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APPLICABILITY ASSESSMENT OF THE VICKERS INDENTATION FOR DETERMINING THE FRACTURE TOUGHNESS OF YTTRIA-STABILIZED ZIRCONIA

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Abstract. Crack growth resistance of ZrO_2-(3-8) mol% Y_2O_3 ceramics was investigated. Young's modulus by the ultrasonic flaw detection method were determined. Vickers hardness and parameters of cracks after Vickers indentation were obtained. Based on the Young's modulus values, Vickers hardness, and parameters of cracks, the fracture toughness of the investigated ceramics was calculated using 9 different equations of the Vickers indentation method.

A comparative analysis of the calculated fracture toughness values with those obtained by the single-edge notch beam method was carried out. It was found that choosing the optimal equation for calculating fracture toughness by the Vickers indentation method is quite difficult and requires comparison with the results of standardized tests. It was shown that to determine crack resistance characteristics of the yttria-stabilized zirconia ceramics, the use of only the Vickers indentation method without comparison with other methods of fracture mechanics is incorrect.

Keywords: YSZ ceramics, Vickers indentation, fracture toughness, Young's modulus, sintering temperature.

Introduction and problem statement

The yttria-stabilized zirconia ceramics (YSZ ceramics) are materials for the manufacture of dental crowns, implants, prostheses, and artificial endoprostheses of bone tissue [1–3]. Not only biomedicine but also mechanical engineering, metallurgy, electronics, energy, and chemical industry are the fields of use of these ceramics [4–7]. YSZ ceramics are widely used in the manufacture of equipment for high-pressure vessels, balls for ball mills, rollers and guides for metal pressure processing, guides for drawing wire, molds for metal extrusion, valves for deep wells, dies for pressing powders, seals bearings, oxygen sensors, resistors of high-temperature induction furnaces, membranes of fuel cells. The reason for their widespread application is low thermal conductivity, high strength, wear resistance, high fracture toughness, high corrosion resistance, biological inertness, and high biocompatibility. The flexural strength of the ceramics is in the range of 900–1200 MPa, their compressive strength is about 2000 MPa and fracture toughness is in a range of 5–10 MPa $m^{1/2}$ [8–10].

The microstructure of the ZrO_2 ceramic is monoclinic at room temperature and up to a temperature of 1127 °C. At high temperatures from 1127 to 2370 °C, the microstructure of this ceramic is tetragonal [8]. Due to the destructive tetragonal-monoclinic martensitic phase transformation, which is accompanied by a volume expansion of ~3–5 %, pure zirconium dioxide is rarely used [11, 12]. Doping zirconia ceramics with yttria allows the complete stabilization of the tetragonal structure at room temperature [2]. The presence of the tetragonal phase in the structure of YSZ ceramics is a significant factor that determines its high fracture toughness [11]. This fracture toughness is caused by the transformation toughening mechanism [13] as a result of the tetragonal-monoclinic phase transformation that occurs in the stress field caused by the propagation of cracks in ceramics. The phase transformation, which occurs in the crack tip vicinity, stops the propagation of the cracks and thus ensures a high fracture toughness of the material [13, 14]. Zirconia ceramics with a content of 2-3 mol.% Y_2O_3 shows the highest tendency to transformation toughening [3].

The strength and wear resistance of the materials from which the products are made are traditionally the main characteristics by which durability is evaluated. However, another key requirement for products made of ceramic materials is high fracture toughness, which characterizes the resistance to the propagation of cracks in the material and largely determines the product resources [8, 15].

There are many experimental methods for determining the fracture toughness of ceramic materials [15–20], particularly chevron-notched beam (CNB), single-edge notch beam (SENB), single-edge V-notched beam (SEVNB), and single-edge pre-cracked beam (SEPB) methods. The SENB method is based on three- or four-point bending of a beam sample with a single-edge U-shaped notch. The SEPB method is based on three- or four-point bending of a beam sample with a pre-crack on one side. The SEVNB method is based on three- or four-point bending of a beam sample with a single-edge sharp V-notch. The CNB method is based on the bending/wedging of a beam/short bar/short rod sample with a chevron notch.

