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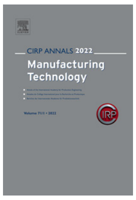

A lapping-based test method to investigate wear behaviour of bonded-abrasive tools

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ABSTRACT

Grinding-wheel wear is a critical factor affecting grinding performance and tool cost. Unfortunately, wear tests – particularly with superabrasives – can be notoriously time-consuming. Therefore, a novel lapping-based method is proposed for investigating wear behaviour of the grit-bond system. Wear tests were performed in (i) lapping, (ii) surface grinding, and (iii) cylindrical grinding for a range of grit-shape aspect ratios and grit-toughness values for the same grit-bond systems. Results showed that all three methods yielded similar trends. This indicates that the lapping tests could be a viable substitute for lengthy grinding tests, resulting in shorter testing times and smaller specimen sizes.

1. Introduction

The term “bonded-abrasive tools” typically refers to grinding wheels and abrasive segments. These are composed of multiple layers of abrasive grits distributed within a bond structure. Although the entire grit-bond system affects the performance of a bonded-abrasive tool, grit and bonded-abrasive-tool manufacturers usually evaluate each of these components individually.

Although an international standard is available [1], grit manufacturers usually develop their own internal test method to quantify grit properties such as toughness and thermal stability. Toughness is a measure of a grit’s resistance to fracture under controlled conditions. For this, the friability impact (*FI*) test [2] is typically used. Thermal stability is more involved and is generally considered as a measure of the grit’s ability to maintain its properties (hardness, toughness, resistance to oxidation and chemical breakdown, etc.) at higher temperatures. Size is an important characteristic. Most abrasive grits are divided into sizes based on sieving, following FEPA and ANSI standards [3,4], where sieves define the upper and lower allowable range of the grit particle sizes. Grit shape has an effect on grinding forces [5,6], specific grinding energy [7], surface topography [8], and the stress distribution at the grit-bond interface [9]. The aspect ratio (*AR*), the ratio of the grit’s greatest length to its shortest width in a two-dimensional projection, is commonly used to quantify the grit shape. Grits with a higher *AR* are referred to as “elongated” or “angular”, while grits with a lower *AR* are referred to as “blocky”. It can be measured using different commercially available instruments such as Morphology 4 or Camsizer.

With regard to the bond or grit-bond system, bonded-abrasive tool manufacturers use a standard three-point bend test to evaluate the quality and strength of bond systems (e.g., ASTM C1161 [10]). Yang et al. tested various vitrified-bond compositions and determined the specific bond components (e.g., Al_2O_3, B_2O_3) that had the greatest effect on fracture strength [11]. Konig and Follinger [12] found that bond type and porosity had a dominant effect on fracture strength [13], whereas grit properties (toughness and thermal stability) had no measurable effect. Furthermore, other researchers proposed evaluating the bond system in terms of additional properties, such as thermal expansion coefficient [11] and thermal conductivity [14]. Jackson et al. focused on the role of vitrified bond and showed that the wheel wear was primarily dependant on the vitrification temperature, whereas specific grit effects were only partially addressed [15].

Research has shown that separate analyses of grits and bond do not provide key performance indicators of the actual grit-bond system used in grinding. For example, Hitchiner et al. [16] showed that tougher grits do not necessarily give higher wear resistance when tested in an actual grit-bond system. In addition, while grit wear was measured in single-grit tests, the performance in the grit-bond system was highly dependant on how that grit was positioned in the bond [17]. Here, the only notable difference was between monocrystalline and polycrystalline grits [17,18]. For these reasons, grit manufacturers and bonded-abrasive-tool manufacturers often perform extensive grinding tests using the grit-bond system to evaluate the combined effect of grits and bonds.

Wheel wear is a key indicator of the overall behaviour of the grit-bond system and is often used to evaluate grinding performance.

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Unfortunately, these tests can be very time-consuming and costly. Therefore, there is a need for a cost-effective, accelerated non-grinding test that can assess the combined attributes of the grit-bond system. Considering this, a novel lapping-based method was developed to evaluate the wear rate of abrasive segments. The main focus was to investigate if the method is sensitive enough to differentiate between different combinations of grit-bond systems, particularly with respect to grit shape and toughness within the bond. cBN segments with different grit aspect ratios (*AR*) and toughness were tested. Considering that cBN segments are also used in grinding wheels, a comparison was made with surface and cylindrical grinding.

