Reducing The Risk of Agglomeration and Shrinkage Ceramic Body from Al_2O_3-ZrO_2 Composition

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ABSTRACT

This study introduces the effect of ceramic composition that consists of Alumina (Al_2O_3)-Zirconia (ZrO_2)-Chromia (Cr_2O_3) compositions on agglomerate and shrinkage for cutting tool development. Shrinkage is a problem in the development of ceramic cutting tools other than the occurrence of particle agglomerate on the body structure. Finer grain size significantly contributes to the ceramic body's shrinkage and agglomeration. This study analyzed grain size and its relationship with shrinkage and agglomerates. The powders were ball-milled with 80 wt% Al_2O_3 -20 wt% ZrO_2 -0.6 wt% Cr_2O_3 and then compacted and sintered at 1400 °C to examine their shrinkage and investigate microstructure by scanning electron microscopy (SEM) machine. The results show that ZrO_2 has a larger particle size of 6.10 µm and Cr_2O_3 has a finer measure of 1.24 µm. When blended with the ball mill, the mix of Al_2O_3-ZrO_2-Cr_2O_3 was obtained is 7.30 µm, showing that the ball mill can uniformly mix all the particles and reduce the risk of agglomeration. The microstructural analysis found that Cr_2O_3 covers and fills up the space between Al_2O_3 and ZrO_2 compared to without Cr_2O_3. The combination of agglomerate and shrinkage of Al_2O_3-ZrO_2-Cr_2O_3 was responsible for the performance of the ceramic cutting tool fabricated.

Keywords: *Agglomeration; Shrinkage; Ceramic; Cutting Tool*

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Introduction

Engineering or advanced ceramics are inorganic non-metallic materials widely used in high-performance engineering applications. The production of advanced ceramic gives the ideal arrangement and a practical, superior other option to conventional materials, for example, metals and plastics. Ceramics can be called oxide-based, carbides, nitrides, and borides. According to Salamon [1] and Bala et al. [2], the desired properties of advanced ceramics are wear resistance, stability against thermal resistance, thermal insulation, electrical insulation, and non-magnetic. Through these properties, ceramic cutting tools are capable of machining AISI 1045 [3]. Besides that, industrial ceramics applications include automotive components, medical, insulation materials, shielding materials army, coating materials, nuclear reactors, and artificial bone.

Nowadays, most ceramic products use Al_2O_3 and ZrO_2 materials because the nature of the two materials enables the production of a compact and sturdy structure. The use of Al_2O_3 powder in the fabrication of ceramic cutting tools is sufficient to produce a robust structure to carry out lathe machining work [4]-[5]. According to Tong et al. [6], Shafeiey et al. [7], and Tuan et al. [8], the refined grains and mechanical properties of the ZrO_2 structure can improve the strength of Al_2O_3 ceramic cutting tools. However, there is a challenging issue when using nano-sized ZrO_2 powder. A high tendency to agglomerate between grains can cause a decrease in the mechanical performance of ceramic cutting tools. As a result of the agglomeration, ZrO_2 to not dispersed uniformly in the composition of the green body [9]. Agglomerate is inevitable due to the fineness of the ceramic powder used in the composition and the need to analyze the condition and its effects on the ceramic powder mixture. The additive material should be considered and studied to strengthen the composition of the Al_2O_3-ZrO_2 ceramic Cr_2O_3 body, such as using a powder. One of the powerful mixtures and additives used for ceramic cutting tools is Cr_2O_3 [3]. According to Manshor et al. [10] and Kunkun et al. [11], Cr_2O_3 is added to Al_2O_3 to provide fracture toughness because it can form a solid isovalent solution.

Green body shrinkage occurs when the particle size changes due to the effect of the sintering. Shrinkage refers to a reduction in the size of the compacted green body after sintering. It is caused by the closure of porosity inside the ceramic body during the sintering process [12]. The microstructure of the ceramic cutting tool is initially in the small grains form, then continues to expand during the sintering process. The sintering process affects the shrinkage rate due to the molecular and grain movement of the solid ceramic body during the sintering process [13]-[14]. There are three stages of transformation during the sintering of ceramic cutting tools. In the initial stage, there are some degrees of atomic mobility among grain particles, and sharply concave necks are formed between individual particles. The process occurs when the grain size changes at the initial stage of sintering, where the microstructure of the ceramic cutting tool consists of porosity between the grains. As the sintering process continues, the pores between the grains continue to close as the grains expand to cover the spaces and voids. This condition causes shrinkage because the pores have been decomposed, and the grains grow to their maximum level (depending on the sintering temperature) [15].