The above-mentioned traditional methods for determining fracture toughness are time- and resource-consuming techniques and also require specially made samples and equipment. Therefore, the Vickers indentation method is of great interest for determining the fracture toughness of ceramics due to the relative simplicity and faster sample preparation and testing compared to traditional methods [8, 15]. The Vickers indentation method is widely used to determine the fracture toughness of ceramic materials, biomaterials, solid biological tissues, etc. [21], but it is not standardized [17].

A disadvantage of the Vickers indentation method is its ambiguity because there is no single equation for determining the indentation fracture toughness of ceramics. An analysis of literary sources showed that many equations were discovered, each of which was proposed by different authors [22–31]. The aim of this work was to determine the fracture toughness of ZrO_2-(3–8 mol.%) Y_2O_3 ceramics by the Vickers indentation method and compare the obtained values with those obtained by the traditional single-edge notch beam method using a three-point bending scheme.

Samples, techniques, and equipment

Zirconia ceramics stabilized with 3-8 mol.% Y_2O_3 obtained under different sintering modes were investigated (Table 1) [32, 33]. In total, 17 variants of ceramics were investigated.

The Vickers hardness of the investigated materials was measured using a NOVOTEST TC-MKB1 microhardness tester under an indentation load of 9.81 N. To calculate the fracture toughness by the Vickers indentation method, the Vickers hardness of each material variant (Table 1) was determined in accordance with the ASTM C 1327 standard by performing 3 indentations. The fracture toughness (critical stress intensity factor) was calculated using nine equations based on the analysis of crack lengths formed by the Vickers indenter during indentation (Fig. 1). Crack lengths were measured using an optical microscope MICROTECH MMT-14C at magnifications of 400 times.

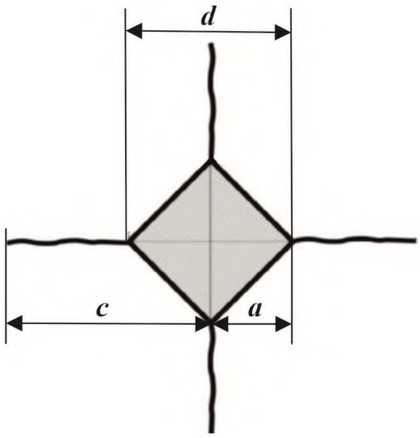
The input data in the equations, such as the indentation load *P*, the average length of the diagonal of the indenter imprint *d*, the length of the radial crack *c*, the Vickers hardness *H*, and Young's modulus *E* were obtained experimentally.

The equations that were used to calculate fracture toughness by the Vickers indentation method are listed in Table 2.

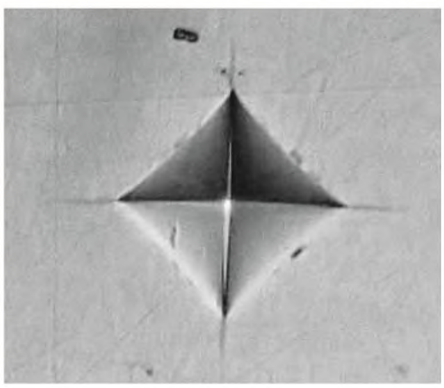
Table 1

Chemical composition and sintering modes of zirconia ceramics stabilized with 3–8 mol.% Y_2O_3

Variant	Y_2O_3 content, mol.%	Sintering mode	
		Sintering temperature, °C	Dwell time, h.
3YSZ–1450	3	1450	2
3YSZ–1500	3	1500	2
3YSZ–1550	3	1550	2
4YSZ–1450	4	1450	2
4YSZ–1500	4	1500	2
4YSZ–1550	4	1550	2
5YSZ–1450	5	1450	2
5YSZ–1500	5	1500	2
5YSZ–1550	5	1550	2
6YSZ–1450	6	1450	2
6YSZ–1500	6	1500	2
6YSZ–1550	6	1550	2
6YSZ–1600	6	1600	2
7YSZ–1550	7	1550	2
7YSZ–1600	7	1600	2
8YSZ–1550	8	1550	2
8YSZ–1600	8	1600	2



a



b

Fig. 1. Images of the imprint and radial crack formed by the Vickers indenter during indentation: (a) schematic image; (b) print image.
Here *d* is a length of the imprint diagonal; *a* is a length of the imprint half diagonal; *c* is a radial crack length

