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REVIEW ARTICLE

MECHANICAL PROPERTIES OF POROUS SILICON CARBIDE CERAMICS: A REVIEW

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Abstract. *Porous silicon carbide (SiC)-based ceramics exhibit exceptional structural and functional properties, such as excellent mechanical, chemical, and thermal stability, and controlled electrical resistivity. Owing to their superior properties, porous SiC ceramics are suitable for various industrial applications, including heatable filters, heating elements, thermoelectric energy converters, fusion reactors, thermal insulators, water purifiers, molten metal and hot gas filters, diesel particulate filters, membrane supports, and catalyst supports. A deeper understanding of the mechanical properties of porous SiC ceramics, coupled with the development of new strategies for tuning these properties, will enable the realization of numerous new applications. In this review, important factors known to determine the mechanical strength of porous SiC ceramics, such as microstructures (necking area) and pore characteristics (porosity, pore size), have been analyzed. With increasing porosity and pore size of porous SiC ceramics, the flexural strength tends to decrease. The flexural strength increases with decreasing pore size at a constant porosity, whereas the flexural strength decreases with increasing porosity at a constant pore size. In addition, the flexural strength of porous SiC ceramics is primarily influenced by the developed necking area between SiC grains, which can be obtained through the doping of soluble atoms into the SiC lattice. Based on these critical factors affecting the mechanical properties, a novel strategy for tuning the flexural strength of porous SiC ceramics is proposed.*

Keywords: *SiC ceramic, porosity, pore size, necking area, mechanical properties.*

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ШОЛУ МАҚАЛАСЫ

КЕУЕКТІ КРЕМНИЙ КАРБИДІ КЕРАМИКАСЫНЫҢ МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІ

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Аңдатпа. *Кремний карбиді (SiC) негізіндегі кеуекті керамика жоғары механикалық, химиялық және термиялық тұрақтылық, сондай-ақ бақыланбалы электр кедергісі сияқты ерекше құрылымдық және функционалдық қасиеттерге ие. Аталған ерекше қасиеттеріне байланысты SiC кеуекті керамикасы әртүрлі өнеркәсіптік қолданбаларға, соның ішінде жылытылатын сүзгілерге, қыздыру элементтеріне, термоэлектрлік энергия түрлендіргіштеріне, термоядролық реакторларға, жылу оқшаулағыштарына, су тазартқыштарға, балқытылған металл және ыстық газ сүзгілеріне, дизель отынына арналған бөлшек сүзгілерге, мембраналық субстраттарға және катализаторларға жарамды. Кеуекті SiC керамикасының механикалық қасиеттерін тереңірек түсіну, осы қасиеттерді теңшеудің жаңа стратегияларын әзірлеу, көптеген жаңа қолдану аяларын жүзеге асыруға мүмкіндік береді. Бұл шолуда кеуекті SiC керамикасының механикалық беріктігін анықтайтын маңызды факторлар, мысалы, микроқұрылым (байланыс аймағы) және кеуек сипаттамалары (кеуектілік, кеуек өлшемі) талданды. Кеуекті SiC керамикасының кеуектілік пен кеуектің өлшемі ұлғайған сайын иілу беріктігі төмендейді. Иілу беріктігі тұрақты кеуектілік кезінде кеуек өлшемінің төмендеуімен артады, ал тұрақты кеуек өлшемінде кеуектіліктің жоғарылауымен иілу беріктігі төмендейді. Сонымен қатар, кеуекті SiC керамикасының иілу беріктігіне ең алдымен SiC түйіршіктері арасындағы дамыған байланыс аймағы әсер етеді, оны SiC торына еритін атомдарды енгізу арқылы алуға болады. Механикалық қасиеттерге әсер ететін осы маңызды факторларға сүйене отырып, кеуекті SiC керамикасының иілу беріктігін реттеудің жаңа стратегиясы ұсынылды.*

Түйін сөздер: *SiC керамика, кеуектілік, кеуек өлшемі, байланыс аймағы, механикалық қасиеттері.*

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ОБЗОРНАЯ СТАТЬЯ

МЕХАНИЧЕСКИЕ СВОЙСТВА ПОРИСТОЙ КЕРАМИКИ ИЗ КАРБИДА КРЕМНИЯ

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Аннотация. *Пористая керамика на основе карбида кремния (SiC) обладает исключительными структурными и функциональными свойствами, такими как превосходная механическая, химическая и термическая стабильность, а также контролируемое электрическое сопротивление. Благодаря своим превосходным свойствам пористая керамика SiC подходит для различных промышленных применений, включая нагреваемые фильтры, нагревательные элементы, термоэлектрические преобразователи энергии, термоядерные реакторы, теплоизоляторы, водоочистители, фильтры для расплавленного металла и горячего газа, сажевые фильтры для дизельного топлива, мембранные подложки и катализаторы. Более глубокое понимание механических свойств пористой керамики SiC в сочетании с разработкой новых стратегий настройки этих свойств позволит реализовать множество новых применений. В этом обзоре были проанализированы важные факторы, которые, как известно, определяют механическую прочность пористой керамики SiC, такие как микроструктура (область соединения) и характеристики пор (пористость, размер пор). С увеличением пористости и размера пор пористой керамики SiC прочность на изгиб имеет тенденцию к снижению. Прочность на изгиб увеличивается с уменьшением размера пор при постоянной пористости, тогда как прочность на изгиб уменьшается с увеличением пористости при постоянном размере пор. Кроме того, на прочность пористой керамики SiC при изгибе в первую очередь влияет развитая область соединения между зернами SiC, которая может быть получена путем введения растворимых атомов в решетку SiC. Основываясь на этих критических факторах, влияющих на механические свойства, предложена новая стратегия настройки прочности пористой керамики SiC на изгиб.*