2. Methodology

Two test set-ups were devised. The aim of both was to assess the feasibility of using lapping tests to capture and quantify the effects of abrasive-grit properties from grits situated in a grit-bond system, avoiding the arduous task of time-consuming grinding tests.

2.1. Lapping set-up

Tests were conducted on a Lapmaster Wolters Model 15 lapping machine (Fig. 1a) equipped with a speed controller and a timer. The lapping plate (diameter 304.8 mm) was made of solid cast iron. The cBN segments were of the same specification as those used for the grinding wheels (described in Section 2.3).

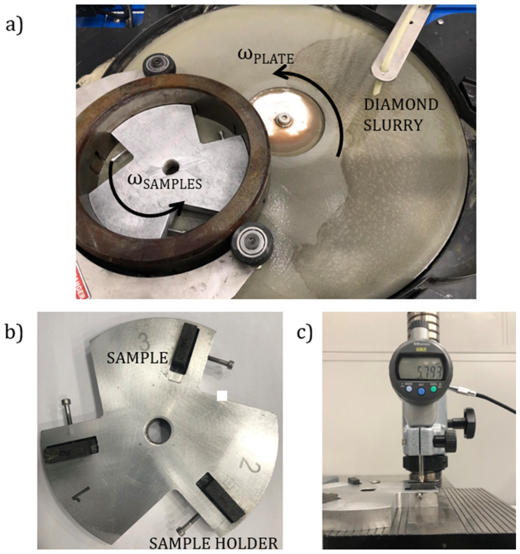

Fig. 1. (a) Lapping set-up, (b) jig holding the cBN segments, and (c) measurements of segment height during the test.

The cBN segments were mounted onto a customised jig (Fig. 1b). Three 120°-spaced segments (width = 8 mm, height = 10.5 mm, length = 25 mm) were lapped simultaneously. The slurry used to accelerate wear of the segments consisted of a diamond-suspension liquid containing 20-μm-diameter (on average) diamond abrasive in 150 ct/L concentration, as is typically used for lapping of hard materials. The segments were conditioned for 60 min to flatten the samples using the same parameters as the lapping tests, with a lapping rotational speed of 72 RPM. Slurry was added at 1 drop/second. The load on the samples was created by the weight of the jig (0.5 kg).

After the conditioning, the segments were lapped for three, 30-min intervals. The height of the sample was measured at the beginning of the test and at the end of each interval using an electronic depth gauge (Fig. 1c) with a resolution of 0.1 µm. The wear rate was calculated in mm^3/min using a linear regression (see example in Fig. 2).

Prior to choosing the lapping parameters, preliminary tests were conducted to find the proper parameters to accelerate the wear rate without masking the effect of the grit-bond combination. This can be done by increasing the weight on the samples or the speed of rotation, while keeping the grit size in the slurry below a certain limit to avoid excessive surface damage. The parameters used in the present work represent the balance between the speed of the test and its repeatability and sensitivity.

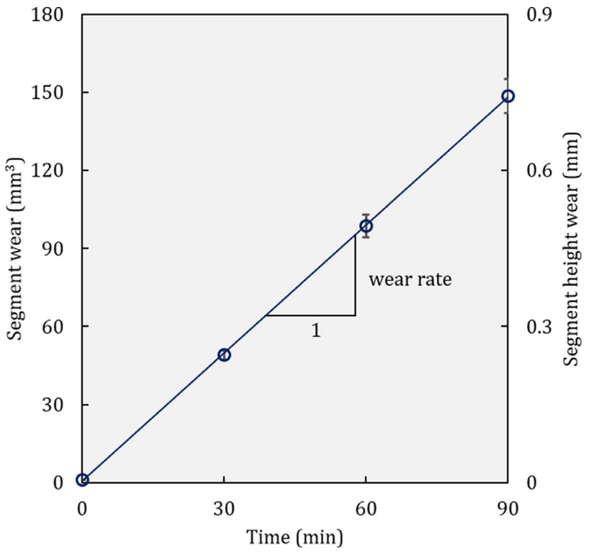

Fig. 2. Example of wear-rate measurements.

