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Advanced Integration of Microwave Kiln Technology in Enhancing the Lost-Wax Glass Casting Process: A Study on Methodological Innovations and Practical Implications

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Abstract: Lost-wax glass casting, an esteemed yet technically demanding art form, traditionally relies on specialized, costly kiln equipment, presenting significant barriers to artists regarding equipment affordability, energy efficiency, and the technical mastery required for temperature control. Therefore, this study introduces an innovative approach by integrating a microwave kiln with standard household microwave ovens, thus facilitating the lost-wax glass casting process. This methodological adaptation allows artists to employ readily available home appliances for glass creation, significantly reducing the process's cost and complexity. Our experimental investigations reveal that, by using a 500W household microwave oven for heating, the silicon carbide (SiC) in microwave kilns can efficiently absorb microwave energy, allowing the kilns to reach temperatures exceeding 700 °C, a critical threshold for casting glass softening. We further demonstrate that by adjusting the number of heating cycles, producing high-quality, three-dimensional(3D) glass artworks is feasible, even for large-scale projects. In addition, the microwave kiln can be used as an effective cooling tool to uniformly cool the formed casting glass. This study presents a possible alternative to conventional kiln technology and marks a paradigm shift in glassmaking, offering a more accessible and sustainable avenue for artists and practitioners.

Keywords: 3D glass artwork; microwave kiln; lost-wax glass casting; high-temperature kilns; casting materials

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1. Introduction

Glass crafts played a pivotal role in the traditional crafts of ancient Egypt. It not only laid the groundwork for contemporary glass crafts but also led to the development of numerous glassmaking techniques. Initially, the focus of glassmaking was on creating jewelry and intricate decorative items. As time progressed, however, the scope of glass craft broadened to include the manufacture of practical glassware [1]. It was not until the Middle Ages that glass began to be widely used in architecture, with stained glass windows being the most common in churches throughout Europe [2]. In ancient times, glass was not commonly used as a material for sculptures. During the glassmaking process, even skilled artisans encountered challenges in making glass under extreme temperatures, whether high or low [3]. At that time, silicate glass was mainly composed of sand, and it could be shaped into various glass artworks through techniques like blowing, casting, and flame working [4]. The creation of these glass artworks is primarily inspired by nature, biological and human structures, geometric shapes, and abstract forms, thereby infusing new artistic styles into glass crafting [5]. However, after centuries of evolution and advancements in technology and science, glass has emerged as a common material for sculpture [6]. By the 20th century, glassmaking techniques had advanced to a level that allowed for practice in individual studios. Rather than adopting factory-style mass production, these artists prioritized experimental approaches to glass art [7]. These artists are not only knowledgeable in the science of glass but are also skilled in the use of hot and cold glass processing techniques to realize their glass creations [5]. The field of glassmaking has seen a notable shift in recent years, with an increasing number of artists exploring the use of microwave kilns for creating small-scale glass and ceramic artworks. A microwave kiln, a compact, refractory material-based tool, is designed to fit within a household microwave oven and uses microwave radiation to rapidly heat and melt glass. This technology, primarily employed for melting small glass objects or glass pieces into functional items and jewelry, offers artists a means to pursue glassmaking with considerations for safety, material conservation, and energy efficiency [8,9].

Although suitable for small-scale production, microwave kilns have traditionally been used primarily for melting flat glass and jewelry making, with few studies confirming their utility in the manufacture of 3D glass artwork. In contrast, lost-wax glass casting is a method known for its complexity and interdisciplinary nature spanning art, science, and materials engineering. This method surpasses the design constraints associated with flat glass, facilitating the creation of more diverse 3D glass artworks. The lost-wax glass casting process involves initially crafting a wax model that is subsequently transformed into a refractory plaster mold. Following dewaxing to achieve a hollow mold, casting glass is poured in. The final step entails firing the mold within a kiln at elevated temperatures, causing the glass to melt and fill the entire mold inside, thereby forming a 3D glass artwork [7,10,11]. However, the lost-wax process, particularly when executed at high temperatures exceeding 1000 °C, presents substantial challenges, including the need for specialized kiln equipment and expertise in temperature control [5]. Particularly in the firing process of glass art, it is crucial to prevent the formation of air bubbles in the glass [12,13]. Although the technology demands a complex production process and strict high-temperature control, it enables artists to actualize their design ideas and create unique glass pieces. Due to the relatively high threshold of lost-wax glass casting technology, a significant investment in kiln equipment and processing tools is required for in-depth exploration and learning of this technique. Moreover, conventional furnaces not only consume a considerable amount of electricity but also tend to emit harmful emissions and increase the ambient temperature. On the other hand, the cost of purchasing kiln equipment poses a significant burden for artists with limited space and funds.

