologies, the statistical measures of the conducted tests will be reported and compared to establish and further refine the test methods for BMAT-T and BMAT-C.

Background

High-stress abrasion

Abrasive wear is commonly categorised into low-stress abrasion and high-stress abrasion, also known as scratching and grinding, respectively [1,2]. Other terms used for high-stress abrasion include high-stress crushing, high-stress grinding and high-stress comminution abrasion — since it is particularly noticeable in comminution operations (e.g. ball mills) in mineral processing. The severity-based approach proposed by Gates [3] classifies abrasive wear into three main categories of mild, severe and extreme modes. This detailed and more accurate approach takes into account the other wear components such as abrasive particle size, shape and constraint as well as the level of contact stress and the dominant damage mechanism. In this scheme, high-stress abrasion is classified under severe wear mode as opposed to mild wear mode for low-stress abrasion.

High-stress abrasion is “progressive material removal from a hard solid surface by the action of hard particles rolling or sliding on that surface with sufficient force to cause fracture of the particles” [4]. The more explicit term ‘high normal stress abrasion’ has been suggested [5] to highlight the dominance of the normal contact stresses over sliding-type contact. As per the Reye–Archard–Khrushchov equation \( W = K.F. \nu/H \), in high-stress abrasion, the magnitude of load \( F \) is higher than in low-stress abrasion — where \( H \) is the hardness of the material and \( K \) is the wear coefficient of the tribo-system. Nevertheless, the load is almost always accompanied by a sliding action, even though the sliding velocity \( \nu \) is relatively low. If velocity is zero, indentation cannot remove any material except by meso- or macro-scale fracture mechanisms, which are outside the scope of abrasion. Pure normal stresses with no tangential components can only cause plastic deformation in non-brittle constituents and/or micro-cracking and micro-fracturing in brittle constituents. In order to efficiently remove the detached cracked and/or the fractured components from plastically-deformed more ductile components, sliding action is required.

In high-stress abrasion, the contact stress levels should be higher than the strength of the abrasive. Therefore, the main distinction between low-stress and high-stress abrasion is whether abrasive
particle is crushed or not [6–11]. However, “within each type [class] there is a stress range that depends on character of the abrasive and its velocity” [6]. That is, the characteristics of the abrasives as well as testing condition contribute to the levels of damage observed. Grinding two different abrasives with constant testing conditions may not result in high-stress abrasion in both cases. Hawk [7] stated that high stress can occur when the third body (abrasive) particles are compressed between two solid surfaces, e.g. between grinding ball and liner or between two grinding balls; not necessarily as a result of abrasive crushing. Consequently, high-stress abrasion is often thought to be three-body type, although two-body high-stress condition can also exist. In any case, crushing of the abrasive is the most commonly cited threshold to distinguish high-stress from low-stress abrasion.

High-stress abrasion is noticeable economically. Avery [6] reports that about $1.5M (1961 values) was annually spent on wear-resistant consumables in Climax mill liners and balls – 88% of total metal loss in the whole plant. Typically, 50% of costs associated with comminution process is due to wear of ball mill liners and grinding media. It is estimated that more than 600,000 tonnes of steel are consumed annually in grinding media. Knowing that comminution expends 30–50% of mining operating costs, the importance of high-stress condition becomes more visible [12].

**Measurement of high-stress abrasion**

The most common laboratory test method used to evaluate material resistance to high-stress abrasion is ASTM G132 pin abrasion test (PAT) [13], including its various geometries such as pin-on-drum, pin-on-plate and pin-on-disc. The main characteristics of PAT is that test surface of the pin specimen constantly traverses fresh abrasive-bonded paper or cloth, under a constant load. Despite the fact that contact stress is limited to levels that can be tolerated by the cloth or paper without tearing (about 6.8 kgf, resulting in nominal contact stress of 2.1 MPa), PAT is generally thought to simulate high-stress abrasion [8], because it continually uses sharp abrasive particles, and the pin sample is exposed to consistent high attack angle of the abrasive particles, due to their constraint [14].

However, PAT is “better described as simulating, rather than producing” [11] the service conditions of liner or grinding media in grinding mills. Gates et al. [5,8] went further, indicating that PAT’s fidelity of simulation is poor, and this test “does not represent high stress abrasion in any industrially meaningful sense”. The reason is that PAT indeed produces performance rankings more similar to low-stress abrasion than high-stress abrasion. The ratio of wear rates between relatively-high-hardness (about 700 HV) and relatively-low-hardness (about 250 HV) materials is around 6 or 7 in low-stress abrasion compared to around 1.5 for high-stress abrasion. PAT does not seem to produce such ‘compressed performance ratio’. In addition, carbide-reinforced alloys such as white cast irons (WCIs) exhibit very high performance in low-stress abrasion, but in high-stress abrasion conditions these alloys generally perform similar to single-phase materials with comparable hardness (such as quenched and tempered steel), mainly due to micro-fracture of carbide particles. PAT does not seem to be able to produce this ‘relative ineffectiveness of carbide-reinforcement’, as expected from a high-stress abrasion test [14].

A hypothesis was developed in the literature studying the tumbling grinding mills such as ball mills, SAG mills and rod mills to explain ‘compressed performance ratio’ and ‘relative ineffectiveness of carbide-reinforcement’ in terms of ‘impact-abrasion’. Gore and Gates [11] showed that in tumbling mills there is no evidence of ‘impact’ in any practical sense. Repetitive impact in large industrial mills can only produce a form of contact-fatigue with no evidence of synergism between it and abrasion.

Other wear tests [15–25] have been proposed for high-stress abrasion testing in attempts to closely simulate the service conditions of ball mills, such as crushing pin-on-disc, ASTM B611 [26] alumina slurry tester, dry-sand steel wheel abrasion test. ASTM G81 jaw crusher abrasion tester [27] has been also used in the literature to produce high-stress abrasion, but it suffers from not achieving time-invariance of test conditions. Despite some level of success that Sare et al. [28] attained with providing an internal reference using split specimens, statistical measures of the data and hence test reliability was poor. Avery [6] used the wet-sand rubber wheel abrasion test to simulate ball mill wet grinding, but rigorous analysis have indicates that rubber wheel abrasion tests such as ASTM G65 [29] and G105 [30] are not capable of producing high-stress abrasion similar to ball mills. These test procedures are now well-accepted methods for evaluation of low-stress abrasion performance of materials.
Ball mill abrasion test (BMAT)

High-stress abrasion can simply be produced in a laboratory ball mill, having similar geometry, motions, and interactions to those of industrial ball mills. It can be claimed that testing conditions exceedingly similar to service conditions can be achieved. Although it has not yet been standardised, some studies [8,10,12,31-36] have used the ball mill abrasion test (BMAT) to ‘reproduce’ industrial ball mill conditions in laboratory-scale ball mills. The BMAT benefits from some advantages compared to above-mentioned benchtop and/or ‘standard’ wear tester as follows:

- The kinematics and contact mechanics in the BMAT match those in the industrial ball mills very closely, without any need for complicated engineering designs or inaccurate assumptions.
- It is naturally ensured that abrasive particles enter and pass through the contact zone between the specimens and counterbodies, i.e. between test specimens and grinding balls or between grinding balls.
- It can be operated in various modes to create different abrasion conditions. It can even produce low-stress abrasion, by using rubber coated balls and/or soft abrasives. The variations in mill rotation speed and other operational parameters make it possible to achieve a wide range of conditions, including different impingement angles.
- It is simple to design and manufacture, with low cost, a robust BMAT apparatus.
- By using various liquids in the slurry to vary pH, the BMAT can be used to study synergistic effects of corrosion, as can occur in industrial ball mills.
- Any type/blend of abrasive/s with wide range of mineral contents, initial particle size distributions and shape can be used. In contrast to other tests, there is no need to use commercial abrasives, fine sand or other approximations; instead, real rock encountered in mining activities can be charged into the BMAT.
- Different modes of the BMAT can facilitate investigations of grinding balls or mill liners, in very similar environment to industrial mills regarding charge media motions, geometry, contact mechanics, etc.
- In the liner mode of the BMAT, 60 block specimens can be tested simultaneously; this number can reach 120 or more for tumbling mode. This ensures that all specimens experience identical testing conditions, thus improving data quality and reliability. Abrasion life of the grinding balls in a broad range of their diameters can be quantified, too.
- Prolonged tests, loading fresh abrasive at intervals, can be run to increase the weight loss of specimens and better highlight the difference in the performance of similar alloys.

Tumbling mills use grinding bodies which are hard and commonly heavier than ore particles. Total volume of the grinding bodies (balls in conventional ball mills), including the interstices, is slightly less than half of the mill volume. As the result of mill shell rotation and its friction (plus lifters effect if present), the grinding media is lifted until they reach to the mill shoulder, where dynamic equilibrium is reached. Depending on the mill rotation speed (expressed as percentage of the critical speed), from mill shoulder; grinding media cascade or cataract down to the toe of the mill charge [37].

Charge motions and working principles of typical ball mills are presented in Fig. 1. Contact forces can be generated from two sources: total weight of the charge materials above the contact point; and normal component of the deceleration vector in collisions of grinding balls with each other or liners. In laboratory-scale ball mills, these two sources are of similar magnitudes [8]. Schematics of the typical ball mills illustrated in Fig. 1 show below zones [37,38]:

i) abrasion, grinding or sliding zone;
ii) cascading or tumbling zone;
iii) cataracting or falling ball zone;
iv) impact, crushing or fracture zone;
v) dead zone; and
vi) empty zone.
Method details

Overview of the testing method

As mentioned in previous section, the ball mill abrasion test (BMAT) is a versatile test method which can be employed to reproduce different abrasion conditions and even other damage mechanisms occurring in industrial ball mills and possibly similar environments. Using rubber-coated grinding balls, the BMAT is capable to be run in low-stress abrasion mode to simulate wet grinding of low-competence mine ores.

This work focuses exclusively on the capabilities of BMAT in performance evaluation of abrasion-resistant materials in high-stress abrasion conditions. Depending on the constraint of the specimens, high-stress abrasion module of the BMAT can be run in tumbling mode (BMAT-T) or liner (or cassette, BMAT-C) mode. In the former, specimens (blocks with generously-rounded edges or grinding balls) are tumbled in the ball mill together with grinding media, abrasive particles (desired type, size and shape) and liquid (water or any other liquid with desired pH) with pre-planned milling parameters and test duration. However, in the BMAT-C, specimen blocks (slightly-rounded edges) are mounted into specimen-holder cassette rings and do not tumble during the test. These mounted specimens experience very close conditions to those of wear plates in the ball mill liners, whereas specimens in BMAT-T have similar kinematics and contact mechanics to the grinding media in industrial comminution environments. However, the evaluation outcomes of both modes are quite similar in terms of relative abrasion resistance for homogenous materials. For inhomogeneous materials, such as hardfacing with weld overlays on a generally mild steel substrate, BMAT-C should be used in order to assess the abrasive wear resistance of the hardfacing.

BMAT-T — tumbling mode of the ball mill abrasion test

Materials and abrasives

For trials to develop testing procedures, and to evaluate statistical performance of the test for a wide range of alloy classes, three materials were selected as representatives of their class: hyper-eutectic high-Cr WCI (CB100); hypo-eutectic high-Cr WCI (CB123); and abrasion-resistant low-alloy steel (Bis500). The chemical compositions, heat treatment cycles and hardness of these alloys are provided in Table 1.

15 specimens of each of the above three alloys were prepared for testing in the BMAT-T. They were cut into blocks of nominal dimension of $52 \times 24 \times 15$ mm. CB100 and CB123 were heat treated as mentioned in Table 1 whereas no heat treatment was conducted on Bis500. All specimens then were surface ground using polymer-bonded ceramic grinding segments under water-cooling to minimise the risk of any thermodynamically-activated transformations and thermal cracking. In order to avoid chipping of the edges and corners of the block specimens, their edges and corners were generously rounded by a belt grinder (linisher) using belts of grit 60 and 80 prior to testing. Attention was paid to engrave the labels as far as possible from the edges to prevent any gross fracture of the edges.
Table 1
Chemical composition, heat treatment cycle, and Vickers hardness of steel specimens.

| Alloy  | Chemical composition | Hardness (HV) | Heat treatment                      |
|--------|----------------------|---------------|-------------------------------------|
| Code   | C Cr Mo Cu Mn Si Ni S P |               | Destabilisation/Tempering           |
| CB100  | 3.39 23.60 1.01 0.03 1.06 0.36 0.89 0.01 0.01 | 857±2        | 1000°C, 2hr / 2 × (180°C, 2hr)     |
| CB123  | 1.71 17.94 0.87 0.02 0.74 0.31 0.75 0.01 0.01 | 702±3        | 1000°C, 2hr / 2 × (180°C, 2hr)     |
| Bis500 | 0.29 1.02 0.27 0.03 0.30 0.32 0.21 0.01 0.02 | 563±4        | received as heat-treated (Q&T)      |

After the test, specimens were washed in water using a nylon brush, ultrasonically cleaned, alcohol rinsed, and immediately dried with filtered compressed air. The observed weight losses of the specimens are in the magnitude of tens of milligrams, so special attention must be paid to the weighing step. For best consistency in weight measurements, the same cleaning procedure was used pre-test and post-test. Cleaned specimens were equilibrated to laboratory temperature and humidity prior to weighing by a precision balance with the resolution of 0.001 g. Three repetitions were done. Any set of measurements with variations greater than the balance's specified and verified reproducibility (2.3 mg) were rejected and a new set of readings was performed.

Greywacke with particle size distribution of ~5 mm was used as the abrasive in the conducted BMAT-Ts. Greywacke is a sedimentary quarry rock with substantial proportions of angular grains of quartz, generally characterised by its hardness and dark colour. For the purpose of these tests, it was sourced from Boral Quarries Ormeau (Kingsholme), crushed using a mill crusher and screened to the mentioned particle size.