2.2. Grinding set-up

Both surface-grinding tests (Blohm MT408) and outside-diameter (OD) cylindrical-plunge grinding tests (EMAG HG 204S) were performed using vitrified-bonded wheels with the same composition as the cBN segments used in lapping tests. The workpiece material was 100Cr6 bearing steel (60–61HRC). The dressing parameters were as follows: dressing overlap ratio U_d=3, dressing depth a_d=0.003 mm, and dressing speed ratio q_d=0.81. In surface grinding, water-based coolant was used (4.5–5.0% concentration at 9 bar). In cylindrical grinding, straight grinding oil was used (at 20 bar). Only half of the wheel width was in contact with the workpiece in order to create a step in the wheel to measure wear height.

The grinding parameters are given in Table 1. It is important to note that in the grinding tests up to two days were needed to obtain sufficient wheel wear, whereas observable wear-rates in lapping were achieved in 2–3 h. For this reason, lapping tests were repeated to determine experimental variability, while grinding tests were performed only once for each grit type. Wear in surface grinding was determined by measuring the change in the step height of a thin piece of metal after plunging it radially into the wheel. Similarly, in cylindrical grinding, the wheel radius wear was evaluated by plunging the wheel into a metal sheet and comparing it to starting wheel geometry.

Table 1
Cylindrical and surface grinding parameters.

Parameter	*Surface grinding*	*OD cylindrical-plunge grinding*
Wheel speed, v_s (m/s)	40	80
Workpiece speed, v_w (mm/min)	24,000	1000
Specific material removal rate, Q' (mm^3/ mm·s)	13.2	40
Grinding wheel diameter, d_s (mm)	300	400

2.3. cBN abrasive segments

The grit aspect ratio (*AR*) and grit toughness were the two main characteristics investigated in these tests. Because a grit manufacturer was involved in this project, a unique opportunity was available to customise grit properties, particularly grit shapes. These customized grits were bonded into the segments for the lapping tests and used in the grinding wheels for the grinding tests. The aspect ratios are summarised in Tables 2 and 3. Table 2 shows the characteristics of grits used in the cylindrical grinding tests (Segments C). Table 3 shows the characteristics of the grits used in the surface-grinding tests (Segments S). The strength and thermal stability of grits used in both grinding wheels were comparable, whereas the aspect ratios were different.

Table 2
Grits (size FEPA B151) used in cylindrical grinding wheels.

Toughness (%)	Thermal stability (%)	Aspect ratio (dimensionless)
61.3	92.4	1.31
60.6	94.7	1.47
59	94.9	1.53
59.1	92.9	1.53

Table 3
Grits (size FEPA B126) used in surface-grinding wheels.

Toughness (%)	Thermal stability (%)	Aspect ratio (dimensionless)
61.2	92.4	1.29
60.8	94.7	1.31
62.4	94.9	1.54
60.6	92.9	1.72

Table 4
Grit types (size FEPA B151) with different toughness.

Toughness (%)	Thermal stability (%)	Aspect ratio (dimensionless)
40.5	79.0	1.47
48.0	79.6	1.44
56.2	94.7	1.49
65.2	95.5	1.42
69.0	89.9	1.30

Additional grits were prepared to investigate the effects of grit toughness, for a similar aspect ratio, on wear rate. These are summarized in Table 4. Note that the weaker grits have generally lower thermal stability. Also, one grit exhibited the lowest *AR* (the blockiest) but was the toughest.

3. Results and discussion

The effect of grit aspect ratio (Tables 2 and 3) on wear rate in lapping tests is shown in Fig. 3. The results in all graphs have been normalised with respect to the highest values. The lapping results show that grits with a higher *AR* (elongated grit) wear faster compared to grits with lower *AR* (blockier grit) Fig. 4.

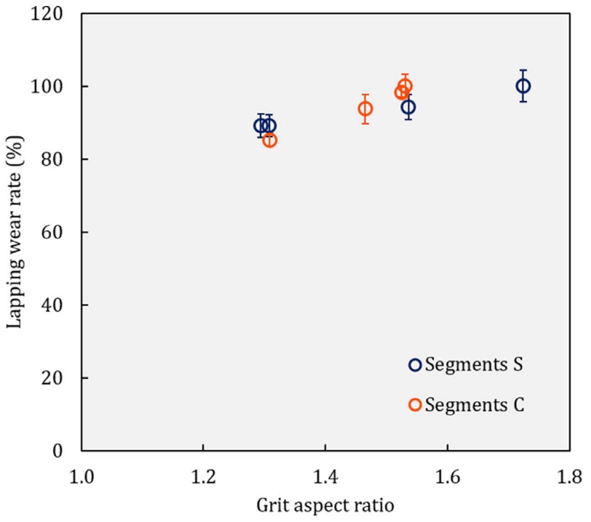

Fig. 3. Lapping wear rate vs. grit aspect ratio.

