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Microstructure and mechanical properties of commercial, bronze-bond, diamond-abrasive tool materials

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Abstract Bronze-matrix, diamond-particle composites are commonly employed as tool materials in grinding applications, in particular for precision grinding of optical materials. However, while tool selection and performance is often rationalized in terms of changes in tool "modulus/stiffness" or "hardness," neither the range and variability of the mechanical properties nor the fundamental microstructural parameters controlling them are well understood. This has hindered quality control and prevented the accumulation of the industrial property-performance data essential to the development of improved tool materials and processes. In this study, bronze-bond diamond-abrasive composite tool materials, with systematic differences in their diamond sizes and concentrations, were obtained from different commercial vendors, characterized mechanically and microstructurally, and the results statistically analyzed. Microstructurally, a size dependent diamond distribution and relatively high levels of porosity ($\sim$10 vol%) were observed. The mechanical properties exhibited a high degree of variability, with statistically significant differences occurring based on the vendor and diamond concentration, but not diamond size. Porosity was shown to be the key microstructural parameter controlling mechanical properties. Porosity depended on vendor, diamond size, and diamond concentration, but large, nonsystematic variations were also observed, indicating that it is not consistently controlled in current commercial materials. Finally, the porosity and mechanical properties were shown to correlate strongly with ultrasonic wave speed over a wide range of tool materials, demonstrating a practical nondestructive method for tool characterization.

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Introduction

Motivation

Metal-bond, diamond-abrasive tools are widely used for the grinding of optical glasses and ceramics. These materials are typically fabricated by conventional (mix, press, and sinter) powder metallurgy techniques, in a variety of shapes, often with the resultant composite fused permanently to a steel shank [1]. Composite mechanical properties (e.g., elastic modulus, hardness, and wear resistance) are known to affect grinding performance, and their importance is recognized implicitly (e.g., in the coding given to "bond hardness"). However, they have not been studied in a quantitative, systematic way. Absent specific property or performance standards, tools must be ordered primarily in terms of ingredients [2–4]. Changes in tool material, to overcome process problems or meet new requirements, are generally done on an ad hoc basis, based primarily on vendor expertise. The normal feedback mechanism, in which the user links properties with performance, is blocked, hindering tool development and process optimization [5]. As a result, little is known about the mechanical behavior of commercial tool materials, or how they are influenced by microstructure, and attempts to correlate grinding performance to mechanical properties have remained fragmentary. As examples, Funkenbusch and Gracewski [6] showed a sharp increase in subsurface damage depth with decreases in tool elastic modulus (ultrasonic wave speed) during grinding of glass, but used tool materials with large (nonsystematic) differences in

diamond size and concentration. Saini [7] showed an influence of wheel hardness grade on the forces generated during grinding of steel, but only used two grades and did not report the actual mechanical properties. The absence of well-established tests and tool property databases also inhibits their use as quality control checks by end-users [5].

In this study, we report the results of a series of experiments designed to characterize the mechanical properties of a systematically selected set of bronze-bond/diamond-abrasive composite tool materials from different commercial vendors. The results are used to determine the effect of the underlying microstructural parameters (diamond size, diamond concentration, and porosity) on the mechanical properties, as well as illustrating the range and variability of properties encountered in current commercial materials. In addition, the strength of the expected correlations between ultrasonic wave speed and other properties is evaluated to see if wave speed measurement can provide a practical, nondestructive method for estimating mechanical properties in the field.

Tool specifications

Bound abrasive tools are composites consisting of an abrasive and a matrix, or bond, intended to hold the abrasive cutting points in place. At present, tools are ordered by specifying the required geometry and material "ingredients" (abrasive, abrasive concentration, and bond material). Diamond is one of the most common abrasives, particularly for the grinding of glasses and ceramics, and is available in a wide range of sizes specified, depending on the vendor, in terms of grit, mesh, or nominal (micron) size. For diamond-abrasive tooling, concentration is normally specified on a special scale with a "100 concentration" corresponding to 25 vol% [1]. Metal, resin, and vitrified bonds are all available commercially [1, 4, 8]. Metal bond tools are generally produced by conventional powder metallurgical techniques [1] and are often differentiated in terms of the type of metal used in the bond (e.g., bronze, cast iron) and a "bond hardness" ranking. The bond hardness is intended to capture the relative rate at which a tool will wear and, although qualitative, represents the only property-based specification commonly available. The bond hardness ranking may be simply descriptive (i.e., soft/medium/hard) or use an alphabetic scale [1] with letters further in the alphabet designating harder bonds (e.g., $T > N$).

