

THE RELATIONSHIP BETWEEN CRYSTALLINE STRUCTURE, MICROSTRUCTURE AND THE MECHANICAL PROPERTIES OF ALUMINA ZIRCONIA COMPOSITE CERAMICS

Aurawan Rittidech^{1,*} and Aekasit Suthapintu²

Received: July 09, 2024; Revised: October 27, 2024; Accepted: November 23, 2024

Abstract

This research studied the relationship between crystalline structure, microstructure and the mechanical properties of composite ceramics between Al_2O_3 and ZrO_2 with 60:40 ratio. Al_2O_3 was doped MgO 6.0 mol% to form AM and ZrO_2 was doped Y_2O_3 , 4.0 mol% to form ZY. Composite ceramics was prepared under two-step sintering method with five different sintering temperature conditions. The x-ray diffraction patterns revealed a phase compositions between Al_2O_3 and ZrO_2 . Rietveld method was used to identify the quantitative phase analysis and obtained a high ratio of $t\text{-ZrO}_2$, $c\text{-ZrO}_2$ phases from the two stage sintering condition with T_1 temperature at 1650°C for 60 min and T_2 temperature at 1550°C for 5 h, and T_1 temperature at 1650°C for 60 min and T_2 temperature at 1500°C for 10 h. The bulk densities values tended to slightly increase with the lower T_2 temperature for the length of holding times. SEM micrographs revealed grain shape and size of grains. The grains were spherical in shape combined with irregular shape. The average grain size of AM as $0.951\text{--}1.205\text{ }\mu\text{m}$ and ZY was $0.739\text{--}0.894\text{ }\mu\text{m}$; the average grain size tended to increase with high T_2 temperature for the length of holding time. EDX identified large grains corresponding to the Al_2O_3 phase and small round oval shapes corresponding with the ZrO_2 phase. Good mechanical properties are found in the samples with sintering conditions temperatures of T_1 temperature at 1650°C for 60 min and T_2 temperature at 1550°C for 5 h; this resulted were given the highest of fracture toughness value of about $0.38\text{ GPa}\cdot\text{m}^{1/2}$. The optimal two stage sintering conditions were obtained from a high ratio of $t\text{-ZrO}_2$ and $c\text{-ZrO}_2$ phases with high bulk densities.

Keywords: Al_2O_3 ; ZrO_2 ; Composite; Ceramics; Two stage sintering

¹ Department of Physics, Faculty of Science Maharakham University, Maharakham, 44150, Thailand. E-mail: aurawan.r@msu.ac.th

² Faculty of science and technology, Rajabhat Maharakham University, Maharakham, 44000, Thailand. E-mail: a.sutthapintu@gmail.com

* Corresponding author

Introduction

Al_2O_3 ceramics have been widely used for structural, electrical and optical application (Roa *et al.*, 2003). To improve its toughness properties of alumina ceramics by adding a second phase is to inhibit the growth of grains (Wang *et al.*, 2000; Samadi *et al.*, 2020). The fracture toughness of Al_2O_3 ceramics has been improved by adding ZrO_2 as the second phase and sintering to form intergranular or intragranular structure. Zirconia is a polymorphic metastable material that exists in three crystallographic phases: monoclinic phase (up to 1170°C), tetragonal phase (1170 - 2370°C), and cubic phase (2370 - 2680°C) (Behbahani *et al.*, 2012). The best mechanical properties of zirconia ceramics is obtained by the tetragonal form fraction at room temperature and provides toughening mechanisms associated with the phase transformation from t- ZrO_2 to m- ZrO_2 under stress (Azhar *et al.*, 2010; Marais *et al.*, 2022). Therefore yttria (Y_2O_3) is used in doping to stabilize the cubic and the tetragonal zirconia crystal systems at room temperature. Rittidech *et al.* (2021) have reported ZrO_2 ceramics with 4 mol% Y_2O_3 addition to support optimal the mechanical properties of zirconia ceramics. Alumina-zirconia composite is a common second-phase toughened ceramic material. As an important engineering material, it is widely used in structural ceramics applications because of its unique mechanical and chemical properties (Calambas Pugalín and Albuno, 2014; Cui *et al.*, 2023). In the preparation of quality ceramics composite, the powder size of substrate is an important factor. This will affect the sintering process. In previous research (Hu *et al.*, 2016) that has reported on the quality composite powder can be used to create carrying out composite ceramics. Moreover, it was also found that the addition of MgO in alumina also reduced sintering temperature and reduced grain growth (Rittidech *et al.*, 2006). The alumina-zirconia system is interesting to study (Hong *et al.*, 1998; Rao *et al.*, 2004). The ceramic composite between AM and ZY at a ratio of 60:40 was therefore selected for investigation due to its good properties and reduced production costs. The process of heat treatment is important in preparation of ceramics. The characteristics of microstructure of Al_2O_3 - ZrO_2 composite ceramics are therefore subject to two important factors : oxide additives and the heating process in using novel sintering techniques. Two-stage sintering process is one of the ways of eliminating grain growth in the final stage of sintering reported by Chen and Wang (2000). Two stage sintering methodologies require heat treatment at the first stage of a high sintering

