SYNTHESIS AND THERMO-MECHANICAL CHARACTERIZATION OF POROUS CERAMIC AND CERAMIC FOAM COMPOSITE

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submitted by

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Chapter 10

Conclusions & Future Directions

10.1 Introduction

This chapter presents the primary findings derived from the research conducted in this thesis. Furthermore, the study addresses various unresolved issues that require further investigation, and consequently, proposes recommendations for future research.

10.1.1 Conclusions

Despite the advancements in ceramic fabrication, transitioning from conventional methods to advanced additive manufacturing, there is still a need for an economical and facile fabrication process that offers enhanced control over porosity and complex shapes, while remaining easily adoptable for mass production in industries. This research effectively addresses this gap by introducing two innovative, cost-effective processes. The state-of-the-art techniques outlined herein have the capability to produce a wide range of porosity and pore morphology, enabling green machining and the generation of gradient microstructures. The methods described, including the use of a fugitive method (utilizing rice husk), as well as the newly developed "Alumina Dissolution Process" and "Sucrose Dehydration Process," exhibit the ability to achieve porosity levels ranging from 20% to 90%. This extended range of porosity, incorporating both open and closed pores within the structures, opens up numerous possibilities for a wide range of applications.

Another challenge addressed in this research is the efficient utilization of industrial solid wastes, aligning with the secondary objective of "Waste valorization." Coal overburden waste, comprising aluminosilicate as its primary component, was selected as a model industrial waste to fabricate porous composites and foams using the newly developed methods. In order to compare and expand the applicability of these waste-derived composites, porous composites were also prepared using the fugitive method with rice husk. Additionally, waste materials such as red mud were employed to enhance the properties of the developed porous composites and increase the utilization of industrial solid waste in porous ceramic fabrication. The thermo-mechanical properties obtained for these porous composites through these processes make them excellent candidates for thermal and filter applications.

Chapter 3 elucidates the development of the "Alumina Dissolution Process" and provides an explanation of the involved mechanisms. This process yields porous alumina with remarkable flexural strength of up to 53.21 MPa and a porosity range of 34.43-59.24%. The resulting samples exhibit exceptional thermal resistance and feature a combination of bimodal pores within a single monolithic matrix.

Key features of the "Alumina Dissolution Process" include:

- Utilizes the dissolution of alumina in aqueous acidic media, specifically sulfuric acid, to fabricate porous alumina or alumina-based porous composites.
- The process is economically viable due to the minimal usage of sulfuric acid, which accounts for less than 10 wt% of the ceramic slurry.
- No additional blowing agents are required to generate pores.
- Blowing agents such as "aluminum sulfate" and "aluminum oxy hydroxide" are developed in situ during the alumina dissolution process, contributing to the generation of secondary pores.
- Primary pores result from water bubble formation inside the slurry, supported by the effective binding properties between ceramic particles due to the presence of sulfates.
- Primary pores are predominantly macropores, while secondary pores are either micro or meso pores.
- Both open and closed pores are present.
- The process allows for the fabrication of bimodal pore structures within a porosity range of 50% to 70%.
- Pore characteristics can be easily tailored through adjustments in slurry loading and sintering temperatures.
- The ability to perform green machining is an added advantage, reducing costs and complexities associated with shaping complex porous structures.
- The process is applicable to fabricating materials with alumina as a minor or major component.
- It has potential for treating industrial solid wastes (containing alumina as one of their components) and converting them into high-end products, such as porous composites.

Chapter 2 outlines the steps for developing ceramic foam using the "Sucrose Dehydration Process" and presents the proposed mechanism. Silica is used as the model material, resulting in silica foam with porosity ranging from 75% to 90% and a minimum thermal conductivity of 0.0943 $Wm^{-1}K^{-1}$.

Salient features of the "Sucrose Dehydration Process" include:

- Dehydration of sucrose, facilitated by sulfuric acid, is employed to generate ceramic foams.
- Sucrose acts as a blowing agent when combined with ceramic powders in the presence of sulfuric acid, inducing foaming in the ceramic-sucrose slurry.
- Sucrose is used to control the porosity of the foams, and the sucrose-to-ceramic weight ratio influences the foaming behavior as well as the physical and thermo-mechanical characteristics of the ceramic foams.
- The process can achieve ceramic foams with a total porosity of 90%.
- The foams primarily consist of open pores, enabling mass transportation and making them suitable for filter applications.
- Closed pores are also present, providing additional porosity and mechanical robustness.
- The process is cost-effective and easily adaptable.
- It can be used to fabricate ceramic foam composites using various types of ceramics.
- The approach allows for the development of microstructural gradients.