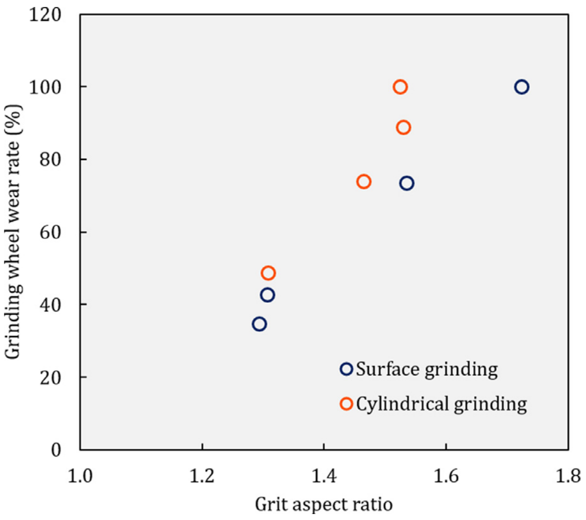

Fig. 4. Grinding wheel wear rate vs. grit aspect ratio in surface and OD cylindrical plunge grinding.

Similar to the lapping tests, grinding wheels (again, with the same grit-bond formulation as the segments) that contained elongated grits wore faster compared to wheels with blockier grits. This observation is independent of the grinding operation (surface or cylindrical), coolant type (oil vs. water-emulsion) and grinding parameters (e.g., specific material removal rate $Q' = 13.2$ vs. 40 $\text{mm}^3/\text{mm}\cdot\text{s}$) – and independent of the concomitant geometric differences such as arc length of contact (longer in surface, shorter in cylindrical). In other words, although the lapping and grinding testing methods used to evaluate the effect of grit aspect ratio on cBN-grit-bond-system wear rate are quite different, they showed surprisingly similar trends.

Compared to lapping, grinding is a more aggressive process, with typical equivalent-chip-thickness values in the range of $h_{eq} = 0.01–0.5$ µm and typical specific energies in the range of 20–200 J/mm^3 [19]. In lapping, the equivalent chip thickness is significantly smaller ($h_{eq} = 10^{-4}–10^{-3}$ µm), while the specific energies are much higher (1000–2500 J/mm^3 [19]). The wheel-wear mechanism in grinding is complex, but can in general be considered as a two-body abrasion process, whereas lapping is considered a three-body-abrasion. Here, the segments are worn out by the rolling diamond generating microfractures on the cBN grits, leaving a surface filled with discrete indentations, which are typical for three-body material removal [20]. There are also signs of bond fracture (see Fig. 5a).

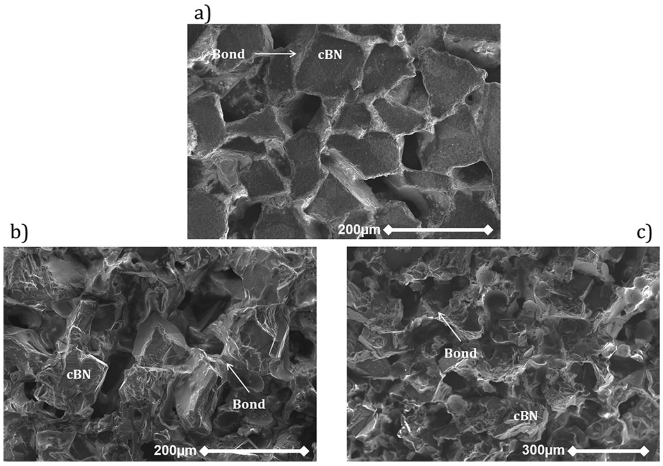

Fig. 5. High-magnification topographical images of (a) lapped segments, (b) grinding-wheel periphery after surface grinding, and (c) grinding-wheel radius after cylindrical grinding.

In surface grinding, a combination of attritious wear and grit and bond fracture was observed (see Fig. 5b). In cylindrical-plunge grinding, the wear was most significant on the wheel radius. The main wear mechanisms were grit and bond fracture (see Fig. 5c). This may explain the greater effect of *AR* in grinding compared to lapping – as elongated grits will show a greater propensity toward grit fracture as opposed to attritious wear.