A perspective of importance is that the wear mode in the BMAT is not always necessarily pure high-stress abrasion as it strongly depends on the nature of the abrasive used, notably its hardness. Soft or minerals like olivine promote something approaching low-stress conditions, since they are not strong enough to transmit the contact stress to the specimen. However, in this set of experiments, white cast iron (WCI) grinding balls and a hard abrasive mineral (greywacke) resulted in substantively high-stress conditions.

BMAT-T apparatus
The principles of the BMAT-T are simple: prepared specimens, along with abrasive minerals, grinding balls and water (or any other liquid), are tumbled in a drum for a pre-determined numbers of intervals and duration. Fig. 2 shows the cross-sectional side view (left) of BMAT-T, containing specimen blocks, grinding balls and abrasive particles in the medium of water whereas the exploded view (right) shows the mill drum, front cover and the small aperture and its lid, used for loading and unloading of the mill.

BMAT-T planner
For maximal relevance and data quality, several key parameters need to be selected and maintained during the testing campaign. For this, a BMAT-T planner has been developed to formulate the testing conditions. These parameters are as follows:

1. Specimens total mass (kg): This is simply the total weight of metallic specimens. It determines the volume occupied by them, to be subtracted from the total enclosed volume of the ball mill. From it is estimated the volume of interstices between the specimens.
2. Makeup charge mass (kg): The total weight of grinding balls should be maximised in proportion to item (1). This maximises the proportion of time that a given specimen is surrounded by grinding balls rather than other block specimens, although specimen-to-specimen interactions are unavoidable. This quantity is restricted by ball mill filling percentage, item (15), which is preferred to be kept between 20% and 45%. Accumulated experience in UQ's Wear Lab indicates that, for operation modes under BMAT-T protocols, a makeup charge mass of about 3 times the specimens’ total mass is optimal, and this is the value aimed for in the tests conducted in this work.
Fig. 2. Side cross-section and exploded views of the BMAT. In the left view, black spheres are grinding balls while dark magenta blocks are the test specimens and semi-round light-brown particles are abrasive minerals. The inner diameter of the mill drum is 600 mm.

(3) Specimens to total metal ratio (%): This is directly determined by (1) and (2), as expressed by Equation 1. Its permissible upper threshold is 33%. The preferred ratio is no more than 25%, which ensures that majority of specimens’ interactions are with makeup balls more so than with other specimens. Similar to (2), this is limited by total mill volume.

\[
\text{ratio spcs/total metal} \% = \frac{\text{spcs total mass} [\text{kg}]}{\text{spcs total mass} [\text{kg}] + \text{makeup charge mass} [\text{kg}]}
\]  \hspace{1cm} (1)

(4) Maximum diameter of makeup charge: The laboratory BMAT is smaller than industrial ball mills, so the size of makeup charge should be selected accordingly. Small makeup balls facilitate a uniform environment for abrasive contact events. This may decrease the grinding efficiency of the mill, but this is not detrimental to the purposes of a wear test. Indeed, for batch testing it is desirable to decelerate the comminution action, so as to preserve the abrasive for longer test durations, in order to maximise specimen weight loss and hence statistical data quality. Similarly, smaller balls increase the frequency of contacts between specimens and balls, again resulting in higher weight loss.

(5) Interstices volume (L): Total mass of metallic charge (specimens + balls) multiplied by a constant value of ‘ratio of interstices volume to ball charge mass’, which has been calculated to be 0.100 L/kg. To calculate this parameter, it is assumed that specimens are spherical, as per the makeup balls. This quantity is needed for planning parameter (6).

\[
\text{interstices volume}[L] = (\text{spcs total mass}[\text{kg}] + \text{makeup charge mass}[\text{kg}]) \times 0.100[L/\text{kg}]
\]  \hspace{1cm} (2)

(6) Interstices wet fill (%): This is a key parameter in planning of BMAT conditions. A campaign of tests should usually maintain a constant value for this parameter. In strong contrast to ball mills used for comminution purposes, in BMAT it is recommended to use values in the range of about 200% to 400%. This decreases comminution rate, allowing longer tests. Higher values also reduce direct metal to metal contact, thus decreasing the probability of chipping in the specimens.

(7) Total pulp volume (L): As expressed in Eq. 3, this is the volume of slurry (abrasive + water) required to achieve the planned interstices fill. It is used to calculate the amounts of water and
abrasive needed for the planned slurry concentration.

\[
total\,pulp\,vol.\,plan[L] = \text{intersticesvolume}[L] \times \text{intersticeswet\,fill.\,plan[\%]} \tag{3}
\]

(8) Mineral type, density, and size: Due to the effects of abrasive mineral (hardness, quartz content, breakage behaviour) and particle size distribution (PSD), these characteristics are recorded to assist with interpretation of the test results. Density is needed for calculation of slurry composition.

(9) Water and solids fraction in slurry (wt%): To select slurry concentration, attention should be paid to the difference between industrial ball mills (continuous operation, typically 55 wt% solids) and laboratory ball mills (usually batch mode). There is a risk of the slurry drying out and becoming pasty, causing specimens to adhere to the mill wall. To prevent this, it may be prudent to increase water, i.e. decrease pulp solids fraction. However, trials showed no tendency for such drying and adhesion, so for best simulation of service conditions, the value of 55 wt% solids was selected for BMAT-T in this work.

(10) Volume fraction of mineral and water (vol%): The density of the mineral is used to calculate the vol% of the mineral and then for water as in Eq. 4.

\[
\begin{align*}
\text{vol}\% \,\text{mineral (vol\%)} &= \frac{\text{wt}\% \,\text{solids, plan [wt\%]} \times \text{Mineral Density [kg/L]}}{\text{wt}\% \,\text{solids, plan [wt\%]} \times \text{Mineral Density [kg/L]} + (\text{wt}\% \,\text{water [wt\%]} \times \text{Water Density [kg/L]})} \\
\text{vol}\% \,\text{water (vol\%)} &= 100 - \text{vol}\% \,\text{mineral (vol\%)} \tag{4}
\end{align*}
\]

(11) Volume of mineral and water (L): These values show how much water and abrasive (in litres) feed are required for the planned total pulp volume (7).

\[
\text{volume \,mineral, \,plan[L]} = \frac{\text{total \,pulp \,vol. \,plan[L]} \times \text{vol}\% \,\text{mineral (vol\%)} }{100} \tag{5}
\]

(12) Mass of mineral and water (kg): It is more convenient to measure water and minerals by their weights. The density of water is of course 1 kg/L. The density of the abrasive is used by Eq. 6 to convert volume of mineral to the required mass of mineral.

\[
\text{mass \,mineral, \,plan[kg]} = \text{volume \,mineral, \,plan[L]} \times \text{mineral density [kg/L]} \tag{6}
\]

(13) Excess pulp volume (L): To maximise the abrasive weight loss of the test, a good excess of abrasive is beneficial as it reduces comminution efficiency and permits longer test intervals.

\[
\text{excess \,pulp \,volume[L]} = \text{total \,pulp \,vol. \,[L]} - \text{intersticesvolume[L]} \tag{7}
\]

(14) Mill dimensions: Mill diameter and length (in mm) are used to calculate its volume. Mill diameter is also used to calculate critical speed of the mill.

