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Drying of a Slip Casting for Tableware Product Using Microwave Continuous Belt Dryer

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To demonstrate the potential of microwave drying in the ceramic industry, microwave demolding of tableware product by a continuous microwave belt drier has been investigated. This study focuses on the investigation of the effects of the irradiation time, sample size, microwave power and location of magnetron on overall drying kinetics. The results show that microwave drying has several advantages over the conventional method such as shorter processing time, volumetric dissipation of energy throughout a product, high energy efficiency, reduced amount of mold usage, and offering product quality. Further quantitative validation of experimental data could be very useful, especially in providing information for processing high-performance microwave drying for developing the ceramic industry in Thailand.

Keywords Microwave; Drying; Ceramic; Tableware; Slip casting

INTRODUCTION

A practical way to distinguish between the various drying processes is to classify them by the heating mode: convective, radiative, and conductive. Drying with internal heat generation, such as dielectric drying, is a special case. See Mujumdar,[1] Devahastin and Mujumdar,[2] and Metaxas[3] for a detailed discussion on these problems.

One of the reasons for the interest in the interaction of microwaves with dielectric materials is the observation, reported by several investigators in the recent literature,[4–15] that microwave heating can lower the sintering temperature in several dielectric materials by several hundred degrees and shorten drying times; reduced drying defects; greater throughput and energy efficient process; lessened floor-space requirements; and environmentally friendly and easy integration into flexible, automated manufacturing systems in comparison with conventional drying methods. It appears that microwaves not only increase the heating efficiency by concentrating the heating process within dielectric materials rather than in the furnace in which the dielectric material is placed, but also have basic consequences such as more efficient atomic diffusion within dielectric materials.

The major concern facing industry today is increasing productivity while reducing operating costs. Conventional drying of ceramics usually will take a long time (20–30 h). Companies are naturally faced with great problems of products being stored for lengthy periods of time until they are dry, resulting in cost of extra dryers, trays, equipment, inefficiency of mold usage, and energy requirement. Thus, there have been many attempts to increase the rate of drying of ceramics in order to decrease drying time.

Recently, the use of microwave energy in the ceramic industry includes drying, calcining, and firing. Microwave drying has been applied to ceramics since the late 1990s.[16–19] However, the drying of ceramic by a continuous microwave belt dryer has not been reported.

The objective of drying is simply to remove water from the ceramic body without causing any damage. The process must be done both efficiently and economically. Water can leave the surface of the ceramic at a given rate depending on air velocity and temperature. To accomplish good drying requires a method that removes the water from the inside of the ceramic to the outside surface at the same rate as the evaporation of surface water.

The objective of this study is to demonstrate the applicability of microwave energy generated by a continuous microwave belt dryer, an energy-saving and production cost–reducing technology, in a slip casting operation for tableware. The study was focused on the investigation of the effect of the irradiation time, sample size, microwave power, and location of magnetron on overall drying kinetics. The quality and mechanical properties for the cases of microwave-dried products and conventional-dried products are discussed. The understanding of the interaction of microwaves with tableware products in general can be obtained.

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MICROWAVE DRYING

Microwaves are electromagnetic waves with frequencies ranging from 0.3 to 300 GHz. The common frequency for commercial microwave systems is 2.45 GHz at a wavelength about 122.4 mm. Microwaves can be transmitted, reflected, or absorbed, depending on the dielectric properties of the dielectric materials of interest. In contrast to conventional drying, the water in the material absorbs microwaves throughout the entire mass so the heating is from within. In general, because of the heat losses at the surface, the interior part achieves higher temperature and dries first. Moisture inside is expelled to the surface with low pressure. This means that the shrinkage begins at the center and progresses to the surface. With microwave drying, the product being dried is hot and dry on the inside and cooler and wetter on the outside. Thus, a surface crust does not develop.