temperature for short holding times, subsequently the second stage at lower sintering temperature for a length holding times. The first-stage high temperature sintering step helps eliminate supercritical pores while the second-stage low temperature sintering step suppresses grain growth (Chen *et al.*, 2000). However, different Al_2O_3 and ZrO_2 contents of composite ceramics will be suitable for two stage sintering using different conditions. The 0.6AM-0.4ZY composite ceramics sample were investigated to find optimal two stage sintering conditions, which are revealed producing appropriate composite ceramics.

In this study, composite ceramics between Al_2O_3 using addition of 6 mol% MgO and ZrO_2 addition of 4 mol% Y_2O_3 with 60:40 ratio under five different firing conditions (TS-1) T_1 temperature at 1650°C for 60 min and T_2 temperature at 1550°C for 5 h (TS-2) T_1 temperature at 1650°C for 60 min and T_2 temperature at 1500°C for 10 h, (TS-3) T_1 temperature at 1650°C for 60 min and T_2 temperature at 1500°C for 5 h, (TS-4) T_1 temperature at 1600°C for 60 min and T_2 temperature at 1500°C for 10 h, and (TS-5) T_1 temperature at 1600°C for 60 min and T_2 temperature at 1500°C for 5 h were prepared by solid state reaction using two stage sintering method. The influence of firing conditions on bulk densification, percentage of shrinkage, phase formation, crystal structure calculated by Rietveld refinement, microstructure and microhardness is also studied.

Experimental

The composite ceramic alumina zirconia was used as matrix powders to which Al_2O_3 was added magnesia; MgO 6.0 mol% to form AM and ZrO_2 was added Y_2O_3 , 4.0 mol% to form ZY. The powder of AM:ZY at 60:40 ratio was mixed in varying proportions and crushing with ball milling technique for 24 h. After grinding, it is powdered and the powder size is selected by sieve. The AM:ZY powders were heated at 1200°C , with soaking times of 2 h. The AM:ZY mixture powders was moulded by a 3MPa hydraulic press to form a round plate with a diameter of 1.5 cm. Samples powder formed into round plate were sintered under two stage sintering with 5 different conditions. These conditions were (TS-1) T_1 temperature at 1650°C for 60 min and T_2 temperature at 1550°C for 5 h (TS-2) T_1 temperature at 1650°C for 60 min and T_2 temperature at 1500°C for 10 h, (TS-3) T_1

temperature at 1650°C for 60 min and T₂ temperature at 1500°C for 5 h, (TS-4) T₁ temperature at 1600°C for 60 min and T₂ temperature at 1500°C for 10 h, and (TS-5) T₁ temperature at 1600°C for 60 min and T₂ temperature at 1500°C for 5 h. Sintering process was implemented in an electrical furnace (Nabertherm, Germany). The density of AM:ZY composite ceramic is obtained by Archimedes' method. X-ray diffracton technique is used to identify the composition phase of AM:ZY composite ceramics (XRD; Bruker model D8 advance). After that, the XRD patterns of all samples were applied to quantitatively analyse the crystal structure by Rietveld method using TOPAS software. The microstructure of AM:ZY composite ceramic were examined using Scanning Electron Microscopy (SEM) (JEOL JSM-840A). The mechanical properties of AM:ZY composite ceramics were identified by microhardness from Vickers and Knoop technique (FM- 700e type D, Future Tech., Japan). The fracture toughness values can be calculated using microhardness of Vickers and Knoop values.

