Improving the quality of surgical scalpels with ceramic blades

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Abstract. The article discusses the issues of increasing resistance to brittle fracture of surgical scalpels with ceramic blades from nanostructured crystals of partially stabilized zirconium dioxide. The statement is substantiated that the strength properties of crystals can be increased by increasing the crack resistance of crystals by alloying with rare-earth elements. The kinetic microindentation method is used to study the characteristics of mechanical properties and crack resistance of samples of alloyed crystals. An assumption about the efficiency of alloying crystals with cobalt is substantiated. The bending strength test of promising crystal compositions is carried out. Based on the study, recommendations are formulated on the use of zirconium dioxide crystals for surgical scalpel blade manufacture.

1. Introduction
Currently, in medical practice for surgical operations, scalpels are used mainly from metals of various alloys. The disadvantages of metal scalpels include the following properties: granular microstructure of metals, which does not allow to obtain high sharpness of the scalpel cutting edge (~ 10 microns for most scalpels); low wear resistance of metal (quick dulling); relatively low chemical resistance to acids, alkalis, water vapor; biological incompatibility with living tissues; high injuries of living tissues during operations (long healing, thrombosis, etc.) [1]. Recently, in Russia, Japan, the USA, China, Korea and other countries, efforts are actively being made to search for non-metallic materials to produce high-performance scalpels based on them. Artificial crystals of diamond, sapphire, silicon, silicon carbide, zirconium dioxide, ceramics of various compositions. These materials have several properties that distinguish them from metal alloys, namely: chemical and biological inertness; hardness; a low coefficient of friction; high abrasion resistance. For the manufacture of an ultra-sharp surgical instrument, single crystals compare favorably with sintered ceramic materials by the lack of granularity that occurs in all ceramics, including those synthesized from nanostructured powders. Sharper scalpels enable to cut tissue without crushing with minimal injury and use throughout the operation, during which the cutting ability of the tool does not change, which facilitates the work of the surgeon. This can significantly reduce tissue injury, which is especially important during operations on internal organs [2]. However, ceramic scalpels have low crack resistance, especially blades made of sapphire ($K_{IC} = 3-4$ MPa·m$^{0.5}$). To improve the mechanical properties of ceramics, dispersion hardening technologies [8], plasma sintering during electric spark treatment [9, 16], sol-gel technology [10], increased strength of ceramics with reduced graphene oxide [18], and others are used. Studies of ceramic materials for crack resistance and bending strength are associated with great complexity due to poor machinability of sample materials and problems of recording the size of cracks. In [11], a comparative analysis of the flexural strength of zirconium oxide ceramics was carried out using various ceramic synthesis.
technologies. The microstructure and bending strength of zirconium oxide ceramics by liquid phase sintering were studied in [12]. The effect of microwave sintering on the crack resistance of zirconium ceramics was studied [13]. In [14], the anisotropy of the properties of PSC crystals along crystallographic axes was considered. In [15], a very large set of experimental data on the flexural strength of alumina ceramics was used to compare Weibull statistics with other statistical data. The reproducibility of ceramic bending strengths in serial production was studied [17]. The highest crack resistance of all ceramics and crystals is possessed by [3, 5] nanostructured partially stabilized zirconium dioxide crystals (PSZ crystals). Functional analogues of scalpels with blades made of PSZ are scalpels with metal blades both reusable and disposable. The main advantages of scalpels with blades from PSZ are perfectly flat cutting edge; high sharpening; high strength and wear resistance; biological compatibility of the blade material with tissues of a living organism; accelerated healing after their use; zero porosity of the blade surface. The number of operating cycles of scalpels with blades made of PSZ crystals is many times (up to 50 times) greater than that of disposable metal scalpels [4]. For widespread use of products made of PSZ crystals in medical practice, it is necessary to increase their crack resistance. In surgical practice, there are cases of scalpels working in conditions of increased bending loads. An effective measure of the effect on the mechanical properties of PSZ crystals is microalloying by rare-earth elements [6, 7]. However, the effect of alloying PSZ crystals on crack resistance and bending strength has been little studied. In [19, 20], the structural features of alloying of PSZ crystals with scandium and cerium oxides were considered. In [21], the effect of valency of series ions on the formation of crystal structure and mechanical characteristics of the crystal were revealed. The effect of the amount of Y2O3 additive on the structure and mechanical properties of PSZ crystals was studied [22]. It has been established that alloying of PSZ crystals is an effective means of increasing ductility and crack resistance of materials based on zirconium dioxide. The concentration range of yttrium oxide was established, providing high values of fracture toughness of materials (2-2.8 mol%).

The aim of the work is to study the effect of microalloying on the fracture toughness of nanostructured PSZ crystals viable for the manufacture of surgical scalpels.