Ключевые слова: *SiC керамика, пористость, размер пор, область соединения, механические свойства.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің ЖТН AP19174518 «Кремний карбиді негізіндегі кеуекті керамиканың электрлік, термиялық және механикалық қасиеттерін зерттеу» гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

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КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Porous silicon carbide (SiC) ceramics are one of the most important advanced ceramic materials which have gained immense attention and have an imporatant role in various industrial fields. Owing to their remarkable properties and versatility they have large potentials for both structural and functional applications (**Fukushima et al., 2008; Ihle et al., 2006; Fukushima et al., 2006; Ohji & Fukushima, 2012; Colombo P., 2008**). The unique combination of properties (e.g., excellent corrosion resistance, high fluid permability, good chemical stabilities, excellent heat resistance, high thermal shock resistance, low thermal expansion coefficient, and excellent mechanical properties) make the porous SiC ceramic a potentially useful material for various advanced applications such as heatable filters, heating elements, thermolectric energy converters, fusion reactors, thermal insulator, water and air purifier, filtration of molten metals and hot gases, diesel particulate filters, membrane supports, and catalyst supports (**Sandra et al., 2016; Dey et al., 2013; Zhou et al., 2011; Eom et al., 2008; Ferraro et al., 2018; Durif et al., 2019; Ding et al., 2006**).

The properties and performances of porous SiC ceramics, especially, mechanical properties are directly related to their microstructures, pore characteristics (e.g., porosity, pore size, and pore morphologies), and necking area. Gomez-Martin et al. (**Gomez-Martin et al., 2016**) reported that the compressive strength of biomorphic SiC ceramics decreased from 115 and to 3 MPa with an increase in porosity from 47 to 72%. The flexural strength of polysiloxane derived porous SiC ceramics decreased from 80 to 10 MPa as the porosity increased from 35% to 70% (**Eom et al., 2008**). To summarize, the strength of porous SiC ceramics decreases with an increase in porosity.

The effect of pore size on the strength of porous SiC ceramics was investigated by many researchers. Eom and Kim reported that with an increase of pore size both compressive and flexural strengths of porous SiC ceramics decreased at the same porosity (**Eom & Kim, 2008**). Hotta et al. reported similar results for porous SiC ceramics prepared by partial sintering technique (**Hotta et.al, 2012**). The compressive strength of porous SiC ceramics increased by starting with smaller SiC particles, which led to a smaller pore size (**Rajpoot S., 2021**). In summary, the strength of porous SiC ceramics increases with a decrease in pore size at the equivalent porosity.

Wan & Wang (**Wan & Wang, 2018**) reported that the compressive strength of porous SiC ceramics increased from 47 MPa to 78 MPa by increasing the necking area between SiC grains at a similar porosity of 54% and 56%. The compressive strength of porous SiC ceramics dramatically increased from 122 to 513 MPa by increasing the bonding area (necking area) between SiC grains at a constant porosity of ~60% (**Fukushima et al.**). She et al. (**She et al., 2002**) reported that the well-developed necks between particles showed flexural strength up to 185 MPa and 88 MPa for porous SiC ceramics prepared from fine and coarse a-SiC powders, respectively. Similar results have been reported for oxidation bonded porous SiC ceramics (**Ding et al., 2006**), silica bonded porous SiC ceramics (**Kim et al., 2020**), and porous recrystallized SiC ceramics (**Zhang et al., 2020**). In summary, the strength of porous SiC ceramics increases with increasing bonding area (necking area) at the equivalent porosity.

The mechanical properties of porous SiC ceramics are fundamental to their performance across a broad range of applications. These properties ensure the materials can withstand various stresses, maintain structural integrity, and provide reliable, long-lasting performance in demanding environments.

2 FACTORS AFFECTING FLEXURAL STRENGTH OF POROUS SIC CERAMICS

Studying the mechanical properties of porous SiC ceramics is essential for several reasons: (1) understanding the mechanical properties allows for the optimization of SiC ceramics for various applications, ensuring they meet specific performance requirements; (2) knowledge of mechanical properties aids in the selection of appropriate materials for specific applications, enhancing efficiency and functionality; (3) insights into mechanical properties facilitate better design and engineering of components, leading to improved reliability and durability; (4) continuous study fosters innovation in the development of new materials and applications, pushing the boundaries of current technology. Mechanical strength is crucial in various application fields of porous SiC ceramics such as aerospace and defense, automotive industry, energy sector, industrial processing, filters, catalysts, biomedical implants, electronics and semiconductors, chemical processing, environmental engineering. For aerospace and defense, automotive industry maintaining structural integrity under various loads is essential. Good mechanical properties ensure that components can withstand stress and avoid failure. In energy sector, electronics and semiconductors a high thermal stability is critical in high-temperature environments. Mechanical properties like strength and toughness at elevated temperatures ensure performance and reliability. Filtration systems for water and air purification in environmental engineering required structural integrity and long-term performance for effective filtration and environmental protection. High thermal conductivity and mechanical strength are critical for efficient heat dissipation and structural integrity in electronic substrates, heat sinks.

