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UNDERSTANDING THE ROLE OF SUSCEPTORS IN HYBRID HEATING AND THE PROPERTIES OF WAXES FOR ENHANCED DEWAXING IN INVESTMENT CASTING

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ABSTRACT

This research investigates the use of microwave hybrid heating (MHH) to address two critical challenges in investment casting: reducing cracks in ceramic moulds during the dewaxing process and minimizing dewaxing cycle time. By incorporating silicon carbide (SiC) as a susceptor material in the ceramic mould shell, microwave energy absorption is enhanced, enabling faster and more uniform heating. Two wax types, HYFILL B289 and SIVUCH L1203, were evaluated for their thermal properties and performances during dewaxing. Results revealed that the addition of SiC significantly improved the mould's dielectric properties, reduced porosity, and increased thermal conductivity, leading to a 53.6% reduction in dewaxing time with no cracking observed. This study demonstrated the potential of MHH as a sustainable and efficient alternative to conventional heating methods for investment casting.

KEYWORD

Microwave Hybrid Heating (MHH), Investment Casting, Ceramic Mould Cracking, Dewaxing Process, Silicon Carbide (SiC) Susceptors

INVESTMENT CASTING

Investing casting also known as "lost wax casting," is one of the oldest and most advanced metallurgical technologies, dating back to over 5,000 years. This process is widely used in various industries, including aerospace, automotive, medical, and sports equipment manufacturing, owing to its ability to produce complex, near-net-shape components with exceptional dimensional accuracy. The flexibility of investment casting allows for minimal material waste, reduced energy consumption, and limited machining requirements, thus making it a highly efficient and sustainable manufacturing method. Despite these advantages, the investment casting process faces significant challenges, particularly during the dewaxing stage.

DEWAXING

Dewaxing a critical step in investment casting, involves removing the wax pattern from the ceramic mould by applying heat. Traditional dewaxing methods, such as autoclaves and flash fire heating, often lead to thermal stress-induced cracks in the green ceramic mould shell (Fabio et al., 2009). Studies indicate that approximately 80% of cracks in green ceramic moulds occur during the dewaxing process, primarily due to excessive thermal expansion of the wax and the weak green strength of the mould caused by high porosity (Yahaya et al., 2016). These cracks compromise the structural integrity of the mould, resulting in defects in the final cast product and increased production costs. Additionally, conventional dewaxing methods are time-intensive, typically requiring 20 to 40 minutes per cycle, which limits production efficiency.

MICROWAVE HEATING

Microwave heating technology offers a promising alternative to conventional heating methods for dewaxing. Unlike traditional heating, which relies on heat conduction, microwave heating converts electromagnetic radiation into thermal energy, thereby enabling rapid and volumetric heating (Deng et al., 2022). However, direct microwave heating faces challenges because most ceramic materials are poor microwave absorbers at room temperature. This limitation can lead to selective heating, thermal runaway, and plasma generation, which hinders the effectiveness of the process. To address these challenges, microwave hybrid heating (MHH) was developed. MHH enhances the dielectric properties of ceramic moulds by incorporating microwave-absorbing materials known as susceptors, such as silicon carbide (SiC), carbon, and alumina (Heuguet et al., 2013). These susceptors facilitate uniform heat distribution and improve the microwave absorption capability of the mould. In this study, SiC particles were incorporated into the backup layers of the ceramic mould shell to enhance their microwave absorption properties. Two types of waxes, HYFILL B289 and SIVUCH L1203, were evaluated for their thermal expansion, melting characteristics, and suitability for microwave dewaxing.

MATERIAL AND METHODOLOGY

Ceramic moulds were prepared using a standard slurry-based process, incorporating silicon carbide (SiC) particles into the backup layers to enhance microwave absorption, dielectric properties, thermal conductivity, and strength. Two wax patterns, HYFILL B289 and SIVUCH L1203, were analyzed for thermal expansion, melting characteristics, and viscosity. The dewaxing process was performed using a modified Panasonic NN-CD87KS microwave oven equipped with SiC susceptors to enable hybrid heating. Moulds were subjected to varying microwave power levels, with key parameters such as dewaxing time, temperature distribution (monitored using thermal imaging cameras), wax removal efficiency, and mould integrity assessed.