Results and Discussion

The XRD patterns of 0.6AM-0.4ZY composite ceramics with two stage sintering different conditions are given in Figure 1. XRD patterns consist of two main phases of alumina and zirconia. Apart from the alpha (α)-Al₂O₃ and monoclinic (*m*), tetragonal (*t*), cubic (*c*) zirconia was found. The main reflections in the pattern form around 2θ as 25, 30, 35, 43, 50, 57 and 59° that closely match the characteristic reflections of Al₂O₃-ZrO₂ (Rao *et al.*, 2004; Rejab *et al.*, 2014). Quantitative phase analysis were studied from Rietveld refinement using the TOPAS program. This results of the parameter refinement provide information on important crystal structures of 0.6AM-0.4ZY samples with dissimilar sintering condition and choosed the XRD refinement pattern of TS-2 condition as shown in Figure 2. The refinement patterns were in accordance with the individual experiment data, represented by GOF factors listed in Table 1. The lattice constant of the AM phase is revealed as between 0.4512-1.3218 nm, while the ZY phase has the composition 3 crystal system as follows: *monoclinic* ZrO₂, *tetragonal* ZrO₂ and *cubic* ZrO₂. It was found that two stage sintering condition by the lower T₂ temperature for the length of holding times were obtained the high proportion phases content of *t*-ZrO₂, *c*-ZrO₂. Table 1 shows the relationships between the crystal structure, shrinkage and densification of 0.6AM-0.4ZY with

different two stage sintering conditions. Composite ceramics density values can be measured by the Archimedes principle. Table 1 contains data about the densities, percentage of shrinkage of 0.6AM-0.4ZY composite ceramics with different two stage sintering condition. The bulk density values is between 3.90-4.47 g/cm³. The composite ceramics that gives optimal density values was obtained in the sample with the two stage sintering condition of TS-1 (T₁ temperature at 1650°C for 60 min and T₂ temperature at 1550°C for 5 h) and TS-2 (T₁ temperature at 1650°C for 60 min and T₂ temperature at 1500°C for 10 h). The highly dense of composite ceramics is obtained by the Y₂O₃ addition in ZrO₂ and MgO in Al₂O₃ using two stage sintering method. Two stage sintering method is allowed by the lower temperature required to achieve a high final density than when using undoped and conventional sintering. The crystalline sizes of AM and ZY phases calculated from the XRD patterns using Scherrer equation are summarized in Table 2. The crystalline sizes values of AM is between in the range 0.893-0.920 μ m and the crystalline sizes of ZY as between 0.708-0.804 μ m. Figure 3(a)-(e) reveals the SEM/EDX microphotographs of surface 0.6AM-0.4ZY composite ceramics with different two stage sintering condition. The microstructure of the sintered 0.6AM-0.4ZY composite ceramics with different two stage sintering condition is appeared in Figure 3, where the ZY phase has a relatively round grain shape, while the AM phase is a large shape and a dark colour that looks square consistent with the other work (Weimin *et al.*, 2008; Rittidech *et al.*, 2015; Zygmuntowicz *et al.*, 2022). The above microstructure results can be supported by EDX analysis (as indicated by arrows in Figure 3(b)). SEM microphotographs in Figure 3(a)-(b) were obtained, i.e., uniform sized grains with well-packed and continuous grain structure while, the samples in Figure 3(d)-(e) had a low well-packed consistent with bulk density results. SEM results confirmed the well packing and continuous grain microstructure from two stage sintering conditions of TS-1 and TS-2 as revealed by high proportion ratios of *t*-ZrO₂ and *c*-ZrO₂ by Rietveld refinement. SEM micrographs of 0.6AM-0.4ZY composite ceramics reveal no abnormal growth of grains in the microstructure. The results is consistent previous reported, in which the Al₂O₃- ZrO₂ composite ceramics suppressed abnormal growth of grain in alumina-based materials (Wang *et al.*, 2009). The grain sizes in SEM micrographs were measured using the linear intercept method (Lee *et al.*, 1994) as shown in Table 2. It can be found that 0.6AM-0.4ZY composite ceramics with different two stage sintering condition obtained AM average sizes of