(15) Mill fill (%): The optimum range for this parameter is 20% to 50%. Mill fills less than 20% cause an excessive impact on the mill wall and reduce the sliding abrasion between specimens and makeup charge. More than 50%, it reduces the sliding action by impeding charge motion. This requirement may constrain the feasible values of other parameters.

\[
\text{mill \,fill \,[\%]} = \frac{\text{total \,pulp \,volume \,[L]} + \text{total \,metal \,charge \,volume \,[L]}}{\text{mill \,fill \,volume \,[L]}} \tag{8}
\]

(16) Critical speed (rpm): This is the rotation speed that causes the specimens or makeup charge to centrifuge [35]. Using makeup charge maximum diameter and the mill diameter, critical speed is calculated by Eq. 9 [37]. Mill rotation speed is usually expressed as the percentage of the critical speed.

\[
\text{critical \,speed \,[rpm]} = \frac{42.3 \times \sqrt{\text{mill \,diameter} \,[m] - \text{makeup \,ball\,max\,diameter}[m]}}{\text{mill \,diameter} \,[m]} \tag{9}
\]
Rotation speeds between 20% and 50% give a sliding action, and 60–70% for cascading action. While cascading is preferred for industrial ball mills, sliding is often more desirable for BMAT, to maximise the rate of abrasive wear of the specimens in proportion to comminution of the abrasive. A rotation speed of 85% produces cataracting, which is sometimes desired to maximise the proportion of high-angle impingement (commonly called ‘impact’), as used in the ball mill edge chipping test (BMECT). A value of 40% was selected for the BMATs in this work. A variable frequency drive is used to adjust the motor input frequency (in Hz) to achieve the planned mill rotation speed (in rpm).

**Statistical evaluation and procedure development of the BMAT-T**

Avery [6] believes that “unless the reproducibility and experimental error of a test are properly established the ranking ability cannot be trusted, whether in the laboratory or in field service. It is a fact, regrettable but unavoidable, that few service tests are acceptably reliable”.

In order to address Avery’s recommendation, statistical evaluations, procedure development and further refinement were conducted on the BMAT-T using the data acquired from high-stress abrasion testing of 15 specimens of three reference alloys (CB100, CB123 and Bis500), each selected from one class of abrasion-resistant alloys. To accurately determine exposed surface area, three thicknesses, three widths and two lengths were measured for each reference specimen.

Excluding preliminary tests, three 20-hour BMAT-T tests were conducted using the parameters listed in Table 2. Most of these parameters have been explained in previous section or are self-explanatory. A specimen’s ‘equivalent diameter’ is the diameter of a sphere having the same volume as the block specimen. This approach can be considered as physically reasonable, because BMAT-T specimens are generously edge-rounded to avoid any chipping events during the tests. In order to calculate this parameter, the average volume of the specimens is calculated, using the specimen’s total mass and average density. This parameter provides an approximate comparison between makeup charge diameter and specimens diameter, assisting with proper selection of the makeup balls diameter.

To normalise the measured mass loss to compensate for variations in specimen size (initial mass and initial surface area), three methods were considered:

A) Single mass-based normalisation: mass loss per initial mass (mg/100 g);
B) Single area-based normalisation: mass loss per initial total surface area (mg/1000 mm²); and
C) Double normalisation: mass loss per initial mas per surface area (mg/[100g.1000 mm²]).
The results of all three tests have been tabulated in Table 3. The scatter plots of these data for single normalisation (methods A and B) are shown in Fig. 3. Specimens numbered 13, 14, and 15 in each alloy series were new specimens but surface-ground and edge-rounded; all other specimens had been previously tested in the BMAT-T several times. Nevertheless, all specimens were run-in for 2 hrs for surface conditioning. Therefore, the difference between these two sub-sets of specimens can be attributed to the amount of edge-roundness.

These acquired weight loss data along with normalised weight losses provide valuable information on reproducibility, reliability (often expressed as accuracy) and statistical quality as well as the best approach for weight normalisation as discussed below:

1. The BMAT is able to reproduce absolute weight loss with negligible errors, so long as abrasive feed and testing conditions are held constant. For example, the average weight losses of Bis500 specimens were 533.5, 529.7, and 531.2 mg for first, second, and third BMAT-T respectively. This shows a relative standard deviation (RSD) of 0.36%, which is excellent for an abrasion test. In the case of CB100, a hyper-eutectic high-Cr WCI, the absolute average weight losses are 294.4, 288.1, and 286.9 mg for the first to third tests respectively. The average weight loss is almost half that of Bis500, but the RSD is slightly higher, 1.4% — still excellent for an abrasion test. For CB123, the absolute average weight loss is 345.7, 338.4, and 340.2 mg respectively, with a RSD of 1.1%. The absolute weight loss data are not given in Table 3.

2. Due to variations in the initial size of the specimens, the raw weight loss data must be normalised to avoid biasing the results. A proper normalisation method will also improve the statistics of the test results. For example, using normalisation method A the average normalised weight losses of Bis500 specimens were 303.3, 302.2, and 304.0 mg/100g for the first, second, and third test respectively. This shows a RSD of 0.3%. If other normalisation methods are used, this value remains almost the same (0.31%, 0.34%, and 0.31% for methods A, B, and C respectively). For CB100, average weight losses normalised by method A are 162.3, 159.0, and 158.6 mg/100g for the first to third BMAT-Ts respectively, with RSD of 1.3%. The values for CB123 are 185.3, 181.7, and 183.0 mg/100g and RSD of 1.0%.

3. Statistical data quality of each dataset, i.e. the RSD calculated based on the 15 individual specimens of each alloy, is indicative of the reliability of the test method. This value is reported as the last row in Table 3. For Bis500, the RSD of the method A normalised weight losses is 2.0%, 1.8%, and 1.9%, for the first to third tests respectively. However, in the case of CB100, these values are 4.2%, 4.9%, and 4.8%; and for CB123 they are 2.2%, 2.4% and 2.5%. The low levels of calculated RSD values indicate that the testing method is very reliable. Also, low variations in the observed RSDs in three conducted tests show that reproducibility of the testing method is excellent for all three materials. Slightly higher observed RSDs for CB100 (hyper-eutectic high-Cr WCI with 39.1 vol% Cr-rich carbides) is mainly due to its low fracture toughness. Also, the BMAT-T is a high-stress abrasion test which promotes the micro-fracture of carbides. Hence, slightly higher RSD in CB100 results should not be attributed to the testing method. Nevertheless, even the maximum observed RSD (4.9% - 2nd BMAT of CB100) still shows a high-quality dataset.

4. Specimens with constant masses but different shapes can potentially expose a significant range of surface areas. On the other hand, abrasive wear is a surface phenomenon, so in the first instance it seems appropriate to take account of the total exposed area. Two other normalisation methods (B and C) were planned to investigate which normalisation method is the best approach.

Table 3 shows that the RSDs for normalisation by mass (method A) are in all cases lower than those for normalisation by surface (method B) and double normalisation (method C). In the current work the specimens are all surface-ground rectilinear blocks, enabling surface area to be measured accurately, but nevertheless normalisation methods using surface area predominantly show more scatter except in one case (method C for 2nd BMAT of CB100) with very negligible improving effect.

