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Dependence of sapphire hardness on loading type and orientation

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The mechanical strength of sapphire in different crystallographic diorections has been studied within a wide loading range. A correlation has been found between the resistance to hig-speed shock and the sapphire crystallography.

Исследована механическая прочность сапфира в различных кристаллографических направлениях в широком диапазоне нагрузок. Установлена связь сопротивлениz высокоскоросному удару с кристаллографией сапфира.

Modern technologies for the growth of large-size and perfect single crystals make it possible to use sapphire in the structures working in extreme conditions under intense dynamic loading. For instance, 6 mm thick sapphire plates withstand efficiently to high-velocity (800 m/s) shock of a chilled steel core [1]. However, the sapphire crystal lattice is strongly anisotropic. In this connection, it is of importance to investigate the efficiency of the sapphire resistance to high-velocity shocks and to the striker penetration depending on the crystal anisotropy. The aim of this work was to study a relation between the sapphire resistance to high-velocity shock and the crystallographic peculiarities of the crystal.

The study was realized on $10\times15\times3$ mm^3 samples cut out of a crystal grown by the Kyropoulos method. The mechanical characteristics was measured on 10×15 mm^2 areas of the basal plane (0001), the prismatic planes $(10\bar{1}0)$, $(11\bar{2}0)$, and rhombohedral plane $(10\bar{1}2)$. All the samples were ground and polished in the same manner.

The microhardness value was determined using a PMT-3 unit at HV = P = 0.5, 1, and 2 N loads. At each load, there at least 10 measurements were done. Moreover, the measurements were performed at loads up to 1kN and high-velocity (930 m/s) interaction with a tungsten carbide striker. The shocks were made along the normal to the sample.

As seen from the microhardness dependence on the load (Fig. 1), a considerable scatter of the results is observed, especially at 0.5–1 N loads. Moreover, the value of microhardness on different planes changes in a different way. Since the indenter penetration depth at the mentioned loads is 1–2 μm, the microhardness is influenced essentially by the surface defects. The hardness rise at the load increasing from 0.5 to 1 N is caused by transition from the defect near-surface layer to the region with constant dislocation density. On the basal plane, the hardness is reduced starting from 2 N load (as will be shown lower, such an effect is especially pronounced at high loads). The most probable hardness values for the planes of sapphire are those presented in the Table. In other words, at the loads ranging between 0.5 and 1 N the microhardness $HV\simeq$ 20 GPa is essentially independent of the orienta-

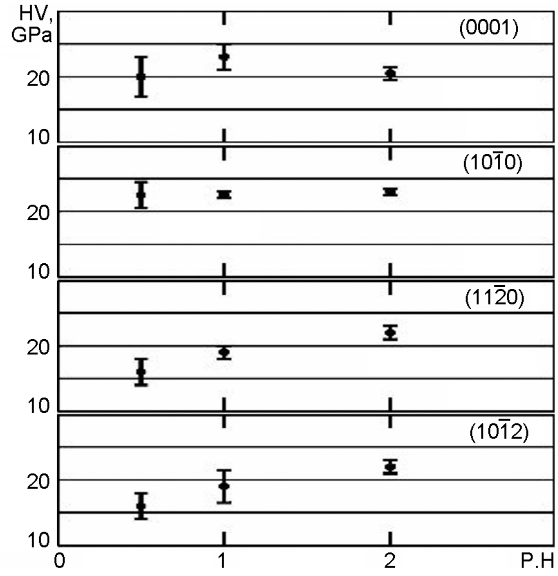


Fig. 1. Sapphire microhardness depending on load on different crystallographic planes.

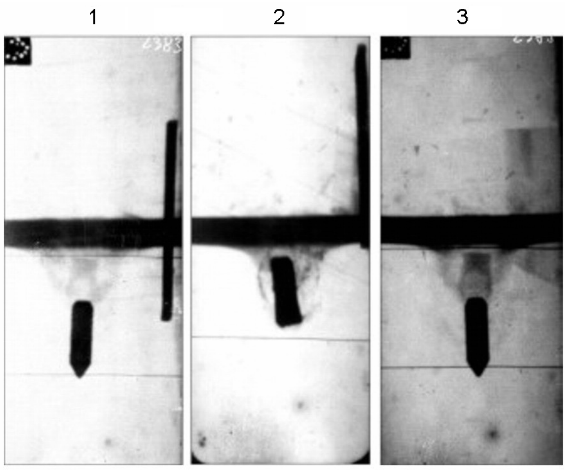


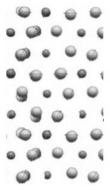
Fig. 2. Punching of 7 mm thick plates made from corundum ceramics: *HV* = 13 GPa (*1*), *HV* = 19 GPa (*2*) and sapphire, *HV* = 22 GPa (*3*) by tungsten carbide striker (*HV* = 17.8 GPa). The shock velocity is 930 m/s.

tion, and is close to the values measured before [2, 3]. First of all, this concerns elastic-plastic penetration not accompanied by brittle failure under indenter.