Subsequent chapters involve the fabrication of porous composites and foams using the developed processes. Coal overburden waste is utilized to produce aluminosilicate-based porous composites, which exhibit excellent thermo-mechanical properties. The fabricated porous aluminosilicate composites (PAC) demonstrate a range of physical properties, including bulk density, porosity, and compressive strength. Values range from 1 to 1.09 g/cm^3, 64.1% to 70.23%, and 15 to 21.99 MPa, respectively. The PAC also exhibits excellent thermal resistivity properties, with a low thermal conductivity of up to 0.28 W/(m·K).

The fabricated functionally graded mullite silicate (FG-MS) foams possess bulk density, porosity, and compressive strength in the range of 0.31-1.34 g/cm^3, 56.25-89.81%, and 2.2-13.8 MPa, respectively. These foams exhibit good thermal resistivity properties, with a low thermal conductivity of up to 0.08 W/(m·K), surpassing the reported thermal insulation properties of other mullite-based material systems.

Additionally, an attempt has been made to further utilize coal overburden waste to enhance its usability. A low-cost approach has been employed to fabricate silicon carbide (SiC) foam by bonding SiC particles using mullite. In-situ development of the mullite phase during the heat treatment process, utilizing coal overburden waste, contributes to this process. The fabricated functionally graded SiC foams have bulk density, porosity, and compressive strength in the range of 0.31-1.34 g/cm³, 56.25-89.81%, and 2.97-15.06 MPa, respectively.

Finally, porous aluminosilicate composites were fabricated using coal overburden waste, red mud, and rice husk. This work aims to widen the porosity range of aluminosilicate-based porous composites using MW, as this is not achieved through alumina dissolution and sucrose dehydration processes. Furthermore, this approach facilitates the utilization of additional waste materials such as red mud and rice husk. The developed porous composites exhibit apparent porosity, compressive strength, and thermal conductivity in the range of 26-54%, 6-28 MPa, and 0.37-0.67 W/m·K, respectively. Rice husk proves to be an affordable source of pore formers, allowing for a wide range of porosity and facilitating the formation of aluminosilicate and other silicate phases through its residual silica content.

Lastly, a comparative analysis based on the offered porosity and pore size range of the three discussed processes (alumina dissolution, sucrose dehydration, and fugitive method using rice husk) is provided to assist readers and researchers in selecting an appropriate methodology for fabricating porous ceramics or ceramic foam composites according to specific application requirements.

10.1.2 Future Directions

Despite the exceptional features of the described processes, there are still opportunities for improvement and further investigation. Due to limitations in time and funding, certain aspects of the research could not be fully explored, but they hold potential value and warrant future investigation.

For the "Alumina Dissolution Process," there is room to explore the role of specific additives in extending the porosity range and enhancing pore characteristics. Investigating the effects of these additives could lead to a broader range of porosity and further optimization of pore characteristics.

In the case of the "Sucrose Dehydration Process," future research can focus on studying pore gradient characteristics and their specific applications. Additionally, exploring the use of additives to enhance the mechanical properties of the resulting foams would be valuable. Reducing the reliance on sulfuric acid in this process would also be beneficial in terms of cost and minimizing its environmental impact.

While the present work successfully demonstrates the conversion of coal overburden waste into porous composites and foams using the developed processes, there is potential for expanding these techniques to other types of industrial solid wastes. Investigating the applicability of the "Alumina Dissolution Process" and "Sucrose Dehydration Process" to different waste materials would contribute to waste valorization efforts and the production of valuable porous composites.

Although the present work primarily focuses on thermal applications, there is potential to extend its applicability to other areas, such as hot flue gas filtration and water treatment. The superior mechanical properties and wide range of porosity exhibited by the developed porous composites make them promising candidates for these applications.

Exploring these future directions will not only enhance the understanding and capabilities of the developed processes but also contribute to advancements in waste valorization and the utilization of porous composites in various industries and applications.