As a result of this phenomenon, the structure of the ceramic cutting tool becomes denser, and it has better physical and mechanical properties. The shrinkage is calculated based on the diameter and thickness of the cutting tool, as the changes in diameter and thickness are more significant for the cutting tool to fit into the holder.

Experimental Procedure

The mixing process of Al_2O_3-ZrO_2-Cr_2O_3 compositions is done using the dry method. Each ceramic powder is weighed evenly with a 4 gram, then placed in a bottle/jar and mixed evenly using a ball mill machine with a 40 rpm rotation speed at 9 hours of rotation time. This ball mill machine produces a finer and uniformly powder mixture. The powder is then poured into a mould and compacted using a mechanical press and press up to 5 tons to get the determined shape of the green body. A Cold Isostatic Press (CIP) machine is used with 300 MPa for 30 seconds to further compact the green body. Then, the green body of Al_2O_3-ZrO_2-Cr_2O_3 is sintered up to 1400 ^{o}C for 9 hours to obtain a solid and compact ceramic body. Figure 1 shows the process of fabricating ceramic cutting tools.

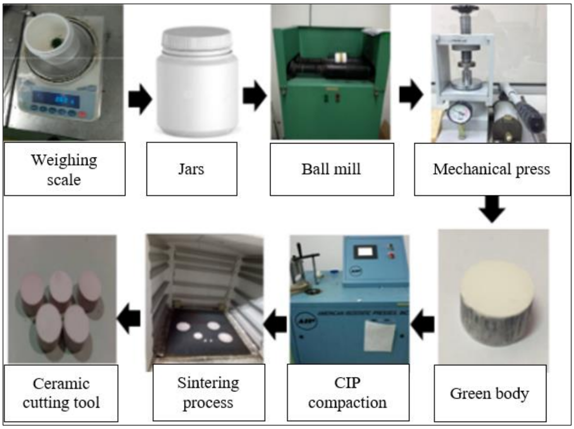


Figure 1: Process cutting tool development

X-ray diffraction (XRD) is an analytical method used to identify the phase of the crystalline material. In this study. XRD was used to detect the presence of Al_2O_3, ZrO_2, and Cr_2O_3 elements inside a single ceramic body. Figure 2 shows the XRD machine used in this study.

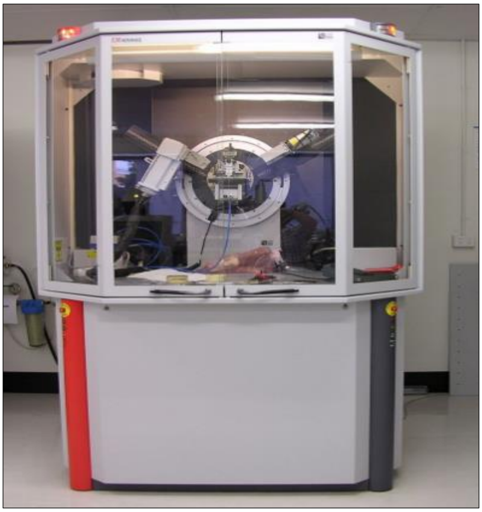


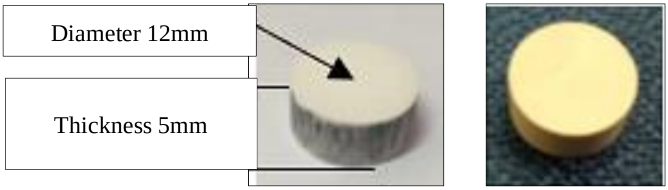
Figure 2: X-ray diffraction (XRD) brand D8 Advance model MSE 4003

Measurement

The grain size and surface contact were measured on each ceramic powder, and then the ceramic mixture was analysed using Malvern master-sizer equipment, as shown in Figure 3. Combination focused 80 wt% Al_2O_3-20 wt% ZrO_2-0.6 wt% Cr_2O_3.