At high-velocity interaction of brittle solids, the ratio of their hardness values is the decisive factor which defines the initial collision stage [4]. In particular, the striker deformation occurs in the case when the block hardness exceeds the striker one. Shown in Fig. 2 is the X-ray image of the interaction of strikers made from the material VK8, *HV* = 17.8 GPa, with corundum ceramic and sapphire (plane (11$\bar{2}$0)) plates. When the block hardness exceeds that of the striker, the latter is broken down. However, despite the fact that the hardness of sapphire is by ≃ 4 GPa higher than the corresponding parameter of tungsten carbide, the striker has not underwent the expected action. We have assumed that the observed effect is connected with the sapphire destruction in the contact zone with the striker.

To check this assumption, the sapphire resistance against penetration was measured at high loads. The measuring technique for brittle materials has been proposed in [5]. According to it, the shape and dimensions of the indentation are retained as an imprint on a thin (≈5 μm) aluminum foil placed onto the sample prior to indentation. This method makes it possible to determine the indentation dimensions from the imprint obtained while detaching the indenter from the sample. The comparison of the imprints obtained at high indenter loads with and without the foil shows that at a load up to 1 kN, the imprints on the foil allow to determine the indentation dimensions (Fig. 3). In both cases, there are no essential distinctions in the indentation shape and dimensions, the difference in the calcu-

Table. Parametrs of crystllographic planes

plane	(0001)	(10$\bar{1}$0)	(11$\bar{2}$0)	(10$\bar{1}$2)
d, Å	2.16	1.37	2.37	3.47
Location of atoms in the interplanar space				
HV, GPa (indenter load, N)	23 (1)	23 (2)	22 (2)	22 (2)