Fig. 6 shows the effect of grit toughness on wear rate in lapping. As expected, the wear rate decreases as grit toughness increases. However, the grit with the highest toughness saw a reversal, with an increase in wear. Similar trends have been observed when using grits with different toughness (Table 4) in cylindrical grinding (see Fig. 7). Once again, wear decreased with increasing the grit toughness. Similar observations have been previously reported by Upadhyaya and Fiecoat [22]. What is the most interesting, however, is that the wear increases for the toughest grit, suggesting the result shown in lapping was most likely not an anomaly. The cause is difficult to ascertain. However, a similar phenomenon was observed by Badger [21], termed “collapse”, where a lack of steady grit-fracture and bond-fracture led to excessive attritious wear, followed by large-scale macro wear due to the large forces acting on the grit-bond system. This indicates that tougher grits require a suitable pairing in the grit-bond system, particularly considering the higher aggressiveness of the grinding operation. If some minimum level of steady grit-fracture is not achieved, even tougher grits will result in greater wear.

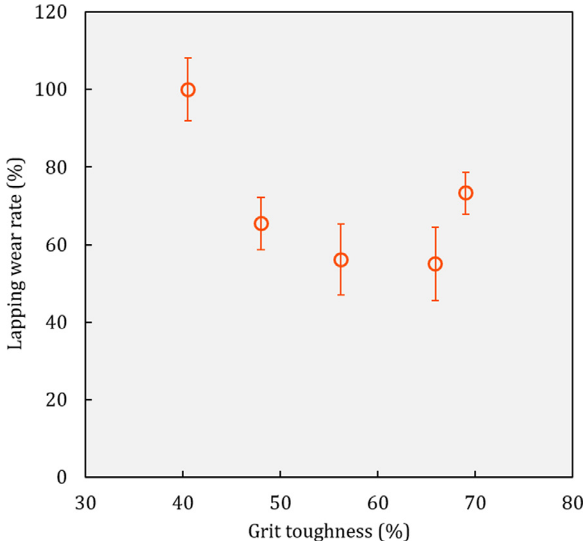

Fig. 6. Lapping wear rate vs. grit toughness.

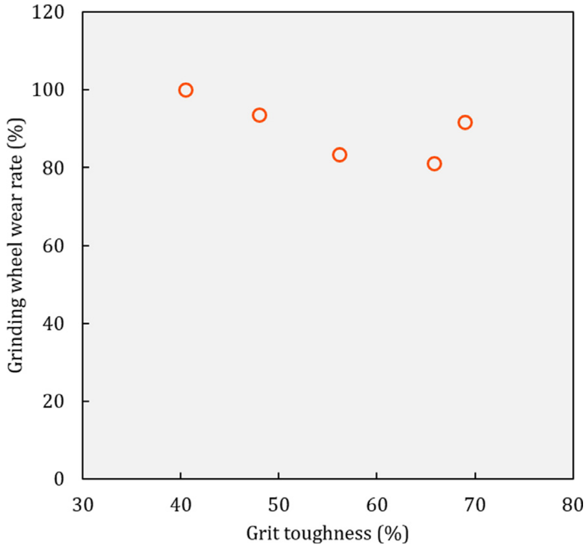

Fig. 7. Wheel wear rate in cylindrical grinding vs. grit toughness.

4. Conclusions

A novel lapping-based method is proposed for evaluation of grit-bond systems used in grinding wheels. Its primary benefits are short testing times and smaller specimen sizes. Lapping and cylindrical- and surface-grinding tests are performed by varying grit toughness and grit aspect ratio in the grit-bond system. The results from lapping agreed largely with the results in grinding. This indicates that the lapping test could be used for screening purposes for both grit manufactures and abrasive-tool manufacturers wishing to reduce time-consuming grinding experiments.

These results confirm that the lapping-based method captures the combined grit-bond system effects, as it can differentiate between several abrasive segments composed of cBN grits with different shapes (aspect ratio) and toughness when used with the same vitrified bond. Grits with higher aspect ratios (elongated grits) exhibit higher wear rates and vice-versa. Then, tougher grits generally exhibit lower wear rates, but only if they are combined with an appropriate bond.

Declaration of Competing Interest

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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