Figure 3: Malvern master-sizer

Specimens were measured at three places using a digital calliper for diameter and thickness before the sintering process was carried out and then averaged. The average diameter and thickness before the sintering process is carried out are 12 mm and 6 mm, respectively. After the sintering process, the same measurement method is performed to obtain an average value to be compared before and after sintering and converted to a percentage. Figure 4 shows the specimen before and after the sintering process is carried out. While for analysis, microstructure and agglomerate identification were carried out using SEM machines, as seen in Figure 5.



(a) (b)

Figure 4: Ceramic cutting tool; (a) before sintering, and (b) after sintering

Figure 5: Scanning electron microscopy (SEM)

Results and Discussion

The study was conducted by identifying the grain size, shrinkage rate, agglomeration, grain contact surface, and microstructure analysis of fabricated ceramic cutting tool by comparing two compositions of Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2-Cr_2O_3. Shrinkage identification was performed to identify the effect on the composition of each powder. At the same time, microstructure analysis determines the causes and consequences of the composition used against powder agglomeration. Powder identification is the first step and the subsequent study about the structure's agglomeration and the effect that causes shrinkage.

Powder characteristics

Figure 6 compares the average grain size after mixing Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2-Cr_2O_3. Since the size of ZrO_2 used in this study only presented around 20% compared to Al_2O_3 (80%), it is expected that the fine ZrO_2 covers the space between the necks of Al_2O_3 grains. Al_2O_3 and ZrO_2 materials can react chemically with each other. However, they have different grain sizes and shapes to produce a compact structure when compaction and sintering. While the properties of the ceramic body from the mixture of Al_2O_3-ZrO_2-Cr_2O_3 powders depended on the grain distribution, which is critically influenced by the processing method. Adding Cr_2O_3, which has a finer grain size and can react chemically to the composition, can close the space between the Al_2O_3 and ZrO_2 neck during the sintering process.

Agglomeration strongly depended on the surface contact area between particles. A bigger surface contact area increased the attraction between the particles due to stronger Van Der Waals forces [16]. As shown in Figure 7, Cr_2O_3 has the largest surface contact area of 4.84 m^2/g, which means this Cr_2O_3 has the strongest tendency to form an agglomerate. On the other hand, the particle size of Al_2O_3 which is dominant in the mixture, has 0.0574 m^2/g, the lowest tendency to form an agglomerate. When Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2-Cr_2O_3 powders ball-milled together, the average surface contact area obtained is 0.61 m^2/g and 0.82 m^2/g, respectively, and slightly lower than ZrO_2 (0.983 m^2/g). This indicates a tendency for Al_2O_3-ZrO_2 to agglomerate almost equivalent to ZrO_2.

Agglomeration

Agglomerate can be prevented using the grinding/ milling method [17]-[18]. Using a ball mill machine is one of the grinding methods indirectly capable of reducing agglomerated powder with a rough surface to a finer material and can mix uniformly with other ceramic powders. During the ball milling process, the ball mill machine grinds and crushes the ceramic powder and mixes it evenly [19]-[20]. The rotational impact from the Al_2O_3-ZrO_2 mixture makes the particles blend homogeneously in the powder bed (bottle/jar) to produce uniform grain distribution for the whole cutting tool structure [21]. The reduction of the Cr_2O_3 surface contact area from 4.84 m^2/g to 0.82 m^2/g after Al_2O_3-ZrO_2-Cr_2O_3 ball milled shows that using this technique capable of removing soft agglomerate that appears in the powder mixture and Figure 8 shows an example of agglomeration of small powder.