In analysis of dielectric heating, the root mean square value of the electric field intensity E is normally used to evaluate the microwave energy absorbed. Thus, the microwave energy absorbed, or local volumetric heat generation term can be defined as:[12]

$$Q = \sigma |E|^2 = 2\pi f \varepsilon_0 \varepsilon_r' (\tan\delta) E^2 \tag{1}$$

where Q is microwave energy absorbed, σ is effective conductivity, f is frequency, ε_0 is permittivity of free space (8.86×10^{-12} F/m), ε_r' is relative dielectric constant, $\tan\delta$ is loss tangent coefficient, and E is electric field intensity.

In the above equation, the microwave energy absorbed is proportional to the frequency of the applied electric field and dielectric loss factor and is proportional to the square of local electric field. This equation is crucial in determining how a dielectric material will absorb microwave energy when it is placed in a high-frequency electric field. However, the interaction between electromagnetic field and dielectric material during applied microwave field depends on the dielectric properties of that materials.

When the material is heated unilaterally, it is found that as the dielectric constant and loss tangent coefficient vary, the penetration depth will be changed and the electric field within the dielectric material is altered. The penetration depth is used to denote the depth at which the power density has decreased to 37% of its initial value at the surface.

$$D_p = \frac{1}{\frac{2\pi f}{v}\sqrt{\frac{\varepsilon_r'\sqrt{1+\left(\varepsilon_r''/\varepsilon_r'\right)^2}-1}{2}}} = \frac{1}{\frac{2\pi f}{v}\sqrt{\frac{\varepsilon_r'\sqrt{1+(\tan\delta)^2}-1}{2}}} \tag{2}$$

where D_P is penetration depth, ε_r'' is the relative dielectric loss factor, and v is microwave speed.

The penetration depth of the microwave power is calculated according to Eq. (2), which shows how it depends on the dielectric properties of the material. It is noted that products with huge dimensions and high loss factors may occasionally overheat a considerably thick layer on the outer layer. To prevent such a phenomenon, the power density must be chosen so that enough time is provided for the essential heat exchange between boundary and core. If the thickness of the material is less than the penetration depth, only a fraction of the supplied energy will become absorbed.

EXPERIMENTAL PROCEDURE

Microwave Dryer Unit

Microwave drying was carried out in a microwave continuous belt dryer (Fig. 1a). The exterior dimensions of the microwave continuous belt dryer are $5300 \times 1200 \times$

