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ZIRCONIUM DIOXIDE AS A BIOMATERIAL; THE MICROSTRUCTURE

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Abstract

Zirconium dioxide is a material which, over the recent years, has been attracting support among dental technicians and dentists, thanks to its chemical composition and mechanical properties, it can replace non-anaesthetic foundations or metal crowns. Additionally zirconium dioxide is a material which is easy to work in. Zirconium dioxide is a polymorphic material demonstrating three phases: monocyclic, cubic and tetragonal. Additionally during the crack propagation the material shows the reinforcing transformation; the replacement of the phase and increasing the volume of the molecules, which inhibits the microcracks in the material. Thanks to such potential, zirconium dioxide has acquired a very high recognition in stomatology and orthodontics. Interestingly, the factor which has a considerable impact on the fatigue life and strength of zirconium dioxide is an adequate treatment and tool operation temperature; the slightest undesired effect can trigger the accumulation of stresses and thus decrease the material strength. A lower mechanical strength can be also due to other conditions, e.g. varied nutrition habits in the patient and the frequency of oral cavity hygiene practises.

Keywords: zirconium dioxide, microstructure, biomaterial, structure reinforcement

1. Introduction

Zirconium dioxide is a ceramic material the dentists have been getting convinced about since the 1990s. Porcelain as a supplement of tooth losses was improved in 1956 when it was baked over the metal core [19]. This technique provided an adequate strength, however, it was not so much aesthetic. Since then attempts have been made to enrich the chemical composition of porcelain to such extent that the tooth restoration is possible only by using porcelain without metal elements. In the early days of dental prosthodontics one could differentiate between the following materials helping the elimination of tooth losses: filedspathic porcelain, mica-reinforced ceramic, leucite-reinforced ceramic, lithium-disilicate ceramic, aluminium trioxide ceramic, zirconium-dioxide-reinforced ceramic [22,23]. It turns out that leucite, lithium-disilicate and aluminium ceramic shows very low strength while applying the multi-section structures. A search has been launched to find the ceramic material of high mechanical strength which would allow for producing dental arches, fixed dental restorations. Such material has been used for a long time already, however in other fields of human life it is zirconium [24,25]. Yet another advantage, despite a high mechanical strength, is an easy treatment also possible using CNC tools, thanks to which the application of zirconium as early as in the 1990s, it was possible to develop a technology which would facilitate the formation of restorations adjusted to the conditions in the patient's oral cavity [14].

2. Microstructure of zirconium dioxide

The most frequent zirconium porcelain used in workshops and dental surgeries is zirconium dioxide 96% ZrO_2 of which mixes with 4% Y_2O_3 [7,17]. The zirconium dioxide crystal grains themselves are 0.2 ÷ 1 μm in size [5,7,21]. Zirconium dioxide is a polymorphic material which can occur in three forms: monocyclic (commonly referred to as slanted), cubic and tetragonal. Depending on the temperature of the environment, the material occurs in one of the following forms: at room temperature it will occur in a monoclinic – monocyclic form. Heating the material to 1170°C, one can note a tetragonal phase and above 2370°C – the cubic one. From the perspective of biomechanics, it is the tetragonal phase which is the best form of the arrangement of the molecules [8,9,10]. Thanks to such additions as yttrium, magnesium and cerium, it is possible to reach that phase at room temperature. Adding 8% of magnesium oxide triggers changes in the volume of the phase during zirconium dioxide cooling. Adding 2 ÷ 3% stops the withdrawal of zirconium dioxide from the tetragonal phase to the cubic phase [6]. During the zirconium dioxide structure crack propagation it changes its phase from the tetragonal one into the monocyclic phase, which triggers the transformation of the molecules; hence the structure reinforcement. Such phenomenon can be referred to as the reinforcing transformation. During that process there is observed a 3 ÷ 5% increase in the volume of the zirconium dioxide molecules, thus decreasing the destruction energy and, in turn, decreasing the crack propagation (Fig. 1) [4,3,1]. The process decreases the dispersion of microcracks in the structure.

