Ceramic restorations based on zirconium dioxide for orthopedic dentistry

Abstract

Currently, ceramics based on solid solutions of zirconium dioxide tetragonal structure are common biomedical materials. In commercially common ceramics of orthopedic dentistry based on zirconium dioxide, the stabilization of the tetragonal shape is achieved by the introduction of yttrium or cerium cations. As a result of this scientific work, a ceramic material based on nanopowders of a system of zirconium dioxide and ytterbium oxide with high strength parameters has been developed. The results of the conducted research allow us to recommend the new Yb–TZP ceramics as an alternative to Y–TZP ceramic materials for restorations in orthopedic dentistry.

Keywords: *zirconium dioxide, ytterbium oxide, Yb–TZP ceramics, Y–TZP ceramics, restoration in orthopedic dentistry*

Introduction

Currently, ceramics based on solid solutions of zirconium dioxide tetragonal structure (TZP) are common biomedical materials. These ceramics have bioinertness, which is combined with good biocompatibility and low invasiveness, as well as high strength characteristics [1-5].

According to scientific research, ceramics based on zirconium dioxide does not cause allergies or signs of incompatibility in the oral cavity [6]. In addition, zirconium dioxide is biocompatible with the mucous membrane and tissues of the oral cavity [7]. High functional stability and corrosion resistance, as well as impeccable aesthetic and mechanical characteristics make up the undeniable advantages of the material [8]. Zirconium dioxide does not participate in galvanic processes and passes X-rays [9]. The use of this material eliminates the problem of temperature sensitivity due to thermal insulation and low thermal conductivity [10]. Three groups of ceramics are used in dentistry: polycrystalline, infiltration and glass ceramics. Glass ceramics and infiltration ceramics are multiphase materials containing crystalline components in addition to the amorphous phase of glass. Zirconium oxide is the only type of polycrystalline ceramics, and in its properties it surpasses other types of ceramics, since it contains very little glass and, therefore, has a high long-term strength [11].

In commercially common ceramics of orthopedic dentistry based on zirconium dioxide, the stabilization of the tetragonal shape is achieved by the introduction of yttrium or cerium cations. It is known that the strength properties of PZT ceramics containing Y^{+3} cations are subject to gradual degradation (Low Temperature Degradation) during prolonged exposure to the body environment, which leads to revision operations. The substitution of the stabilizing cation Y^{+3} for Ce^{+4} favors an increase in the stability of strength properties in the biological medium [12,13]. However, such ceramics do not meet the requirements of aesthetic orthopedic dentistry for the color rendering of the material.

The aim of this work was to develop a ceramic material based on nanopowders of a system of zirconium dioxide and ytterbium oxide with high strength parameters, stable during prolonged stay in the biological environment, and having a color rendering close to natural teeth for restorations in orthopedic dentistry.

Materials and Methods

The synthesis of precursors of powders of the ZrO_2–Yb_2O_3 system containing 95-97% ZrO_2 (Yb–TZP) was carried out by the hydrolysis sol-gel method using 1 M solutions of $ZrOCl_2$; $Yb(NO_3)_3$ salts according to the procedure described in [14,15]. The initial powders were obtained after heat treatment of gel-like precipitates (hydrogels) at final temperatures of 450°, 750° and 950°C.

Blanks from synthesized powders - disks ∅20 mm and prisms 32x7x3 mm - were compacted by semi-dry pressing [16].

Sintering was carried out in electric furnaces in an air environment at a final temperature of 1500°C.

The relative density and porosity of sintered ceramic samples were determined by the method of hydrostatic weighing (Archimedes). The method of low-temperature adsorption (adsorption-structural analyzer "TriStar -3000") was used to measure the specific surface of powders [17].

The bending strength was determined by the three-point bending method on the Instron 5581 universal testing machine. The speed of movement of the traverse of the test machine is -0.5 mm/min [18].

In order to assess the stability of the properties of Yb–PZT ceramics during prolonged exposure to a living organism, a method of accelerated aging due to hydrothermal treatment of ceramic samples according to ISO 13356-2008 was used. The accelerated aging test was performed at a temperature of 134°C and a pressure of 2 bar.