Addressing these challenges, this study proposes an innovative approach that integrates the microwave kiln with lost-wax glass casting techniques. This integration aims to simplify the traditional high-temperature glass firing process, potentially transforming it into a more accessible and time-efficient practice. Compared with previous studies that focused on the use of microwave kilns for flat glass art and the challenges of high-temperature control in traditional lost-wax glass casting, this study provides a novel approach to creating three-dimensional glass art without the need for traditional high-temperature kilns. By doing so, it opens the door for creating unique, intricate 3D glass art pieces. Additionally, the study explores the potential of increasing the thickness of refractory gypsum in microwave kiln applications, aiming to enhance our understanding of the glass firing process within this novel context. Through this approach, the study seeks to lower the technical barriers inherent in traditional lost-wax glass casting, thereby expanding the creative possibilities for artists in the realm of glassmaking and potentially revolutionizing the field with this accessible, innovative technology. This innovation not only offers a more convenient method for glass art practitioners to create 3D pieces but also broadens the application range of microwave kilns.

2. Materials and Methods

2.1. Microwave Kiln

The microwave kiln is a white cylindrical glass-melting refractory tool consisting of a lid and a base. The top of the lid has a central hole that allows smoke to escape and also serves as a means to observe the glass melting process. Additionally, it is composed of two different materials. The white part is made of ceramic fiber, a material known for its fire-resistant properties, whereas the interior of the kiln is made of silicon carbide (SiC), primarily used to absorb microwave radiation within the microwave oven for rapid heating effects, as illustrated in Figure 1. This tool offers significant advantages for creating small glass sculptures. Under normal operation, placing the microwave kiln in a medium-sized home microwave oven with a power of 1100 W can rapidly heat it to temperatures exceeding 900 °C within 5–10 min, causing the glass within the microwave kiln to melt. In terms of both glass firing and cooling times, it reduces more than half the time and decreases electricity consumption compared to professional kilns, thereby enhancing production efficiency [14,15]. The microwave kiln is a very practical tool for studios with limited space and funds or for individual creators.

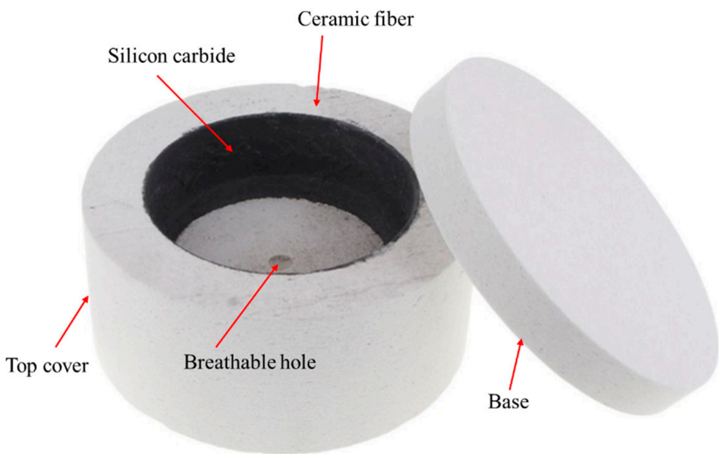

Figure 1. Schematic diagram of the microwave kiln.

It is noteworthy that, in the case of glass firing using a microwave kiln, unlike professional kilns, there is no microcomputer temperature controller. Therefore, when melting glass in a microwave kiln placed inside a microwave oven, observation of the glass melting process is required through the hole in the kiln's lid. Due to the limited view from the hole, it is common practice to remove the microwave kiln from the microwave oven after the firing process is completed and then lift the lid of the kiln for further observation of the melted glass. As usage increases, the microwave kiln's internal heating material, silicon carbide, undergoes wear and tear from microwave heating. This deterioration not only impairs the kiln's heating efficiency but may also lead to silicon carbide fragments dislodging from the kiln's lid and falling onto the glass artwork, causing defects. Consequently, the decision to replace the microwave kiln should be based on careful consideration of its usage conditions. Additionally, factors such as the microwave oven's output power and the size and design of the glass can affect the firing temperature and the number and duration of the firing cycles.