grain as between 0.951-1.205 μm and ZY average sizes of grain as between 0.739-0.894 μm . When comparing the grain size of $\text{Al}_2\text{O}_3\text{-ZrO}_2$ (Y_2O_3) composite ceramics by normal sintering (Rittidech *et al.*, 2013), $\text{Al}_2\text{O}_3\text{-ZrO}_2$ (Y_2O_3) composite ceramics undoped MgO using two stage sintering (Rittidech *et al.*, 2015) and 0.6AM-0.4ZY composite ceramics with dissimilar two stage sintering condition, it can be found that the average grains size of 0.6AM-0.4ZY composite ceramics from the present work were showed smaller size of grains from the other two method. An important reason why the two stage sintering method produces a high density materials with small grain sizes is to heat at high temperature of the first stage of T_1 for the short holding time and give the second stage at lower sintering temperature of T_2 for the length of holding times, thus inhibition of grain growth. There are also confirmed from previous researchs (Rittidech *et al.*, 2006; Rittidech *et al.*, 2021) that, the addition of magnesia in alumina also affects the control of grain size. The proportion of elements of 0.6AM-0.4ZY composite ceramics is investigated using energy dispersive x-ray (EDX) technique as shown in Table 3. The mechanical properties of 0.6AM-0.4ZY composite ceramics with two sintering different conditions were investigated by measuring microhardness by Knoop and Vickers techniques and then calculating the fracture toughness values. The sample from TS-2 condition was selected to display as indentation of microhardness in Figure 4(a-b). Figure 5 shows the relationship between fracture toughness values and 5 conditions of two stage sintering. It was found that the fracture toughness values increased with lower T_2 temperature during holding times. The sample of 0.6AM-0.4ZY composite ceramics with 2 sintering conditions of TS-1 and TS-2 were revealed a high

proportion of tetragonal zirconia and cubic zirconia phases. The characterization of 0.6AM-0.4ZY composite ceramics with sintering conditions of TS-1 and TS-2 were supported that increases in hardness were due to the well-packed and continuous grain structure, corresponding to densities and phase analysis. The fracture toughness values of all compositions was higher than that of the $\text{Al}_2\text{O}_3\text{-ZrO}_2$ with only doped Y_2O_3 . The highest value for fracture toughness was demonstrated by 0.6AM-0.4ZY composite ceramics with two sintering conditions of TS-1, which corresponds to the highest percentage fraction in the tetragonal phase and cubic phase by XRD. It had high densification and optimal microstructure revealed by SEM.

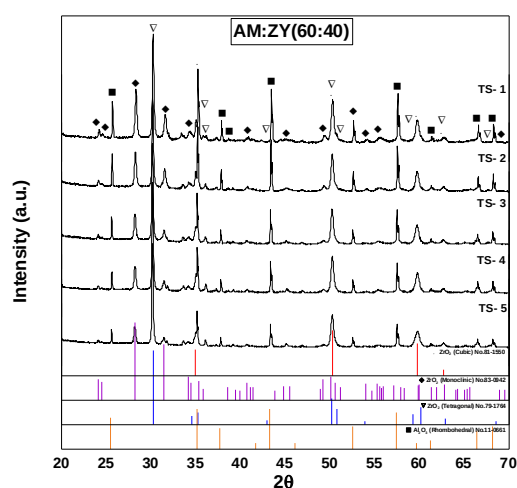


Figure 1. XRD patterns of 0.6AM-0.4ZY composite ceramics with different two stage sintering conditions

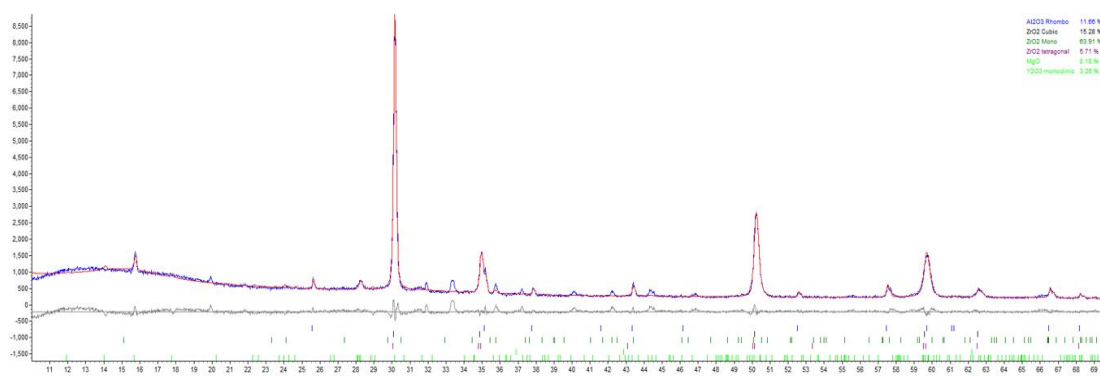


Figure 2. Rietveld refinement of 0.6AM-0.4ZY composite ceramics with two stage sintering of TS-2 condition

