P. Rattanadecho[1]
e-mail: ratphadu@engr.tu.ac.th

N. Suwannapum

Faculty of Engineering,
Thammasat University (Rangsit Campus),
Pathumthani, Thailand 12120

A. Watanasungsuit
Faculty of Engineering and Industrial Technology,
Sillpakorn University,
Rajamakanai Road, Amphoe Muang,
Nakorn Pathom, Thailand 73000

A. Duanduen
National Metal and Materials Technology Center,
Pathumthani, Thailand 12120

Drying of Dielectric Materials Using a Continuous Microwave Belt Drier (Case Study: Ceramics and Natural Rubber)

In this study, the drying of dielectric materials by a continuous microwave belt drier has been investigated experimentally. Most importantly, it focuses on the investigation of drying phenomena under microwave environment. In this analysis, the effect of the irradiation time, sample sizes, and microwave power level (number of magnetrons (800W/1 magnetron)) on overall drying kinetics and mechanical properties are studied. The dielectric materials studied are classified into two types including ceramics (microwave demolding of tableware product) and natural rubber. The results showed that using the continuous microwave applicators technique has several advantages over the conventional method such as shorter processing times, volumetric dissipation of energy throughout a product, and high energy efficiency compared with other process, and it offers improvements in product quality. The results presented here provide a basis for fundamental understanding of microwave-heating of various kinds of dieletric materials. Further quantitative validation of experimental data could be very useful, especially in providing information for processing high performance microwave drying for developing the ceramics and rubber industries in Thailand. [DOI: 10.1115/1.2386166]

Keywords: microwave, drying, ceramic, natural rubber, microwave belt drier

Introduction

Microwave drying is one of the most interesting methods for drying materials. Microwaves are electromagnetic waves within frequency bands of 300 MHz to 300 GHz. The common frequency for commercial microwave systems is 2.45 GHz with a wavelength about 122.4 mm. Unlike other heat sources such as conventional heating, where heat is applied externally to the surface of the material, microwave irradiation penetrates and simultaneously heats the bulk of the material. When properly designed, microwave drying systems have several advantages over conventional mechanical methods including reducing the drying times, high energy efficiency, and offering improvements in product quality for various industrial applications.

A number of analyses of the microwave heating process in dielectric materials has appeared in the recent literature [1–28]. Earlier studies have shown that microwaves can efficiently dry the dielectric materials. Excellent reviews of the drying techniques in dielectric materials using microwave energy have been presented by Mujumdar [1], Metaxas [2], and Schubert and Regier [3].

It is well known that for a given microwave system, a load (sample) placed in different locations inside the applicator absorbed microwaves differently. Furthermore, despite the high number of stimulated modes, often a nonuniform field distribution that is constant in time will develop. This field distribution depends mainly on the cavity size, the product geometry, and the dielectric properties of the material to be processed. In contrast to single mode application, normally this nonuniform field distribution, which would result in a nonuniform heating pattern, is not desired, since it is difficult to control. An undesired nonuniform heating pattern can be prevented by changing the field configuration either by varying cavity geometries (e.g., mode stirrer) or by moving the product (on a conveyer belt or turntable).

As mentioned above, the continuous microwave applicators technique was possibly introduced soon after the oil shock took place. Since then, this tendency remain unchanged even today. Energy conservation, labor savings, and rationalization of production are seriously promoted in the high energy consuming ceramic and rubber industries. Particularly, drying and forming processes in the manufacturing of rubber products need a lot of time and energy, which results in a lack of rationality. Thus, only the introduction of some continuous production system through the efficient use of a rational energy source can solve this problem. In general, rubber is a bad conductor of heat. The rubber sponges having intricate hollow structures are regarded as heat insulators. For this reason, the drying for the rubber samples having cross section took a long time for heat transfer into the center of the sample. Why the continuous rubber drying systems by means of microwaves have rapidly been introduced in the recent years is understood to be the result of acknowledgment on an unparalleled property that the rubber itself generates heat by the absorption of microwave energy.

Although a number of studies has been conducted on simply microwave heating process, as such, most of them were carried out using a domestic microwave oven and a single- or multimode cavity with nonmovable materials.

However, the drying of dielectric materials by a continuous microwave belt drier has not been systematically reported on in numerical simulation and experimental work. Numerically, the main difficulty with modeling industrial cavities is their physical size; the large dimensions mean that many grid points are required to accurately model the system, which implies that a significant amount of computational resources are required. The simulation results for industrial scale that have been published to date have either used symmetry or special features of the cavity's design to model just a small fraction of the cavity. Alternatively, they have been restricted to using coarse grids and therefore produced re-

[1]Corresponding author.