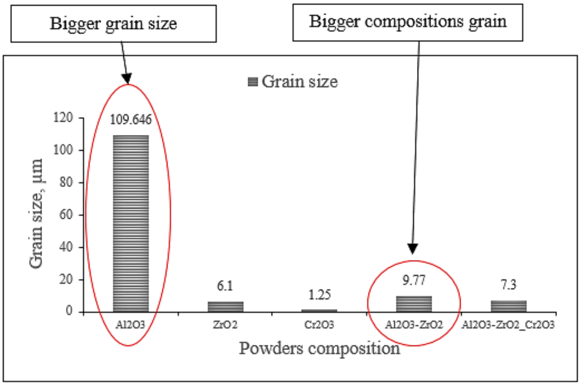


Figure 6: Comparison of average grain size

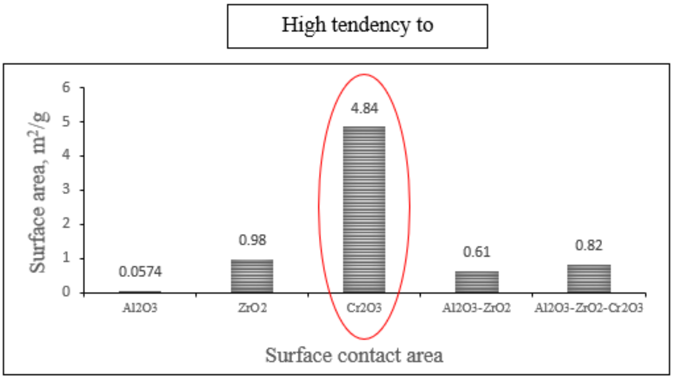


Figure 7: Comparison of surface contact area

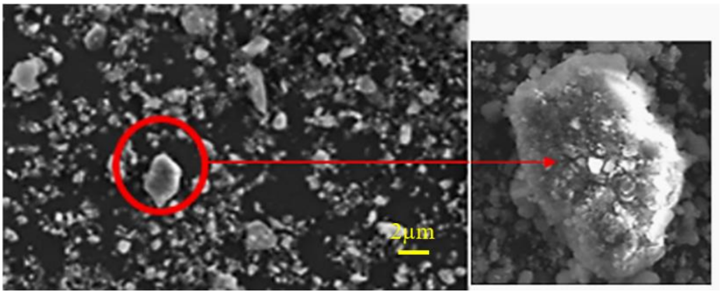


Figure 8: Agglomeration of small powder

Figure 9(a) shows an X-ray diffraction (XRD) pattern of the percentage difference between ZrO_2 against Al_2O_3 content. Analysis shows that Al_2O_3 and ZrO_2 can merge or consolidate because of chemical reactions during when sintering process. While Figure 9(b) indicates that Cr_2O_3 can react with Al_2O_3 when sintered. It's in line with the study conducted by Manshor et al. [10]; Al_2O_3 reacts with Cr_2O_3 because it can form a solid solution isovalent. However, Figure 7 generally does not show ZrO_2 and Cr_2O_3 consolidating or responding. Since Cr is hardly soluble in Zr, the ion of Cr should be dissolved and diffuse through the surface of Al_2O_3. Cr_2O_3 is added to the Al_2O_3-ZrO_2 composition that has been dissolved when the sintering process is carried out [22]. This vaporised Cr_2O_3 could be heterogeneously distributed to the upper surface area of Al_2O_3-ZrO_2, resulting in partial grain growth to the surface, and some of the Al_2O_3 grain can consolidate and merge with Cr_2O_3.

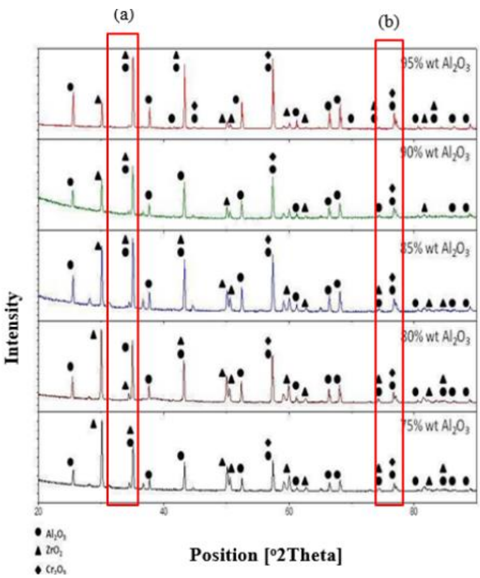
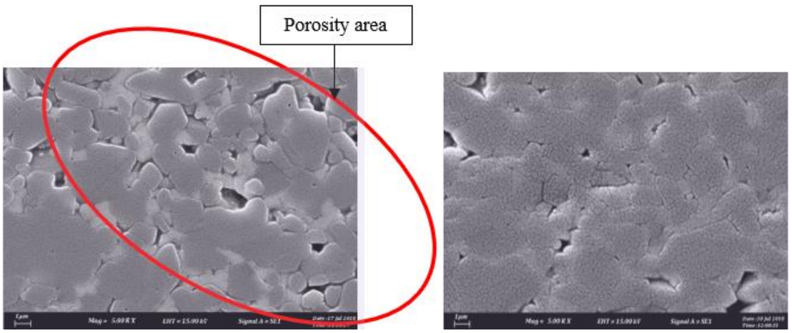