2.2. Casting Glass

Lost-wax glass casting utilizes casting glass blocks with a coefficient of expansion (COE) of 96 as the creative material. This type of casting glass is also known as lead crystal glass, containing 24% to 40% lead oxide (PbO). The most notable characteristics of casting glass are its lower processing temperature, higher fluidity for easy molding, and considerable transparency and refractive index [16,17]. It is frequently utilized as an important material in the production of high-quality tableware [18]. Furthermore, this leaded glass can be recycled and re-melted to form new glass [19]. In this study, the casting glass size is a circular disk with a diameter of 100 mm and a thickness of 15 mm. Before firing, the casting glass needs to be cleaned and wiped dry. Then, it is shattered into small pieces and granules using a tungsten steel hammer. These glass fragments are then placed into a refractory gypsum mold, preparing for the heat processing stage.

2.3. Casting Refractory Gypsum

During the lost-wax glass casting process, the preparation of refractory materials capable of withstanding high temperatures is essential in the pre-manufacturing stage of heat processing. Refractory plaster molds are composed of adhesives, modifiers, quartz sand, and other refractory materials. They possess a robust structure capable of enduring high temperatures and exhibit excellent fire-resistant properties, making them suitable for various high-temperature casting applications. Refractory gypsum is typically mixed with water and then poured into a wax model to create a thick refractory plaster mold. This is followed by a high-temperature dewaxing process, where the wax is melted away, leaving behind a hollow refractory plaster mold. Casting glass is then placed inside this mold, and subsequently, the assembly is put into a kiln. The glass is heated to high temperatures until it melts and takes the shape of the mold's interior. Subsequently, after firing and molding in the kiln, the refractory plaster molds have to be dismantled to remove the glass work, a process that can lead to mold breakage, so these refractory molds are generally used only once and are not suitable for repeated use [11,19,20].

2.4. Lost-Wax Glass Casting

Casting is one of the oldest technological crafts in the world [13]. Early humans had already mastered the use of simple tools to create wax models, which were then placed in sand molds for heating. Subsequently, the wax was poured out to obtain a hollow sand mold, into which molten metal was poured and left to cool and solidify, ultimately yielding metal tools [21]. This intricate production process is defined as lost-wax casting. Over time and through the centuries, the casting technique has been widely adopted in various countries to create jewelry, idols, and other art forms. This is evidenced by ancient artifacts discovered in Egypt, Central and South America, Greece, Mexico, China, and India [22]. Throughout the development of casting techniques, ancient Egyptians as early as 3000 BC not only knew how to utilize metal for lost-wax casting but also mastered the transformation of metal into glass materials, giving rise to the earliest known lost-wax glass casting [3]. The uniqueness of lost-wax glass casting lies in the glass's ability to produce varying refractions and color effects with changes in light angle. This allows for the observation of the glass's internal fluidity, resulting in a rich array of visual effects [23]. With the Syrian's discovery of glass blowing, artisans crafted a wide array of items, including glasses, bowls, and other everyday objects. As demand surged and glassware spread throughout the Roman Empire, the older technique of lost-wax glass casting gradually faded into obscurity [24]. It was not until the late 19th century that the French ceramic artist Henri Cros made significant improvements to the lost-wax glass casting technique. Compared to the ancient version of lost-wax glass casting, which only allowed for partial glass objects on the surface of artworks, Henri Cros' modification involved melting the primary components of glass at high temperatures and then processing them into glass materials. Subsequently, these glass materials were broken down or ground into granules or powder and placed into refractory gypsum molds to cast integrated glass artworks. At the time, artists in European countries extensively utilized this glass-casting technique in their arts and crafts designs [5,25–27].

Up to the present day, lost-wax glass casting has evolved into a comprehensive production process. This process includes creating wax models and replicating them in refractory gypsum molds, followed by high-temperature dewaxing to obtain hollow refractory gypsum molds. Casting glass material is then placed inside these molds and kiln-fired. Finally, the refractory gypsum molds are dismantled, and the pieces are ground and polished to create exquisite glass artwork [25]. This study aims to verify the feasibility of implementing lost-wax glass casting using a microwave kiln. For the heat processing stage, a combination of a microwave oven and a microwave kiln is used to produce 3D glass artwork, with the production process illustrated in Figure 2.