Contributed by the Manufacturing Engineering Division of ASME for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received November 23, 2005; final manuscript received August 24, 2006. Review conducted by K. Rajurkar.

sults of low accuracy [4]. A second difficulty with industrial scales is that they are often designed for use as part of a continuous system with the product moving through the cavity on a belt (this work). This means that simulations with the product in a variety of positions are needed to correctly characterize the system. Practically, it is common when designing a large industrial cavity to construct smaller pilot plant systems to test the principle and then to scale up. It is quite possible, however, to encounter problems in the scaled-up version of the cavity that were not present in the prototype, especially when building multimode cavities.

The objective of this study is to demonstrate the applicability of microwave energy, an energy-saving and production-cost-reducing technology, in a dielectric drying. The study is the microwave drying of dielectric materials in a continuous microwave belt drier where a series of 14 magnetrons of 800 W each with total power of 11.2 kW was installed. The experimental results from this study could help to identify some of these potential problems during the practical design stage. This study is of great importance from the practical point of view because it shows the possibility of application of microwave drying of dielectric materials on an industrial scale, especially in a continuous system.

Microwave and Dielectric Material Interactions

In convective drying, dry air is used to take away surface water saturation from the dried sample, therefore creating a pressure gradient between the surface and inner part, which causes moisture migration from inside the sample to the surface. In this process, the gradient temperature will enhance the ability of dry air to remove water from the surface and increase the moisture migration rate within the sample. But there are many disadvantages with this method. Among these are low energy efficiency and lengthy drying time during the falling rate period. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced heat transfer. In contrast to conventional drying, microwave heating is volumetric and nonuniform. Samples dried less than a few skin depths in thickness. The resonance effect can occur inside the material, which results in the field distribution not having an exponential decay from the surface. In some cases the highest field strength, and therefore power density, can actually occur in the center of the sample. This is caused by the interference of waves reflected from the back side of sample. This mechanism pushes moisture out of product with great efficiency, as the moisture content of the product decreases.

Industrial applications mostly need continuous processing due to the high throughputs desired. Therefore, continuous microwave applicators have been developed. Today's microwave system in industrial applications may be differentiated into two groups by the number and power of microwave sources, namely, high-power single magnetron and low-power multi-magnetron devices (this work). Whereas for a single-mode unit only a single source is possible, in all other systems, the microwave energy can be irradiated optionally by one high-power magnetron or several low-power magnetrons. Whereas common industrial high-power magnetrons have longer operating lifetimes, low-power magnetrons have the advantage of very low prices, due to the high production numbers for the domestic market [3].

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 [5]:

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

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 the 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

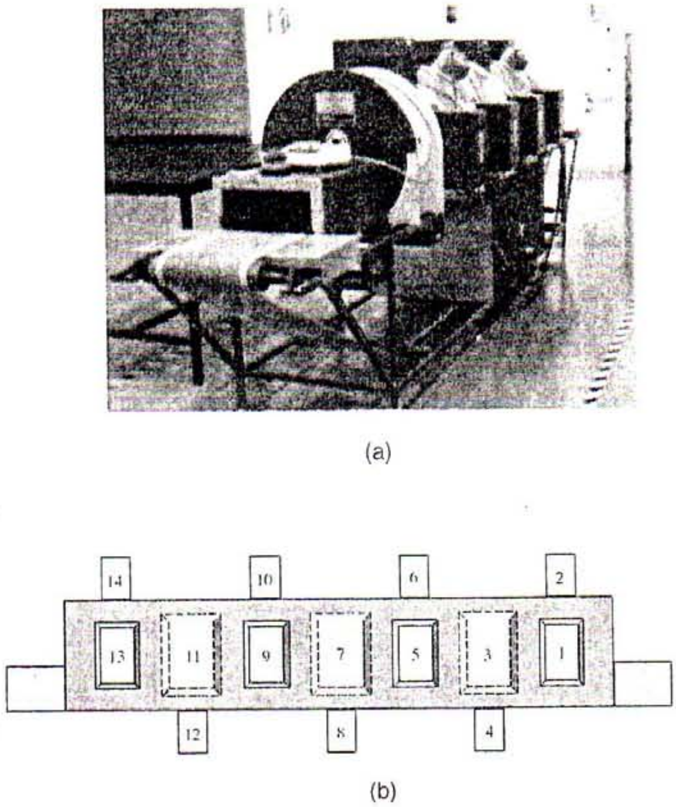

Fig. 1 Experimental apparatus: (*a*) microwave continuous belt drier and (**b**) location of 14 magnetrons

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 the applied microwave field depends on the dielectric properties of that material.

