

A STUDY ON SiC SUSCEPTOR CONFIGURATION FOR MICROWAVE HYBRID HEATING

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Abstract

Microwave hybrid heating (MHH) is a novel method to enhance ceramic sintering at high temperatures. The heating mechanism by MHH involves two directions of heat transfer for materials: microwaves heat the sample from the inside out, while the susceptor provides conventional heating from the outside. This unique heating mechanism offers several advantages, including uniform heating, rapid sintering, and enhanced microstructure and properties of materials. This study investigates the configuration of silicon carbide (SiC) susceptors for microwave hybrid heating. The microwave oven (multi-mode, 2.45 GHz, 1.2 kW) was modified with a ceramic insulator housing to maintain the temperature in the chamber. The effects of different configurations of SiC susceptors and microwave powers on the heating rate and maximum temperature were investigated. SiC susceptor plates were placed in the microwave oven using 3 different configurations, and for each condition, the microwave power was varied at 40, 60, 80, and 100% (480, 720, 960, and 1,200 W). The temperature in the microwave chamber was recorded until it reached 900°C or after 30 min of heating. Using two plates of SiC susceptor at 100 % power resulted in the highest heating rate of 62°C/min to reach 925°C. The results of this study offer guidance for the selection of appropriate heating conditions for individual ceramic materials, which can lead to more effective sintering processes.

Keywords: Microwave hybrid heating; microwave sintering; silicon carbide; susceptor; SiC susceptor

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Introduction

Microwave technology has shown promising prospect in the field of materials processing, particularly in ceramic sintering. Compared to conventional sintering methods, microwave sintering offers advantages such as reduced processing time, improved microstructure and mechanical properties, and energy efficiency (Madhan and Prabhakaran, 2019; Lyra *et al.*, 2019; Zeng *et al.*, 2019; Guillén *et al.*, 2021).

However, certain types of ceramic materials may not be able to absorb microwave energy effectively, leading to low sintering temperatures. Furthermore, microwave heating can result in temperature differences between the core and surface of the material due to the heat being primarily generated within the material (Bhattacharya and Basak, 2016). To overcome these issues, microwave hybrid heating (MHH) techniques have been developed. These methods incorporate a susceptor, which absorbs microwave energy and converts it to heat, allowing for both microwave and conventional heating to occur simultaneously. MHH process allows for the sample to be heated from the inside out via microwaves, while the susceptor provides conventional heating from the outside in. This technique has been shown to enhance the heating rate and provide more uniform heating of the material, resulting in improving of sintered products (Huang *et al.*, 2009; Bhattacharya and Basak, 2016). The utilization of MHH techniques has the potential to significantly improve the efficiency of ceramic sintering processes, leading to advances in the development of new materials with superior properties.

The interaction of materials with microwaves is an important factor in the success of microwave heating for materials processing. The ability of a material to absorb microwave energy and convert it into heat is determined by its penetration depth (d_p) and loss tangent ($\tan\delta_e$) value (Mishra and Sharma, 2016). A material with a high penetration depth (d_p) can absorb microwave energy more effectively, while a high $\tan\delta_e$ value indicates the ability to convert this energy into heat. An effective susceptor material should possess both these parameters, with a high penetration depth and a high value of $\tan\delta_e$. The selection of an appropriate susceptor material is thus important in achieving successful microwave hybrid heating of ceramic materials.

Table 1 presents the penetration depth (d_p) and loss tangent ($\tan\delta_e$) of microwave absorber materials (Bhattacharya and Basak, 2016; Mishra and Sharma, 2016). Carbon materials, such as carbon black, graphite and activated carbon, have a high value of

$\tan\delta_e$ and a penetration depth in the order of centimeters. However, carbon tended to decompose at temperatures above 600°C, which renders them unsuitable for used as susceptor at high temperatures. On the other hand, silicon carbide (SiC) has excellent penetration depth (d_p) and loss tangent ($\tan\delta_e$) and is highly stable at high temperatures. SiC demonstrates excellent suitability as a susceptor in microwave hybrid heating systems due to its high melting point of approximately 2,470°C (Taneja *et al.*, 2021). Moreover, SiC exhibits remarkable stability, as oxidation typically occurs at much higher temperatures, around 1,300-1,600°C (Chen *et al.*, 2021). Therefore, SiC is a good candidate for use as a susceptor for high temperature application (Huang *et al.*, 2009; Satapathy, 2009; Yahaya *et al.*, 2013; Bhattacharya and Basak, 2016; Bhoi *et al.*, 2019).

The efficiency of heating in MHH process is dependent on the design of susceptor. To achieve efficient heating, the susceptor should provide pre-heating to the material to allow for uniform heating throughout the sample, but it should not completely block the microwave energy from reaching the material. The amount and position of the susceptor can also impact the efficiency of heating. A larger amount of susceptor material can absorb more microwave energy, but it can also block more of the energy from reaching the material being heated. The position of the susceptor can also impact the efficiency, with a well-designed susceptor configuration allowing for efficient heating of the material.