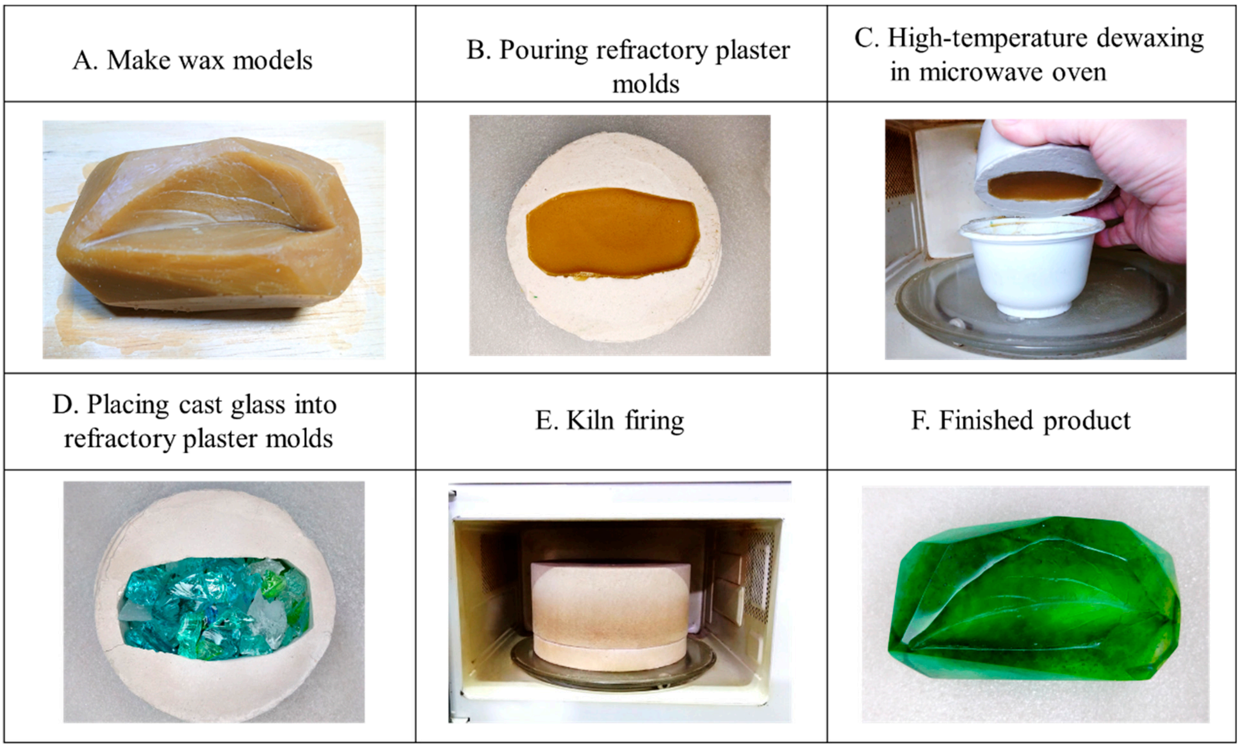

Figure 2. Schematic diagram of the lost-wax glass casting production process.

2.5. Experimental Procedures

To confirm the innovative application of the microwave kiln in lost-wax glass casting technology, two sizes of microwave kilns were used in the heat processing stage to produce 3D glass artworks.

The large kiln measures diameter 195 mm × height 110 mm externally and diameter 135 mm × height 45 mm internally. The small kiln measures diameter 120 mm × height 45 mm externally and diameter 75 mm × height 45 mm. A 500 W household microwave oven was utilized for the process. In addition, three different sizes and shapes (from small to large) of refractory plaster molds with a thickness of over 1 cm were prepared for testing, as shown in Figure 3:

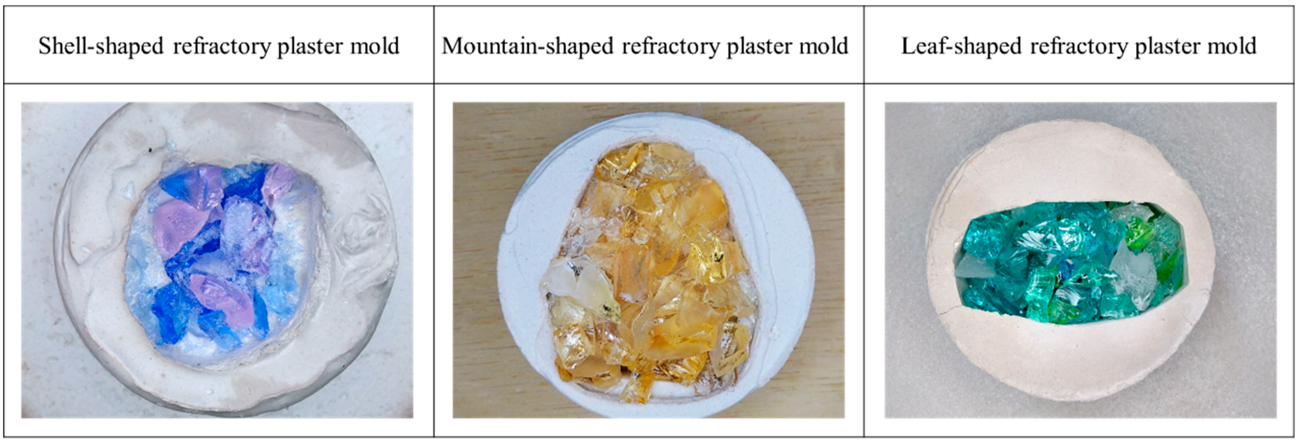

Figure 3. Schematic diagram of refractory plaster molds.