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.

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

where D_P is penetration depth, ε_r'' is 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 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 Procedures

Microwave Drier Unit. Microwave drying was carried out in a microwave continuous belt drier (Fig. 1(*a*)). The microwave cavity was cylindrical with exterior dimensions of $5300 \times 1200 \times 1600$ mm^3. The drier operates at a frequency of 2.45 GHz with

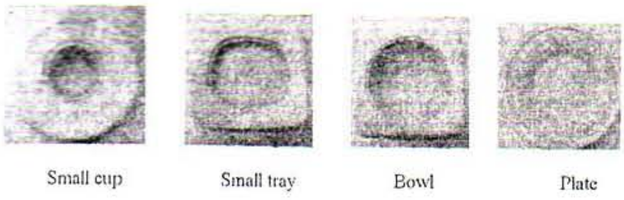

Fig. 2 Tableware samples cast in four different size and shapes of mold

maximum working temperature of 230°C. The microwave power was generated by means of 14 compressed air-cooled magnetrons of 800 W each for a maximum of 11.2 kW. The power setting could be adjusted individually in 800 W steps. In the continuous processing equipment, two open ends were essential, through which the material to be heated up on the belt conveyer is put in and taken out. In this equipment, leakage of microwaves is prevented by the countermeasure in tandem with a combination of a mechanical blocking filter and a microwave absorber zone filter, each to be provided at the open ends. The microwave leakage was controlled below the DHHS (U.S. Department of Health and Human Services) standard of 5 mW/cm^2 [6]. The magnetrons were arranged in a spiral around the cylinder cavity (Figs. 1(*a*) and 1(*b*)). The microwave power was then directed into the drier 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. An infrared camera was used to measure the temperature of the sample (accurate to ±0.5°C).

During the experiments, the uncertainty of our data might be due the variations in humidity, room temperature, and microwave power level. The calculated uncertainties in all tests are less than 2.95%.

Drying Process

Drying of Ceramic (Microwave Demolding of Tableware Product). The tableware body selected for the drying test was white porcelain clay (PEA, Compound Clay, Co. Ltd), which had 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 ($\varepsilon_r'=5.9$ and tan $\delta=0.0024$). The clay slurry was cast in plaster molds ($\varepsilon_r'=3.2$) of four different sizes and shapes (Fig. 2). For comparison, the cast samples were demolded in the continuous microwave belt drier and a conventional oven at 100°C. Drying time, microwave power, speed of continuous belt, sample size, and also mold life were varied. Weight change, surface temperature of the 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. In order to investigate the mechanical property of tested materials, the modulus of rupture (MOR) was measured by a three-point bending method following the ASTM standard [7].

Natural Rubber. The tested samples used were molded natural rubber ($\varepsilon_r'=5.9$ and tan $\delta=0.0024$) with thicknesses of 3, 6, and 9 cm. For comparison, the samples were dried in the continuous microwave belt drier or a conventional solar drying. Drying time, microwave power, speed of continuous belt, and sample size were varied. Weight change and surface temperature of samples were measured following each experiment. All temperatures were recorded with a hand-held optical thermometer. The moisture loss from a test sample was determined from the weight change after drying. The quality of the rubber product and its microstructure were also investigated.

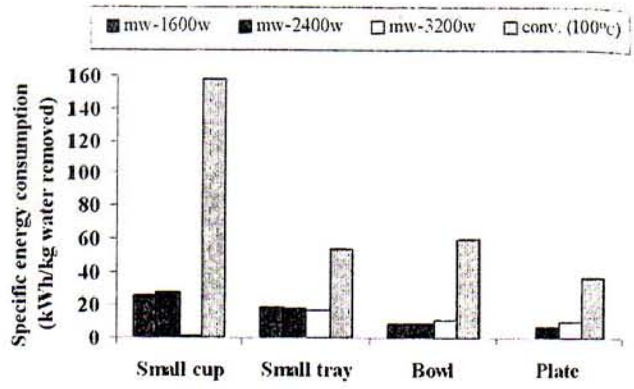

Fig. 3 Preliminary results of specific energy consumption

Results and Discussion

Microwave Demolding of Tableware Product

Demolding Time. Microwave energy can be used to efficiently demold the tableware products (Figs. 3 and 4). To evaluate the energy consumption during drying by microwave continuous belt drier, this value is expressed in term of the electrical energy consumed per mass of moisture removed from the demolding products. It is found that the reduction in energy consumption for demolding products under microwave energy is more than 40% when compared with those dried 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 are 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 2 or more. In case of conventional drying, as the surface is dried while the interior is 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 nonuniform shrinkage.