RESULT AND DISCUSSION

Table 1 and Figure 1 summarizes the relationship between temperature (T) and the thermal expansion coefficient (α) for both HYFILL B289 MOD S Wax and SIVUCH L1203 Wax, demonstrating a distinct trend influenced by material behavior under thermal stress. For HYFILL B289 MOD S Wax, α increases significantly from $42.42 \times 10^{-6}/°C$ at 30°C to a peak value of $73.73 \times 10^{-6}/°C$ at 45°C, suggesting a thermal softening effect that facilitates greater molecular movement and expansion. However, beyond this point, α decreases to $65.16 \times 10^{-6}/°C$ at 50°C and further to $54.57 \times 10^{-6}/°C$ at 55°C, likely due to structural relaxation or saturation in thermal expansion capacity. In contrast, SIVUCH L1203 Wax exhibits a much lower α, rising gradually from $9.19 \times 10^{-6}/°C$ at 30°C to a peak of $52.16 \times 10^{-6}/°C$ at 40°C, indicating its relatively stable structure under heating. Beyond 40°C, the coefficient declines sharply to $33.79 \times 10^{-6}/°C$ at 50°C and drops further to $1.83 \times 10^{-6}/°C$ at 55°C, highlighting superior dimensional stability compared to HYFILL B289 MOD S Wax. This behavior reflects the reduced susceptibility of wax to thermal stress and its suitability for precision casting applications (Araki et al., 1998). Comparatively, the ceramic shell exhibits an exceptionally low thermal expansion coefficient, maintaining values between $1.42 \times 10^{-6}/°C$ at 30°C and $0.85 \times 10^{-6}/°C$ at 55°C. This stability confirmed the ability of the ceramic to resist thermal deformation, which is critical for mould integrity during heating and wax expansion. Overall, the significant disparity between the waxes and ceramic shell highlights the need for careful process control to minimize the thermal stresses and prevent cracking during dewaxing.

Table 1: Thermal expansion coefficient (α) for pattern waxes and ceramic mould shell

T (˚C)	Thermal expansion coefficient α (10^{-6} /˚C)		
	HYFILL B289 S Wax	SIVUCH L1203 Wax	Ceramic mould shell
30	42.4210	9.1887	1.4211
35	58.7380	43.4067	1.4014
40	68.6437	52.1629	1.2079
45	73.7290	46.5747	0.1044
50	65.1626	33.7855	0.9361
55	54.5684	1.8381	0.8504

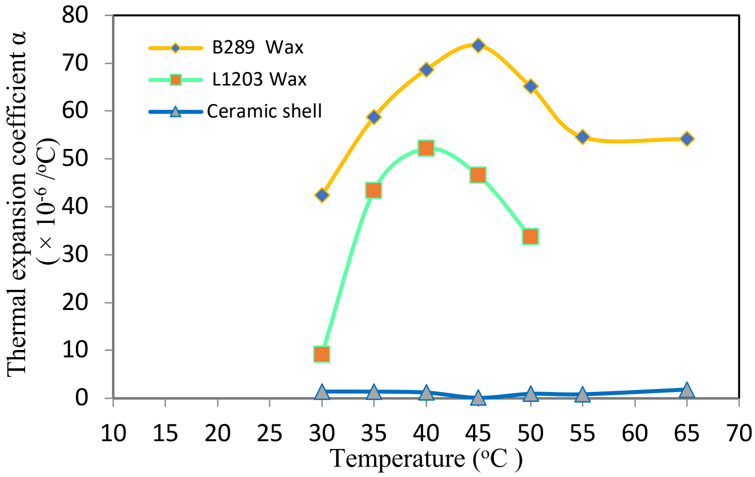

Figure 1: Thermal expansion coefficient as a function of temperature for samples material

The relationship between the SiC content (wt. %) and the thermal conductivity of ceramic moulds demonstrates a clear increasing trend, as shown in Figure 2. Initially, at 0% SiC, the thermal conductivity was approximately 4 W/m · K, reflecting the baseline behavior of the ceramic material. With the addition of SiC at 2.5 wt. %, the thermal conductivity significantly rises to about 6.5 W/mK, followed by further increases to approximately 7.5 W/mK and 9.5 W/mK at 5 wt.% and 7.5 wt.%, respectively. This progressive enhancement in the thermal conductivity can be attributed to the intrinsic properties of silicon carbide, which has a higher thermal conductivity than the ceramic matrix. SiC particles act as thermal bridges within the ceramic structure, reducing the thermal resistance and facilitating the heat transfer. Furthermore, the consistent increase in the thermal conductivity, as confirmed by the high R^2 value (96.6%), indicates a strong correlation between the SiC content and thermal performance. However, slight variations in the error bars suggest minor deviations due to material inhomogeneity or particle distribution at lower SiC concentrations. Overall, the addition of SiC enhances the thermal conductivity of ceramic moulds, which is beneficial for improving the heat transfer during casting processes, thereby reducing defects and enhancing mould performance.