Understanding the mechanical properties of porous SiC ceramics is fundamental for optimizing their performance across diverse applications, ensuring that these materials meet the rigorous demands of modern technology and industry.

2.1 POROSITY

Porosity is a critical factor that influences the mechanical strength of porous SiC ceramics. The relationship between porosity and mechanical strength is generally inverse; as porosity increases, the mechanical strength tends to decrease. This reduction in strength is due to the introduction of voids within the material, which act as stress concentrators and reduce the load-bearing cross-sectional area.

Studies have shown that the mechanical strength of porous SiC ceramics decreases exponentially with increasing porosity. For instance, a ceramic with higher porosity might exhibit significantly lower strength compared to a ceramic with lower porosity. The reduction in strength can be attributed to the fact that pores disrupt the continuity of the material, leading to easier crack initiation and propagation under applied stress.

Figure 1 shows the flexural strength of porous SiC ceramics as a function of the porosity. Generally, the flexural strength of porous SiC ceramics decreases with increasing the porosity. The flexural strength of porous SiC ceramics sintered in an argon and nitrogen atmospeheres increase from 8.6 to 32.9 MPa and from 8.1 to 28 MPa with increasing the B_4C content from 0 to 1.5 vol%, respectively (**Kultayeva & Kim, 2022**). The increases in the flexural strength of these porous SiC ceramics is (1) owing to the decreased porosity from 68.2% to 58.3% and from 70.3% to 61.7%, respectively; with the increasing B_4C content; (2) the wide necking area developed between SiC grains which was provided by the B_4C derived B-doping into the SiC lattice. It is well defined that the flexural strength of porous SiC ceramics increase with decreases in porosity and an increased bonding area between SiC grains in struts.

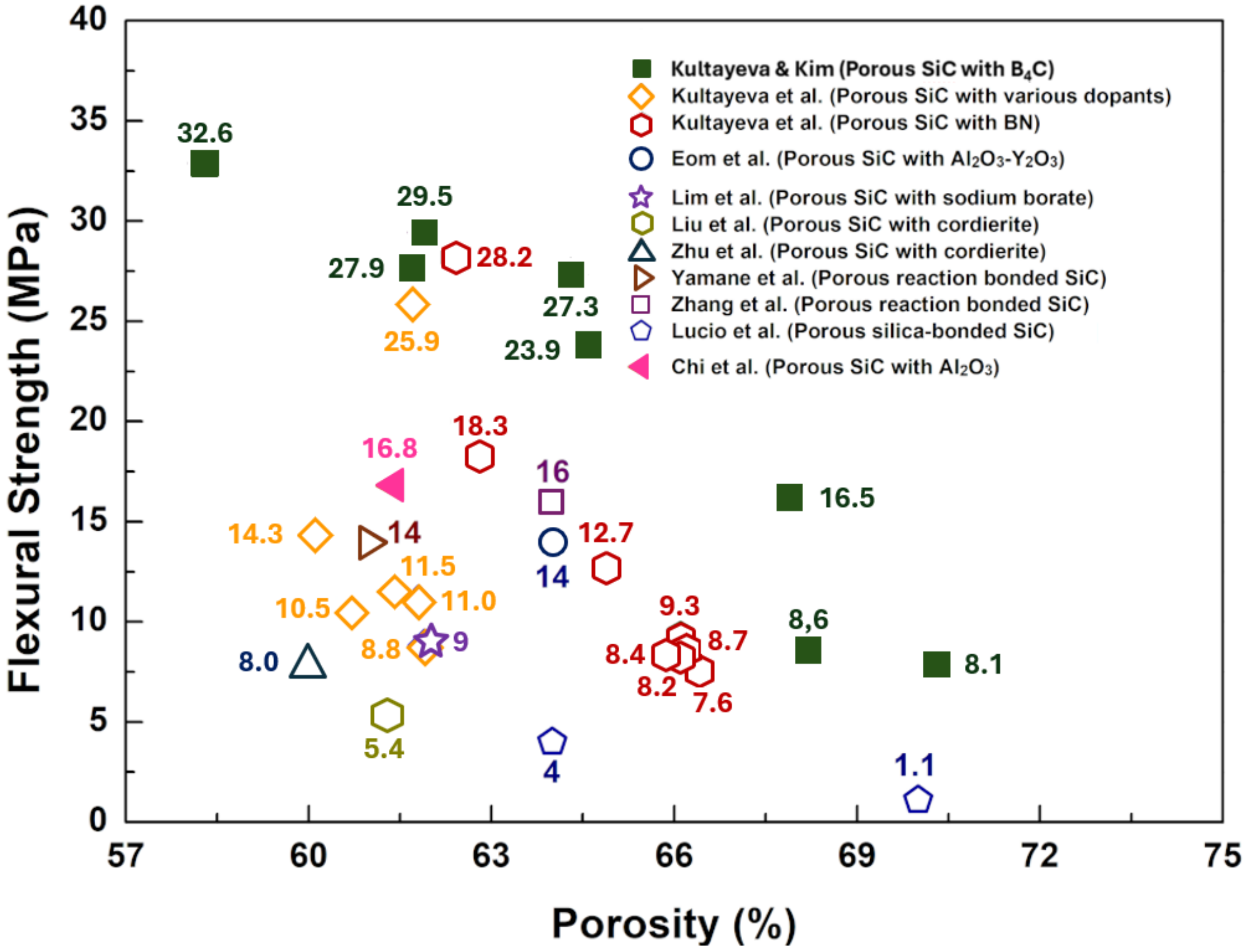

Figure 1 – Flexural strength of porous SiC ceramics as a function of porosity.