Qualitative analysis of the phase composition of ceramics before and after hydrothermal treatment was carried out on an Ultima IV diffractometer (X-ray radiation, nickel filter), angle interval 2θ=20-70° [19]. Phase identification was performed using the PDF2 radiometric data bank.

The evaluation of the color characteristics of ceramic samples was carried out on the Spectron-M2 apparatus. In the CIE color system (CIE L*A*B*), three parameters L*, A* and B* are used to determine the color. The value of L* is consistent with the idea of the lightness of the object. Parameters A* and B* allow you to express the color of the object and its saturation. A sample of barium sulfate was used as a reference. The value ∇E characterizes the deviation from the standard.

Results and discussion

The degree of crystallization of the synthesized powders increases in proportion to the increase in the temperature of the heat treatment of gel-like precipitation from 450°C to 950°C. The main phase of the powders is represented by a solid solution based on zirconium dioxide, the structure of which is being improved from pseudocubic to tetragonal, which is illustrated in Figure 1, where fragments of diffractograms of powders obtained at temperatures of 450°, 750° and 950°C are presented.

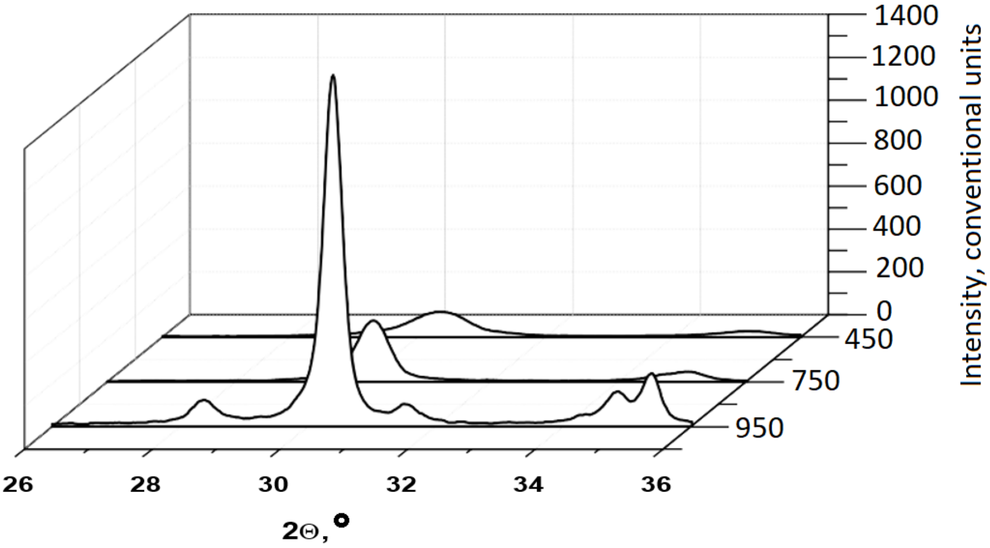

Figure 1. Fragments of diffractograms of Yb–TZP powders

Powders (Yb–TZP) obtained at a temperature of 950°C have a high dispersion, a specific surface area of at least 20 m^2/g, which corresponds to the size of individual particles of no more than 50 nm. This fact is illustrated in Figure 2, where an electronic snapshot of the powder is presented.