A variety of techniques have been proposed to provide a more quantitative method for characterizing/specifying tool properties. These include crushing strength [9–11], force required to dislodge grains during ploughing of a groove along the tool [11], ultrasonic wave speeds and elastic modulus [6, 12, 13], conventional metallurgical hardness or microhardness [13–15], and compliance at various size scales [7]. However, while many of these techniques have potential, each of these studies focused on a limited selection of tool materials and none of them systematically examined the role of composite microstructure in determining properties. As a result, and in spite of efforts to build-up an organizational framework for developing standards, tools must still be ordered primarily in terms of their ingredients without any quantitative specification available for properties [2, 3].

Materials and methods

Bronze-bond/diamond-abrasive tool materials were purchased in pellet form from three different commercial vendors. All pellets were approximately 12 mm in diameter and 3 mm thick.

For two of the vendors, a "medium" bond hardness was specified and pellets were ordered with all nine combination of three different diamond concentrations (25, 50, and 75 corresponding to 6.25, 12.5, and 18.75 vol%, respectively) and three different diamond grits (fine, medium, and coarse). Note that, although specifications were matched as closely as possible, differences in the diamond sizes between the vendors resulted in small difference in nominal sizes. Specifically, for vendor I the nominal sizes were 3, 12, and 100 μm for fine, medium, and coarse grits, respectively. For vendor II, the corresponding sizes were 3, 15, and 76 μm.

The third vendor was unable to provide pellets to custom specifications, but did supply nine different types of "standard" pellets, corresponding to all combinations of three nominal bond specifications ("soft," medium," and "hard") and three diamond sizes (2, 4, and 180 μm). The diamond concentrations in these pellets were low (1.25, 2.62, and 5.75 vol%) and linked to the bond specification, with higher diamond concentration corresponding to decreasing bond hardness. Because of the large difference in specifications (compared to the first two vendors) and the linkage between concentration and bond hardness, data collected from these pellets could not be used in the statistical analysis of diamond size and concentration effects on material properties. However, this data were included in analysis of porosity effects and nondestructive testing.

Density was measured by the Archimedes method using a precision balance (Fisher Scientific XA Analytical Balance, 0.1 mg resolution) and water. Acoustic measurements were made with a pulse emitter/detector, coupled to one face of the pellet using an acoustic gel. The time required for a pulse to transit the pellet and return was measured by reading the time between matching points (peaks and valleys) on the waveform displayed using an oscilloscope. Both pressure (longitudinal) and shear wave

speed were measured. Rockwell *F* hardness was used to determine the metallurgical hardness of the pellets. The hardness of each pellet was taken as the average of five measurements on the pellet. Elastic modulus (E) of each sample was calculated from the density (ρ), pressure wave speed (c_p), and shear wave speed (c_s):

$$E = \frac{3\rho c_s\left(c_p^2 - \frac{4}{3}c_s^2\right)}{\left(c_p^2 - c_s^2\right)} \quad (1)$$

Due to the diamond abrasive within the composites, conventional, quantitative metallography was impractical for these materials. As an alternative, samples were prepared by lightly sand-blasting and/or etching pellet surfaces and examined using scanning electron microscopy.

Results

Microstructure

All sample examined showed microstructural features characteristic of powder-metallurgy fabrication and consistent with the specified diamond size and concentration. For the coarse grit materials (Fig. 1), well-dispersed diamonds were observed. For fine grits (Fig. 2), a tendency for diamonds to segregate along the matrix powder boundaries was apparent. Although it was not always possible to differentiate between pores and diamond/matrix particle fall out, significant levels of porosity were also apparent in many of the materials. In general, the diamonds appeared to be in good contact with the matrix. However, fine diamonds were sometimes observed lining the surface of large pores (Fig. 3), suggesting possible difficulties with full integration of the diamonds into the matrix in some materials.