The scatterplots of normalised weight loss using methods A and B for all tests and alloys are presented in Fig. 3. The solid datapoints represent the data for normalisation by mass (method A) and hollow points for normalisation by surface area (method B). The horizontal lines indicate the average normalised weight loss in each test (solid line for method A and dashed line for method B). As the double normalisation does not show any merit compared to above two methods, it was not included.
| Spec No. | Bis500 – abrasion resistant steel | CB100 – slightly hyper-eutectic high-Cr WCI | CB123 – hypo-eutectic high-Cr WCI |
|---------|----------------------------------|---------------------------------------------|-----------------------------------|
|         | 1st BMAT | 2nd BMAT | 3rd BMAT | 1st BMAT | 2nd BMAT | 3rd BMAT | 1st BMAT | 2nd BMAT | 3rd BMAT |
| A       | B        | C        | A        | B        | C        | A        | B        | C        | A        | B        | C        |
| 1       | 304.7    | 101.1    | 59.3     | 305.6    | 101.1    | 59.5     | 309.1    | 101.9    | 60.1     | 169.0    | 55.5     | 30.8     | 166.5    | 54.6     | 30.3     | 166.4    | 54.5     | 30.3     |
| 2       | 294.4    | 99.8     | 56.2     | 294.3    | 99.5     | 56.2     | 298.2    | 100.5    | 57.0     | 160.2    | 51.6     | 30.2     | 155.3    | 50.0     | 29.3     | 157.5    | 50.6     | 29.7     |
| 3       | 310.4    | 101.1    | 62.2     | 308.9    | 100.3    | 61.9     | 312.5    | 101.2    | 62.6     | 157.3    | 51.5     | 29.3     | 154.0    | 50.3     | 28.6     | 153.4    | 50.1     | 28.5     |
| 4       | 299.3    | 99.9     | 58.3     | 299.7    | 99.7     | 58.3     | 305.8    | 101.4    | 59.5     | 163.3    | 53.4     | 30.0     | 159.6    | 52.2     | 29.3     | 157.4    | 51.4     | 28.9     |
| 5       | 297.8    | 100.6    | 56.8     | 298.5    | 100.5    | 56.9     | 297.7    | 99.9     | 56.8     | 172.2    | 56.3     | 31.4     | 167.7    | 54.8     | 30.6     | 167.4    | 54.6     | 30.6     |
| 6       | 301.3    | 101.8    | 57.5     | 300.1    | 101.1    | 57.3     | 301.8    | 101.3    | 57.6     | 158.1    | 51.7     | 28.9     | 151.9    | 49.5     | 27.7     | 151.7    | 49.4     | 27.7     |
| 7       | 313.7    | 101.8    | 62.8     | 313.5    | 101.4    | 62.8     | 316.9    | 102.2    | 63.5     | 166.5    | 54.7     | 30.4     | 159.6    | 52.3     | 29.1     | 160.2    | 52.4     | 29.2     |
| 8       | 310.3    | 101.0    | 62.2     | 310.5    | 100.7    | 62.3     | 311.0    | 100.5    | 62.4     | 162.9    | 53.6     | 29.5     | 157.3    | 51.7     | 28.5     | 157.4    | 51.6     | 28.5     |
| 9       | 296.7    | 100.5    | 56.5     | 294.9    | 99.6     | 56.2     | 298.8    | 100.6    | 56.9     | 155.0    | 50.9     | 28.3     | 149.1    | 48.9     | 27.2     | 150.1    | 49.1     | 27.4     |
| 10      | 299.6    | 99.7     | 58.1     | 300.4    | 99.7     | 58.2     | 301.3    | 99.7     | 58.4     | 154.9    | 51.0     | 27.9     | 151.9    | 50.0     | 27.4     | 151.7    | 49.8     | 27.4     |
| 11      | 299.8    | 99.8     | 58.4     | 300.7    | 99.8     | 58.6     | 304.4    | 100.7    | 59.3     | 169.9    | 55.8     | 30.9     | 165.6    | 54.3     | 30.1     | 166.8    | 54.6     | 30.4     |
| 12      | 298.0    | 99.5     | 57.8     | 299.9    | 99.8     | 58.2     | 302.1    | 100.3    | 58.6     | 151.5    | 49.9     | 27.2     | 147.9    | 48.7     | 26.6     | 146.0    | 48.0     | 26.2     |
| 13      | 310.3    | 100.9    | 56.7     | 302.6    | 106.8    | 55.3     | 299.1    | 105.2    | 54.6     | 173.8    | 59.1     | 31.0     | 176.5    | 59.9     | 31.5     | 174.2    | 59.0     | 31.1     |
| 14      | 303.2    | 108.3    | 54.9     | 299.7    | 106.7    | 54.2     | 298.8    | 106.1    | 54.1     | 162.7    | 54.9     | 29.3     | 163.5    | 55.1     | 29.4     | 160.7    | 54.1     | 28.9     |
| 15      | 309.6    | 110.5    | 56.7     | 303.6    | 108.0    | 55.3     | 303.1    | 107.4    | 55.1     | 157.1    | 53.5     | 28.1     | 158.6    | 53.9     | 28.4     | 157.6    | 53.5     | 28.2     |
| Ave.    | 303.3    | 102.3    | 58.3     | 302.2    | 101.6    | 58.1     | 304.0    | 101.9    | 58.5     | 162.3    | 53.6     | 29.5     | 159.0    | 52.4     | 28.9     | 158.6    | 52.2     | 28.9     |
| RSD     | 2.0%     | 3.7%     | 4.1%     | 1.8%     | 2.9%     | 4.5%     | 1.9%     | 2.3%     | 4.9%     | 4.2%     | 4.7%     | 4.3%     | 4.9%     | 5.8%     | 4.7%     | 4.8%     | 5.5%     | 4.8%     | 2.2%     | 2.3%     | 2.7%     | 2.4%     | 2.9%     | 2.7%     | 2.5%     | 2.9%     | 2.8%     |

A: single mass normalisation — mass loss per initial mass (mg/100gr)
B: single area normalisation — mass loss per surface area (mg/1000mm²)
C: double normalisation — mass loss per initial mass per surface area (mg/(100g.1000100mm²)

Table 3

Normalised BMAT-T weight loss of reference alloys during the three 20 hr tests, calculated based on three different normalisation methods. The two bottom rows show the average normalised weight loss and relative standard deviation (RSD) in the calculation of the average (in %).
Fig. 3. Scatter-plots of normalised mass loss of Bis500, CB100 and CB123 after each of three BMAT-T tests. The horizontal lines indicate the average normalised weight loss in each test; solid line for method A and dashed line for method B of normalisation.
in this analysis. The best scatter pattern for the data is to randomly scatter around the average value (the horizontal line).

In Fig. 3 the scatter patterns of solid data points initially appear random, but closer inspection shows almost consistent patterns from one test to the next. From this it can be concluded that the majority of the scatter of points either side of the average line is not a random test-to-test variability, but indeed represents genuine differences between nominally identical specimens. These differences could be local metallurgical and/or microstructural variations in the source stock. The fact that the wrought plate Bis500 shows lower deviations than the WCIs tends to confirm that microstructural variability is very probably a contributing factor. Alternatively, the scatter could be due to variations in precise size or shape, beyond what can be accurately compensated by the normalisation process.