2. Materials and equipment
Samples from PSZ crystals with impurities of rare-earth elements were made in the form of plates 10*10*2 mm in size. Tests to determine the mechanical properties of PSZ crystals were carried out on a MNT Z_AE_000 kinetic microhardness meter manufactured by CSM Instruments according to ISO/DIS 14577_1: 2002 with a Vickers m-indenter according to the procedure [X]. The quantitative analysis of the samples was carried out by electronic microanalysis on the CAMEBAX SX-50 installation. Bending tests were carried out on an Instron model 1115 machine. In the experiments, the load (P) and deflection (f) of the sample were recorded in the coordinates (P ~ f) of the diagrammatic apparatus of the machine. The test procedure for determining the bending strength was developed [23] considering the characteristics of the PSZ material: anisotropy, brittleness, limited size of the material samples, and high hardness.

3. Results and discussions
Studies of the irreversible loss coefficients of PSZ crystals suggest that it is of practical interest to use PSZ crystals in friction units with a stabilizing additive content of 2.8% Y2O3. From the experiments it follows that in the process of microindentation, cracks form starting from a certain threshold value, and the onset of crack formation depends on the orientation of the sample, since all crystals have a pronounced anisotropy of mechanical properties. It has been established that in the case of alloying with neodymium oxide of PSZ crystals with different contents of stabilizing yttrium oxide 2.8 mol%), the total content of stabilizing oxides is the dominant factor influencing the nature of the formation of the domain structure. With an increase in the concentration of stabilizing oxide, the twin structure becomes more homogeneous and dispersed (Figure 1).
Figure 1. Structures of PSZ crystals of the compositions ZrO₂-2.8 mol% Y₂O₃ and ZrO₂-3.7 mol% Y₂O₃, additionally alloyed with neodymium oxide (0.04-0.34 mol%).

Microhardness, elastic modulus, and the irreversible loss coefficient of PSZ crystals of various compositions were measured. The results are shown in Table 1.

Table 1. Results of measurements of mechanical properties of PSZ crystals by the kinetic microindentation method at a load of 3N

| Composition                  | HV, GPa | E, GPa | K_{upr} | K_{upr} |
|------------------------------|---------|--------|---------|---------|
| 2.8 mol.% Y₂O₃ + 0.1 weight % CeO₂ | 16.6    | 197    | 0.526   | 0.474   |
| 2.8 mol.% Y₂O₃ + 0.6 weight % CeO₂ | 16.3    | 205    | 0.532   | 0.468   |
| 2.8 mol.% Y₂O₃ + 1 weight % CeO₂  | 17.0    | 234    | 0.552   | 0.448   |
| 2.8 mol.% Y₂O₃ + 0.1 weight % Nd₂O₃ | 11.1    | 133    | 0.486   | 0.514   |
| 2.8 mol.% Y₂O₃ + 0.6 weight % Nd₂O₃ | 12.7    | 75     | 0.404   | 0.596   |
| 2.8 mol.% Y₂O₃ + 0.9 weight % Nd₂O₃ | 15.8    | 192    | 0.535   | 0.465   |
| 2.8 mol.% Y₂O₃ + 0.3 weight % CeO₂ + 0.9 weight % Nd₂O₃ | 16.8    | 195    | 0.518   | 0.482   |
| 2.8 mol.% Y₂O₃ + 0.6 weight % CeO₂ + 0.3 weight % Nd₂O₃ | 15.7    | 147    | 0.478   | 0.522   |
| 2.8 mol.% Y₂O₃ + 0.9 weight % CeO₂ + 0.3 weight % Nd₂O₃ | 12.2    | 55     | 0.337   | 0.663   |

As follows from the table, alloying of PSZ crystals significantly affects the elastoplastic and mechanical properties of PSZ crystals. For non-oriented samples of PSZ crystals, with an increase in molar% Y₂O₃ (1 mol%; 2 mol%; 2.5 mol%) and a corresponding decrease in molar% CeO₂ (1.8 mol%; 0.8 mol%; 0.3 mol%), the microhardness and Young modulus increase. The sample composition ZrO₂-2.5 mol% Y₂O₃ + 0.3 mol% CeO₂ has the highest values of microhardness and elastic modulus. Table 2 shows the results of measuring crack resistance of synthesized samples.
Table 2. The results of determining the crack resistance of PSZ crystals, based on ZrO$_2$ + 2.8 mol% 