The flexural strength of porous SiC ceramics sintered with BN additive in an argon atmosphere gradually decreased from 28.2 to 9.3 MPa with increasing the porosity from 62.4 to 66.1%. In contrast, the flexural strength of porous SiC ceramics sintered with BN additive in nitrogen atmosphere was very insensitive (7.6–8.7 MPa), it was attributed to the insensitivity in porosity (65.9%–66.4%) (**Kultayeva et al., 2021**). Porous SiC ceramics sintered with 1.5 vol% BN additive in two different atmosphere content two different types of porosities: (1) the artificial porosity resulting from the sacrificial template and (2) the residual porosity obtained from the incomplete densification of the struts. The increase of flexural strength of porous SiC ceramics sintered in argon atmosphere was due to partial deancification of the struts during sintering. However, the insensitivity of flexural strength of porous SiC ceramics sintered in nitrogen atmospehere was attributed to the negligible densification of the struts. It is well-documented that the an N_2 atmosphere retards the densification of SiC, owing to the decreased diffusivity of Si and C atoms in SiC and retarded mass transport during sintering under an N_2 atmosphere. Therefore, the flexural strength of porous SiC ceramics sintered in Ar atmosphere increased with an increase in the BN content because of the partial densification, i.e. decreasing porosity.

The flexural strength with bonding material such as sodium borate and cordierite are 9 MPa at 62% porosity (**Lim et al., 2013**) and 5.4–8 MPa at 60%–62% porosity (**Liu et al., 2009; Dey et al., 2013; Zhu et al., 2007**), respectively. The flexural strength of porous reaction-bonded SiC ceramics are 14–16 MPa at 61%–64% porosity (**Yamane et al., 2011; Zhang et al., 2009**).

These results suggests that the porosity is an essential to the mechanical properties of porous SiC ceramics and significantly influenced by decreasing the flexural strength because they act as a starting point for failure. However, it is worth noting that controlled porosity can enhance certain properties such as thermal shock resistance and fracture toughness. By optimizing the porosity, it is possible to achieve a desirable balance between mechanical strength and other functional properties.

2.2 PORE SIZE

The size of the pores within SiC ceramics also plays a crucial role in determining their mechanical strength. Smaller pores are generally less detrimental to mechanical strength compared to larger pores. This is because larger pores create larger stress concentrations, which can significantly weaken the material and make it more susceptible to fracture.

Experimental investigations have demonstrated that reducing the average pore size can lead to an increase in the mechanical strength of porous SiC ceramics. For example, ceramics with average pore sizes in the range of a few micrometers exhibit higher strength compared to those with pore sizes in the range of tens or hundreds of micrometers.

Figure 2 shows comparison of the flexural strength of porous SiC ceramics as a function of pore size with published values in the prior literature in the pore size range of 4–23 µm. As shown, the flexural strength of B-, N-, and undoped porous SiC ceramics are 25.9, 11.5, and 8.8 MPa at a pore size of ~9 µm, ~12 µm, and ~20 µm, respectively (**Kultayeva et al., 2021**). The flexural strength of porous SiC ceramics with 5.8 wt% Al_2O_3-Y_2O_3-MgO is 15 MPa at a pore size of ~7 µm (**Chae et al., 2009**). The flexural strength of porous SiC ceramics with cordierite are 5.4, 7.0, and 8.0 MPa at a pore size of ~4 µm, ~23 µm, and ~4.9 µm, respectively (**Liu et al., 2009; Dey et al., 2013; Zhu et al., 2007**).

The flexural strengths of porous SiC ceramics with BN additive are 9.3 MPa, 12.7 MPa, 18.3 MPa, and 28.2 MPa at a pore size of ~9.1 µm, ~8.9 µm, ~8.1 µm, ~7.0 µm, respectively (**Kultayeva et al., 2021**). Recently, Das et al. reported that the flexural strength of gradually decreased from 116.3 MPa to 43.9 MPa with an increase in pore size from 7 to 98 µm at constant porosity while the strength decreased from 116.3 to 58.7 MPa with increasing porosity from 40%

to ~63% at the same pore size of 7 µm. (**Das et al., 2024**). An increase in the pore size of porous ceramics implies an increase in the critical defect size, leading to a decrease in the flexural strength when the pore size is sufficiently large to become a critical defect.

Given the significant variability in the data observed in the flexural strength versus pore size plot, pore size does not seem to be the primary factor affecting the flexural strength of porous SiC ceramics when the additive composition and necking area differ. It seems that the flexural strength of porous SiC ceramics is primarily influenced by the additive chemistry (necking area) and secondarily by the pore size when the porosities are in the range of 58%–67%.