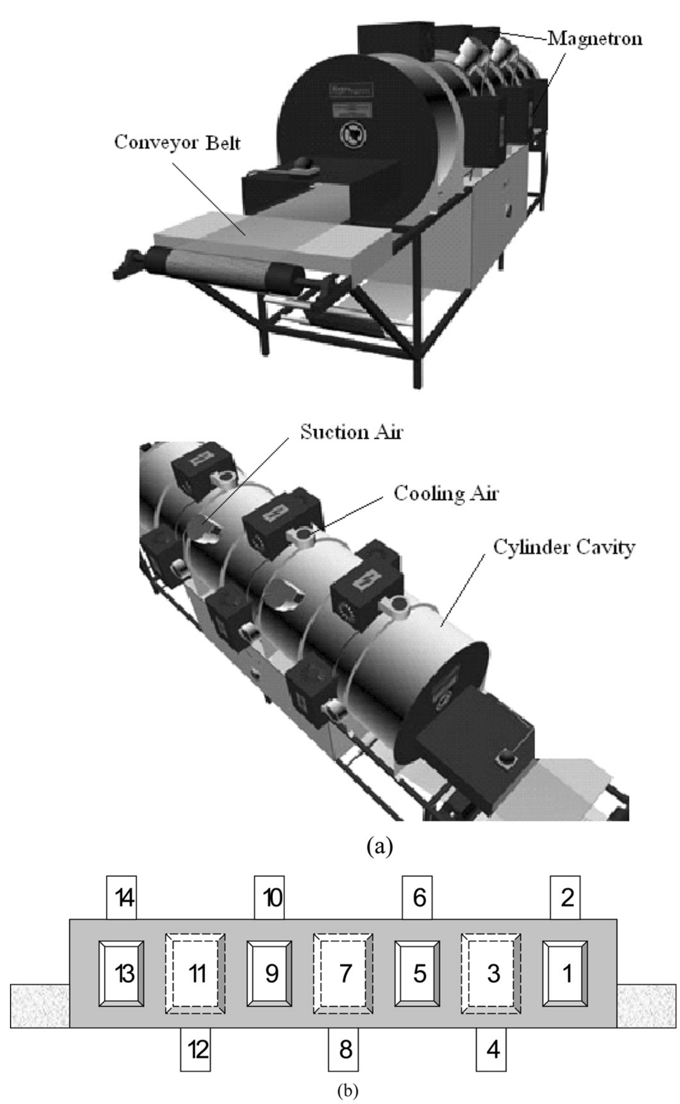

FIG. 1. (a) Microwave continuous belt dryer for drying tableware products, (b) location of 14 magnetrons.

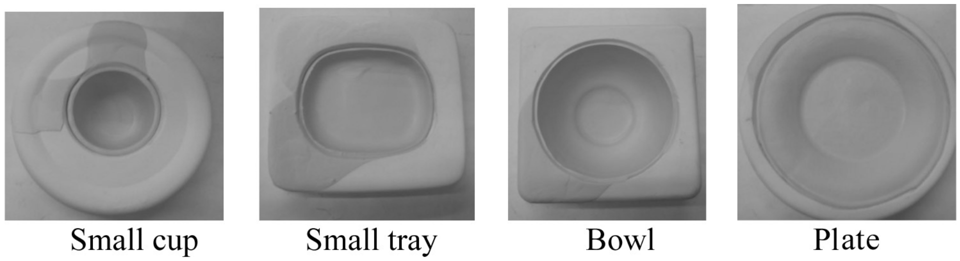

FIG. 2. Tableware samples cast in 4 different size and shapes of mold.

1600 mm. The dryer operates at a frequency of 2.45 GHz with maximum working temperature of 230°C. The microwave power was generated by means of 14 compressed air-cooled magnetrons of 800 watts each for a maximum of 11.2 kW. The power setting could be adjusted individually in 800 W steps. The microwave cavity was cylindrical with rectangular openings at both ends.[19] These openings were equipped with microwave absorbing material to keep microwave leakage well below the DHHS standard of 5 mW/cm^3. The magnetrons were arranged in a spiral around the cylinder cavity (Fig. 1a and b). The microwave power was then directed into the dryer by means of waveguides. The sample to be dried (Fig. 2) passes through the drier on an air-permeable microwave transparent conveyor belt. The speed of the conveyor belt was adjustable up to 2 m/min. In the cavity, microwaves penetrate the sample, heating the water until it diffused to the surface. The humid air was then drawn out of the cavity by a suction system. The dried product leaves the cavity through another opening for further characterization.

Drying Process

The tableware body selected for the drying test was white porcelain clay (PEA, Compound Clay Co. Ltd, Thailand), which had a high casting rate and was suitable for forming tableware. A typical chemical composition is 60.50% SiO_2, 27.60% Al_2O_3, 3.65% K_2O, 1.14% Na_2O, 0.52% Fe_2O_3, 0.11% MgO, 0.09% CaO, 0.03% TiO_2, and 5.51% L.O.I. The clay was mixed with distilled water with a ratio of 20:3 or 87% solid content. The clay slurry was cast in plaster molds of 4 different sizes and shapes (Fig. 2). For comparison, the cast samples were demolded in the microwave belt drier and a conventional oven at 100°C. Drying time, microwave power, speed of continuous belt, sample size, and mold life were varied. Weight change, surface temperature of sample, and temperatures of the mold were measured following each experiment. Repeated tests were also conducted to confirm result validity. All temperatures were recorded with an optical thermometer. The moisture loss from a test sample was determined from the weight change after demolding. The modulus of rupture (MOR) was measured by a 3-point bending method.