The design of the susceptor is an important consideration in achieving efficient microwave-assisted heating in MHH processes. The objective of this study is to examine the parameters of a microwave hybrid heating system, including microwave power, number of susceptors, and susceptor layout. The experiment was conducted utilizing a modified microwave oven to investigate

Table 1. The penetration depth (d_p) and loss tangent ($\tan\delta_e$) of microwave absorber materials (Bhattacharya and Basak, 2016; Mishra and Sharma, 2016)

Materials	d_p (cm)	$\tan\delta_e$
SiC	1.93	0.37
Carbon black (20 μm)	5.75	0.23
Graphite powder (20-80 μm)	1.34–2.09	0.36–0.67
Activated carbon	0.7–3.43	0.31–0.9
Charcoal	6–11	0.14–0.38
Carbon fiber	0.5–0.7	0.45–0.5
Carbon nanotube	0.2	1.11

the most efficient condition to employ SiC susceptors in microwave hybrid heating.

Experimental Methods

In this study, microwave oven (Sharp, model R-390, multi-mode, 2.45 GHz, 1.2 kW) was utilized. Additionally, an alumina-silica ceramic fiber board housing was inserted inside the microwave chamber as an insulator to prevent heat loss.

SiC plate used as susceptor in this experiment has a thickness of 1.2 cm. The SiC plate was cut to 2 sizes. The dimension of SiC plates that was placed at left- and right-side of the sample was 8.5 cm × 6.0 cm in height × width. On the other hand, the SiC plate placed at the bottom of the sample had dimensions of 10 cm × 10 cm in height and width. To evaluate efficiency of the microwave hybrid heating, the experiment was designed in three different configurations, each with a different number of SiC plates, as displayed in the Figure 1.

Furthermore, different microwave power levels to identify the most efficient power level for sintering was examined. For this experiment, microwave powers at 20, 40, 60, 80, and 100% (240, 480, 720, 960, and 1,200 W) were utilized.

The temperature within the microwave oven was measured using a Type K thermocouple. The thermocouple probe was carefully inserted at the top of the microwave oven, ensuring that it was positioned near the sample being heated. The test was conducted for 30 min or until the temperature reached 900°C.

Result and Discussion

An investigation was conducted to examine the correlation between the number of SiC susceptor plates, the electrical power of a microwave oven, and the resulting temperature inside the microwave cavity. According to Table 1, SiC has a high penetration depth of 1.93 cm and a high loss tangent value of 0.37. The SiC susceptor used in this study had a thickness of 1.2 cm. Therefore, microwave energy can effectively penetrate the susceptor, allowing for efficient heating. From the experiment results, it was found that the temperature inside the microwave oven increased with time, and an increase in electrical power also resulted in an increase in temperature.

Figure 2 shows the temperature profiles in the microwave oven when using one SiC susceptor

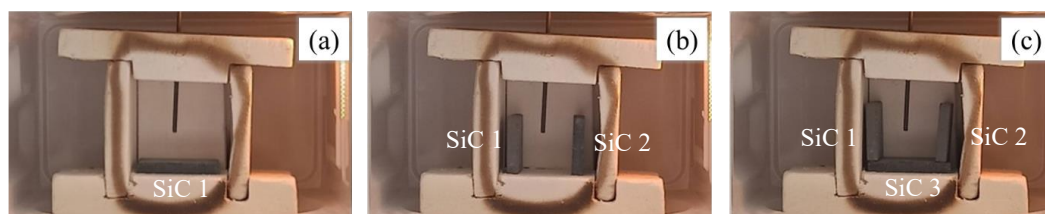


Figure 1. The configuration of silicon carbide susceptor plates inside the microwave: (a) one susceptor plate, (b) two susceptor plates, and (c) three susceptor plates

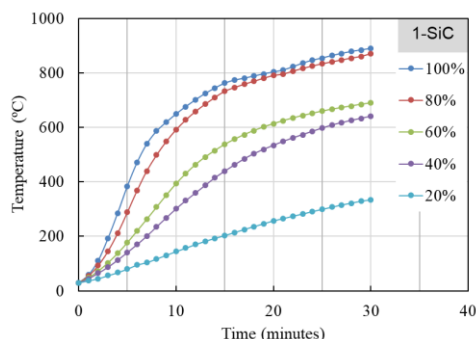


Figure 2. Temperature profiles in the microwave oven when using one SiC susceptor plate, with microwave powers at 20, 40, 60, 80, and 100%