A shell-shaped mold, diameter 6 cm × height 2 cm in height, holds 30 g of casting glass to produce an artwork of length 3.5 cm × width 2 cm × height 1 cm.

A mountain-shaped mold, diameter 8 cm × height 3.5 cm in height, holds 60 g of casting glass to produce an artwork of length 3.5 cm × width 2 cm × height 5.5 cm.

A leaf-shaped mold, the largest, at a diameter of 9.5 cm × height 4 cm in height, holds 219 g of casting glass to produce an artwork of length 7.5 cm × width 4 cm × height 3 cm.

3. Results and Discussion

In this study, refractory plaster with a thickness of over 1 cm was placed inside a microwave kiln and then heated using a microwave oven. This process successfully produced 3D glass artworks of different sizes. Simultaneously, key factors in the kiln firing process were established, including (1) the output power of the microwave oven, (2) heating duration, (3) number of heating cycles, (4) kiln firing temperature, and (5) cooling time after kiln firing.

The output power and heating time of the microwave oven are very important for the microwave kiln to absorb microwave radiation. These two factors directly affect the degree of melting of the casting glass in the refractory plaster mold. Therefore, effective control of the heating time not only ensures that the casting glass melts uniformly but also prevents overheating, which can lead to air bubbles in the casting glass.

3.1. The First Cast Glass Trial Firing

To investigate the effects of a 500-watt household microwave oven and a microwave kiln on three types of refractory plaster molds of varying shapes, sizes, and glass weights, this study aimed to identify the softening point of the cast glass and the optimal firing time. Experimentally, a shell-shaped mold with a diameter of 6 cm × height 2 cm was placed in a small microwave kiln. Additionally, a mountain-shaped mold with a diameter of 8 cm × height 3.5 cm, and a leaf-shaped mold, the largest, with a diameter of 9.5 cm × height 4 cm, were placed in a large microwave kiln. Subsequently, the microwave kiln was placed in the microwave oven for the initial trial firing of the glass.

As shown in Table 1. Due to the three different molds with different weights of glass used, the first-time trial firing time was set to 15 min for the shell-shaped mold and 30 min for the mountain-shaped mold and leaf-shaped mold to obtain the first cast glass trial firing temperature. As shown in Figure 4, the refractory plaster molds for the shell shape were microwaved for 15 min, and the temperature inside the microwave kiln reached 650.6 °C, which caused the cast glass to melt into the shape inside the mold. However, the temperatures of the cast glass inside the refractory plaster molds for the mountain shape and the leaf shape came to 550 °C and 275.8 °C, respectively, indicating that the cast glass had not yet reached the melting point. Therefore, a second cast glass trial firing will be conducted.

Table 1. Time and temperature for first casting glass trial firing.

Mold Shaping	Glass Weight	Heating Duration	Kiln Temperature
Shell-shaped mold	30 g	15/min	650.6 °C
Mountain-shaped mold	60 g	30/min	550 °C
Leaf-shaped mold	219 g	30/min	275.8 °C

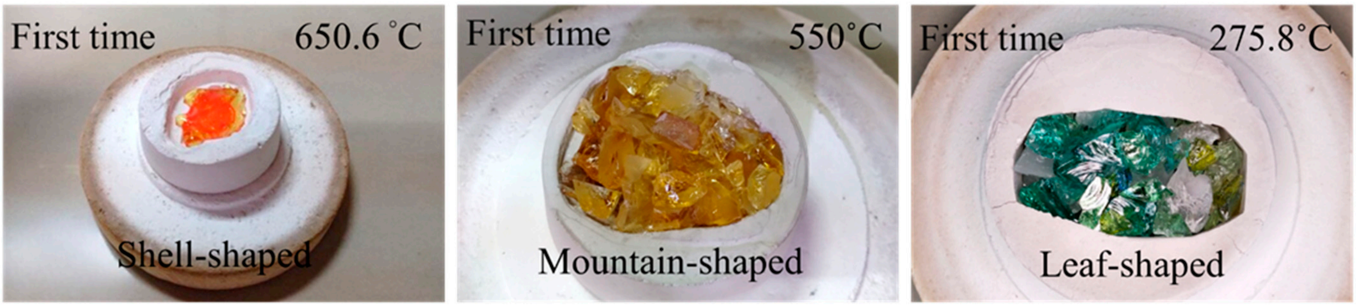

Figure 4. Results of the first cast glass trial firing.