Table 2

Equations for estimating the fracture toughness of brittle ceramic materials, according to references, and corresponding parameters for calculations

Reference No.	Units for corresponding parameter in equations				Equations for estimating the fracture toughness of brittle ceramic materials	Units	Eq. No.
	Vickers hardness *H*	Young's modulus *E*	Radial crack length *c*	Length of the imprint half diagonal *a*			
Lawn, Swain [22]	kgf/mm^2	–	mm	–	$K_{Ic} = 0.0177\left(\frac{HP}{c}\right)^{1/2}$	MPa m$^{1/2}$	(1)
Lawn, Fuller [23]	–	–	m	–	$K_{Ic} = 0.0726\left(\frac{P}{c^{3/2}}\right)$	Pa·m$^{1/2}$	(2)
Evans, Charles [24]	–	–	m	–	$K_{Ic} = 0.0752\left(\frac{P}{c^{3/2}}\right)$	Pa·m$^{1/2}$	(3)
Tanaka [25]	–	–	m	–	$K_{Ic} = 0.0725\left(\frac{P}{c^{3/2}}\right)$	Pa·m$^{1/2}$	(4)
Niihara, Morena [27]	–	GPa	mm	mm	$K_{Ic} = \frac{0.0424(PE/a)^{0.5}}{(c/a)^{1.57}}$	MPa·m$^{1/2}$	(5)
Anstis, Chantikul [28]	GPa	GPa	m	–	$K_{Ic} = 0.016\left(\frac{E}{H}\right)^{1/2}\left(\frac{P}{c^{3/2}}\right)$	Pa·m$^{1/2}$	(6)
Lawn, Evans [29]	GPa	GPa	m	–	$K_{Ic} = 0.014\left(\frac{E}{H}\right)^{1/2}\left(\frac{P}{c^{3/2}}\right)$	Pa·m$^{1/2}$	(7)
Blendell [30]	MPa	MPa	m	m	$K_{Ic} = 0.0285H^{0.6}E^{0.4}a^{0.5}\ln\left(\frac{8.4a}{c}\right)$	MPa·m$^{1/2}$	(8)
Lankford [31]	MPa	MPa	m	m	$K_{Ic} = 0.0735H^{0.6}E^{0.4}a^{0.5}\left(\frac{c}{a}\right)^{-0.56}$	MPa·m$^{1/2}$	(9)

Note. The indentation load *P* for Eqs. (2)–(9) is given in N and for Eq. (1) in kg.

Young's modulus values of zirconia ceramics stabilized with 3–8 mol.% Y_2O_3 were determined by the ultrasonic wave transition method using an ultrasonic flaw detector (Panametrics Epoch III) to measure the velocities of ultrasonic waves passing through the material [34]. The velocities of the transverse and longitudinal waves were determined as the ratio of the sample thickness to the corresponding transition time. Based on the experimentally obtained velocities of propagation of longitudinal and transverse ultrasonic waves in the sample, as well as the density of the samples (by the pycnometer method), the Young's modulus was calculated according to the Eq. (10):

$$E = \rho C_T^2 \frac{3C_L^2 - 4C_T^2}{C_L^2 - C_T^2}, \quad (10)$$

where C_L is the velosity of longitudinal ultrasonic wave propagation, km/s; C_T is the velosity of transverse ultrasonic wave propagation, km/s; ρ is the density, g/cm^3; *E* is the Young's modulus, GPa.

Results and discussion

The parameters measured for calculation of the Vickers hardness, in particular, the parameter of the cracks formed as a result of Vickers indentation of a sample, as well as the experimentally determined Young's modulus values are shown in Table 3.

