Investigation of micromechanical properties of fused alumina and silicone carbide grains

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Abstract. Micromechanical properties of abrasive material grains of fused alumina and silicone carbide are investigated applying the microindentation method. Such parameters as microhardness, microbrittleness, and microstrength were evaluated depending on the penetration depth of the Vickers diamond pyramid to the 0.5 — 5.0 µm thick surface under analysis. The microhardness parameter is the stress required for formation of a brittle failure area within the pyramid imprint. The microbrittleness criterion defines the ratio of the brittle failure area within the imprint and the imprint area. The power-law dependence of the parameters on the pyramid penetration depth is established: the lower the depth, the higher are microhardness and microstrength, yet the lower is microbrittleness. The obtained results enable creation of a standard basis, forecasting of the performance level of abrasive tools, refractory and wear-resistant items, filters, and special ceramics.

Mechanical characteristics for all actual, primarily structural materials are the main parameters that determine their purpose and performance level [1, 2].

Abrasive materials are used as individual particles (grains) for cutting elements to manufacture such abrasive tools as honing disks, segments, sticks, and heads. Grains are attached to tools by bonding (ceramic, bakelite, rubber, epoxy, magnesian). They can be used both as pastes and loose abrasives [3, 4].

The second significant option is using abrasive materials as components of refractory materials and items. Option three is using them as part of the composite materials for components of wear-resistant items, filters, and special ceramics [5, 6].

Abrasive materials mainly include the alumina class materials: monocrystalline alumina, brown and white fused alumina, as well as zirconium, titanium, chrome, and chrome-titanium alloyed fused alumina. Materials of the silicone, zirconium, tungsten carbide class have the same importance. Such super hard materials as natural and artificial diamonds, cubic boron nitride are distinguished as a separate class.

Brown and white fused alumina, certain alloyed fused alumina, and black and green silicone carbide are the most practicable [7].

Due to powder-like features of abrasive materials, studying their micromechanical characteristics is of scientific and practical interest. The microindentation method was applied for this purpose [8, 9]. It consists in indentation of a square-section diamond pyramid into the grinding face of the studied abrasive grains at specific load. The imprint size is used for evaluation.
Grains of both fused alumina and silicone carbide abrasive materials with the grit size of 400 — 1250 µm were studied. Quartz sand particles were used for comparison. A microhardness tester with a diamond pyramid was used; the apex angle is 136° (figure 1).

Microhardness is one of the parameters. It is determined using the following formula:

\[ H = \frac{1854P}{d^2} \]  

wherein \( H \) is Vickers pyramid microhardness, GPa; \( P \) is the pyramid load, N; \( d \) is the square imprint diagonal, µm.

![Figure 1. Microindentation diagram.](image)

The microhardness value is determined using formula (1) with consideration of the load value and the obtained imprint diagonal value. The microhardness values of the tested materials are shown in figure 2 in logarithmic coordinates depending on the imprint depth \( h = d/7 \). It is apparent that its value varies, decreasing at a higher pyramid load and a deeper imprint. At this stage, it can be concluded that it is inappropriate to evaluate microhardness of abrasive materials using the microhardness numbers obtained on the basis of a large number of imprints at the same or two randomly chosen load values. It is necessary to plot microhardness against the pyramid penetration depth into the grinding face. Various abrasive materials should be compared by the microhardness numbers for surface layers with equal thickness.

Dependence of the microhardness \( H \) on the imprint depth \( h \) according to figure 2 for all curves is described by the following formula:

\[ H = H_0 h^z = H_0 h^{-0.18} \]  

wherein \( H_0, z \) are dimensional and dimensionless constants of this formula; \( h = d/7 \) is the Vickers pyramid imprint depth, µm.

Applying the least square method, it was found that the dimensionless constant \( z = -0.18 \) is the same for all the materials tested. It is indicative of the same nature of elastic-plastic strain of various abrasive materials in case of square diamond pyramid indentation. The dimensional constant \( H_0 \) of the formula
is microhardness of the surface layer with the thickness of one unit (for example 1 µm) and can be used as a numerical benchmark of abrasive grain microhardness.

According to formula (2), the numerical values of $H$ and $H_0$ will be equal at $h = 1$. Thus, the microhardness criterion $H_0$ can be determined on the basis of figure 1 at $h = 1.0 \mu m$.

All the tested abrasive materials are significantly distinguished by microhardness; besides, this difference is traced reliably within a very wide range of pyramid loads. In order to use the microhardness criterion $H_0$ in practice, it is sufficient to determine microhardness of the tested abrasive sample at two various pyramid load values (for example 1.0 N and 2.0 N) and then calculate the criterion $H_0$ using formula (2).