RESULTS AND DISCUSSION

Demolding Time

Microwave energy can be used to efficiently demold the tableware products (Figs. 3 and 4). The reduction in energy consumption for demolding products under microwave energy is more than 40% when compared with drying at 100°C in a conventional oven. It is possible to observe from Fig. 4 that for microwave drying the product dries quickly throughout without the shrinkage phenomena that arises for the product due to uniform heating. It is clear that demolding times were drastically reduced compared to conventional drying, from 10 min to less than 6 min. The results show that microwave drying can yield a considerable gain in drying time, by a factor of two or more. In the case of conventional drying, as the surface was dried while the interior was still wet, the dry layer offered resistance to the heat transport, resulting in a reduction of the evaporation rate as well as drying rate and also causing non uniform shrinkage. Varying the product size revealed that a longer time was required for demolding larger samples because of higher internal moisture levels (Fig. 4). As seen in Fig. 5 and Table 1, a higher demolding time of the larger product (e.g., plate) resulted in a higher weight loss and also led to a lower product temperature due to heat loss from the surface. In any case,

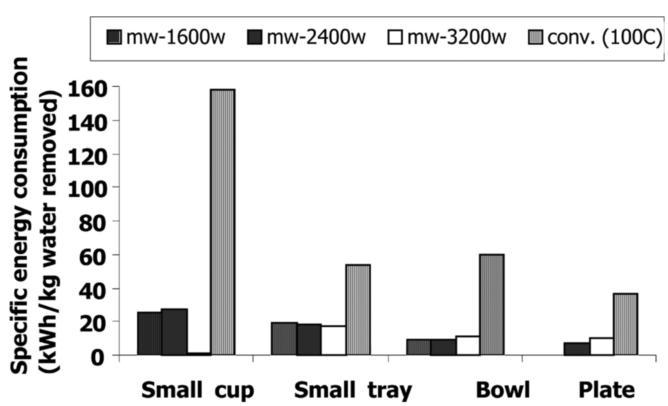

FIG. 3. Preliminary results of specific energy consumption.

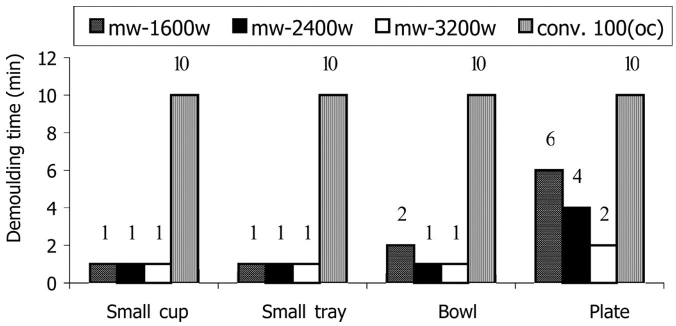

FIG. 4. Demolding time for tableware under conventional vs. microwave drying.

TABLE 1
Product temperature measured just after demolding under microwave and conventional drying

	Product temperature surface (°C)			
	MW drying			Conventional drying
Product	1600 W	2400 W	3200 W	
Small cup	51.4	55.6	57.1	100
Small tray	46.9	50.0	54.8	100
Bowl	48.5	47.0	55.4	100
Plate	46.0	48.0	53.8	100

the temperature of the product rarely exceeded 60°C for microwave drying.

By increasing the microwave power (Table 1), it is found that the product temperature increased in all types of product because the electric field strength increases as the microwave power levels increase (Eq. (1)). In a smaller size product, as microwave power increased, the weight loss of the product increased but there was no difference in the demolding time. The cup and tray samples were still demolded within 1 min. The reason for this result is faster volumetric dissipation of temperature throughout the product, resulting in higher rates of heat loss from the surface.