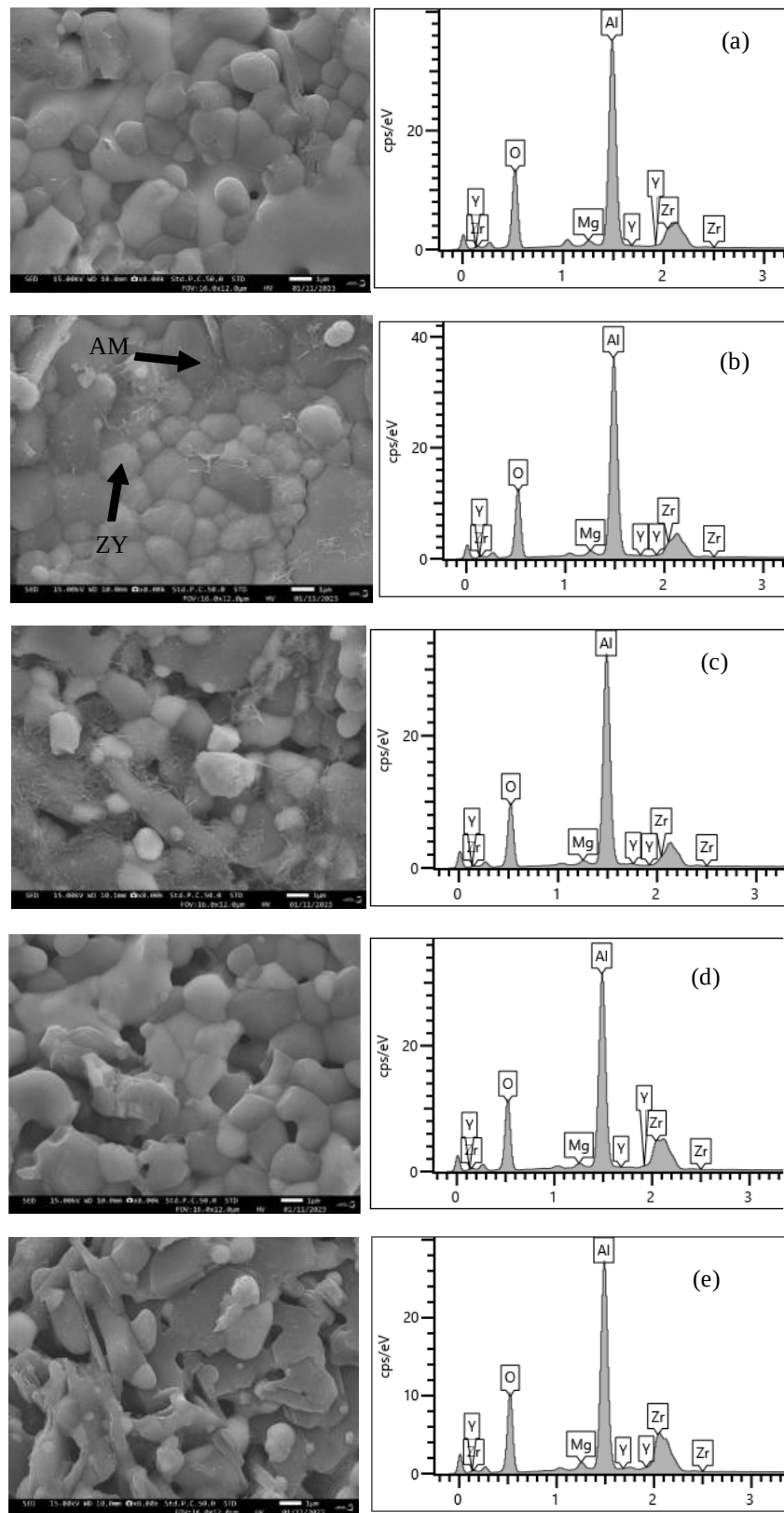


Figure 3. SEM/EDX micrographs of 0.6AM-0.4ZY composite ceramics with different two stage sintering conditions (a) TS-1 (b) TS-2 (c) TS-3 (d) TS-4 (e) TS-5