Figure 9: XRD pattern wt.% ZrO_2 on Al_2O_3

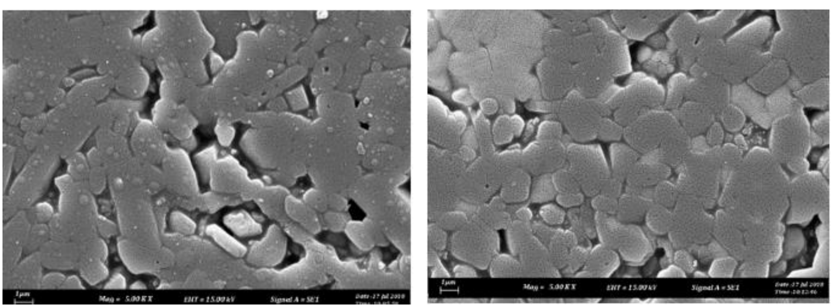
The microstructure composition in Figure 10(b) shows more compactness with a significant reduction in porosity on the surface of the ceramic cutting tool. Cr_2O_3 can help cover the spaces between ZrO_2 and Al_2O_3 grains on the necks. The diagram can be interpreted clearly that 0.6 wt% Cr_2O_3 is enough to accelerate grain growth and can help strengthen the composition of Al_2O_3 80 wt% and ZrO_2 20 wt%. Compared with Figure 10(a), there is much porosity on the surface, and proved by the cross-section in Figure 11(a), the cross-section has much porosity and is seen like patches inside the cutting tool.

However, each grain is seen to be firmly bonded to each other and is better than Figure 11(b). This phenomenon is due to the evaporation that occurs on Cr_2O_3 in the ceramic body. The sintering process causes Cr_2O_3, in the composition of Al_2O_3 and ZrO_2 in the solid body, to evaporate and redeposit over the ceramic surface, which in turn reacts to the Al_2O_3 on the ceramic body surface [23]. The addition of Cr_2O_3 to Al_2O_3-ZrO_2 significantly affects the quality of ceramic cutting tools; the ZrO_2 proportion is ideal for reinforcing the grain position, and the addition of Cr_2O_3 helps to strengthen the surface of the cutting tool by covering the porosity between Al_2O_3 and ZrO_2.



(a) (b)

Figure 10: Surface comparison between (a) Al_2O_3-ZrO_2, and (b) Al_2O_3-ZrO_2-Cr_2O_3



(a) (b)

Figure 11: Cross-section comparison between (a) Al_2O_3-ZrO_2, and (b) Al_2O_3-ZrO_2-Cr_2O_3

Shrinkage

Table 1 shows a composition between Al_2O_3 and ZrO_2, while the significant difference in diameter shrinkage between Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2-Cr_2O_3 can be seen in Figure 12. The shrinkage of Al_2O_3-ZrO_2 composition is higher than Al_2O_3-ZrO_2-Cr_2O_3. The apparent difference is due to the presence of Cr_2O_3 on Al_2O_3-ZrO_2, which reinforces the surface of the ceramic mixture. The Cr_2O_3 added to the Al_2O_3 and ZrO_2 materials evaporates during the firing process. Then the Cr_2O_3 covers the surface of the ceramic mixer, which becomes more robust and has the advantage of wear resistance and heat resistance [12]. According to Renold and Ramesh [24], the shrinking will change during the sintering process by adding additives to the ceramic mixture, and the size of the additive particles affects the order of ceramic shrinkage. Using Cr_2O_3 as an additive to Al_2O_3 and ZrO_2 is very helpful in toughening the synthesised ceramic body through the ceramic body observation, as seen in Figures 8 and 9.

Table 1: Powder composition between Al_2O_3, ZrO_2, and Cr_2O_3

Composition	Al_2O_3 (%)	ZrO_2 (%)	Cr_2O_3 (%)
A	95	5	
B	90	10	
C	85	15	0.6
D	80	20	
E	75	25	