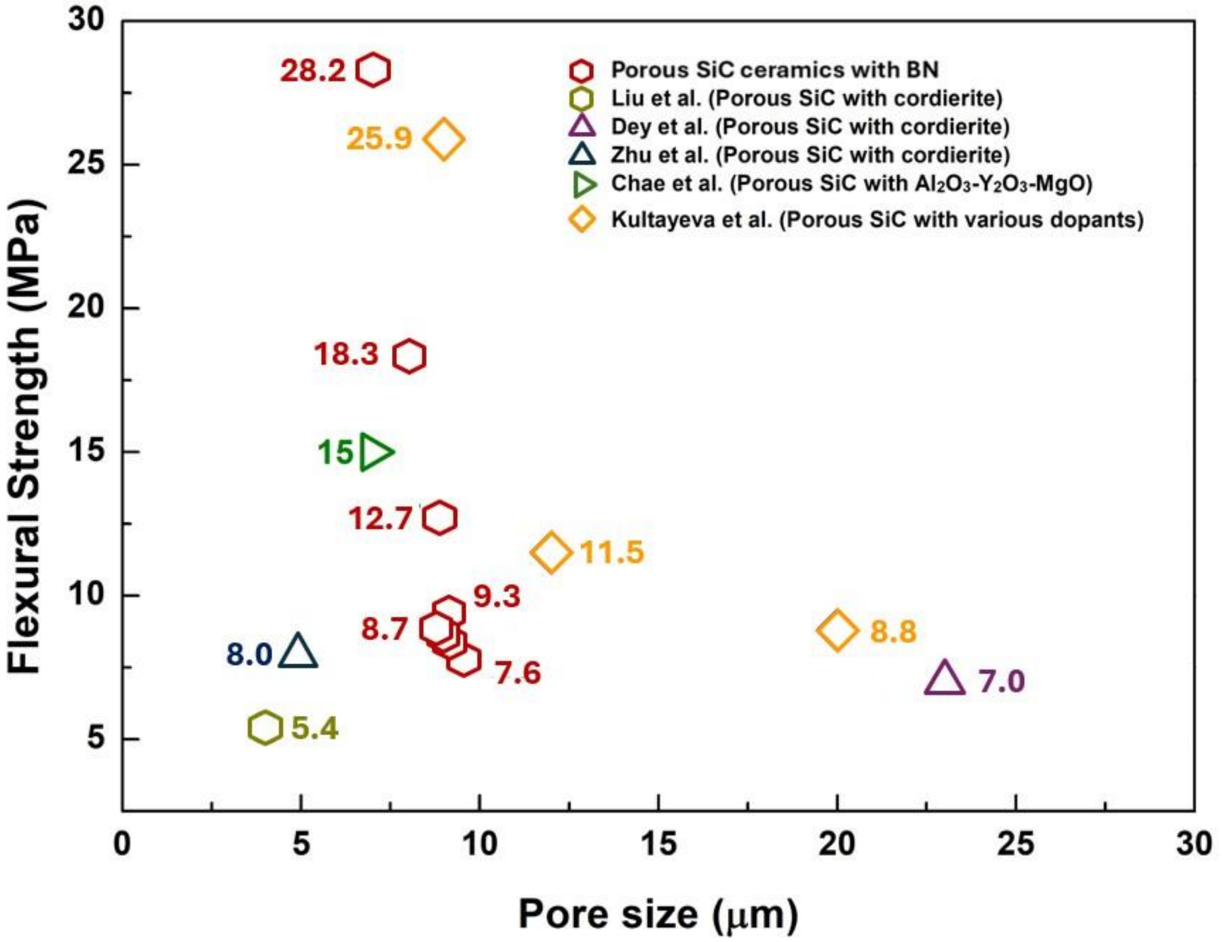

Figure 2 – Flexural strength of porous SiC ceramics as a function of pore size (author's material).

2.3 NECKING AREA

The neck area between SiC grains is a key factor for porous SiC ceramics. The necking area refers to the regions where particles within the porous structure are bonded together. In porous SiC ceramics, the necking area significantly influences mechanical strength. A larger necking area implies stronger bonding between particles, which can enhance the material's overall mechanical strength.

Research has shown that increasing the necking area can improve the load transfer between particles, thereby increasing the mechanical strength of the porous structure. Techniques such as sintering at higher temperatures or for longer durations can promote neck growth and enhance bonding strength. However, excessive sintering can lead to densification and a reduction in porosity, which might not be desirable for certain applications.

Optimizing the necking area involves balancing the sintering conditions to achieve sufficient bonding without compromising the desired porosity. This optimization is crucial for tailoring the mechanical properties of porous SiC ceramics to specific application requirements.

Table 1 shows the comparison of the flexural strength data of porous SiC ceramics at an equivalent porosity of ~62%. From the **Figure 1** and **Table 1** it can be seen that the flexural strengths of porous SiC ceramic with 1 vol% B_4C, porous SiC ceramic with 1 vol% BN were 29.5 and 28.2 MPa, respectively, at an equivalent porosity of approximately 62 %. In contrast, the flexural strengths of porous SiC ceramic with 1 vol% Sc_2O_3, porous SiC with sodium borate, undoped porous SiC ceramic, porous SiC with cordierite, porous reaction bonded SiC, and porous SiC with Al_2O_3 were 10.5 MPa, 9 MPa, 8.8 MPa, 5.4 MPa, 14 MPa, and 16.8 MPa, respectively, at an equivalent porosity of approximately 62 %.