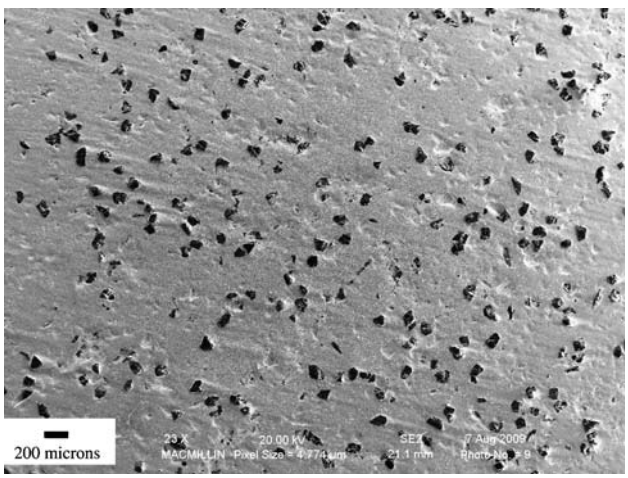

Fig. 1 SEM micrograph of coarse (100 μm), 25 concentration (6.25 vol%) diamond composite sample from vendor I. Diamonds (*black particles*) appear uniformly distributed

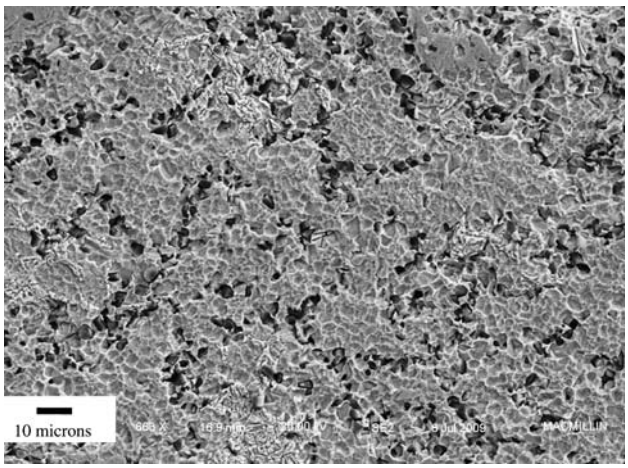

Fig. 2 SEM micrograph of fine (3 μm), 75 concentration (18.75 vol%) diamond composite sample from vendor I. Segregation of diamonds (*black particles*) along prior particle boundaries can be observed

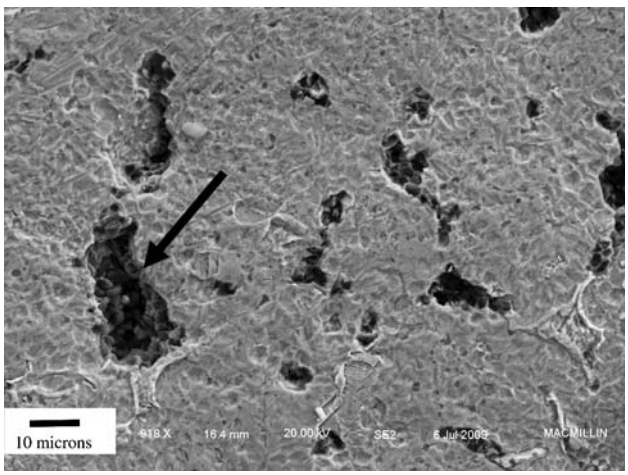

Fig. 3 SEM micrograph of fine (3 μm), 75 concentration (18.75 vol%) diamond composite sample from vendor II. *Black particles* are diamond. Notice diamond lining the surface of the large pore on the left (indicated by the *arrow*)

Bond compositions are generally held as proprietary information, but energy dispersive X-ray analysis was used to check and compare the materials. Consistent with their designation as bronze bonds, all of the bonds were found to be copper with tin as the primary alloying element. The "medium" bonds from the three vendors all had similar tin concentrations, with the soft and hard bonds from the third vendor distinguished principally by lower and higher tin contents, respectively.

Porosity for all samples was calculated from the nominal diamond concentration and the measured density of the pellets using the following equation:

$$P = 1 - \frac{\rho_{\text{measured}}}{\rho_{\text{diamond}} V_{\text{diamond}} - (1 - V_{\text{diamond}})\rho_{\text{bond}}} \quad (2)$$

where P is the volume fraction porosity, V the volume fraction, and ρ the density. For these calculations, 3.5 and 8.8 g/cm^3 [16, 17] were taken as estimates of the diamond (ρ_{diamond}) and bond (ρ_{bond}) densities, respectively. This equation is only an estimate, a point emphasized by the calculation of a small (1.3%) "negative porosity" for one pellet specification in the current dataset (Fig. 4a), but does provide a reasonable basis for making comparisons. Apparent trends were observed in the porosity level as a function of concentration, grit size, and vendor. However, there was also considerable scatter about these trends and high variability from pellet to pellet.