3.2. The Second Cast Glass Trial Firing

Since the temperature of the refractory plaster mold for the mountain shape reached 550 °C during the first trial firing, and the cast glass was evaluated to be only 60 g, the second trial firing time was set to 15 min of microwave heating. Under these conditions, the internal temperature of the microwave kiln reached 681.3 °C, causing the cast glass to melt into the shape of the interior of the mold. On the other hand, for the leaf-shaped refractory plaster mold, the temperature reached 275.8 °C during the first trial firing, and the cast glass was evaluated to be 219 g. The second trial firing time was set to 20 min of microwave heating; at this time, the temperature inside the microwave kiln reached 500 °C, and the cast glass began to soften but did not reach a completely molten state (as shown in Table 2). According to Figure 5, the result of the second casting glass trial firing, therefore, the third glass trial firing will be carried out.

Table 2. Time and temperature for second casting glass trial firing.

Mold Shaping	Glass Weight	Heating Duration	Kiln Temperature
Mountain-shaped mold	60 g	15/min	681.3 °C
Leaf-shaped mold	219 g	20/min	500 °C

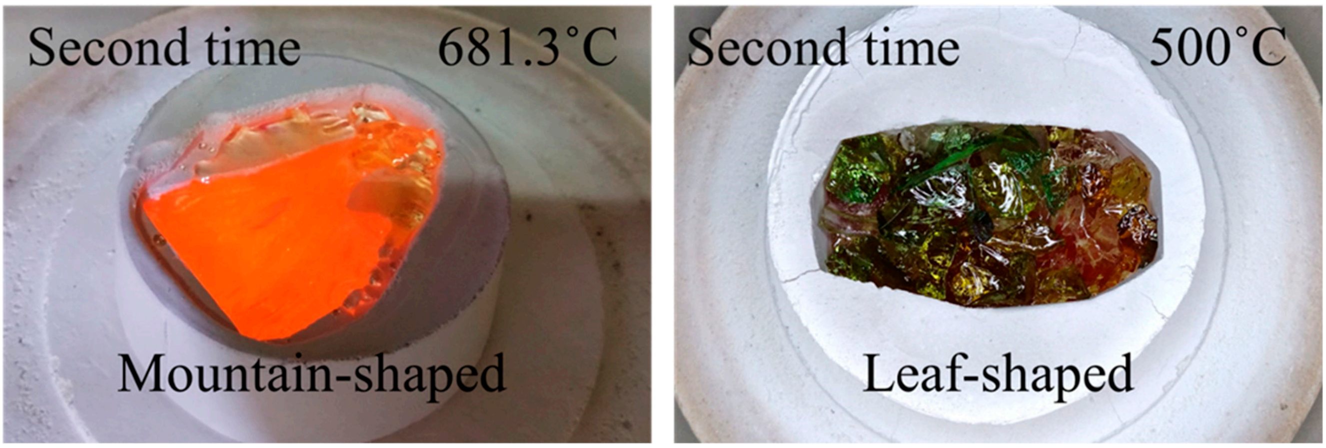

Figure 5. Results of the second cast glass trial firing.

3.3. The Third Cast Glass Trial Firing

During the second trial firing, the temperature of the casting glass in the refractory plaster mold for leaf shaping reached 550 °C; therefore, the third trial firing time was set to 15 min of microwave heating. At this time, the temperature inside the microwave kiln reached 771.7 °C (as shown in Table 3), causing the cast glass to melt into the shape inside the mold, as shown in Figure 6.

Table 3. Time and temperature for third casting glass trial firing.