Table 1

Comparison of the flexural strength data of porous SiC ceramics at an equivalent porosity of ~62%

Porous SiC ceramics	Porosity (%)	Flexural strength (MPa)	Remark
Porous SiC ceramic with B_4C	61.9	29.5	**Kultayeva & Kim, 2022**
Porous SiC ceramic with Sc_2O_3	61	10.5	**Kultayeva et al., 2021a**
Porous SiC ceramic with BN	62.4	28.2	**Kultayeva et al., 2021**
Porous SiC with sodium borate	62	9	**Lim et al., 2013**
Undoped porous SiC ceramic	61.9	8.8	**Kultayeva et al., 2021a**
Porous SiC with cordierite	61.3	5.4	**Liu et al., 2009**
Porous reaction bonded SiC	61	14	**Zhang et. al., 2009**
Porous SiC with Al_2O_3	61.4	16.8	**Chi et al., 2004**

Recently, Kultayeva et al. reported that the B-doping into SiC lattice was very effective in forming a wide necking area and strong bonding between SiC grains, leading to excellent flexural strengths. As shown in **Figure 3 (a) and (c)**, porous SiC ceramic prepared from B contained additives such as B_4C and BN showed well-developed necking area between SiC grains compared to porous SiC ceramic with SC_2O_3 or undoped porous SiC ceramic. It was attributed to the strong bonding between SiC grains created by incorporation of B_4C- and BN-derived B atoms into SiC lattice leading to enhanced mass transport of the Si and C atoms. The grain morphology observation of the undoped porous SiC ceramic **Figure 3 (d)** shows that the lower flexural strength was attributed to the narrower necking area between equiaxed SiC grains.

This literature data analysis suggests that the porosity and pore size does not appear to be the major factors influencing the flexural strength of porous SiC ceramics. It seems that the flexural strength of porous SiC ceramics is primarily influenced by the additive chemistry (necking area) and secondarily by the pore size when the porosities are in the range of 58%-67%.

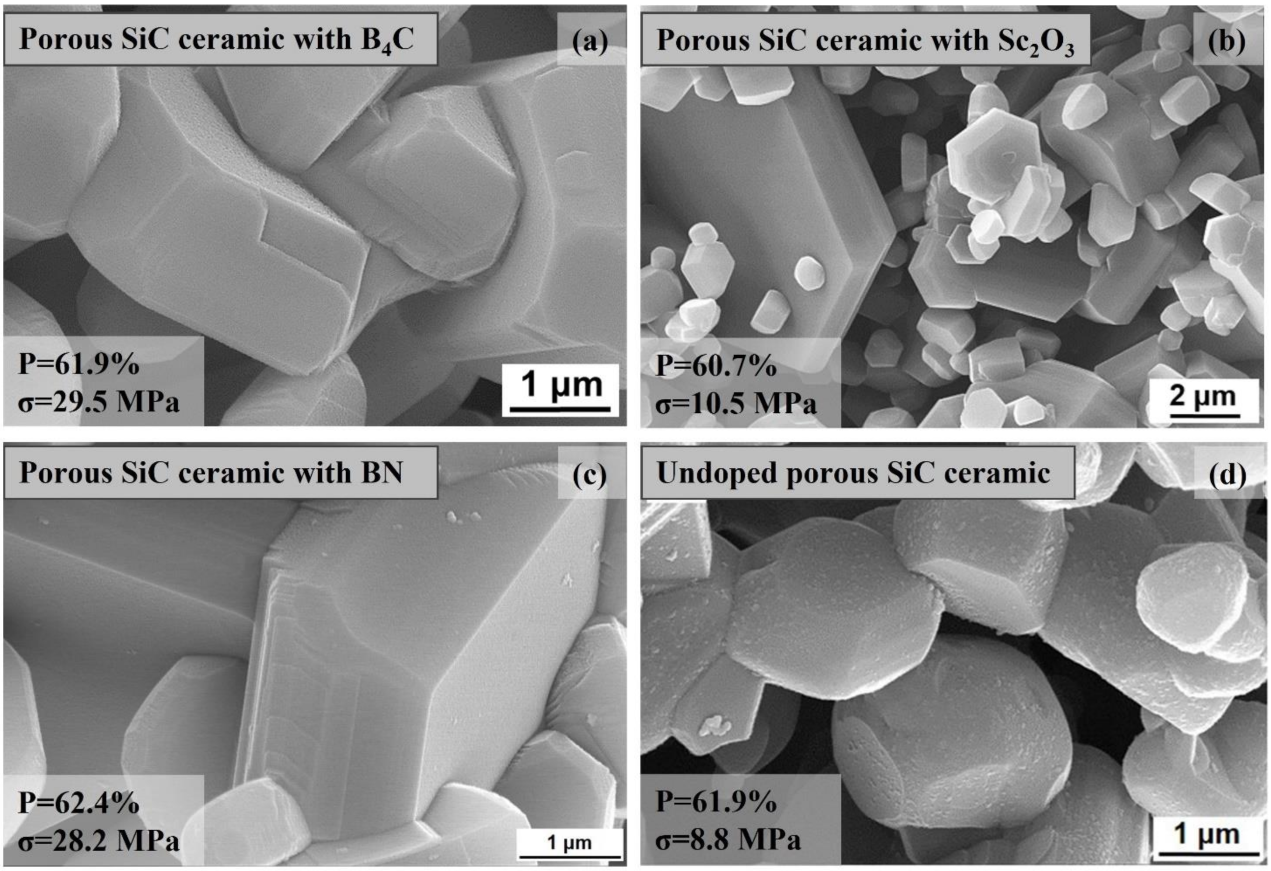

Figure 3 – Fracture surfaces of porous SiC ceramics with controlled porosity: (a) porous SiC ceramic with B_4C (**Kultayeva & Kim, 2022**), (b) porous SiC ceramic with Sc_2O_3 (**Kultayeva et.al, 2021a**), (c) porous SiC ceramic with BN (**Kultayeva et.al, 2021**) undoped porous SiC ceramic (**Kultayeva et.al, 2021a**).