Varying the product size revealed that longer time is 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 for 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, the temperature of the product is

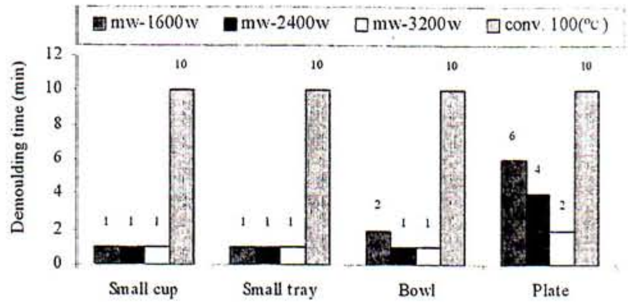

Fig. 4 Demolding time for tableware under conventional versus microwave drying

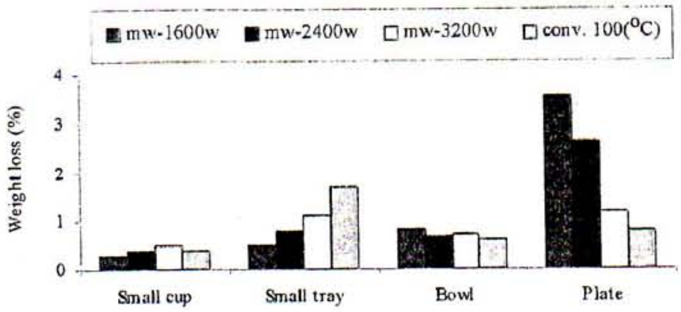

Fig. 5 Weight loss of various types of tableware under conventional versus microwave drying

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

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

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 is no difference in the demolding time. The cup and tray samples are still demolded within 1 min. The reason for this result is due to faster volumetric dissipation of temperature throughout the product resulting in higher rates of heat loss from the surface.

The drying behavior is quite different in the case of drying a larger product, e.g., plate. The demolding time of the plate sample is inversely proportional to the increase of microwave power. The higher microwave power level that is used, the greater energy that is absorbed by moisture inside a product. This enabled moisture to start migrating through the outside wall of the mold faster. Therefore, the product being dried shrunk and could be demolded in a shorter time. This leads 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) is required under irradiation of 1600 W and resulted in a higher weight loss of 3%. This can summarize again that, when using a lower power level a longer time, the irradiated energy is higher and therefore drying rates are higher.

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

Product	Product temperature surface (°C)			
	MW drying			Conventional
	1600W	2400W	3200W	drying
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

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 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 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 for six times) results in a higher product weight loss 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 drier, the moisture can continue to vaporize more and more from the surface, resulting in nonuniform shrinkage of the sample. Thus the product can be demolded with a higher weight loss, indicating incomplete drying

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

Mould	Product temperature (°C)			Mould temperature (°C)		
	1600w	2400w	3200w	1600w	2400w	3200w
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

Table 4 The effect of irradiation technique and mold life

Mould Type	Old mould		New mould	
Duration time	1min-6 times	6 min	1min – 5 times	5 min
%Wt. loss	3.53	2.63	3.50	2.06
Appearance				

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 presented in term of modulus of rupture (MOR) after drying with different drying conditions is shown in Fig. 6 where the different sample sizes were tested. It is found that the microwave-dried products (dried at 2400 W) seem to have higher strength than those dried at 100°C in a conventional oven. This is because microwave-dried products exhibit less shrinkage corresponding to a better microstructure arrangement. The average strengths of microwave- and conventional-dried products obtained were 888 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, prediction, 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.

Microwave Drying of Natural Rubber. The natural rubber used in this experiment was molded rubber prepared by the method recommended by the Agricultural Department. The main interest of this experiment is how the thickness of samples and number of magnetrons (microwave power level) used for drying affect the rubber product. Some results are presented in Figs. 7–10.