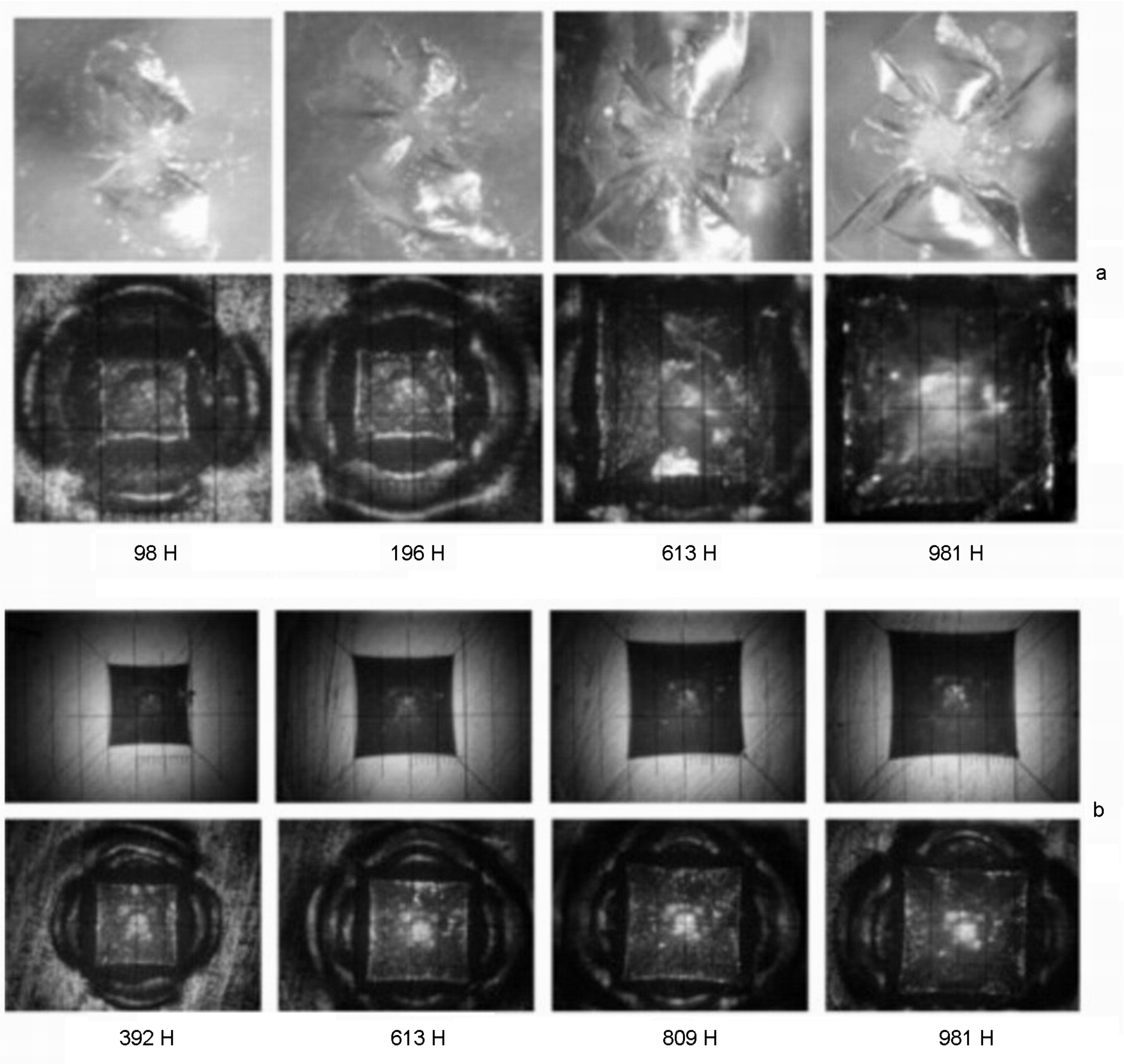


Fig. 3. Vickers pyramid indentations at high indenter loads on the plane $(11\bar{2}0)$ of sapphire (a) and tungsten carbide (b) without foil (upper row) and with foil (lower row).

lated effective hardness (HV_{eff}) values does not exceed 2 %. The legitimacy of using foil was shown for tungsten carbide. This material possesses rather high destruction viscosity, and the Vickers pyramid indentations obtained on its surface at high loads are clear and non-destroyed.

As follows from HV_{eff} – load dependence (Fig. 4), the resistance of all the planes to the indenter penetration decreases, the largest (by a half) decrease occurring on the basal plane. This fact may be connected with a large interplanar distance (d = 2.16 Å) in the C axis direction. The plane $(10\bar{1}0)$ characterized by small interplanar distances (see the table) and large number of aluminum atoms located between the crystallographic planes, turns out to be most resistant. The distance between the planes $(11\bar{2}0)$ is larger than that between

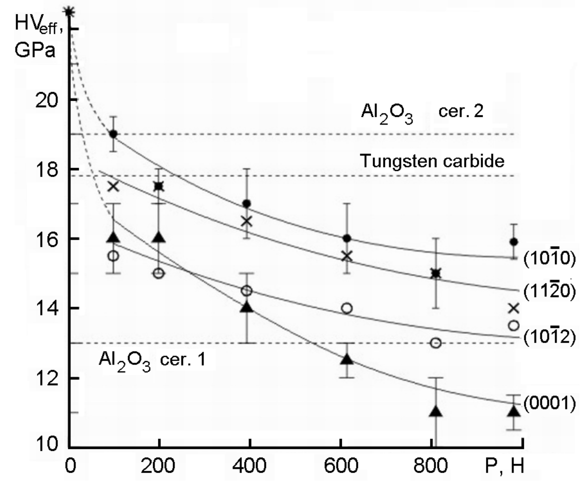


Fig. 4. Resistance of sapphire to indenter penetration with foil depending on load for different crystallographic planes.

the basal planes, but the number of aluminum atoms in the interplanar space is larger, too. Fig. 4 also presents the HV_{eff} – load dependences for two corundum ceramics of different density and hardness. As is seen, their resistance to indenter penetration does not reduce as the load increases. Moreover, for the ceramics with hardness exceeding that of tungsten carbide, there is observed an effective shortening (deformation) of the striker at 1 kN load. This means that, if corundum ceramics with a transparency close to that of sapphire will be obtained in the future, it will compete with sapphire in articles such as transparent armour.

Thus, at high loads, the resistance of sapphire to indenter penetration reduces as the load grows, but the character of such a reduction in different crystallographic directions has essential distinctions which seem to be connected with the interplanar distance value and the number of aluminum atoms inside this space. The resistance of brittle solids to indenter penetration at high loads (e.g. at P=1 kN) may form a basis to predict the results of their high-velocity interaction.

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Залежність твердості сапфіру від типу навантаження

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Досліджено механічну міцність сапфіру у різних кристалографічних напрямах в широкому діапазоні навантажень. Встановлено зв'язок опору высокошвидкістному удару з кристалографією сапфіру.