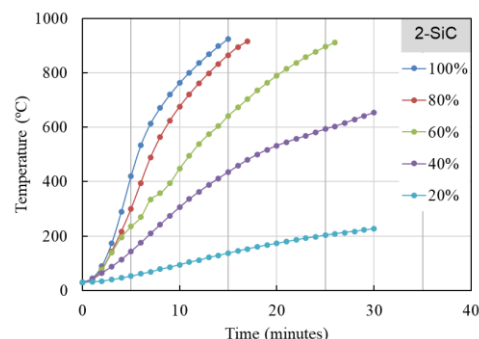


Figure 3. Temperature profiles in the microwave oven when using two SiC susceptor plates, with microwave powers at 20, 40, 60, 80, and 100%

plate. With a single SiC susceptor and 20% electrical power, the highest temperature reached only 334°C after 30 min. Upon increasing the electrical power to 40% and 60%, the maximum temperature rose to 640°C and 689°C respectively, after 30 min. Similarly, when increasing the electrical power to 80% and 100%, the temperature followed a similar increasing pattern, with maximum temperatures of 870°C and 889°C, respectively, after 30 min. However, using only one SiC susceptor plate resulted in a slower rate of temperature increase compared to using two SiC susceptors.

Figure 3 shows the temperature profiles in the microwave oven when using two SiC susceptor plates. When the electrical power was set at 20% and held for a duration of 30 min, the maximum temperature reached was only 226°C. Subsequently, when the electrical power was increased to 40%, the maximum temperature increased to 650°C. Further increasing the electrical power to 60%, 80%, and 100% resulted in a rapid temperature rise, reaching a maximum of 900°C before the 30 min. The applying of 60% electrical power resulted in the temperature inside the oven reaching 912°C at 26 min, while 80% electrical power achieved a temperature of 915°C at 17 min. Finally, the highest temperature of 925°C was attained within only 15 min by increasing the electrical power to 100%.

Figure 4 illustrates the temperature profiles in the microwave oven when using three SiC susceptor plates. When applying 20% electrical power, the maximum temperature reached was 314°C. Increasing the electrical power to 40% and 60% resulted in maximum temperatures of 591°C and 888°C, respectively. Applying 80% electrical power resulted in a maximum temperature of 888°C. Finally, when using 100% electrical power, the

maximum temperature achieved inside the oven was 913°C after 30 min.

It was observed that increasing the number of SiC susceptor from two plates to three plates did not result in an increase in the heating rate. Conversely, the use of three susceptor plates resulted in a decrease in the heating rate. This reduction in efficiency can be attributed to wave interference and reduced microwave energy absorption caused by an excess of susceptors. The presence of too many susceptors can impede the propagation of microwaves, causing standing waves and a reduction in penetration depth. In microwave heating, standing waves can occur when there is interference between the waves reflected from different surfaces within the oven. When microwaves encounter a reflective surface, such as a metal or SiC susceptor, they can be reflected back towards the source. If these reflected waves combine with incoming waves, they can create areas of high and low intensity that remain fixed in space, leading to standing wave patterns. Therefore, this result in this research clearly indicated that it is important to carefully optimize the number and placement of susceptors in order to achieve high heating efficiency in microwave hybrid heating.

In this research, the optimal heating conditions for microwave hybrid heating (MHH) were investigated, and it was found that using two silicon carbide susceptor plates provided the most efficient heating. By applying microwave power at 100% (1,200 W), the oven temperature reached a maximum of 925°C in 15 min. This heating rate averaged at 62°C/min, which is comparatively higher than other conditions. In addition to the observed effects of the number of SiC plates and microwave power levels on temperature, the position of SiC within the chamber has a significant impact on the temperature distribution in the microwave hybrid heating system due to variations in microwave absorption and reflection angles. In future research, it is important to examine the effect of the position of SiC susceptor on the temperature profile within the chamber.

Conclusions

This study investigated the effectiveness of different configurations of silicon carbide (SiC) susceptors in microwave hybrid heating (MHH) for sintering ceramics. The results suggest that the use of two SiC susceptor plates with microwave power at 100% (1,200 W) is the most effective configuration for achieving a high heating rate of 62°C/min to reach the target temperature of 925°C within 15 min. It was also observed that increasing the number of SiC

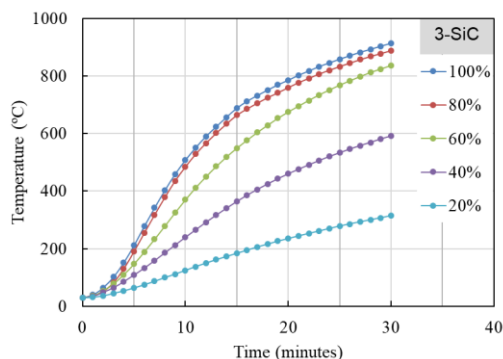


Figure 4. Temperature profiles in the microwave oven when using three SiC susceptor plates, with microwave powers at 20, 40, 60, 80, and 100%

susceptors (three plates) led to a decrease in heating rate due to the impedance of microwave absorption. The findings of this study provide guidance for selecting appropriate heating conditions to enhance the sintering process and improve the properties of materials. Further studies can explore the applicability of MHH for sintering of various kinds of material and optimizing the heating parameters for specific applications.

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