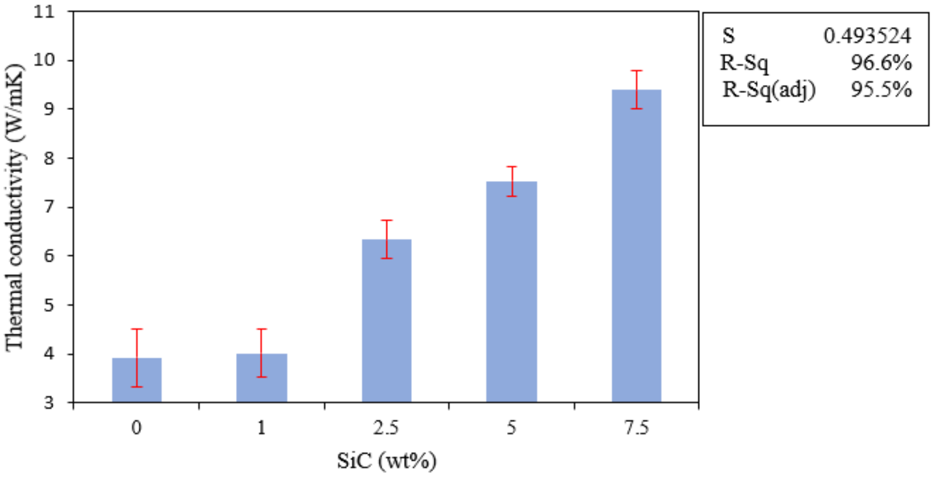

Figure 2: Thermal conductivity of ceramic moulds with various SiC wt.%

Figure 3 illustrates the relationship between the SiC content (wt. %) in ceramic moulds and dewaxing time, showing a clear and consistent reduction in dewaxing time as the SiC content increases for both HYFILL B289 S Wax and SIVUCH L1203 Wax. At 0% SiC, the dewaxing times are at their peak, recorded at 20.5 minutes for HYFILL B289 S Wax and 19 min for SIVUCH L1203 Wax. However, as SiC content increases to 1%, dewaxing time decreases significantly to 14.75 minutes and 13.30 minutes, respectively. This trend continues with further reductions observed at 2.5% SiC, where dewaxing times drop to approximately 10.25 minutes for HYFILL B289 S Wax and 9 minutes for SIVUCH L1203 Wax. At 7.5% SiC, the dewaxing time reaches its lowest values of 8.80 minutes and 7.25 minutes for HYFILL and SIVUCH waxes, respectively. This decrease can be attributed to the enhanced thermal conductivity of the ceramic moulds with increasing SiC content, which accelerated the heat transfer during the dewaxing process. SiC particles act as thermal conductors, allowing wax to melt more efficiently and escape faster from the ceramic mould. Additionally, the superior thermal properties of SiC reduce its thermal resistance, thus minimizing the time required to achieve complete wax removal. Overall, the inclusion of SiC in ceramic moulds significantly improves the efficiency of the dewaxing process, with higher SiC content resulting in shorter dewaxing times.

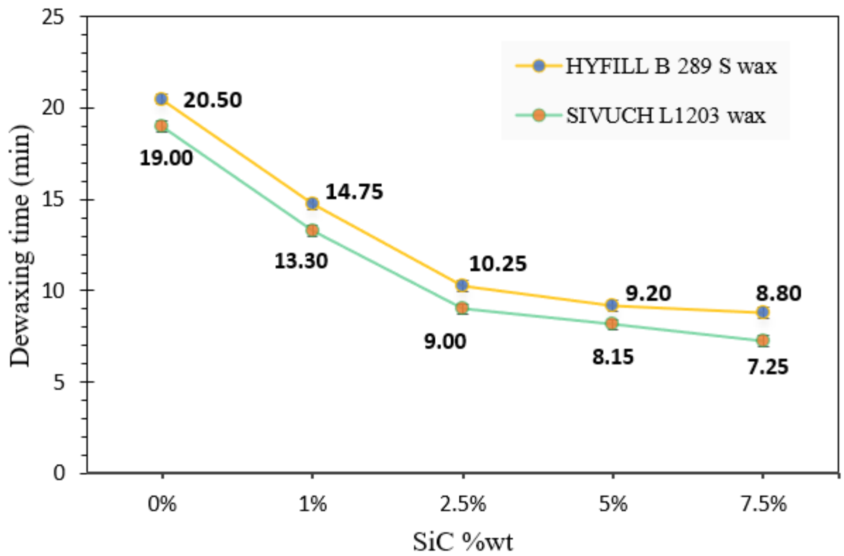

Figure 3: Effect of increasing the percentage of SiC on dewaxing time

CONCLUSION

This study demonstrates the effectiveness of microwave hybrid heating (MHH) as a sustainable and efficient alternative to conventional dewaxing methods in the investment-casting process. The incorporation of silicon carbide (SiC) as a susceptor material significantly enhanced the thermal conductivity and dielectric properties of the ceramic moulds, enabling uniform and rapid heating. By reducing the thermal stresses during the dewaxing process, MHH successfully eliminated cracking in the moulds, which is a common issue in traditional autoclave and flash fire methods. The use of MHH also reduced dewaxing time by 53.6%, significantly improving production efficiency. Additionally, the evaluation of two wax types, HYFILL B289 and SIVUCH L1203, revealed that SIVUCH L1203's lower thermal expansion and viscosity made it more suitable for microwave-based dewaxing. These results highlight the potential of MHH to address critical challenges in investment casting, offering improved mould integrity, reduced cycle times, and enhanced process sustainability. This approach provides a foundation for further research and industrial adoption of advanced heating technologies in casting applications.

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