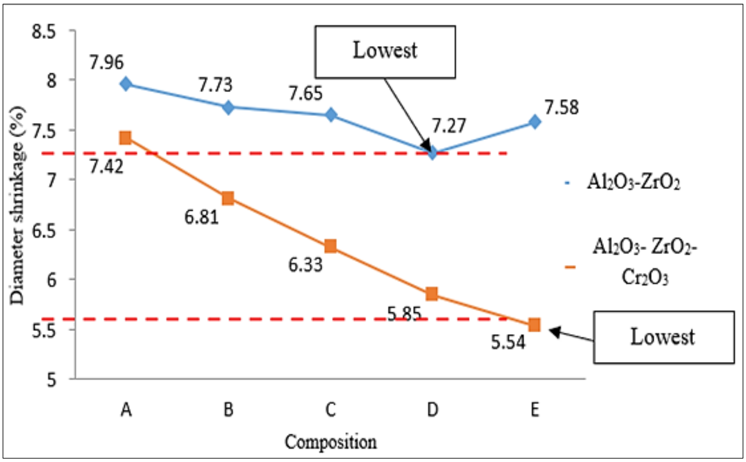


Figure 12: Comparison of diameter shrinkage

The addition of Cr_2O_3 against Al_2O_3-ZrO_2 is seen to have much impact on the thickness shrinkage, as seen in Figure 13. The addition of the Cr_2O_3 powder increases the strength of the surface of the ceramic cutting tools. However, the thickness difference in the cutting tool diameter does not matter very much because it depends on the tool holder used. In many instances, the thickness of the cutting tool can be changed on the tool holder, which is adjustable in the range of 5 to 7 mm [3]. Although the percentage of thickness shrinkage increases, it does not exceed 10% and is still in the range of shrinkage percentage for Al_2O_3-ZrO_2. This shrinkage occurs due to adding Cr_2O_3 to Al_2O_3 and ZrO_2 powder. The addition of Cr_2O_3 is seen to help overcome excessive shrinkage; however, the use of ZrO_2 based on percentage impacts the shrinkage. Shrinkage cannot be avoided because ZrO_2 blocks vary when sintered; the higher the ZrO_2 percentage, the higher the percentage of shrinkage that will occur [25].

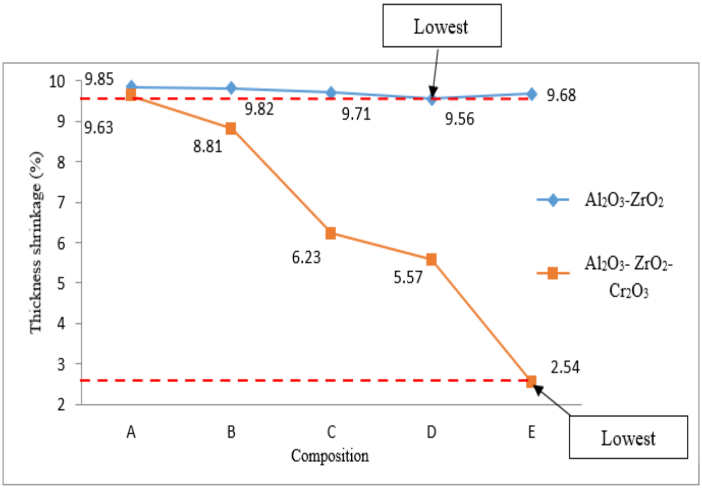


Figure 13: Comparison of thickness shrinkage in millimeters (mm)

Conclusion

The shrinkage rate comparison between two ratio compositions of Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2-Cr_2O_3 was studied to identify the effects of the mixture. Agglomeration occurred due to the grain size and the impact of the contact area. It was analysed in detail to determine the cause of agglomerate and shrinkage in the composition used. Further studies need to be carried out with a mixture of other materials that can reduce the shrinkage and porosity resulting from agglomerate by researching a mixture of compositions other than Cr_2O_3, for example, a mixture of Mg, B4N against Al_2O_3-ZrO_2. Based on this study, it can be concluded that:

i. Cr_2O_3 grains are the smallest at 1.25 µm, and the surface contact is the largest at 4.84 m^2/g compared to the grain size of Al_2O_3 and ZrO_2 grains.