The parallel specifications for pellets ordered from the first two vendors, allowed the porosity data to be analyzed using an analysis of variance (ANOVA) approach based on a full factorial experimental design between three factors

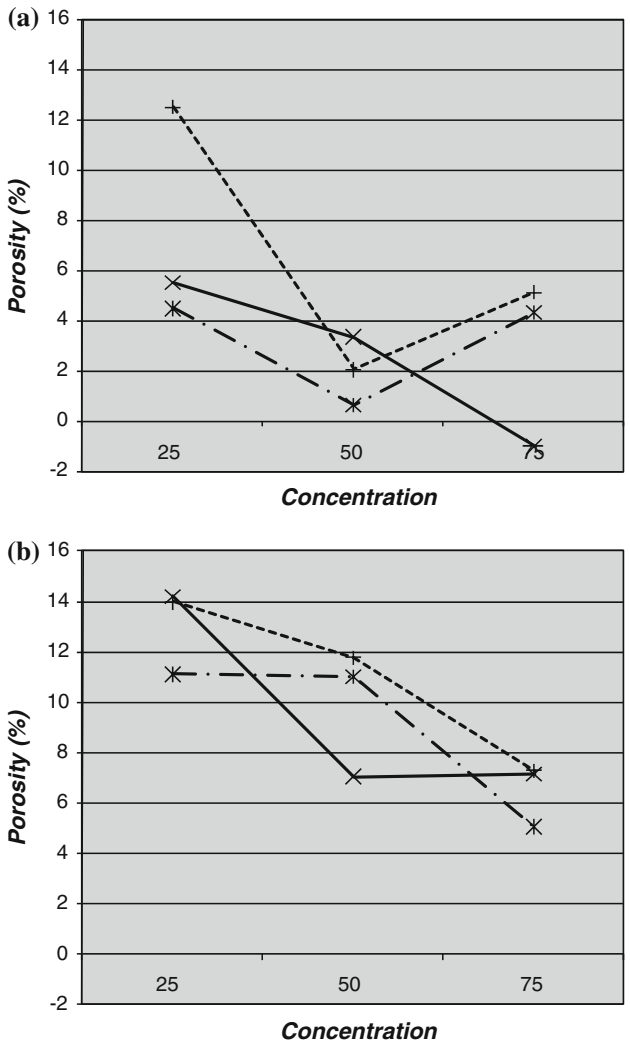

Fig. 4 Porosity as a function of diamond concentration and grit size. **a** Vendor I, **b** vendor II. x = fine, * = medium, and + = coarse grit

Table 1 ANOVA for porosity

Effect	SS	DOF	MS	F	% SS
A. Vendor	**747**	**1**	**747**	**56.6**	**27.5**
B. Grit size	**147**	**2**	**74**	**5.6**	**5.4**
C. Concentration	**522**	**2**	**261**	**19.8**	**19.2**
A × B	22	2	11	0.8	0.8
A × C	68	2	34	2.6	2.5
B × C	67	4	17	1.3	2.5
A × B × C	**192**	**4**	**48**	**3.6**	**7.1**
Error	950	72	13	–	35.0
Total	2,716	89	–	–	–

Bold indicates effects judged significant at a 99% confidence

(vendor, diamond concentration, and grit size), with replication, provided by the testing of five pellets of each specification, used for the error estimate [18]. Results of the ANOVA are presented in Table 1. The effects of each factor and interaction are presented in terms of both the F-ratio and the % sum of squares (% SS). The F-ratio (along with the degrees of freedom) permits the statistical significance of the effects to be evaluated, while the % SS provides a rough measure of their relative (practical) importance. The ANOVA table shows a relatively large error contribution to the variance (35%), reflecting the large pellet to pellet variability. However, statistically significant effects can still be identified, due to the large amount of data (degrees of freedom) available. The three primary factor effects (vendor, diamond concentration, and grit size) were all identified as significant at a 99% confidence level and are indicated in bold in the table. In addition, the three factor interaction was judged significant, indicating that the porosity is also influenced by particular combination(s) of all three factors (The same results are obtained if a 95% confidence is used.).

Figure 4 shows the porosity results in graphical form. Porosity is seen to decrease with increasing diamond concentration and with decreasing grit size. Both of these trends are consistent with the SEM observations and with expectations from powder packing/consolidation [19, 20]. Fine powers are able to fill the interstices in the packing of the matrix particles and, for low fine particle fractions, this effect is increased by increases in diamond concentration. Comparing Fig. 4a and b, there is also a clear overall difference in the average porosity levels of pellets from the two vendors, in spite of their matched specifications. Average porosity level thus represents a clear microstructural distinction between the materials provided by the two vendors. In spite of these overall trends, the "scatter" in Fig. 4 is an indication that much of the observed variation in porosity is nonsystematic and porosity is not consistently controlled in current commercial materials.