| №  | CeO$_2$, weight% | Nd$_2$O$_3$, weight% | CeO$_2$:Nd$_2$O$_3$, weight% | Co$_2$O$_3$, weight% | $K_{IC}$, MPa $\cdot$ m$^{-1/2}$ |
|----|-----------------|----------------------|-----------------------------|---------------------|-------------------------------|
| 1  | -               | -                    | -                           | -                   | 10.5                          |
| 2  | 0.1             | -                    | -                           | -                   | 9.9                           |
| 3  | 0.6             | -                    | -                           | -                   | 11.1                          |
| 4  | 1.0             | -                    | -                           | -                   | 10.4                          |
| 5  | 0.1             | 0.6                  | -                           | -                   | 9.5                           |
| 6  | 0.9             | 0.6                  | -                           | -                   | 10.6                          |
| 7  | 0.9             | 0.6                  | -                           | -                   | 9.1                           |
| 8  | 0.6+0.9         | 0.9                  | -                           | -                   | 14.6                          |
| 9  | 0.6+0.6         | 0.9+0.3              | -                           | -                   | 8.9                           |
| 10 | 0.9+0.3         | 0.6+0.9              | -                           | -                   | 9.2                           |
| 11 | 0.1             | 0.6                  | -                           | -                   | 9.6                           |
| 12 | 0.3             | 0.6                  | -                           | -                   | 11.2                          |

PSZ crystals have anisotropy of mechanical properties (Table 3). A factor that has an important role in ensuring the stability of mechanical properties of scalpels in mass production.

Table 3. Comparison of hardness of PSZ crystals in the (100) orientation and non-oriented crystals at a load of 1 N

| Composition | HV (100) | HV |
|-------------|----------|----|
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.1 weight%Ce | 1617 | 1707 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.6 weight%Ce | 1685 | 1666 |
| ZrO$_2$-2.8v mol%Y$_2$O$_3$ +1 weight%Ce | 1752 | 1728 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.1 weight%Nd | 1471 | 1666 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.6 weight%Nd | 1599 | 1774 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.9 weight%Nd | 1668 | 1676 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.1 weight%Co | 1722 | 1709 |
| ZrO$_2$-2.8 mol%Y$_2$O$_3$ +0.3 weight%Co | 1621 | 1798 |

Bending tests were carried out on samples with dimensions of 25x5x5 mm in the delivery state according to three point patterns with recording the load-deflection diagram. Stress limit $\sigma_m = 1.5P_m/lbh^2$, where $P_m$ is the breaking load, $l$ is the distance between the supports, $b$ is the width of the sample, and $h$ is the height of the sample. The test results are shown in Table 4.
Table 4. Flexural strength of alloyed PSZ crystals.

| Additive | Weight % | Strength Gm (MPa) |
|----------|----------|-------------------|
| Co       | 0.3      | 940               |
| Co       | 0.3      | 1078              |
| Nd       | 0.5      | 946               |
| Nd       | 0.9      | 556               |
| CeO₂     | 0.6      | 497               |

The experiments show that the most promising for use in friction units are samples of a PSZ crystal of the composition ZrO₂-2.8 mol% Y₂O₃ + 0.3 wt% CoO, since in the load interval 0.5 - 9 N (technical limits of the device’s capabilities) no cracks are observed, and the flexural strength is highest.

Scalpels from PSZ crystal are a qualitatively new tool, previously not serially produced. Zirconium dioxide-based material refers to difficult to process materials such as diamond and sapphire. As a result of studies, it was found that PSZ crystals lend themselves to dimensional machining with a diamond tool. The established grinding regimes for articles made of PSZ crystals made it possible to form a cutting edge of a scalpel blade substantially sharper than a metal scalpel (Figure 2).

Figure 2. Comparison of blades of general surgical scalpels

Granular microstructure of metals does not allow to obtain a sharpness of the cutting edge of scalpels of less than 10 microns for most scalpels. For ceramic scalpels, the cutting edge size can be adjusted to ~ 1 μm, for crystalline ~ 0.1 μm, which is 2 orders of magnitude smaller than for metal scalpels.

Advantages of scalpels made of PSZ crystals: smooth cutting edge; high sharpening; high strength and wear resistance; biological compatibility of the blade material with tissues of a living organism; accelerated healing after their use.

Conclusions

According to the results of studies of the mechanical properties of experimental samples of nanostructured PSZ crystals, it was found that crystals of the compositions ZrO₂-2.8 mol% Y₂O₃ + 1 weight% CeO₂ and ZrO₂-2.8 mol% Y₂O₃ + 0.3 weight% CoO possess the best properties by the plasticity criterion (irreversible loss ratio). An analysis of crack formation in the process of microindentation of PSZ crystals has been performed. It was found that for PSZ crystals of the composition ZrO₂-2.8 mol% Y₂O₃ + 0.3 wt% CoO when loading the Vickers indenter in the load interval 0.5 - 9 N, cracking is not observed. For serial production of surgical scalpels, it is promising to use crystals of PSZ composition, namely ZrO₂-2.8 mol% Y₂O₃ + 0.3 wt% CoO.
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