Table 1. Parameters obtained from Rietveld analysis and densities, percentage of shrinkage of 0.6AM-0.4ZY composite ceramics with different two stage sintering conditions

Two stage sintering condition	Phase present	Lattice parameter				Phase content (%)	GOF	Density (g/cm ³)	Shrinkage (%)
		<i>a</i> (nm)	<i>b</i> (nm)	<i>c</i> (nm)	β (°)				
1	Al ₂ O ₃	0.4512	0.4512	1.3015	98.7	58.12	1.8	4.47	15.12
	m-ZrO ₂	0.5121	0.5185	0.514		16.43			
	t-ZrO ₂	0.3842	0.3842	0.5213		10.94			
	c-ZrO ₂	0.5179	0.5179	0.5179		15.5			
2	Al ₂ O ₃	0.4558	0.4558	1.3017	98.68	59.32	2.13	4.38	15.19
	m-ZrO ₂	0.52	0.5129	0.5044		16.9			
	t-ZrO ₂	0.3735	0.3735	0.5018		9.37			
	c-ZrO ₂	0.5125	0.5125	0.5125		14.89			
3	Al ₂ O ₃	0.4602	0.4602	1.3021	98.73	59.22	4.03	4.01	12.82
	m-ZrO ₂	0.5327	0.5309	0.524		20.21			
	t-ZrO ₂	0.3844	0.3844	0.5021		9.09			
	c-ZrO ₂	0.5152	0.5152	0.5152		11.42			
4	Al ₂ O ₃	0.4571	0.4571	1.311	98.96	58.66	2.39	3.96	11.97
	m-ZrO ₂	0.532	0.5315	0.5271		20.43			
	t-ZrO ₂	0.3951	0.3951	0.51		8.91			
	c-ZrO ₂	0.5168	0.5168	0.5168		12.58			
5	Al ₂ O ₃	0.4674	0.4674	1.3218	98.27	58.55	2.95	3.9	12.1
	m-ZrO ₂	0.5435	0.5401	0.5296		22.23			
	t-ZrO ₂	0.3846	0.3846	0.5023		7.58			
	c-ZrO ₂	0.5179	0.5179	0.5179		13.22			

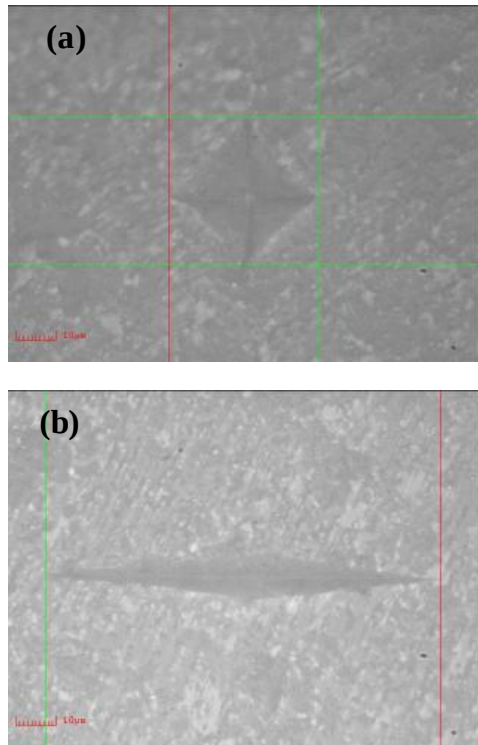
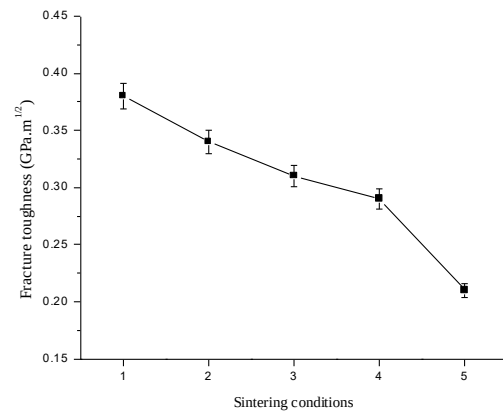
**Figure 4. Indentation of microhardness of 0.6AM-0.4ZY composite ceramics with two stage sintering of TS-2 condition (a) Vickers (b) Knoop****Figure 5. The relationship between fracture and different two stage sintering conditions 0.6AM-0.4ZY composite ceramics**