Mechanical properties

Both elastic modulus and hardness of the pellets exhibited an apparent dependence on the tool specifications (vendor, diamond concentration, and grit size), but also showed considerable scatter. To identify the significant effects, therefore, an ANOVA was applied to the full factorial datasets from the first two vendors. Replication, provided by the testing of five pellets of each specification, was again used for the error estimate.

ANOVA results for the elastic modulus and hardness are shown in Tables 2 and 3, respectively. Both ANOVA tables show a relatively large error term, reflecting the large pellet to pellet variability. For both the modulus and hardness, the same three effects (vendor, diamond concentration, and the three factor interaction) were identified as significant at a 99% confidence level and are indicated in bold in the tables. For the modulus (Table 2), use of a lower, 95%, confidence level would result in all factors and interactions (with the single exception of the vendor/diamond-concentration interaction) being judged statistically significant. However, these effects have minimal practical importance, as shown by their low % SS. For the hardness (Table 3), reducing the confidence level to 95% would not result in any additional effects being judged statistically significant.

The elastic modulus and hardness results are shown in graphical form in Figs. 5 and 6, respectively. Since the grit size was not found to be significant, results for the three grit sizes have been combined for each vendor and concentration. An increase in mechanical properties with concentration is expected based on the extreme mechanical properties of diamond. However the actual effects are seen to be modest. In contrast, the vendor to vendor differences are large, even though nominal specifications were matched between the two vendors.

Table 2 ANOVA for elastic modulus

Effect	SS	DOF	MS	*F*	% SS
A. Vendor	**27,344**	**1**	**27,344**	**132.6**	**45.1**
B. Grit size	1,312	2	656	3.2	2.2
C. Concentration	**6,323**	**2**	**3,162**	**15.3**	**10.4**
A × B	2,778	2	1,389	6.7	4.6
A × C	1,255	2	613	3.0	2.1
B × C	2,427	4	607	2.9	4.0
A × B × C	**4,402**	**4**	**1,100**	**5.3**	**7.3**
Error	14,850	72	206	–	24.5
Total	60,691	89	–	–	–

Bold indicates effects judged significant at a 99% confidence

Table 3 ANOVA for hardness

Effect	SS	DOF	MS	*F*	% SS
A. Vendor	**9,850**	**1**	**9,850**	**113.0**	**48.2**
B. Grit size	512	2	256	2.9	2.5
C. Concentration	**995**	**2**	**497**	**5.7**	**4.9**
A × B	346	2	173	2.0	1.7
A × C	480	2	240	2.8	2.3
B × C	646	4	161	1.9	3.2
A × B × C	**1,336**	**4**	**334**	**3.8**	**6.5**
Error	6,278	72	87	–	30.7
Total	20,443	89	–	–	–

Bold indicates effects judged significant at a 99% confidence

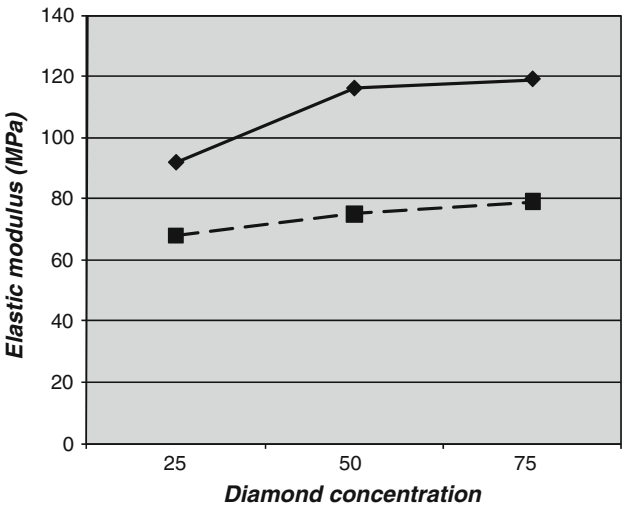

Fig. 5 Elastic modulus as a function of diamond concentration. Diamond = vendor I, square = vendor II