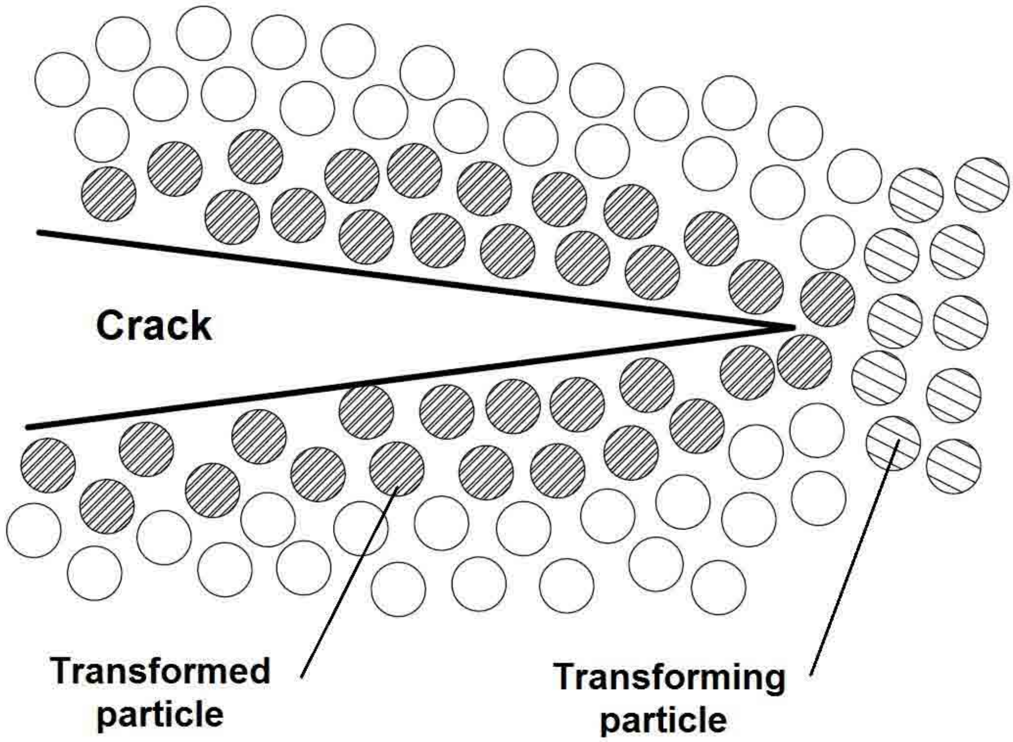

Fig. 1. Diagram of the crack propagation with a change in the phase from tetragonal to monocyclic [2].

Zirconium dioxide with supplementary ingredients, stabilizing the structure, has been highly recognized in such areas as dental braces; the grips correcting the tooth position in the oral cavity, endodontics as hinges, dowels supporting the tooth, single teeth and fixed dentures [11,12]. Analysing the strength, one must note that preparing the material itself, the zirconium dioxide, bonded with another supplementing element, plays a very big role. The dental labs preparing the surfaces use fine cutters the operation of which does not disturb the arrangement of the material structure molecules, namely an increase in strength. Operating coarse cutters triggers considerable defects in the material structure and thus high stresses. Similarly during operation one shall consider the effect of temperature which plays an essential role in the structural changes and even triggers reverse transformation [13,16].

3. Summary

Over the recent years one can note a growing interest in the material such as zirconium dioxide. Thanks to various chemical bonds, yttrium, magnesium and cerium, it is possible to adjust the microstructure to the required application in orthodontics or endodontics of the oral cavity. Zirconium demonstrates high mechanical strength and easy treatment. Thanks to special CNC devices and the CAD/CAM software, the dental technicians can make dental crowns and arch bridges. A special process of ceramic burning taking even up to 11 hours at the temperature of 1400°C and the accompanying contraction reaching 18 ÷ 25% point to a high material life [13, 15]. The only problem has been, so far, a low number of studies which would determine whether the material ages, under which conditions it ages and what affects that process. It can be due to other material work conditions in the oral cavity, various nutrition habits in the patient as well as the frequency of the oral cavity hygiene practises. An interesting phenomenon which occurs in the zirconium dioxide material during the crack propagation is its self-strengthening, the so called self-repair potential [20]. Material ions go through various phases and increase their volume even up to 5%, thanks to which the material microcrack propagation decreases. The strength is also affected by the material preparation process itself as well as its treatment. The application of the adequate tools; fine cutters which, while at work, do not trigger a considerable temperature increase, will not result in a change in the material phase and, as a result, high stress concentrations [25].

References

[1] Bitter K., Meyer-Luckel H., Priehn K., Martus P., Kielbassa A.M., *Bond strengths of resin cements to fiber – reinforced composite posts.* Am J Dent 19, pp.138–42, 2006.

[2] Butler E.P., *Transformation toughned zirconia ceramics.* Mat Sci Tech 1 pp.417 – 32,1985.

[3] Chevalier J., *What future for zirconia as a biomaterial?* Biomater., 27, pp. 539-546,2006.