Table 2. Average grain sizes and crystalline size of 0.6AM-0.4ZY composite ceramics with different two stage sintering conditions

Two stage sintering condition	Average grain size AM (μm)	Average grain size ZY (μm)	Crystalline size AM (μm)	Crystalline size ZY (μm)
1	1.205	0.894	0.92	0.768
2	1.192	0.833	0.896	0.804
3	0.975	0.739	0.901	0.754
4	0.987	0.804	0.912	0.708
5	0.951	0.856	0.893	0.801

Table 3. Chemical compositions of 0.6AM-0.4ZY composite ceramics with different two stage sintering conditions

Two stage sintering condition	Compositions (at%)				
	Al(K)	Zr(K)	Mg(K)	Y (K)	O(K)
1	34.2	29.05	1.2	0.59	33.5
2	30.15	28.98	1.08	0.82	30.06
3	32.51	29.17	0.99	0.79	32.57
4	32.84	27.95	0.89	0.91	31.82
5	31.84	28.26	0.91	0.84	32.84

Conclusions

The 0.6AM-0.4ZY composite ceramics with five different two sintering conditions were successfully prepared. The influence of heat treatment was investigated by characterization of shrinkage, density, quantitative phase analysis microstructure and mechanical properties. The main criterion which forced the phase composition, microstructure analysis, mechanical properties were dissimilar five sintering conditions. It was found that the lower T_2 temperatures for the length of holding times resulted in optimal characterization of samples. The 0.6AM-0.4ZY composite ceramics with two sintering conditions of T_S - T_1 temperature at 1650°C for 60 min and T_2 temperature at 1550°C for 5 h had optimal dense samples, a high fracture toughness values. These samples had a high percentage proportion of t -ZrO₂, c -ZrO₂ phases, and they exhibited a high bulk densities of ceramic with a uniformity of microstructure of the grain.

Acknowledgement

The authors would like to thank for the supporting grant from Mahasarakham University and Thailand Science Research Innovation (TSRI), Thailand.

References

- Azhar, A.Z.A., Mohamad, H., Ratnam, M.M., and Ahmad, Z.A. (2010). The effects of Mgo addition on microstructure, mechanical properties and were performance of zirconia-toughened alumina cutting inserts. *Journal of Alloys and Compounds*, 497(1-2):316-320. <https://doi.org/10.1016/j.jallcom.2010.03.054>
- Behbahani, A., Rowshanzamir, S., and Esmaeilifar, A. (2012). Hydrothermal synthesis of zirconia nanoparticles from commercial zirconia. *Procedia Engineering*, 42:908-917. <https://doi.org/10.1016/j.proeng.2012.07.483>
- Calambas Pugalín, H.L., and Albuno, M.P. (2014). Sintering, microstructure and hardness of different alumina-zirconia composites. *Ceramics International*, 40:5,289-5,298. <https://doi.org/10.1016/j.ceramint.2013.10.102>
- Chen, I.W. and Wang, X.H. (2000). Sintering dense nanocrystalline ceramics without final-stage grain growth. *Nature*, 404:168-171.
- Cui, K., Shen, X., Zhang, Y., Wang, H., Mao, H., and Zhu, J. (2023). Microstructure, phase evolution, mechanical properties and slag corrosion resistance of ZrO₂ reinforced Al₂O₃-Cr₂O₃ composites. *Journal of Materials Research and Technology*, 25:5,520-5,537. <https://doi.org/10.1016/j.jmrt.2023.07.002>
- Hong, J.S., De la Torre, S.D., Miyamoto, K., and Gao, L. (1998). Crystallization of Al₂O₃/ZrO₂ solid solution powders prepared by coprecipitation. *Materials Letter*, 37(1-2):6-9. [https://doi.org/10.1016/S0167-577X\(98\)00057-3](https://doi.org/10.1016/S0167-577X(98)00057-3)
- Hu, J., Tian, X., Hu, C., Luo, Y., Peng, H., and Luo, J. (2016). Preparation of Al₂O₃-ZrO₂ composite powder by coprecipitation method in an alcohol-water solution and its sintering behavior. *Journal of Ceramic Processing Research*, 17(11):1,181-1,187.