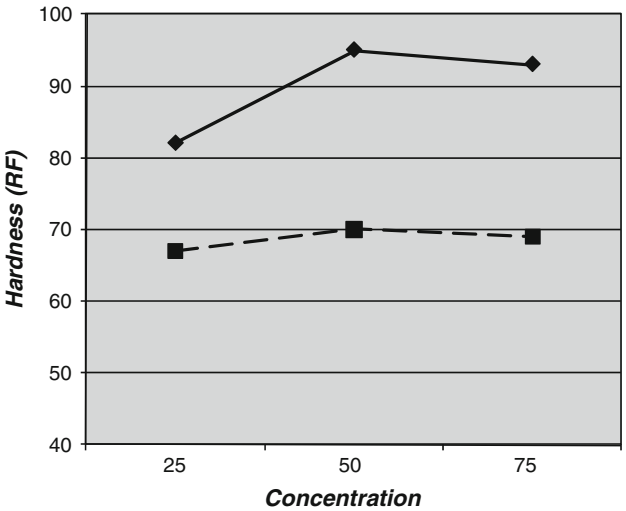

Fig. 6 Hardness (Rockwell F) as a function of diamond concentration. Diamond = vendor I, square = vendor II

Discussion

In spite of matching material specifications ("medium" bond hardness, diamond concentration, and grit size) as closely as possible between the first two vendors, it is apparent from Figs. 5 and 6 that vendor differences are the dominant factor influencing the mechanical properties of the tool materials. In the ANOVA, vendor differences accounted for over 45% of the total variance (% SS) measured for both modulus and hardness, between 4 and 10 times the effect of changes in the diamond concentration. Since proper functioning during grinding requires controlled wear ("self-sharpening" [1]), higher mechanical properties are not necessarily better. However, in the absence of quantitative information properties, both vendor selection and any tuning of properties must be "art" rather than knowledge driven. And, even for a single vendor, there is a great deal of variability in the properties. It is important, therefore, to explore the underlying causes of the observed property differences and to identify an effective nondestructive test for them.

Porosity

Possible sources of the large vendor to vendor property differences observed include subtle differences in bond composition and microstructure, differences in the properties of the diamond used by different vendors, and differences in the bond-diamond adhesion. However, since porosity often plays a key role in powder metallurgy fabricated materials and since testing revealed significant variations in the level of porosity among the materials (Fig. 4), porosity is a likely microstructural source for both inter- and intra-vendor variations observed in composite mechanical properties.

Figure 7 shows the modulus plotted against the porosity, with the additional data from the third vendor now also included. Note that, to account for the underlying influence of diamond concentration on modulus, the modulus has been normalized against its theoretical, isostress, value, appropriate given the relatively high modulus and equiaxed shape of the diamond abrasive [21]:

$$\frac{1}{E_{\text{isostress}}} = \frac{V_{\text{diamond}}}{E_{\text{diamond}}} + \frac{V_{\text{bond}}}{E_{\text{bond}}} \tag{3}$$

where V is the volume fraction and E the elastic (Young's) modulus. E_{bond} is taken as 110 GPa [16], representative of copper and phosphor (tin-based) bronzes, and E_{diamond} as 1050 GPa [17].

A strong correlation is evident, supporting the hypothesis that porosity is the main factor controlling the variations in the modulus among these materials. $R^2 = 0.65$ is obtained for a simple least squares linear fit to all of the data. However, a very high proportion of the remaining variance is attributable to the two points below the line in the center of the plot. If these two outliers are removed from the calculation, a linear fit (shown) can account for a much higher percentage of the observed variance in the modulus ($R^2 = 0.84$).

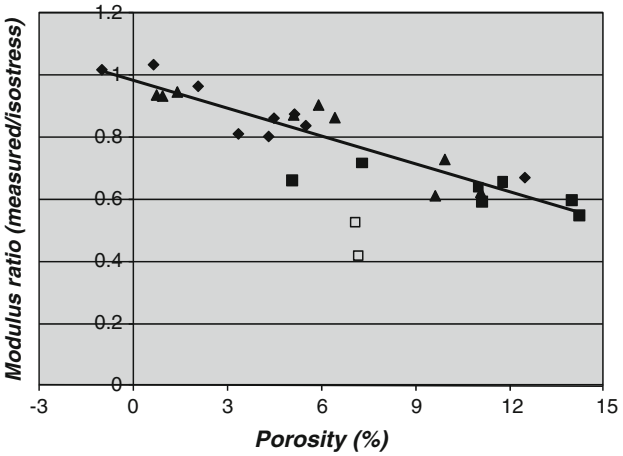

Fig. 7 Normalized elastic modulus (measured/isostress) versus porosity. Diamond = vendor I, square = vendor II, triangle = vendor III, *hollow squares* are outliers excluded from least squares linear fit (*solid line*)

The cause of the outliers is not clear, but both of these points represent similar combinations of the three factors examined in the ANOVA. Specifically, they represent pellets produced by one of the vendors (vendor II), with high concentrations (12.5 and 18.75 vol%) of the finest diamond size (3 μm). With high concentrations of fine powder, surface effects become more important and powder metallurgy fabrication techniques can be complicated by problems with flow, settling, agglomeration, bonding, etc. (e.g., Fig. 3). Anecdotal evidence from optical fabrication operations also suggests that this may be an issue for some vendors.