Table 3

Mechanical properties and parameters of imprints and lengths of cracks formed by the Vickers indenter during indentation

Variant	The average length of the diagonals of the indenter imprint *d*, μm	Radial crack length *c*, μm	Vickers hardness *HV1*, GPa	Young's modulus, *E*, GPa
1	2	3	4	5
3YSZ–1450	44.75	23.00	9.08	195
	44.00	23.25	9.40	
	42.63	21.38	10.01	
3YSZ–1500	41.38	20.75	10.63	196
	42.50	21.25	10.07	
	40.50	20.50	11.09	
3YSZ–1550	39.00	20.25	11.96	197
	40.38	20.75	11.16	
	41.25	20.75	10.69	
4YSZ–1450	43.25	21.75	9.73	195
	40.63	21.13	11.02	
	39.63	19.88	11.59	
4YSZ–1500	40.00	20.88	11.37	196
	39.00	19.75	11.96	
	40.00	20.75	11.37	
4YSZ–1550	40.88	20.63	10.89	199
	41.25	21.00	10.69	
	40.88	20.63	10.89	
5YSZ–1450	38.00	19.63	12.60	201
	38.50	19.88	12.27	
	37.50	19.00	12.94	
5YSZ–1500	40.63	20.38	11.02	200
	38.25	20.00	12.43	
	40.88	20.88	10.89	
5YSZ–1550	38.38	19.63	12.35	203
	38.63	19.63	12.19	
	38.00	19.88	12.60	
6YSZ–1450	39.63	20.63	11.59	207
	38.88	20.25	12.04	
	39.88	20.38	11.44	
6YSZ–1500	39.38	20.13	11.73	203
	38.75	19.38	12.12	
	40.88	20.88	10.89	

Continuation of Table 3

1	2	3	4	5
6YSZ–1550	37.75	19.13	12.77	207
	40.13	20.38	11.30	
	39.38	20.00	11.73	
6YSZ–1600	39.50	20.75	11.66	209
	37.63	18.88	12.85	
	40.13	21.88	11.30	
7YSZ–1550	43.38	21.75	9.67	183
	44.00	22.00	9.40	
	43.25	21.63	9.73	
7YSZ–1600	41.25	21.13	10.69	193
	40.00	20.13	11.37	
	39.25	19.88	11.81	
8YSZ–1550	40.38	20.63	11.16	195
	41.00	20.75	10.82	
	43.13	22.00	9.78	
8YSZ–1600	40.00	20.63	11.37	210
	38.75	19.63	12.12	
	39.75	20.00	11.51	

Note. Average values of Young's modulus are given.

A comparative analysis of fracture toughness by the Vickers indentation method using the above-mentioned Eqs. (1)–(9) (Table 2) with the fracture toughness by the single-edge notch beam (SENB) method [32,33] for all variants of YSZ ceramics was carried out.

It should be noted that the invariant values according to Eq. (1) were obtained by the authors of the work [22] only for a narrow range of ceramic materials (namely, for SiC). Eqs. (1) – (4) do not take into account Young's modulus, and Eqs. (2)–(4) in addition to Young's modulus also do not take into account the Vickers hardness of the investigated ceramics. When calculating fracture toughness according to Eqs. (6)–(9), it should be noted that they contain Young's modulus and Vickers hardness, which are not present in Eqs. (1)–(4). The difference between Eq. (6) and Eq. (7) is observed only in experimentally determined coefficients [28, 29]. Therefore, the advantages or disadvantages of each of these coefficients can only be proven experimentally. The use of Eq. (8) and Eq. (9) can be limited because they contain power functions that must be determined experimentally.

Therefore, to assess the applicability of the equations given in the Table 2, it is necessary to compare the fracture toughness values calculated according to the equations and estimated by the SENB method (Table 4).

The level of the equation optimality was determined on the assumption that it is correct to use the equation if a difference between calculated values and those determined by the SENB method is less than 10 % [15].