The other necessary parameter microbrittleness $y$ was evaluated using the following formula:

$$y = \frac{Dcp^2 - d^2}{d^2}$$

(3)

wherein $d$ and $D_{cp}$ are arithmetic mean diagonal dimensions of the imprint and damage zone, correspondingly.

Figure 2. Microhardness $H$ of abrasive material grains depending on the penetration depth $h$ of the diamond pyramid into the grinding face, 1 — chrome fused alumina 34A; 2 — chrome-titanium fused alumina 91A; 3 — white fused alumina 24A; 4 — brown fused alumina 15A; 5 — black silicone carbide 54C; 6 — green silicone carbide 64C; 7 — quartz sand SiO$_2$.

The microbrittleness dimensionless criterion defines the ratio of the brittle failure area within the obtained imprint and the whole imprint area. In fact, it is a manifestation of plastic properties of apparently quite brittle abrasive materials, a ratio value of brittle and plastic properties. The value of $y$ is higher for more brittle materials. For perfectly plastic materials, $y = 0$. Dependence of microbrittleness on the imprint depth is shown in figure 3. Besides, the given functions are described using the following formula:
Wherein \( y_0, k \) are dimensional and dimensionless constants.

Applying the least square method, it was found that the dimensionless constant \( k = 0.82 \) is the same for all the abrasive materials tested and does not depend on the brittle behavior. It is indicative of the single nature of the brittle failure within the imprint, which accompanies elastic-plastic strain of materials in case of pyramid indentation. The constant \( y_0 \) depends heavily on the brittle behavior of abrasive materials and therefore can be used as a benchmark of their microbrittleness. According to formula (4), the numerical values of \( y \) and \( y_0 \) can be determined on the basis of figure 3 at \( h = 1 \) µm.

It is not necessary to apply a wide load range to use the microbrittleness criterion in practice. It is sufficient to take two different values of pyramid load (1.0 N and 2.0 N), determine microbrittleness at each load on the basis of 25 — 50 imprints, and calculate the microbrittleness criterion \( y_0 \) applying formula (4).

The breakdown degree of the abrasive grain grind face depends on both stresses and the grain strength properties. It is evaluated according to the microstrength parameter determined using the following formula:

\[
\sigma = \frac{1000 \rho}{D_{cp}^2}
\]  

The microstrength parameter is the stress required for formation of a unit of the brittle failure area within the pyramid imprint.

Dependences of microstrength on the grinding face imprint depth are shown in figure 4. These experimental dependences are described by the following formula:

\[
\sigma = \sigma_0 h^x = \sigma_0 h^{-1}
\]

Wherein \( \sigma_0, x \) are dimensional and dimensionless constants.

Applying the least square method, it was found that the dimensionless constant \( x = -1.0 \) is the same for all the abrasive materials tested and does not depend on their brittle behavior. Along with constancy \( k = 0.82 \), it is indicative of the single nature of the abrasive material brittle failure, which
accompanies their elastic-plastic strain in case of pyramid indentation. The dimensional constant $\sigma_0$ depends heavily on the brittle and strength behavior of abrasive materials and therefore can be used as a benchmark of their microstrength. According to formula (6), the numerical values of $\sigma$ and $\sigma_0$ will be equal at $h = 1$. Thus, the microstrength criterion $\sigma_0$ equal $\sigma$ can be determined on the basis of Figure 4 at $h = 1$ µm. It is apparent that all the tested materials are distinguished by the microstrength criterion. To be used in practice, it is sufficient to take two different values of pyramid load, determine on the basis of 25 — 50 imprints at each load, and calculate the microstrength $\sigma_0$ applying formula (6).

![Figure 4. Microstrength of abrasive material grains, 1 — 34A; 2 — 91A; 3 — 24A; 4 — 15A; 5 — 54C; 6 — 64C; 7 — SiO$_2$.](image)

Considering the stated above, the following conclusions can be made. As compared to the known corresponding parameters of abrasive materials by leading foreign companies, the analysis results revealed the following. In terms of micromechanical properties of abrasive grains, home-produced materials are level with foreign samples. Though silicone carbide materials are inferior in terms of microhardness. Microbrittleness and microstrength of white and chrome-titanium fused alumina are level with the foreign samples analyzed.

The suite of failure (brittleness) monitoring methods along with the strength assessment of individual abrasive grains during micromechanical tests applying a microhardness tester enable quality evaluation and certification of fused alumina/silicone carbide abrasive materials under commercial and research conditions, as well as preparing the basis for development of a standard on quality control of abrasive grain materials’ micromechanical parameters. Ultimately it can result in planning of effective operation of abrasive tools, wear-resistant and refractory items, filters, and special ceramics.

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