ii. The tendency of agglomeration in single Cr_2O_3 grain is very high because of the large surface area due to the small grain size.
iii. The Al_2O_3-ZrO_2 mixture increased grain size to 9.77 µm and recorded a surface area of 0.61 m^2/g compared to a single ZrO_2 and Al_2O_3 that only recorded 6.10 µm and 0.98 m^2/g, respectively.
iv. The Cr_2O_3 addition of as much as 0.6 wt% against Al_2O_3-ZrO_2 can help reduce agglomerate, which is the grain size increases to 7.30 µm and surface area of 0.82 m^2/g.
v. Al_2O_3-ZrO_2 and Al_2O_3-Cr_2O_3 can chemically react with each other through consolidation. While ZrO_2 and Cr_2O_3 cannot react chemically because Cr_2O_3 can't dissolve with ZrO_2, there will be evaporation.
vi. Observation on the microstructure of Al_2O_3-ZrO_2-Cr_2O_3 is much denser than Al_2O_3-ZrO_2, which features high porosity. The vaporation of Cr_2O_3, when sintered, shows that it redeposits to the surface and chemically reacts to the Al_2O_3 on the surface of the ceramic body. While the microstructure on the cross-section or the inside of Al_2O_3-ZrO_2-Cr_2O_3 shows porosity, it is still better than the Al_2O_3-ZrO_2 mixture.
vii. The shrinkage rate of Al_2O_3-ZrO_2 is higher than Al_2O_3-ZrO_2-Cr_2O_3, where the shrinkage is very significant with each addition of wt% ZrO_2. It's caused by the result of the evaporation processes of Cr_2O_3 that occurs and leaves an empty space in the composition of the mixture.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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References

[1] T. A. Otitoju, P. U. Okoye, G. Chen, Y. Li, M. O. Okoye, and S. Li, “Advanced ceramic components: Materials, fabrication, and applications”, *Journal of Industrial and Engineering Chemistry,* vol. 35, pp. 34-65, 2020.

[2] S. G. Bala, K.R. Venkata, S. Janardhan, K. Shiprath, H. Manjunatha, M. Ramesha, P. N. V. Krishna, S. Ramesh, and B. T. Anil, “Metal and metal oxide based advanced ceramics for electrochemical biosensors-a short review”, *Frontier in Material*, vol. 8, pp. 1-9, 2021.

[3] T. Norfauzi, A. B. Hadzley, U. A. A. Umar, M. M. FAIZ, M. F. Naim, and A. A. Aziz, “Comparison Machining Performance of Al_2O_3, ZTA and ZTA Doped Cr_2O_3 cutting tools on AISI 1045”, *Material Research Express*, vol. 6, no. 1, p. 016547, 2018.

[4] H. A. Bakar, N. Fahmi, F. Mokhtar, N. F. Tamin, U. A. A. Azlan, and R. Izamshah, “Fabrication and machining performance of powder compacted alumina based cutting tool”, *MATEC Web of Conferences*, vol. 150, no. 04009, pp. 1-5, 2018.

[5] G. Edwin, R. Mirosław, P. Sergey, S. Dmitry, C. Leszek, and M. Tomasz, “Effect of SiC addition to Al_2O_3 ceramics used in cutting tools”, *Materials*, vol. 13, no. 22, p. 5195, 2020.

[6] E. Bódis, K Molnár, J. Móczó, and Z. Károly, “preparation and characterization of fibrous alumina and zirconia toughened alumina ceramics with gradient porosity”, *Nanomaterials*, vol. 12, pp. 4165. 2022.

[7] W. Wang, J. Chen, X. Sun, G. Sun, Y. Liang, and J. Bi, “Influence of additives on microstructure and mechanical properties of alumina ceramics”, *Materials*, vol. 15, p. 2956, 2022.

[8] M. M. Coutinhoa, and A. C. P. Nascimentoa, “Four-point bending fatigue behavior of Al_2O_3-ZrO_2 ceramic biocomposites using CeO_2 as dopant”, *Materials Research*, vol. 25, no. 20220199, pp. 1-10, 2022.

[9] Rylski, and K. Siczek, “The effect of addition of nanoparticles, especially ZrO_2-based, on tribological behavior of lubricants”, *Lubricants*, vol. 8, no. 3, pp. 1- 23. 2020.

[10] A. Fiorati, F. Florit, A. Mazzei, S. Buzzaccaro, B. Rossi, R. Piazza, R. Rota, and L. D. Nardo, “Dispersions of zirconia nanoparticles close to the

phase boundary of surfactant-free ternary mixtures", Langmuir, vol. 37, no. 14, p. 4072–4081. 2021.

[11] H. Manshor, A. Z. Azhar, R. A. Rashid, S. Sulaiman, E. C. Abdullah, and Z. A. Ahmad, "Effects of Cr_2O_3 addition on the phase, mechanical properties, and microstructure of zirconia toughened alumina added with TiO_2 (zta–TiO_2) ceramic Composite", *International Journal of Refractory Metals and Hard Materials*, vol. 61, pp. 40–45, 2016.