For the specimens numbered 13, 14 and 15, the hollow data points are always above the average dashed line, and this is evident for all tests. As mentioned earlier, these are newer specimens. Their surface condition is similar to the others, due to the run-in step, but the edge-rounding radius of curvature is slightly lower than the older specimens which have been frequently used for other testing campaigns. Re-considering their weight loss values (not given in this report) reveals that they wear more than others during the test although careful examination of the specimens did not show any sign of chipping or gross fracture. Normalisation based on simple calculated surface area, \(2 \times (L \times W + L \times T + W \times T)\), cannot readily correct for variations in edge radius. However, normalisation by measured weight can do so reasonably accurately. Normalisation by weight is also very streamlined, not requiring any extra measurements of specimen dimensions. More importantly, in all alloys/tests, it shows lower RSD.

Statistical data quality has been maximised by ensuring that all specimens were in a tight range of initial weights (6.5%, 2.8% and 6.5% RSD) and surface area (3.3%, 1.4% and 1.2% RSD). They also had very consistent shape (aspect ratio). With these controls in place, the simple first-order correction provided by normalisation by initial mass is sufficient to avoid bias due to size variations.

(5) Fig. 4 shows the cumulative weight losses of all 15 specimens of each reference alloy as well as their average value, with a thick dashed line with hollow points. It also presents RSDs of all specimens at the end of each interval. These RSD values are calculated based on the cumulative weight losses at the end of each interval, so they are not the same as the values for each test as given in the last row of Table 3. Regression lines were fitted to the average values of each alloy with the given Eq. and R-squared.

In the weight loss versus test duration (or equivalent sliding distance) charts, called ‘characteristic weight loss’ charts, the slope of lines indicates the wear rate. Therefore, wear rate of the alloy (or representative specimen which is the average of all specimens) is simply equal to the coefficient of ‘x’ in the regression lines; i.e. 15.11, 7.98, and 9.14 mg/100g.hr, for Bis500, CB100, CB123 respectively. These values can be used to judge the performance of the alloys. In addition, R-squared values which are equal to 1 (within four decimal place accuracy) for all three alloys indicate that there is a perfect correlation between the data points and the regression lines. That is, all weight losses at the end of each interval are accurately located on this line. Therefore, including the weight loss data after second and third intervals does not change the initial fitted line; the three segments of the lines (related to each interval) show identical slopes.

As a practical outcome, 20 hr BMAT-T is adequately long to give accurate wear rates. Also, considering the RSD graphs, no improvement in the reliability of the test was observed for 40 hr and 60 hr tests. This is consistent with the above (1) and (2), that BMAT is capable of reproducing absolute weight losses in different tests with identical testing conditions, and more accurately if normalised weight losses are used.

**BMAT-C — cassette mode of the ball mill abrasion test**

**Materials and abrasives**

In the light of statistical assessments and further procedure refinement of the BMAT-T and because of the less number of specimens that can be mounted in the specimen-holder cassette rings, for the statistical analysis of BMAT-C, it was judged that an abrasion-resistant homogenous material should be sufficient. For this reason, Bis500 (see the chemical composition and hardness in Table 1) was
Fig. 4. Cumulative normalised weight loss of a) Bis500, b) CB100, and c) CB123 versus cumulative test duration. The secondary axes show the RSD of normalised (method A) weight loss at the end of each interval. Thick dashed lines with hollow points represent the average of all 15 specimens. Regression lines have been fitted to this average values with indicated equation and R-squared.
selected for this part of work. It was established in the previous sections that the variabilities higher than that in the test data of Bis500 can be safely attributed to the metallurgical inhomogeneities of the materials. In particular, under high-stress abrasion conditions, in high-Cr WCs with reinforcing particulate carbides micro-fracture of Cr-rich carbides and their fall-off as relatively large segments during the following sliding events, is believed to be the main reason for comparatively higher data scatter in these alloys than that of homogenous steels, without particulate phases.

12 block specimens of Bis500 were cut using a water-cooled abrasive cut-off saw to the nominal dimensions of $50 \times 25 \times 22$ mm and surface ground. The edges of the test surface (nominal size of $50 \times 25$ mm, facing the centre of the mill drum) were only slightly rounded to the radius of 1–1.5 mm, because these specimens will be mounted in the specimen-holder rings and will not be tumbled in the mill drum. Details of surface grinding and edge-rounding have been given in section 2.2.1.

Four BMAT-C tests were conducted under two different abrasive rocks: MtMarrow basalt (less-competent) and Tumbulgum quartzite (competent). Basalt is a fine-grained igneous rock in which the primary minerals are Na-Ca feldspars and pyroxenes. Its hardness, calculated using the proportion and the Mohs hardness of the mineral contents, is 5.6 HM (Mohs). Quartzite is a medium-grained igneous metamorphic rock composed of very high quartz content, giving it a hardness of about 7 HM. Two tests were performed under each abrasive, so the results, in addition to the statistical assessment of the method, will provide the reproducibility measure of the high-stress abrasive wear test conducted in BMAT-C, similar to BMAT-T.

Since only one face of the specimens will be exposed to the abrasion environment, resulting in lower absolute weight loss of the specimens, longer test durations and/or preferably greater number of test intervals should be used to obtain higher mass losses and hence better statistical measures and more distinct and reliable alloy rankings. In terms of the abrasive characteristics, therefore, coarser feed particle size distribution is recommended. So, relatively coarse basalt and quartzite particles (9.5 – 13.2 mm) were used in the tests. In addition, due to the potential for variability in batches of abrasives from a given supplier, abrasives from the same batch and same crushing/screening procedures were used.

All the specimens were thoroughly cleaned after the tests: they were soaked in water, pre-washed with nylon brush, soaked in detergent-water solution, washed again with nylon brush, soaked in methanol, washed once more, and finally ultrasonically-cleaned in an attempt to remove the compacted adherent layer of abrasive from the worn surface, then rinsed with methanol and immediately dried with filtered compressed air. At least three readings were done for each pre- and post-weight.

In the BMAT-C, as specimens are mounted into specimen-holder rings, the only practical normalisation method is based on the area of the exposed test surface because specimen mass and the size of other faces of the specimen do not play any role. Therefore, the dimensions of the exposed face of the specimens were measured accurately using 0.01 mm accuracy Vernier caliper. Three width and two length measurements were conducted and the average values were used for subsequent calculations.

**BMAT-C apparatus**

The cassette or liner mode of BMAT employs two specimen-holder cassette rings and two spacer rings. Fig. 5 shows exploded view of the BMAT-C apparatus with all its components. Two spacer rings are used in either ends of centrally placed specimen-holder rings to prevent the shading of the specimens by the back and front (lid) plates of the mill drum. Each specimen-holder ring can accommodate 30 block specimens; hence in total 60 specimens can be tested simultaneously. This is one of the advantages of the BMAT, enabling all specimens to experience equal conditions. Each specimen is secured by two grub screws (or set screws) on the specimen-holder ring. There are two other grub screws in the back of specimens and are used to adjust the level of protrusion of the test surface of the specimens. It is important to make sure specimens are not shadowing adjacent specimens.