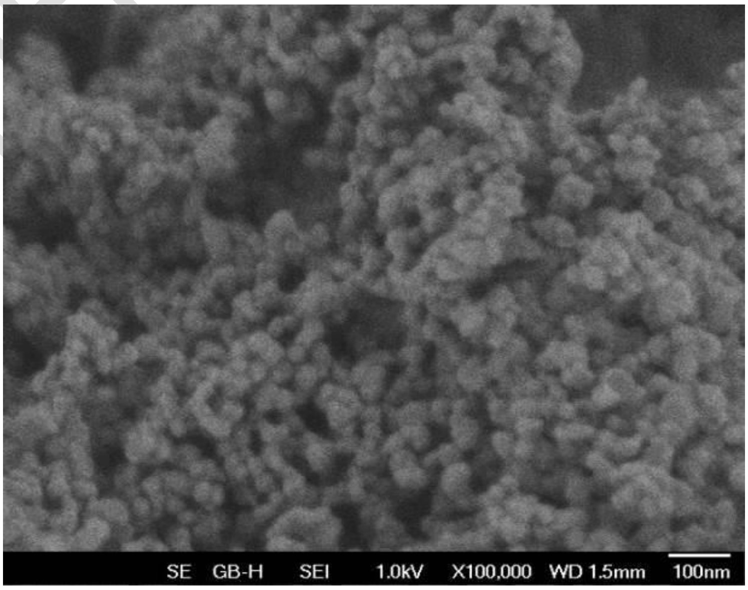

Figure 2. Electronic micrography of powder

The high dispersion of the powders led to the achievement of a dense state of ceramic samples after sintering. At the final sintering temperature of 1500°C, the relative density of Yb–TZP samples reaches 99% of the theoretical density. The microstructure of Yb–TZP ceramics is dominated by grains ranging in size from 300 to 500 nm, which is confirmed by the electronic image of the ceramic surface shown in Figure 3.

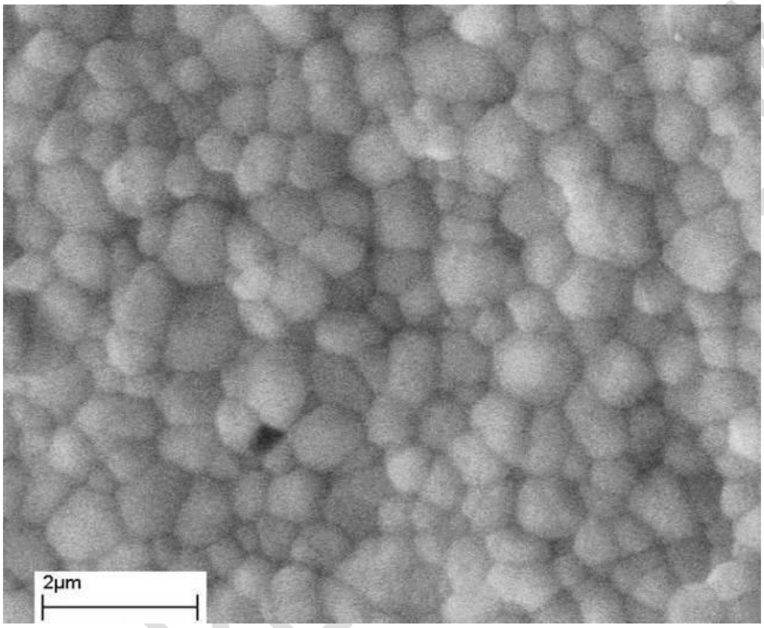

Figure 3. Microstructure of sintered ceramics Yb–TZP

The effect of hydrothermal treatment on the phase composition of Y–TZP and Yb–TZP ceramics was compared. It was found that two phases corresponding to solid solutions based on ZrO_2 tetragonal and monoclinic modifications are identified on the surface of the samples, as shown in Figure 4.