Analyzing fracture toughness values obtained for 3YSZ–1450 ceramic it was found (Fig. 2), (Table 5) that Eq. (7) shows the best match of fracture toughness values with those estimated by the traditional method of fracture mechanics. The values obtained by Eq. (7) differ by only 4% from the values obtained by the SENB method. The values obtained by Eqs. (6), (2) and (4) differ by 19%. The values obtained by other equations differ by more than 23 %.

Table 4

Fracture toughness determined by the Vickers indentation and SENB methods

Variant	Fracture toughness K_{Ic} calculated by the Eqs. (1) – (9), MPa·$m^{1/2}$									Fracture toughness K_{Ic} determined by the SENB method [32,33], MPa·$m^{1/2}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
3YSZ–1450	3.67	6.67	6.91	6.66	11.99	6.66	5.83	8.90	10.76	5.60
3YSZ–1500	4.03	7.49	7.76	7.48	12.81	7.10	6.22	9.37	11.35	5.97
3YSZ–1550	4.18	7.63	7.90	7.62	12.67	7.03	6.15	9.51	11.50	7.56
4YSZ–1450	4.06	7.46	7.73	7.45	12.61	7.00	6.12	9.36	11.32	5.54
4YSZ–1500	4.25	7.71	7.98	7.69	12.58	6.99	6.12	9.55	11.54	6.68
4YSZ–1550	4.08	7.54	7.81	7.53	12.84	7.12	6.23	9.47	11.46	6.41
5YSZ–1450	4.54	8.28	8.57	8.27	13.12	7.28	6.37	9.96	12.05	10.59
5YSZ–1500	4.23	7.72	8.00	7.71	12.83	7.12	6.23	9.62	11.64	9.31
5YSZ–1550	4.48	8.14	8.43	8.13	13.08	7.27	6.36	9.93	12.01	10.55
6YSZ–1450	4.28	7.72	8.00	7.71	12.89	7.16	6.27	9.78	11.81	4.95
6YSZ–1500	4.29	7.90	8.18	7.89	13.14	7.29	6.38	9.76	11.81	6.20
6YSZ–1550	4.39	8.07	8.36	8.06	13.36	7.41	6.48	9.94	12.03	5.96
6YSZ–1600	4.32	7.73	8.00	7.71	12.80	7.12	6.22	9.83	11.87	5.50
7YSZ–1550	3.75	7.00	7.25	6.99	12.16	6.74	5.89	8.83	10.69	6.70
7YSZ–1600	4.21	7.76	8.03	7.75	12.73	7.06	6.18	9.48	11.48	6.78
8YSZ–1550	4.00	7.34	7.61	7.33	12.52	6.95	6.08	9.29	11.24	4.62
8YSZ–1600	4.31	7.92	8.21	7.91	13.35	7.40	6.48	9.91	11.99	5.29

Note. Average fracture toughness values are given.

Table 5

The ratio of the fracture toughness determined by the Vickers indentation and SENB methods

Variant	The ratio of K_{Ic} values calculated by Eqs. (1) – (9) and by the SENB method								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
3YSZ–1450	0.66	1.19	1.23	1.19	2.14	1.19	1.04	1.59	1.92
3YSZ–1500	0.68	1.26	1.30	1.25	2.15	1.19	1.04	1.57	1.90
3YSZ–1550	0.55	1.01	1.05	1.01	1.68	0.93	0.81	1.26	1.52
4YSZ–1450	0.73	1.35	1.40	1.35	2.28	1.26	1.11	1.69	2.04
4YSZ–1500	0.64	1.15	1.20	1.15	1.88	1.05	0.92	1.43	1.73
4YSZ–1550	0.64	1.18	1.22	1.18	2.00	1.11	0.97	1.48	1.79
5YSZ–1450	0.43	0.78	0.81	0.78	1.24	0.69	0.60	0.94	1.14
5YSZ–1500	0.45	0.83	0.86	0.83	1.38	0.77	0.67	1.03	1.25
5YSZ–1550	0.43	0.77	0.80	0.77	1.24	0.69	0.60	0.94	1.14
6YSZ–1450	0.87	1.56	1.62	1.56	2.60	1.45	1.27	1.98	2.39
6YSZ–1500	0.69	1.27	1.32	1.27	2.12	1.18	1.03	1.57	1.91
6YSZ–1550	0.74	1.35	1.40	1.35	2.24	1.24	1.09	1.67	2.02
6YSZ–1600	0.79	1.41	1.46	1.40	2.33	1.30	1.13	1.79	2.16
7YSZ–1550	0.56	1.05	1.08	1.04	1.82	1.01	0.88	1.32	1.60
7YSZ–1600	0.62	1.15	1.18	1.14	1.88	1.04	0.91	1.40	1.69
8YSZ–1550	0.87	1.59	1.65	1.59	2.71	1.50	1.32	2.01	2.43
8YSZ–1600	0.82	1.50	1.55	1.50	2.52	1.40	1.23	1.87	2.27