It is of significant importance to ensure specimens are protruded from the specimen-holder rings. This guarantees that specimens’ surfaces are completely exposed to consistent interactions...
Fig. 5. Exploded view of BMAT-C apparatus, showing specimen-holder rings (cyan), spacer rings (yellow), mill components (beige) and specimens (magenta) mounted into specimen holders;

with the grinding media and abrasive particles, and not shaded by the upper and lower flanges of the specimen-holder rings. Development trials showed that 2–4 mm protrusion is adequate for this purpose. However, this can potentially increase the possibility of edge-chipping of the block specimens protruded from the rings since their long edges are not anymore protected by the flanges of the specimen rings. By rounding the edges of the test surface of the specimens, edge-chipping can be successfully avoided.

A significant amount of development was done to improve the practicality of the BMAT-C test. Technique developments included:

- Prevention of relative rotational movement between the two specimen-holder rings and between the specimen-holder and the spacer rings;
- Improved methods for installation and alignment of the specimens into the specimen rings; and
- Tools and techniques to load the heavy assembly into the mill and remove it after the tests.

**BMAT-C planner**

Due to the introduction of specimen-holder and spacer rings, there are some differences between planning for BMAT-T (the more conventional tumbling mode of operation) and BMAT-C. An Excel-based planner was developed, taking account of all details specific to the BMAT-C as well as those common with the BMAT-T. The parameters used in BMAT-C planner will be described below in accordance with those of BMAT-T (as explained in section 2.2.3). Similar parameters are not explained again.

1. Specimens total mass (kg): This is total mass of specimens. Although they are not tumbling in this test, this value is used to calculate the volume occupied by the specimens to be subtracted from the total volume of the mill.
2. Makeup charge mass (kg): Unlike BMAT-T, this parameter is not a function of (1), as specimens are mounted in the specimen-holder rings. In this work, makeup charge was selected to be
30 kg for the BMAT-C. The ratio of specimens to total metal charge is irrelevant in BMAT-C, since specimens will only experience interactions with grinding balls.

(3) Cassette rings mass (kg): Total mass of specimen-holder rings as well as back and front spacer rings is used to calculate the volume occupied by the rings, to be subtracted from mill nominal volume.

(4) Maximum diameter of makeup charge balls: Same as BMAT-T.

(5) Interstices volume (L): Specimens are excluded from the calculation by Eq. 2 as they are mounted into rings with ~2 mm protrusion and are not part of tumbling materials in the drum.

(6) Interstices wet fill (%): In BMAT-C this parameter needs to account for the slurry getting trapped in gaps inside and behind the cassette rings. For confidence in test conditions it is necessary to accurately calculate the volume of this out-of-action space and add it to planned total pulp volume as (7) below. This space will be filled by slurry at initial stages of the tests.

(7) BMAT-C total pulp volume (L): The volume of the slurry which needs to be charged to achieve the planned interstices wet fill, taking account of the volume which entraps in the dead space.

$$BMAT-C_{\text{Total pulp vol. plan}}(L) = \text{interstices volume}(L) \times \text{interstices wet fill, plan}[%] + \text{volume of dead space}$$  

(10)

(8) Mineral type, density, and size: Same as BMAT-T.

(9) Water and solids fraction in the slurry (wt%): Since just one face of the specimens is exposed to the abrasion environment in the BMAT-C, much longer test durations are needed to achieve acceptable weight losses. This requires selection of lower solid fractions compared to the BMAT-Ts with all six faces of specimens involved in abrasion action.

(10) Volume fraction of the mineral and water (vol%): Same as BMAT-T.

(11) Volume of mineral and water (L): Same as BMAT-T.

(12) Mass of mineral and water (kg): Same as BMAT-T.

(13) Mill dimensions: In addition to nominal mill diameter and length, diameter of ‘action space’ in BMAT-C is important, as this is the relevant parameter for calculation of critical speed and the volume of action space to be used in mill fill percentage. Inner diameter of the specimen-holder rings is used as the diameter of action space.

(14) Dead space volume (L): This value is calculated for BMAT-C by subtracting the volume occupied by the rings and specimens as well as the action space from the nominal volume of the mill. Specimens total mass (1) and cassette rings mass (3) are converted to volume for this purpose. As mentioned in (6) above, this value is important for accurate planning for interstices wet fill.

(15) Mill fill (%): Similar to BMAT-T, the optimum range for this parameter is 20% to 50%. It adds the volume of metal (only balls here) to the total pulp volume and divides the summation by the action volume of the mill. Therefore, in BMAT-C, two values can be calculated for mill fill percentage: a) using the volume of planned pulp plus the dead space; b) using only planned pulp volume. Initial loading of the ball mill starts with “Mill Fill 1” (a), but once the dead space is filled with pulp material, it will continue with “Mill Fill 2” (b). It is critical to ensure that the quantity mill fill 2 is high enough to produce reasonable abrasion action in the mill; otherwise other parameters (for example interstices fill plan) are to be adjusted accordingly.

(16) Critical speed (rpm): It is calculated similar to BMAT-T by Eq. 9. But it needs to be noted that ‘mill action diameter’ needs to be used instead of the nominal diameter.

**Statistical evaluation of the BMAT-C**

For statistical assessment of the developed methodology for the BMAT-C and the planned testing parameters (Table 4), 12 specimens of Bis500 were prepared and mounted into the specimen-holder rings; 6 specimens in each ring. It is noted that these tests were conducted along with another performance evaluation campaign. To eliminate the effect of specimen position in the specimen-holder rings, if there is any, specimens were evenly distributed in the rings as per pattern set out in Table 5. In this table, X01 to X08 represent the experimental alloys of the performance evaluation campaign, mentioned above.

BMAT-C parameters including charge plan, interstices fill, mill rotation speed, mineral supply, and mill filling plan used in this work have been given in Table 4. All these parameters have been
explained in section 2.2.3 and section 2.3.3 above. To increase the measured weight loss and hence the statistical quality of the data, 4 intervals of 20 hr were applied. At the end of each interval, mill drum was emptied, mill and grinding balls were thoroughly washed and then planned amount of fresh abrasive and water, as per Table 4, were charged into the mill for the next interval. Post-weighing was performed at the end of the last interval, after cleaning process outlined in section 2.3.1.

Calculated weight loss of each specimen (using pre- and post-weight of the specimen) was first converted to the volume loss using the alloy density, carefully measured using Archimedes method, then to the thickness loss by dividing the calculated volume loss by the area of the exposed surface. This thickness loss is independent of the specimen’s initial weight and size. Therefore, no further normalisation will be required. The initial weight and surface area of the specimens had little variations (less than 2.9%). This has been shown to further improve the data quality.

Fig. 6 shows the average thickness loss and the relative standard deviation (RSD) of the Bis500 specimens in specimen-holder ring A, ring B and both rings (overall) in each of Test 1 and Test 2.
Fig. 6. a) Average thickness loss (solid lines) and b) relative standard deviation (dashed lines) of Bis500 specimens, BMAT-C tested in basalt (green) and quartzite (red), two repeats: Test 1 (brown) and Test 2 (blue).
after BMAT-C under basalt and quartzite. For all of these four BMAT-C tests, mill charge, interstices fill, rotation speed, abrasive characteristics and mill filling were kept constant (Table 4). Test 2 is the repeat of Test 1, aiming to assess reproducibility of the developed test method and test parameter for BMAT-C.