Figure 8 shows the measured hardness versus the porosity. A strong correlation is again evident, indicating that porosity differences can also explain most of the variation in measured hardness values ($R^2 = 0.79$). The two "outlier" points from Fig. 2 occupy somewhat similar positions in Fig. 3 but are not clearly separated from the main body of the data and so have not been excluded from the linear fit.

Finally, Fig. 9 shows the effect of porosity on the longitudinal wave speed. Funkenbusch and Gracewski [6] found a large increase in the sub-surface damage generated by a set of experimental grinding tools when the measured longitudinal wave speed fell below a "critical value" and were also able to correlate the wave speed differences to changes in the volume fraction of porosity. Figure 9, which includes the six data points from reference [6] along with the much more extensive dataset collected here, confirms the strong correlation between wave speed and porosity

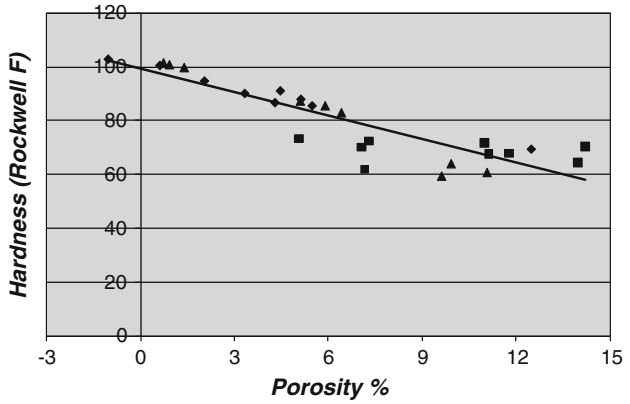

Fig. 8 Hardness versus porosity. Diamond = vendor I, square = vendor II, triangle = vendor III, *solid line* is least squares linear fit

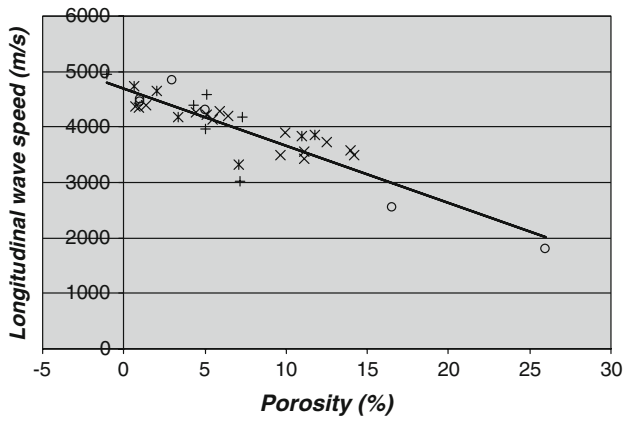

Fig. 9 Porosity versus longitudinal wave speed coded by diamond concentration. x = low (<0.063), * = medium (0.125), and + = high (0.1875) vol% diamond. *Line* is a least-squares fit. *Circles* are additional data taken from reference [6]

level, with $R^2 = 0.78$ for a least-squares line fit. Data for different diamond concentrations, as well as vendors and diamond sizes, all follow the same correlation, confirming the dominant effect of porosity.

Nondestructive testing

In contrast to the other measurements examined here, ultrasonic wave speeds may be easily and nondestructively made on a wide variety of tool shapes and sizes [22]. Moreover, since wave speed is used directly in the determination of elastic modulus (Eq. 1), a strong correlation between them is certain. Figure 10 shows the nearly perfect correspondence between longitudinal wave speed and elastic modulus, which can be fit extremely well ($R^2 = 0.985$) to a linear calibration line over the full range of vendors, bonds, diamond concentrations, and diamond sizes tested here.