Mold Shaping	Glass Weight	Heating Duration	Kiln Temperature
Leaf-shaped mold	219 g	15/min	771.7 °C

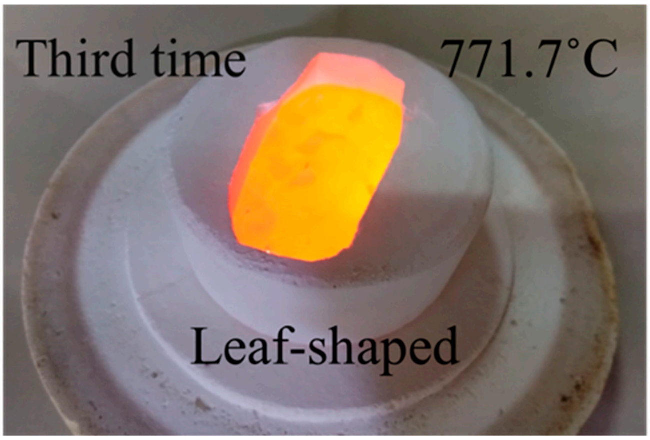

Figure 6. Results of the third cast glass trial firing.

3.4. The Casting Glass Cooling

As shown in Figure 7, when the casting glass in the three different shapes of refractory plaster molds is melted into the shape inside the molds, then it enters the cooling stage. When the shell-shaped cast glass reaches the softening point, the cooling process begins. After three hours, the temperature inside the microwave kiln was reduced to room temperature. The casting glass for the mountain and leaf shapes reached the softening point and started to cool down. After 5 and 8 h, respectively, the internal temperature of the microwave kiln was also reduced to room temperature.

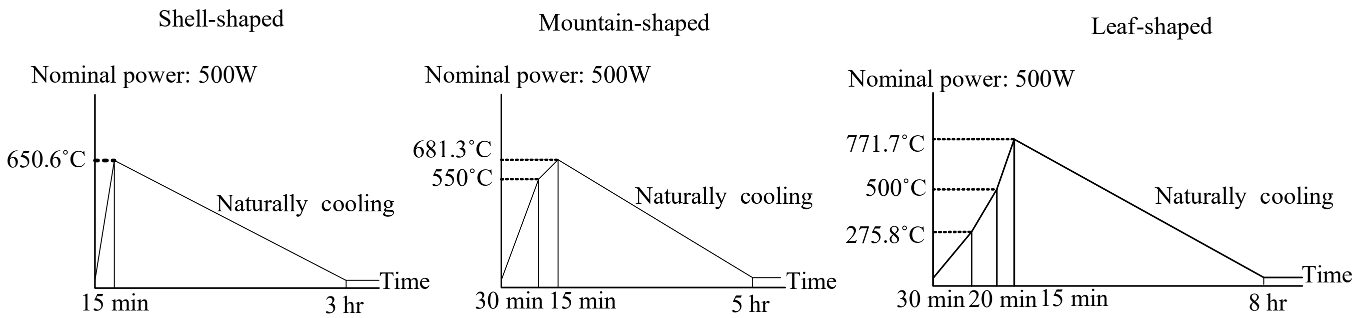

Figure 7. Casting glass firing temperature curves.

3.5. Finished 3D Glass Artwork

As shown in Figure 8, the kiln firing results show that the cast glass in the three different shapes of refractory plaster molds can be softened uniformly during the melting process after one to three different kiln firing times and temperatures. This method prevents excessive glass fluidity due to rapid heating, thereby avoiding defects such as excessive air bubbles on the surface and inside the 3D glass artwork. In this study, it was found that there was a temperature difference between the refractory plaster mold and the cast glass during the kiln firing process. Notably, refractory plaster molds quickly absorb and dissipate heat, whereas cast glass absorbs heat quickly but dissipates it slowly. Therefore, to create 3D glass artwork, the larger the refractory plaster mold and the heavier the weight of the cast glass, the number of heat cycles will need to be increased to ensure consistent temperatures inside and outside the mold.

Figure 8. 3D glass artwork in different shapes.

3.6. Comparison of a Microwave Kiln and a Conventional Kiln in 3D Glass Artworks

As shown in Figure 9, a mountain-shaped 3D glass artwork serves as an example. The same cast glass and refractory plaster molds were used and then fired in both the microwave kiln and the traditional kiln, respectively. Subsequently, a close-up examination of the back of the 3D glass artwork revealed that, while some tiny air bubbles exist in the pieces fired in the microwave kiln, fewer air bubbles were present in those fired in the traditional kiln. In other words, the quality of 3D glass artwork fired in a microwave kiln already approaches that of pieces fired in professional kilns.