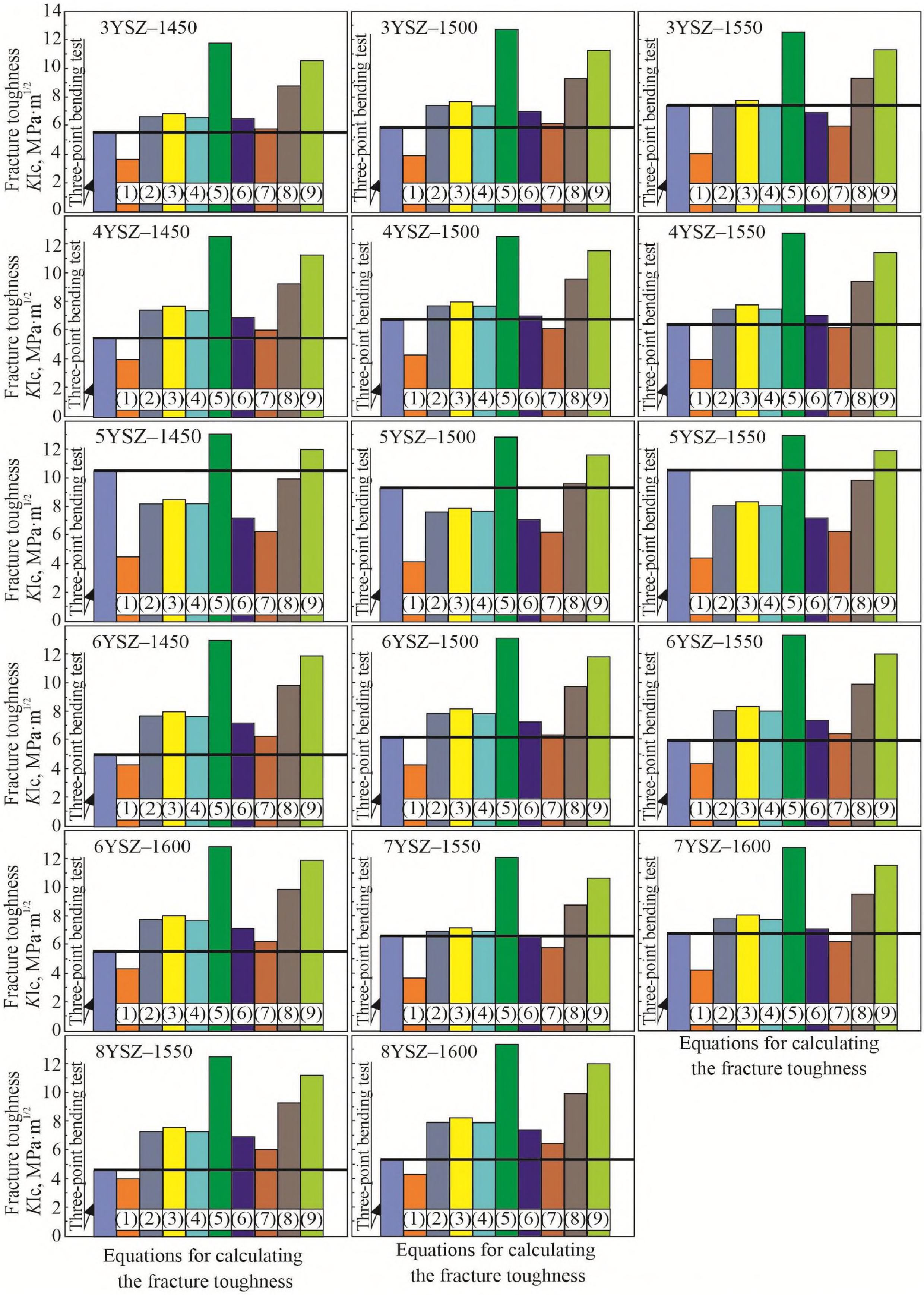


Fig. 2. Comparison of fracture toughness determined by the Vickers indentation (calculated by Eqs. (1)–(9)) and SENB methods

For 3YSZ ceramic sintered at a temperature of 1500 °C, it was found that Eq. (7) shows the best match of fracture toughness values with those estimated by the traditional method of fracture mechanics. The values obtained by Eq. (7) differ by only 4% from the values obtained by the SENB method. The values obtained by Eq. (6) differ by 19 % (Fig. 2), (Table 5). The values obtained by Eqs. (1)–(5) and (8), (9) differ by more than 25 %.

For 3YSZ–1550 ceramic it was revealed that Eqs. (2) and (4) show the best agreement of fracture toughness values with those determined by the SENB method. The values obtained by Eqs. (2) and (4) differ by less than 1 % from the values obtained by the traditional method. The values obtained by Eq. (3) differ by 5 %, and those obtained by Eq. (6) differ by 7 %. The fracture toughness values obtained by all other equations differ by more than 19 %.

For 4YSZ ceramic sintered at a temperature of 1450 °C, it was found that Eq. (7) shows the best match of fracture toughness and differs only by 11 % from the value obtained by the SENB method. The values obtained by Eqs. (1)–(4), Eq. (6), and (8) differ by 26–69 %, and by Eqs. (5) and (9) by more than 2 times (Fig. 2), (Table 5).

For 4YSZ–1500 ceramic, it was found that Eq. (6) shows the best match of fracture toughness and differs by only 5 % from the value obtained by the SENB method, while Eq. (7) differs by 8 %. The values obtained by all other equations differ by more than 15 %.