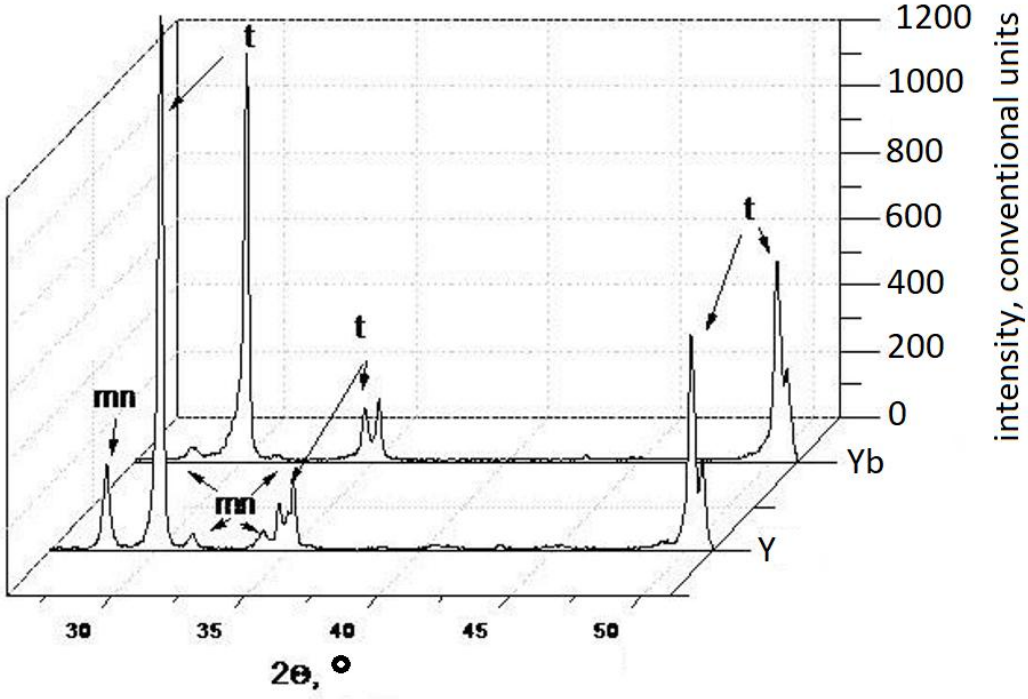

Figure 4. Fragments of diffractograms of the surface of Y–TZP and Yb–TZP samples after exposure to hydrothermal treatment

It can be stated that as a result of hydrothermal treatment, a greater amount of M–ZrO_2 phase is formed in the phase composition of Y–TZP ceramics in comparison with Yb–TZP ceramics. This fact indicates a greater stability of the developed ceramics.

The parameters of the strength characteristics of the developed Yb–PZT material before and after accelerated aging under the influence of hydrothermal treatment are presented in Table 1.

Table 1. Average values of mechanical characteristics of Yb – PZT ceramics

Parameters	Strength, MPa		Crack resistance, GPa		Resistance to degradation of mechanical properties, MPa·m ½	
	Original	Hydrothermal treatment	Original	Hydrothermal treatment	Original	Hydrothermal treatment
Values	900	900	9.0	9.2	12.0	12.0
∇	±50		±0,2		±0,4	

The developed material Yb–PZT complies with the requirements of the international standard ISO 13356-2008 for strength, crack resistance and resistance to degradation of mechanical properties in conditions of low-temperature aging.

The color characteristics of the samples of the previously developed ceramics Ce–TZP and Yb–TZP were determined, the results are presented in Table 2.

Table 2. Color characteristics of samples

№	Sample	A	B	L	∇E
1	The standard	0,012	0,086	100,046	0,00
2	Yb– TZP	-0,72	2,737	90,116	10,35
3	Ce–TZP	-1,029	14,175	84,695	20,98

It was revealed that the developed ceramics Yb–TZP in terms of color characteristics is more close to the standard than ceramics Ce–TZP, respectively ∇E =10 and 21 units.

Conclusion

A ceramic material based on nanopowders of a system of zirconium dioxide and ytterbium oxide with high strength parameters has been developed.

The positive effect on the stability of the phase composition and strength properties of TZP ceramics under conditions of accelerated low-temperature aging of the replacement of the Y^{+3} cation stabilizing the tetragonal form of zirconium dioxide with the Yb^{+} cation has been established.

The developed Yb–TZP ceramics are close to the standard in terms of color characteristics.

The results of the study allow us to recommend Yb–TZP ceramics as an alternative to Y–TZP ceramic materials for restorations in orthopedic dentistry. Preliminary economic calculation shows that the introduction of Yb-TZP ceramics is economically justified and will not be more expensive than using standard Y-TZP ceramic.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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