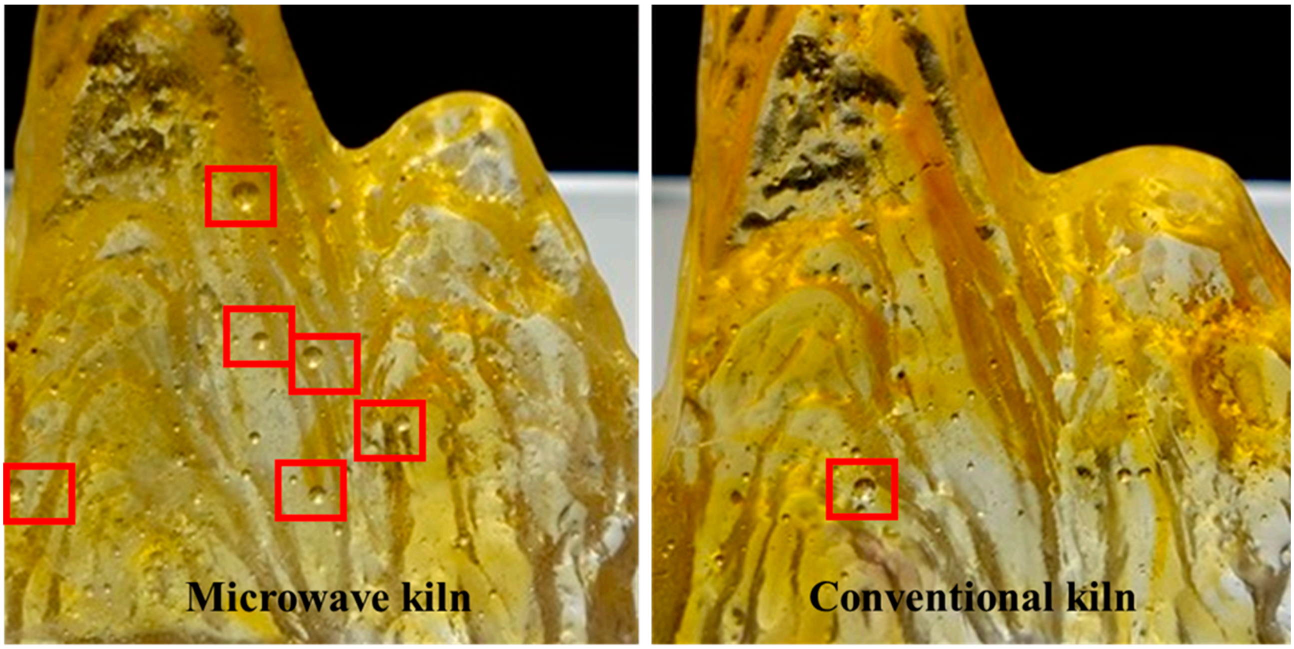

Figure 9. Comparison of the number of air bubbles in 3D glass artworks fired in different kilns.

4. Conclusions

This study utilized a microwave kiln in combination with a household microwave oven as an alternative to traditional kiln equipment, exploring the feasibility of implementing lost-wax glass casting with the goal of lowering the technical threshold and reducing production costs. This innovative approach challenges conventional reliance on traditional kiln equipment and offers a more accessible and cost-effective solution for glass artists and hobbyists. It significantly reduces the entry barrier and operational costs for producing small-scale 3D glass artworks, making it an attractive option for individual artists and small studios.

According to the data from the temperature curves of three different cast glass kiln firings, using a small microwave kiln to produce shell-shaped cast glass required only

15 min to reach high temperatures of around 650 °C, sufficient for creating 3D glass artworks. In contrast, larger volumes of mountain and leaf-shaped glass artworks required a large microwave kiln, 2 to 3 rounds of kiln firing, and observation. The firing duration for these larger pieces ranged from 45 min to over an hour to reach temperatures around 770 °C. Additionally, the glass cooling time for these larger artworks varied from 5 to 8 h before proceeding to the subsequent cold processing and grinding procedures. A critical contribution of this research lies in its detailed investigation of the optimal conditions required for producing 3D glass artworks. The study meticulously examined the interactions of several factors, such as microwave output power, heating duration, number of heating cycles, kiln firing temperature, and post-firing cooling time. These elements are crucial for ensuring the uniform melting of cast glass within refractory plaster molds, thereby preventing common defects like excessive air bubbles that compromise the integrity and aesthetics of the final artwork.

Moreover, this study demonstrated that silicon carbide (SiC) inside the microwave kiln was able to produce a uniform heating effect on refractory plaster molds and casting glass when absorbing microwave radiation. This finding underscores the potential for using SiC to enhance the quality and consistency of microwave-assisted glass casting. Finally, based on the findings of this study, the feasibility of producing 3D glass artworks can be further explored by considering the modification of microwave absorbers and applying them to the production process of dewaxed glass casting. This suggests new avenues for research and application in the field of glass art production.

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