- Lee, W.E. and Rainforth, W.M. (1994). *Ceramics Microstructure Property Control by Processing*. 1th ed. Chapman&Hall, London, 590p.
- Marais, F., Sigalas, I., and Whitefield, D. (2022). The effects of the addition of tetragonal-ZrO₂ on the mechanical properties of MgAl₂O₄ - ZrO₂ composites. *Ceramics International*, 48(1):563-568. <https://doi.org/10.1016/j.ceramint.2021.09.134>
- Rao, P.G., Iwasa, M., Wu, J., Ye, J., and Wang, Y. (2004). Effect of Al₂O₃ addition on ZrO₂ phase composition in the Al₂O₃-ZrO₂ system. *Ceramics International*, 30(6):923-926. <https://doi.org/10.1016/j.ceramint.2003.10.014>
- Rejab, N.A., Azhar, A.Z.A., Kian, K.S., Ratnam, M.M., and Ahmad, Z.A. (2014). Effects of MgO addition on the phase, mechanical properties, and microstructure of zirconia-toughened alumina added with CeO₂ (ZTA-CeO₂) ceramic composite. *Materials Science and Engineering A*, 595:518-524. <https://doi.org/10.1016/j.msea.2013.11.091>
- Rittidech A., Somrit R., and Tunkasiri, T. (2013) Effect of adding Y₂O₃ on structural and mechanical properties of Al₂O₃-ZrO₂ ceramics. *Ceramics International*, 39:s433-s436. <https://doi.org/10.1016/j.ceramint.2012.10.108>
- Rittidech, A. and Suekwamsue, N. (2015). Influence of yttria additives on structural, microstructural and mechanical properties of alumina-zirconia composites prepared by two-stage sintering. *Ceramics International*, 41:s123-s126. <https://doi.org/10.1016/j.ceramint.2015.03.118>
- Rittidech, A., Portia, L., and Bongkarn, T. (2006). The relationship between microstructure and mechanical properties of Al₂O₃-MgO ceramics. *Material Science and Engineering A*, 438-440:395-398. <https://doi.org/10.1016/j.msea.2006.02.176>
- Rittidech, A., Wantrong, S. and Chommi, S. (2021). Effect of oxides doping on characterization of zirconia ceramics, *Journal Ceramics Processing Research*, 22(2):1-5.
- Roa, P.G., Iwasa, M., Tanaka, T., Kondoh, I., and Inone, T. (2003). Preparation and mechanical properties of Al₂O₃-15wt.%ZrO₂ composites. *Scripta Materialia*, 48(4):437-441. [https://doi.org/10.1016/S1359-6462\(02\)00440-2](https://doi.org/10.1016/S1359-6462(02)00440-2)
- Samadi, M., Huseien, G.F., Mohammadhosseini, H., Lee, H.S., Abdul Shukor Lim, N.H., Tahir, M.M., and Alyousef, R. (2020). Waste ceramic as low cost and eco-friendly materials in the production of sustainable mortars. *Journal of Cleaner Production*, 266:1,218-1,225. <https://doi.org/10.1016/j.jclepro.2020.121825>
- Wang, C.J., Huang, C.Y., and Wu, Y.C. (2009). Two-step sintering of fine alumina-zirconia ceramics. *Ceramics International*, 35(4):1,467-1,472. <https://doi.org/10.1016/j.ceramint.2008.08.001>
- Wang, H.Z., Gao, L., and Guo, J.K. (2000). The effect of nanoscale SiC particles on the microstructure of Al₂O₃ ceramics. *Ceramics International*, 26(4):391-396. [https://doi.org/10.1016/S0272-8842\(99\)00069-3](https://doi.org/10.1016/S0272-8842(99)00069-3)
- Weimin, M., Lei, W., Renguo, G., Xudong, S., and Xikun, L. (2008). Sintering densification, microstructure and transformation behavior of Al₂O₃/ZrO₂(Y₂O₃) composites. *Materials Science and Engineering A*, 447(1-2):100-106. <https://doi.org/10.1016/j.msea.2007.06.058>
- Zygmuntowicz, J., Tomaszewska, J., Jelen, J., Piotrkiewicz, P., Wachowski, M., Torzewski, J., and Urowski, R.Z. (2022). Comprehensive analysis of the microstructure, properties and environmental performance of Al₂O₃-ZrO₂ composites obtained via centrifugal slip casting. *Chemical Engineering Science*, 263:1,180-1,186. <https://doi.org/10.1016/j.ces.2022.118086>