[12] C. Kunkun, Z. Yingyi, F. Tao, H. Shahid, S. A. Tahani, W. Jie, Z. Xu, and A. Shafaqat, "Effects of Cr_2O_3 content on microstructure and mechanical properties of Al_2O_3 matrix composites", *Coatings*, vol. 11, no. 2, p. 234, 2021.

[13] F. Thummler, and R. Oberacker, "Introduction to powder metallurgy", *Materials Characterization*, vol. 5803, no. 95, pp. 80037-80049, 2014.

[14] A. B. Hadzley, T. Norfauzi, U. A. A. Umar, A. A. Afuza, M. M. Faiz, and M. F. Naim, "Effect of sintering temperature on density, hardness and tool wear for alumina-zirconia cutting tool", *Journal of Mechanical Engineering and Sciences*, vol. 13, no. 1, pp. 4648-4660, 2019.

[15] E. E. E. Gültekin, "The effects of heating rate and sintering temperature on the strength, firing shrinkage, and bulk density of porcelain tiles", *Journal of the Australian Ceramic Society*, vol. 54, pp. 39–46, 2018

[16] S. Somiya, "Handbook of advanced ceramics-materials, applications, processing, and properties", in Handbook of Advanced Ceramics-Materials, Applications, Processing, and Properties, 2nd Ed. Academic Press, 2013, pp. 51–60, 2013.

[17] N. F. Amat, A. Muchtar, S. A. Muhammad, M. J. Ghazali, and Y. Norziha, "Preparation of presintered zirconia blocks for dental restorations through colloidal dispersion and cold isostatic pressing", *Ceramics International*, vol. 44, no. 6, pp. 6409–6416, 2018.

[18] C. H. Haron, A. Muchtar, and N. F. Kundor, "Keutuhan permukaan bahan keluli perkakas setelah pengisaran hujung menggunakan perkakas karbida bersalut", *Jurnal Teknologi*, vol. 41, no. 1 pp. 29–42, 2004.

[19] S. N. Grigoriev, and M. A. Volosova, "Comprehensive analysis of internal and surface defects of ceramics", *The International Conference on Nanomaterial, Semiconductor and Composite Materials*, vol. 65, no. 20040, pp. 1-4, 2016.

[20] K. E. H. K. Ishak, S. Saad, S. F. S. Hashim, and H. Hussin, "Statistical analysis of dry grinding of mica in planetary mill", *Journal* of *Science & Technology,* vol. 30, no. 3, pp. 2191-2204. 2022.

[21] K. Rajaonarivony, X. Rouau, K. Lampoh, J. Y. Delenne, and C. M. Laigle, "Fine comminution of pine bark: how does mechanical loading influence particles properties and milling efficiency?", *Bioengineering*, vol. 6, no. 4, p. 102, 2019.

[22] P. L. Guzzo, A. A. A. Tino, and J. B. Santos, "The onset of particle agglomeration during the dry ultrafine grinding of limestone in a planetary ball mill", *Powder Technology*, vol. 284, pp. 122–129, 2015.
[23] W. Guo, Q. He, A. Wang, T. Tian, C. Liu, L. Hu, H. Wang, W. Wang, and Z. Fu, "Effects of ball milling on the densification behavior, microstructure, and mechanical properties of TiB_2–SiC ceramics", *Journal of Materials Research and Technology*, vol. 15, pp. 6700-6712, 2021.
[24] T. Norfauzi, A. B. Hadzley, U. A. A. Azlan, A. A. Afuza, M. M. Faiz and M. F. Naim, "Fabrication and machining performance of ceramic cutting tool based on the Al_2O_3-ZrO_2-Cr_2O_3 compositions", *Journal of Materials Research and Technology*, vol. 8, no. 6, pp. 5114-5123, 2019.
[25] E. S. Renold and T. Ramesh, "Shrinkage characteristics studies on conventional sintered zirconia toughened alumina using a computed tomography imaging technique", *International Journal of Refractory Metals and Hard Materials*, vol. 54, pp. 383–394, 2016.
[26] E. Salahi, "Sintering behaviour and mechanical properties of alumina/zirconia multilayers composite via nano-powder processing", *Ceramics International*, vol. 40, no. 2, pp. 2717–2722, 2014.