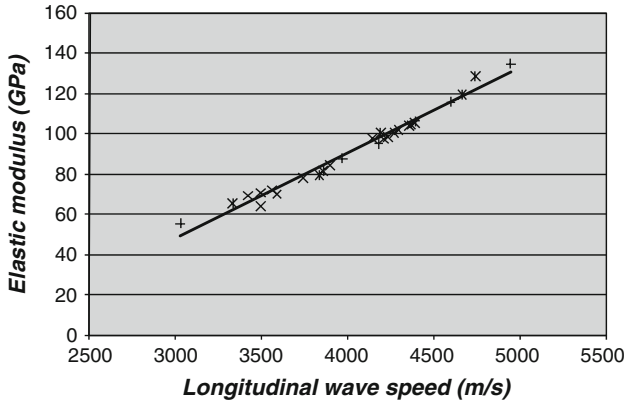

Fig. 10 Calibration of elastic modulus against longitudinal wave speed. Data points coded by diamond concentration. x = low (<0.063), * = medium (0.125), and + = high (0.1875) vol% diamond. *Line* is a least-squares fit

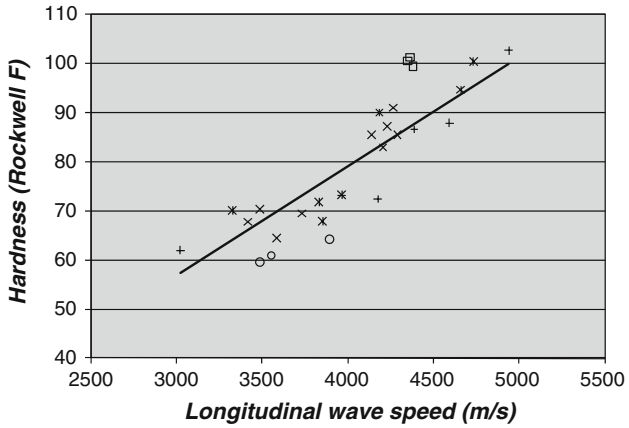

Fig. 11 Hardness versus longitudinal wave speed, coded by diamond concentration and nominal bond hardness. x = low (<0.063), * = medium (0.125), and + = high (0.1875) vol% diamond (all with medium bond hardness). ○ = soft bond hardness and □ = hard bond (both with <0.063 vol% diamond). *Line* is a least-squares fit to the medium bond hardness data

Similarly, Fig. 11 shows the measured hardness plotted versus longitudinal wave speed. Data are again coded in terms of diamond concentration but with the six materials identified as having "hard" or "soft" hardness bonds (Table 1) separately marked. A strong correlation is evident ($R^2 = 0.84$ for a linear fit to the medium bond data), with data for the different diamond concentrations again spread out along the least-squares line. Thus, wave speed provides an effective nondestructive means of estimating the metallurgical hardness of all of the medium bond hardness composites.

Data for the "hard" and "soft" bond designations follow the trend for the medium bonds in the sense that hard bonds have relatively high wave speeds and soft bonds low wave speeds. However, they are shifted relative to the overall

trend formed by the medium hardness data. Within the current dataset, the vendor designations of hard/soft corresponded to maxima/minima in the metallurgical hardness, but not necessarily elastic properties. Hence, while wave speed is useful for estimating hardness, comparison among composites with different nominal bond hardnesses adds an additional dimension. The hard (soft) bond materials achieve a hardness comparable to the maximum (minimum) observed for the medium bonds, even though their elastic properties (reflected through the wave-speed) are somewhat lower (higher) than the comparable medium bond materials. Further investigation of how composite mechanical properties change with vendor bond hardness designation is currently underway.

Conclusions

In this study, the microstructures and mechanical properties of bronze-bond, diamond-abrasive tool materials from three different commercial vendors were measured and analyzed. Composite specifications were chosen to cover a wide range of diamond sizes and concentrations. Based on these results, it is concluded:

1. Large differences exist in both the average value and consistency of the properties of nominally identical tool materials ordered from different vendors.
2. Commercial tool materials contain a wide range of porosity (from $\sim$0 to 14 vol%). In general, porosity decreases with decreasing diamond size and increasing diamond concentration, as expected from particle packing considerations. However, the vendor is the most important factor in determining composite porosity.
3. Smaller diamonds are less uniformly distributed within the composites and tend to be clustered along prior particle boundaries.
4. Increased diamond concentration produces an increase in both the elastic modulus and hardness of the composites. Diamond size does not have a statistically significant effect on either elastic modulus or hardness.
5. Porosity is the single strongest determinant of the composite mechanical properties, but is not consistently controlled in current commercial materials.
6. Measurement of ultrasonic wave speed provides an effective means for nondestructive testing of diamond composite tools. Both the elastic modulus and the hardness may be estimated from measurement of the longitudinal wave speed.

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