The drying behavior was quite different in the case of drying a larger product; e.g., a plate. The demolding time of the plate sample was inversely proportional to the increase of microwave power. The higher microwave power used, the greater energy absorbed by moisture inside a product. This enabled moisture to start moving through the mold to the outside wall of the mold faster. Therefore, the product being dried shrank and could be demolded in a shorter time. This led to a smaller amount of weight loss. As seen in Figs. 4 and 5, under 3200 W, the plate could be demolded within 2 min yielding a 1% weight loss, whereas a longer demolding time (6 min) was required under irradiation of 1600 W and resulted in a higher weight loss of 3%.

Mold Life

Table 2 reveals that the demolding time depends on the mold life. It increases as the mold is used for a longer time. The decrease in efficiency of the mold after a number of casts may be because small clay particles became drawn along with moisture into the mold and thus the capillary flow inside the mold was interrupted. However, a clear difference in demolding time is only observed in conventional drying cases. With microwave drying, the effect of mold life on the demolding time is not significant, especially as microwave power is increased. The service life of the mold has yet to be determined. Nevertheless, as a result of the shorter drying time, the molds are less exposed to energy and any chemical attack. Therefore, their service lives were expected to increase, and hence fewer molds would be needed. Because less material is handled, kept in stock, and processed, the production cost may be reduced.

Table 3 presents the differences in temperatures of the mold and the just-demolded product. Only minor temperature differences are observed when low microwave power is applied. A clear difference in temperature is obtained with product dried under high microwave power. The products tend to reach higher temperatures than the mold. The reason for this effect is that product and mold are different materials, which absorb and convert microwave energy into heat differently depending on their dielectric properties. In addition, with different ranges of pore sizes of these

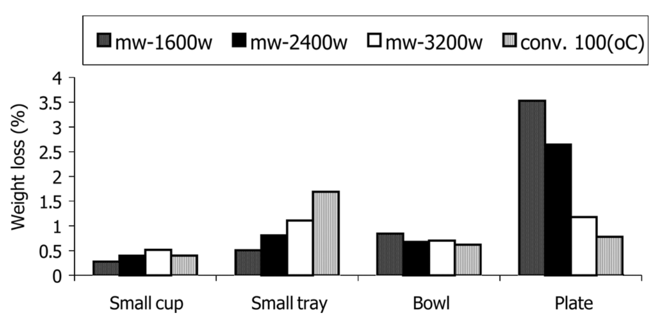

FIG. 5. Weight loss of various types of tableware under conventional vs. microwave drying.

TABLE 2
The effect of the mold life on the demolding time of plate products

	Demolding time (min)			
	MW drying			Conventional drying
Mold	1600 W	2400 W	3200 W	
Old	6	4	2	10
New	5	4	2	5

TABLE 3
The temperature of the plate product and mold just after demolding using microwave energy

	Product temperature (°C)			Mold temperature (°C)		
Mold	1600 W	2400 W	3200 W	1600 W	2400 W	3200 W
Old	46.2	62.1	65.2	44.5	52.7	57.2
New	42.5	50.2	64.6	43.8	49.2	56.9

two materials, the moisture removal ability is somewhat different. From a macroscopic point of view, the ease with which the moisture can move in the liquid phase depends on the nature of the matrix structure within the materials. In truly capillary porous materials, a natural redistribution of the moisture occurs from within the materials as the surface water evaporates. However, many materials have structures in which the pores are too large or discontinuous for this to take place. In other materials, the water is held in a matrix, which makes water liquid movement impossible.