3 CONCLUSIONS

This article reviews the major factors affecting the mechanical strength of porous SiC ceramics. The following are the main conclusions:

(1) The flexural strength of porous SiC is influenced by its porosity, i.e. with an increase in porosity the flexural strength decreases. This is because pores or voids in porous SiC reduce the amount of solid material present and therefore weaken the overall structure.

(2) The flexural strength of the porous SiC ceramics increases by decreasing pore size because of the decreased defect (pore) size. In addition, the flexural strength of porous SiC can be successfully tuned for various application requirements by adjusting the pore size while keeping the porosity fixed.

(3) The flexural strength of porous SiC can be successfully tuned for different applications by precisely control of the doping soluble atoms into SiC lattice. Incorporation of soluble B atoms into SiC lattice was very effective strategy to increase the flexural strength by forming a wide necking area between SiC grains. Generally, the flexural strength of porous SiC ceramics was dependent on the necking area (strong bonding area) and homogeneously distributed pores.

4 FUTURE WORK

By developing novel strategies for tuning the flexural strength of porous SiC ceramics, a multitude of new applications can be realized in the near future. The effect of the initial α- and β-phase content (different polytypes of SiC) on the properties of porous SiC ceramics has not yet been thoroughly investigated. Exploring the impact of these different polytypes on the mechanical properties of pure porous SiC ceramics presents an intriguing area for future research. Advances in processing techniques and a deeper understanding of the microstructural factors will enable the development of porous SiC ceramics with tailored mechanical properties. This will open up possibilities for a wide range of high-performance applications, enhancing the versatility and functionality of these advanced materials.

REFERENCES

1. **Fukushima M., Zhou Y., Youshizawa Y.I.** (2008). Fabrication and microstructural characterization of porous silicon carbide with nano-sized powders. Materials Science and Engineering: B, 148, 211–214, https://doi.org/10.1016/j.mseb.2007.09.026
2. **Ihle J., Martin H.P., Herrmann M., Obenaus P.** (2006). The influence of porosity on the electrical properties of liquid-phase sintered silicon carbide. International Journal of Materials Research, 97, 649–656, https://doi.org/10.3139/146.101285
3. **Fukushima M., Zhou Y., Miyazaki H., Yoshizawa Y.I., Hirao K., Iwamoto Y., Yamazaki S., Nagano N.** (2006). Microstructural characterization of porous silicon carbide membrane support with and without alumina additive. Journal of American Ceramic Society, 89 (5), 1523–1529, https://doi.org/10.1111/j.1551-2916.2006.00931.x
4. **Ohji T., Fukushima M.** (2012). Macro-porous ceramics: processing and properties. International Materials Reviews, 57 (2), 115–131, https://doi.org/10.1179/1743280411Y.0000000006
5. **Colombo P.** (2008). In praise of pores. Science, 322 (5900), 381–383, https://doi.org/10.1126/science.1162962
6. **Sandra F., Ballestero A., NGuyen V.L., Tsampas M.N., Vernoux P., Balan C., Iwamoto Y., Demirci U.B., Miele P., Bernard S.** (2016). Silicon carbide-based membranes with high soot particle filtration efficiency, durability and catalytic activity for CO/HC oxidation and soot combustion. Journal of Membrane Science, 501, 79–92, https://doi.org/10.1016/j.memsci.2015.12.015
7. **Dey A., Kayal N., Chakrabarti O., Murilo D.M. Innocentini, Chacon W.S., Coury J.R.** (2013). Evaluation of air permeation behavior of porous SiC ceramics synthesized by oxidation-bonding technique. International Journal of Applied Ceramic Technology, 10 (6), 1023–1033, https://doi.org/10.1111/j.1744-7402.2012.02847.x
8. **Zhou Y., Fukushima M., Miyazaki H., Yoshizawa Y.I., Hirao K., Iwamoto Y., Sato K.** (2011). Preparation and characterization of tubular porous silicon carbide membrane supports. Journal of Membrane Science, 369, 112–118, https://doi.org/10.1016/j.memsci.2010.11.055
9. **Eom J.H., Kim Y.W., Song I.H., Kim H.D.** (2008). Processing and properties polysiloxane derived porous silicon carbide ceramics using hollow microsphere as templates. Journal of the

European Ceramic Society, 28(5), 1029–1035, https://doi.org/10.1016/j.jeurceramsoc.2007.09.009