[4] Conrad H. J., Seong W. J., Pesun I. J., *Current ceramic materials and systems with clinical recommendations: A systematic review.* J. Prosthet. Dent., 98,pp. 389-404, 2007.

[5] Della Bona A., Kelly J.R., *The clinical success of all-ceramic restorations.* J Am Dent Assoc 139, pp. 8–13, 2008.

[6] Denry I., Kelly J.R., *State of the art of zirconia for dental applications.* Dent Mater 24, pp. 299–307, 2008.

[7] Dejak B., Kacprzak M., Suliborski B., Śmielak B. *Struktura i niektóre właściwości ceramik dentystycznych stosowanych w uzupełnieniach pełnoceramicznych w świetle literatury.* Protet. Stomol., LVI 6, pp. 471-477, 2006.

[8] Garvie R. C., Hannink R. H., Pascoe R. T., *Ceramic steel?* Nature 258, pp. 703-704, 1975.

[9] Garvie R.C., Nicholson P.S., *Structure and thermodynamical properties of partially stabilized zirconia in the CaO – ZrO_2 system.* J Amer Ceram Soc 55, pp.152 -7, 1972..

[10] Gupta T.K., Bechtold J.H., Kuznickie R.C., Cado L.H., Rossing B.R., *Stabilization of tetragonal phase in polycrystalline zirconia.* J Mater Sci 13, pp.1464,1978.

[11] Kelly J. R., Denry I.: *Stabilized zirconia as a structural ceramic: An overview.* Dent. Mater., 24,pp. 289-298,2008.

[12] Lasek K., Okoński P., Mierzwińska – Nastalska E., *Tlenek cyrkonu – właściwości fizyczne i zastosowanie kliniczne.* Protet. Stomatol., LIX 6, pp. 415 – 422, 2009.

[13] Nakamura K., Kanno T., Milleding P., Ortengren U., *Zirconia as a dental implant abutment material: a systematic review.* Int J Prosthodont. 23,pp. 299-309, 2010.

[14] Rieth P.H., Reed J.S., Naumann A.W., *Fabrication and flexural strength of ultra-fine grained yttria-stabilised zirconia.* Bull Am Ceram Soc 55, pp. 717, 1976.
[15] Ruff O., Ebert F., Stephen E., *Contributions to the ceramics of highly refractory materials: Ii. System zirconia-lime.* Z Anorg Allg Chem 180, pp. 215–24.
[16] Subbarao E.C., *Zirconia – an overview. In: Heuer AH, Hobbs LW, editors. Advances in ceramics, vol. 3. Science and Technology of Zirconia*. Elsevier ,pp. 1 - 24 Amsterdam 1981.
[17] Sundh A., Molin M., Sjörgen G.*, Fracture resistance of yttrium oxide partially stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing.* Dent. Mater., 21,pp. 476-482,2005.
[18] Szczyrek P., *Historia zastosowania ceramiki w stomatologii.* Protet. Stomatol., LIII 2,pp. 112-114, 2003.
[19] Theunissen, Bouma J.S., Winnbust A.J.A., Burggraaf A.J.*, Mechanichal properties of ultra-Þne grained zirconia ceramics.* J Mater Sci 27, pp.:4429 – 38,1992.
[20] Trzebiatowski W.: *Chemia nieorganiczna*, Wyd. PWN, Warszawa 1969,
[21] Sahafi A., Peutzfeldt A., Asmussen E., Gotfredsen K., *Bond strength of resin cement to dentin and to surface-treated posts of titanium alloy, glass fiber, and zirconia.* J Adhes Dent 5,pp.153–62, 2003.
[22] Sahafi A., Peutzfeldt A., Asmussen E., Gotfredsen K., *Retention and failure morphology of prefabricated posts.* Int J Prosthodont;17, pp. 307–12, 2004.
[23] Sahafi A., Peutzfeldt A., Asmussen E., Gotfredsen K., *Effect of surface treatment of prefabricated posts on bonding of resin cement.* Oper Dent 29, pp.60–8, 2004.
[24] Perdigao J., Geraldeli S., Lee I.K., *Push-out strengths of tooth-colored posts bonded with different adhesive systems.* Am J Dent;17, pp. 422–6, 2004.
[25] Xible A.A., De Jesus Tavarez R., de Arauho C.R.P., Bonachela W.C., *Effect of silica coating and silanization on flexural and composite-resin bond strengths of zirconia posts: an in vitro study.* J Prosthet Dent 95, pp. 224–9, 2006.