As can be seen from Fig. 6 (b), the RSDs are very low. This indicates that the testing procedure has a high degree of reliability. More competent (or hard) abrasive rock types produces higher weight losses, resulting in even better statistical measures — overall RSD of 1.4% and 1.8% for quartzite compared to overall RSD 3.6% and 2.5% for basalt in Test 1 and Test 2 respectively. The overall statistical reliability is lower than 3.6% for all combinations of abrasive and rings. This shows that the selected procedure, including mill charge details, number of intervals, duration of each interval, etc. are appropriate.

The average thickness losses (Fig. 6 (a)) and their RSD for Ring A and Ring B are quite similar for all tests and abrasives. This observed inappreciable differences in wear rates (expressed as thickness loss) or RSDs as function of location between the two specimen holder rings indicates that specimens tested in different rings can be statistically-reliably compared.

The average thickness loss of the specimens in various rings/abrasives as well as their overall values are extremely similar in these two tests. This highlights very high reproducibility of the BMAT-C and the selected testing procedure. The observed lower RSDs of Test 2 in basalt than Test 1 is not statistically significant nor practically meaningful, as unlike basalt, RSDs of Test 2 in quartzite is higher than that of Test 1. It is noted that thickness loss data for these two abrasives and the conducted two tests do not indeed support the RSD increase in quartzite or RSD decrease in basalt. In quartzite, the average weight loss increases (only slightly) from Test 1 to Test 2; this is expected to improve statistical measures and hence decrease the RSD in Test 2 compared to Test 1. In basalt, the overall average thickness losses are almost the same for both Test 1 and Test 2, 61.1 and 61.2 μm respectively. So no changes in the statistical variabilities are expected. Again, the negligible changes in these values form Test 1 to Test 2 are not statistically significant and the different direction of these changes highlights its randomness. However, as suggested by BMAT-T, where higher RSDs are observed for other alloys, such greater statistical scatter must be due to genuine metallurgical variations within the specimens of that alloy, rather than being due to ‘random’ scatter in the testing procedure.

The variability of the test results, expressed as RSD, in the BMAT-C testing of 16 experimental dual-reinforced high-Cr WCIs show a maximum RSD of 6.6% and 5.6% in basalt and quartzite respectively. The minimum RSD value is 2.2% and 1.8% for the same abrasives. Average RSD in the testing of these alloys is less than 5% (4.7% for basalt and 3.8% for quartzite). As mentioned, the high-stress abrasion performance of these experimental alloys evaluated using this method is not the main focus of this work; the relevant results and discussion have been comprehensively reported in [39–41]. Nevertheless, the statistical data quality of these alloys are given here in order to show the reliability of the developed test method in the performance evaluation of heterogeneous alloys. As mentioned, higher variation in the wear data of the WCIs compared to the homogenous steel is attributed to the heterogeneity of the specimens. But these RSDs are still gratifyingly low for an abrasion test.

Concluding remarks

The BMAT-T is capable of reproducing absolute weight losses of the alloys in various tests. However, normalisation of weight losses results in better data quality, particularly if the variation in the specimen size is not negligible. Indeed, normalisation must be performed to take the initial size of the specimens into account. Among the three possible normalisation methods, normalising based on the initial mass develops better data quality and is less laborious. It is able to normalise the data for differences in edge radius of the specimens. It gives a relative standard deviation (RSD) of average weight loss of homogenous abrasion-resistant steel during 3 × 20 hr tests as 0.3%. For white cast irons (WCIs) with high and low carbides volume fraction (CVF), this value is 1.3% and 1.0% respectively. This is excellent statistics.

The acquired very low RSDs for weight loss data of 15 specimens of three abrasion-resistant reference alloys illustrate the BMAT-T's excellent reliability and reproducibility. The higher RSDs observed in the hyper-eutectic high-CVF WCI are related to the low fracture toughness of this
alloy and micro-fracture of carbides (particularly massive primary carbides) and fall off of the large fractured carbide segments as the dominant wear mechanism.

Cumulative normalised weight losses of the alloys in the BMAT-T, plotted against cumulative test duration, show almost perfect correlation with the regression line, highlighting that a 20-hour test is adequately long for wear rate considerations. Longer tests do not improve the statistics, so are unnecessary. However, in the BMAT-C longer test durations or preferably higher number of test intervals are needed as only one face of the specimen is exposed to the abrasion environment. The outcomes of this work showed that four 20-hour intervals is sufficient to obtain high quality data and distinctively rank the experimental alloys, provided that the testing parameters and protocols, as developed in this work, are followed. These include charge plan, mill rotation speed, interstices fill plan and mill fill plan as well as the procedure for loading the mill with fresh abrasive and water (as per test plan) after washing it out at the end of each interval.

In the BMAT-C, the only viable normalisation method for the weight loss data is based on the surface area of the test specimens exposed to the abrasion. This is because the initial mass of the specimens does not play any role in the interactions with grinding balls or abrasive or other specimens since all the specimens are mounted into specimen-holder rings, not tumbling in the mill drum. The normalised weight loss data, expressed as thickness loss, give better indications of the wear life of the materials in industrial sense.

The methodology developed for high-stress abrasion testing using the BMAT-C resulted in very good statistical quality of the data. RSD shows a maximum of 3.9% for the homogenous abrasion-resistant steel tested in basalt in ring A. In quartzite the statistics were even better, with maximum RSD of 1.9% (ring A), attributable to the higher weight losses produced by the harder and more competent abrasive. Considering all specimens, in both rings A and B, further improves the overall RSDs. These trivial RSD values confirm the high reliability of the data produced by the BMAT-C.

The observed extremely similar thickness loss and RSD values in both Test 1 and Test 2, highlights the very high reproducibility of the BMAT-C data. In addition, the data statistics in any of specimen-holder rings are quite similar. This shows that specimens of the two rings can be reliably compared, if the developed specimen distribution pattern is followed.

For the BMAT-C testing of 16 experimental white irons, the developed method resulted in maximum RSDs of 6.6% and 5.6% and average RSDs of 4.7% and 3.8% in basalt and quartzite respectively. The higher data variation in WCI compared to the homogenous steel is attributed to the heterogeneity of the WCI specimens. Nevertheless, these RSDs are satisfactorily high reliability measures for high-stress abrasion testing.

As a final caveat, it is not being claimed that the testing conditions of the BMAT are identical to the industrial ball mills. There can be a number of differences which could influence the exact values of wear lives or benefit ratios in practice. However, it is clear that the simulation ability of the BMAT-T (for grinding media and mill liner) and BMAT-C (mainly for mill liner) is an order of magnitude superior than that of traditional benchtop abrasion test apparatuses. Moreover, with moderate effort, the conditions of the laboratory BMAT can readily be tailored to improve the fidelity of match with a given target industrial mill.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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