For 4YSZ ceramic sintered at a temperature of 1550 °C, it was revealed that Eq. (7) shows the best match of fracture toughness and differs only by 3 % from the value obtained by the SENB method, and by Eq. (6) by 11 %. The values obtained by all other equations differ by more than 18 %.

For 5YSZ–1450 ceramic it was found that Eq. (8) shows the best match of fracture toughness and differs only by 6% from the value obtained by the traditional method, and by Eq. (9) by 14 %. The values obtained by all other equations differ by more than 19 %.

For 5YSZ–1500 ceramic it was revealed that Eq. (8) shows the best match of fracture toughness and differs only by 3 % from the value obtained by the traditional method. The values obtained by all other equations differ by more than 14 %.

Analyzing the values of fracture toughness obtained for 5YSZ–1550 it was found that Eq. (8) shows the best match of fracture toughness and differs only by 6 % from the value obtained by the SENB method, and obtained by Eq. (9) differs by 14 %. The values obtained by all other equations differ by more than 20 %.

For 6YSZ ceramic sintered at a temperature of 1450 °C, it was revealed that Eq. (1) provides the best agreement with the results of fracture toughness determined by the traditional method of fracture mechanics (Fig. 2), (Table 5). The difference between the fracture toughness values obtained by Eq. (1) and the the values obtained by the SENB method is 13 %. Eqs. (6) and (7) give values that are overestimated by 45 % and 27 %, respectively.