The effect of mold life on weight loss of the product is shown in Table 4. As expected, a product cast in a new mold shows less percent weight loss. This corresponds to a faster demolding time as previously discussed. It is also observed that the duration of microwave irradiation time influences the weight loss of the product. Step drying (1 min drying, 6 times) results in a higher weight loss product compared to continuous drying for 6 min. However, with a higher weight loss, the color of the step-dried product is still light brown, while the continuous-dried product has a white color. This indicates that the continuous-dried product is more completely dried. This result is thought to be because of the effect of microwave energy accompanied with the effect of additional drying by convection in the step-drying method. Every time the dried sample is removed from the dryer, the moisture can continue to vaporize more and more from the surface, resulting in non uniform shrinkage of the sample. Thus the product can be demolded with a higher weight loss, indicating incomplete drying as compared to the continuous-dried product.

The quality of the microwave-dried products is observed to be similar to that of the conventional-dried products. The strength of tableware after drying is shown in Fig. 6, where the different sample sizes were tested. The microwave-dried products (dried at 2400 W) seem to have higher strength than those dried at 100°C in a conventional oven. The average strength of microwave- and conventional-dried products obtained were 888 kPa and 765 kPa, respectively. Considering thermal runaway effect, it is well known that the temperature dependence of the dielectric properties varies according to the material in question and is often very complex. The values of these properties may increase with temperature or decrease with temperature. At room temperature, the ceramic exhibits a rapid increase in the loss factor with increasing temperature. In such cases, when this phenomenon, known as thermal runaway, is apparent, damage such as poor product quality and sample cracking may occur to the product being heated.

In this study, great care must be taken to monitor temperatures and turn off the microwave power before the danger period commences. In some instances when this phenomenon cannot be controlled, especially for materials where the moisture content is close to bone dry or where dried-out areas may occur in the product, microwave heating may not be feasible. Understanding, predicting, and preventing or controlling thermal runaway present a major challenge to the development of microwave processing.

The next steps in research in this problem will be to develop a mathematical model to verify the experimental data, and the phenomenon of thermal runaway will be clearly discussed.

TABLE 4
The effect of irradiation technique and mold life

Mold type	Old mold		New mold	
Duration time	1 min, 6 times	6 min	1 min, 5 times	5 min
%Wt. Loss	3.53	2.63	3.50	2.06
Appearance				

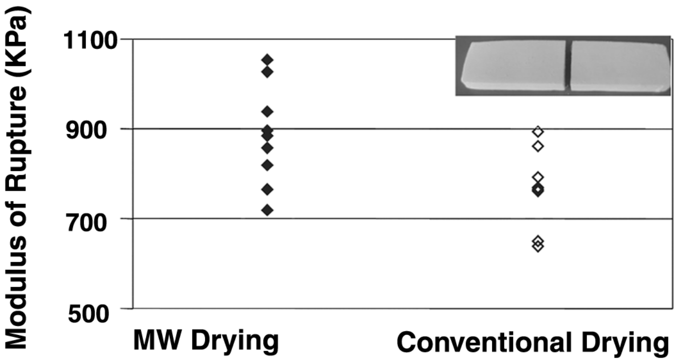

FIG. 6. Modulus of rupture (MOR) of tableware product.

CONCLUSIONS

Microwave drying permits quicker drying at lower temperature, resulting in a 40% reduction in energy consumption for what is normally an energy-intensive process. This can lead to a reduction of mold usage. Depending on the complexity of the molded product, microwave drying of tableware can yield a considerable time saving, by a factor of two or more. In addition, the quality and mechanical properties, i.e., strength of microwave-dried products, seem to be improved. Though the life of the mold has yet to be determined, it is expected that the large reduction in mold usage would have a positive influence on costs, energy consumption, and waste disposal. Overall, when handling a microwave continuous belt dryer correctly, we can conclude that it will realize the following advantages, compared to other microwave heating systems (i.e., fixed sample):

1. faster, reproducible, and more homogeneous heating (high product quality);
2. faster heating of thicker layers because the magnetrons are arranged in a spiral around the cylinder cavity (Fig. 1), which corresponds to the microwaves, and can penetrate further into the multi-plane of material;
3. immediately ready for operation and control of heat capacity without delay, well suitable for process automization;
4. no heat storage losses;
5. low specific energy consumption.

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