10. **Ferraro C., Garcia-Tunon E., Barg S., Miranda M., Ni N., Bell R., Saiz E.** (2018). SiC porous structures obtained with innovative shaping technologies. Journal of the European Ceramic Society, 38(3), 823–835, https://doi.org/10.1016/j.jeurceramsoc.2017.09.048
11. **Durif C., Wynn M., Balestrat M., Franchin G., Kim Y.W., Leriche A., Miele P., Colombo P., Bernard S.** (2019). Open-celled silicon carbide foams with high porosity from boron-modified polycarbosilanes. Journal of the European Ceramic Society, 36(16), 5114–5122, https://doi.org/10.1016/j.jeurceramsoc.2019.08.012
12. **Ding S., Zhu S., Zeng Y., Jiang D.** (2006). Effect of Y_2O_3 addition on the properties of reaction-bonded porous SiC ceramics. Ceramics International, 32 (4), 461–466, https://doi.org/10.1016/j.ceramint.2005.03.024
13. **Gómez-Martín A., Orihuela M.P., Becerra J.A., Martínez-Fernández J., Ramírez-Rico J.** (2016). Permeability and mechanical integrity of porous biomorphic SiC ceramics for application as hot-gas filters. Materials & Design, 107, 450–460, https://doi.org/10.1016/j.matdes.2016.06.060
14. **Eom J.H., Kim Y.W.** (2008). Effect of template size on microstructure and strength of porous silicon carbide ceramics. Journal of the Ceramic Society of Japan, 116(1358), 1159-1163, https://doi.org/10.2109/jcersj2.116.1159
15. **Hotta M., Kita H., Matsuura H., Enomoto N., Hojo J.** (2012). Pore-size control in porous SiC ceramics prepared by spark plasma sintering. Journal of the Ceramic Society of Japan, 120(1402), 243–247, https://doi.org/10.2109/jcersj2.120.243
16. **Rajpoot S. Ha J.H., Kim Y.W.** (2021). Effects of initial particle size on mechanical, thermal, and electrical properties of porous SiC ceramics. Ceramics International, 47(6), 8668–8676, https://doi.org/10.1016/j.ceramint.2020.11.238
17. **Wan P., Wang J.** (2018). Highly porous nano-SiC with very low thermal conductivity and excellent high temperature behavior. Journal of the European Ceramic Society, 38(2), 463–467, https://doi.org/10.1016/j.jeurceramsoc.2017.09.037
18. **She J., Yang J.F., Kondo N., Ohji T., Kanzaki S., Deng Z.Y.** (2002). High-strength porous silicon carbide ceramics by an oxidation-bonding technique. Journal of the American Ceramic Society, 85(11), 2852–2854, https://doi.org/10.1111/j.1151-2916.2002.tb00542.x
19. **Kim Y.H., Kim Y.W., Seo W.S.** (2020). Processing and properties of silica-bonded porous nano-SiC ceramics with extremely low thermal conductivity. Journal of the European Ceramic Society, 40(7), 2623–2633, https://doi.org/10.1016/j.jeurceramsoc.2019.11.072
20. **Zhang J.F., Zhou X.N., Zhi Q., Zhao S.** (2020). Microstructure and mechanical properties of porous SiC ceramics by carbothermal reduction and subsequent recrystalization sintering. Journal of Asian Ceramic Societies, 8(2) 255–264, https://doi.org/10.1080/21870764.2020.1728045
21. **Kultayeva, S.; Kim, Y.-W.** (2022). Electrical, thermal, and mechanical properties of porous silicon carbide ceramics with a boron carbide additive. International Journal of Applied Ceramic Technology, 20 (2), 1114–1128, https://doi.org/10.1111/ijac.14113
22. **Kultayeva, S.; Kim, Y.-W.; Song, I.-H.** (2021). Influence of sintering atmosphere and BN additives on microstructure and properties of porous SiC ceramics. Journal of the European Ceramic Society, 41(14), 6925-6933, https://doi.org/10.1016/j.jeurceramsoc.2021.07.039
23. **Lim K.Y., Kim Y.W., Song I.H.** (2013). Porous sodium borate-bonded SiC ceramics. Ceramics International, 39, 6827–6834, https://doi.org/10.1016/j.ceramint.2013.02.014

24. **Liu S., Zeng Y.P., Jiang D.** (2009). Fabrication and characterization of cordierite-bonded porous SiC ceramics. Ceramics International, 35, 597–602**,** https://doi.org/10.1016/j.ceramint.2008.01.025
25. **Dey A., Kayal N., Chakrabarti O., Caldato R.F., Andre C.M., Innocenti D.M. Murilo.** (2013). Permeability and nanoparticle filtration assessment of cordierite-bonded porous SiC ceramics. Industrial & Engineering Chemistry Research, 52, 18362-18372, https://doi.org/10.1021/ie402876v
26. **Kultayeva, S., Kim, Y.-W., Song, I.-H.** (2021a). Effects of dopants on electrical, thermal, and mechanical properties of porous SiC ceramics. Journal of the European Ceramic Society, 41(7), 4006–4015, https://doi.org/10.1016/j.jeurceramsoc.2019.11.045
27. **Zhu S., Ding S., Xi H., Li Q., Wang R.** (2007). Preparation and characterization of SiC/cordierite composite porous ceramics, Ceramics International, 33, 115–118, https://doi.org/10.1016/j.ceramint.2005.07.006
28. **Yamane H., Shirai Y., Morito H., Yamada T., Hasegawa Y., Ikeda T.** (2011). Fabrication of porous SiC ceramics having pores shaped with Si grain templates, Journal of the European Ceramic Society, 31, 409–413, https://doi.org/10.1016/j.jeurceramsoc.2010.10.025
29. **Zhang Z., Wang F., Yu X., Wang Y., Yan Y., Li K., Luan Z.** (2009). Porous silicon carbide ceramics produced by a carbon foam derived from mixture of mesophase pitch and Si particles. Journal of the American Ceramic Society, 92, 260–263, https://doi.org/10.1111/j.1551-2916.2008.02842.x
30. **Chi W., Jiang D., Huang Z., Tan S.** (2004). Sintering behavior of porous SiC ceramics, Ceramics International, 30, 869–874, https://doi.org/10.1016/j.ceramint.2003.10.006
31. **Das, D., Lucio, M.D.S., Kultayeva, S., Kim, Y.-W.** (2024). Effect of pore size on the flexural strength of porous silicon carbide ceramics. Open Ceramics, 17, 100251, https://doi.org/10.1016/j.oceram.2023.100521