Analyzing the values of fracture toughness obtained for 6YSZ–1500 it was found that Eq. (7) provides the best agreement with the results of fracture toughness determined by the traditional method (Fig. 2), (Table 5). The difference between the values obtained by Eq. (7) and the results of determining fracture toughness by the SENB method is 3%. Eq. (6) gives values that are overestimated by 18 %. The calculation according to other equations differs by 1.27-2.12 times from those obtained by the traditional method. For 6YSZ–1500 there is generally a better agreement between the calculated fracture toughness values compared to 6YSZ–1450 ceramic.

For 6YSZ ceramic sintered at a temperature of 1550 °C, it was revealed that Eq. (7) provides the best agreement with the results of fracture toughness determined by the traditional method of fracture mechanics (Fig. 2), (Table 5). The difference between the values obtained by Eq. (7) and the results of determining fracture toughness by the SENB method is 9 %. Eq. (6) gives values that are overestimated by 24 %.

For 6YSZ–1600 ceramic it was found that Eq. (7) provides the best agreement with the results of fracture toughness determined by the SENB method (Fig. 2), (Table 5). The difference between the values obtained by Eq. (7) and the results of determining fracture toughness by the traditional method is 13 %. Eqs. (1) and (6) give values that differ by 21 % and 30 %, respectively. The calculation according to other equations differs by 1.35–2.24 times from those obtained by the SENB method.

Analyzing the values of fracture toughness obtained for 7YSZ–1550 it was revealed that Eq. (6) provides the best agreement with the results of fracture toughness determined by the traditional method (Fig. 2), (Table 5). The difference between the values obtained by Eq. (6) and the results by the traditional method is less than 1 %. Eqs. (2), (3), and (4) give values that differ by 5 %, 8 %, and 4 %, respectively. The values obtained by all other equations differ by more than 12 %.

For 7YSZ ceramic sintered at a temperature of 1600 °C, it was found that Eq. (6) provides the best agreement with the results of fracture toughness determined by the SENB method (Fig. 2), (Table 5). The difference between the values obtained by Eq. (6) and the results by the traditional method is 4 %. Eq. (7) gives values that differ by 9 %. The values obtained by all other equations differ by more than 14 %.

Analyzing the fracture toughness values obtained for 8YSZ–1550 it was revealed that Eq. (1) provides the best agreement with the results of fracture toughness determined by the SENB method. The difference between the values obtained by Eq. (1) and the results by the traditional method is 13%. Eqs. (6) and (7) give values that differ by 50 % and 32 %, respectively.

Analyzing the values of fracture toughness obtained for 8YSZ–1600 it was found that Eq. (1) provides the best agreement with the results of fracture toughness determined by the traditional method (Fig. 2), (Table 5). The difference between the values obtained by Eq. (1) and the results of determining fracture toughness by the SENB method is 18 %. Eqs. (7) and (6) give values that differ by 23 % and 40%, respectively.

In summary, it can be stated that, in general, the best results are shown by Eqs. (6) and (7), which take into account the Young's modulus and Vickers hardness and differ only by experimentally determined coefficients. However, there are exceptions, in particular, for YSZ ceramics with high fracture toughness (over 9.3 $MPa \cdot m^{1/2}$). The values obtained when calculating according to Eqs. (9) and (10) are the closest to the values obtained by the SENB method. Eqs. (6) and (7) are not correct to use for yttria-stabilized zirconia ceramics with low fracture toughness (4.62–5.29 $MPa \cdot m^{1/2}$). For these ceramics, Eq. (1) showed the best agreement with data obtained by the traditional method.

Conclusions

Different crack morphology, features of crack nucleation and propagation, and errors in determining the length of a radial crack make it difficult to calculate fracture toughness of YSZ ceramics using the Vickers indentation method.

Choosing the optimal equation is quite difficult and requires comparison with the results of standardized tests.

Fracture toughness values obtained only by the Vickers indentation method can be used for ranking materials and for comparison with results obtained by standardized methods. To estimate the crack growth resistance characteristics of YSZ ceramics, using only the Vickers indentation method is incorrect.

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