Figure 7 shows the drying kinetics versus the microwave power level and thickness of samples at 20% of weight loss constant. Considering the same thickness of samples, it is found that the drying time would be decreased if the number of magnetrons (microwave power level) increases. The conclusion of this relation is that drying time is directly varied to thickness of samples. On the other hand, the number of magnetrons is inversely varied to drying time. It is likely because the increase in the number of magnetrons increases the time interval of the energy absorbed within the samples. As a consequence, samples are quickly heated and

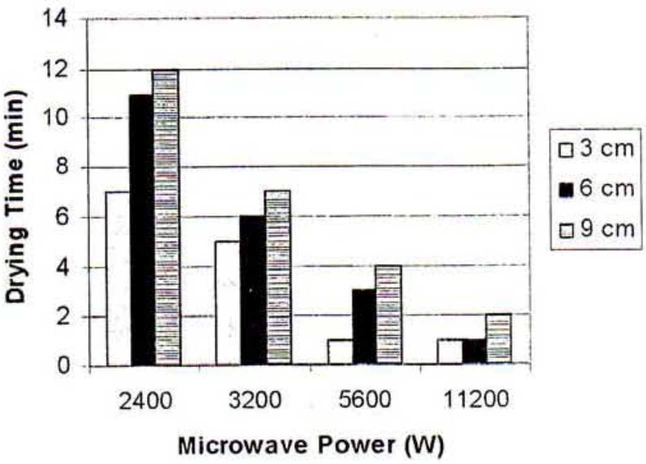

Fig. 7 Drying kinetics versus microwave power level at 20% of weight loss constant

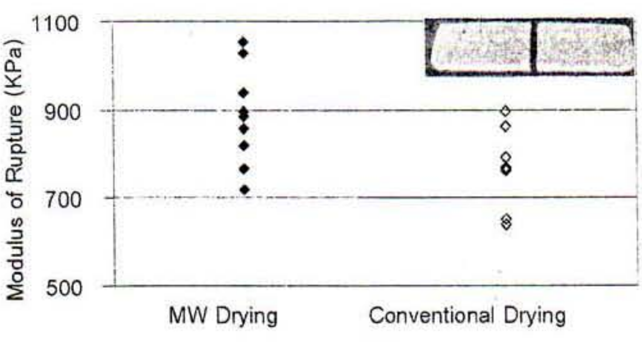

Fig. 6 Modulus of rupture (MOR) of tableware product

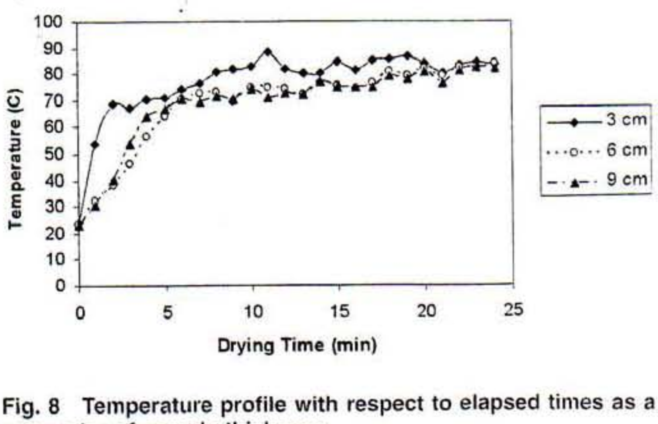

Fig. 8 Temperature profile with respect to elapsed times as a parameter of sample thickness

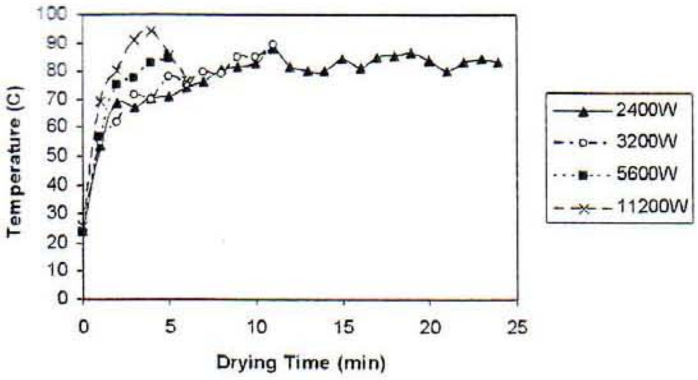

Fig. 9 Temperature profile with respect to elapsed times as a parameter of microwave power level

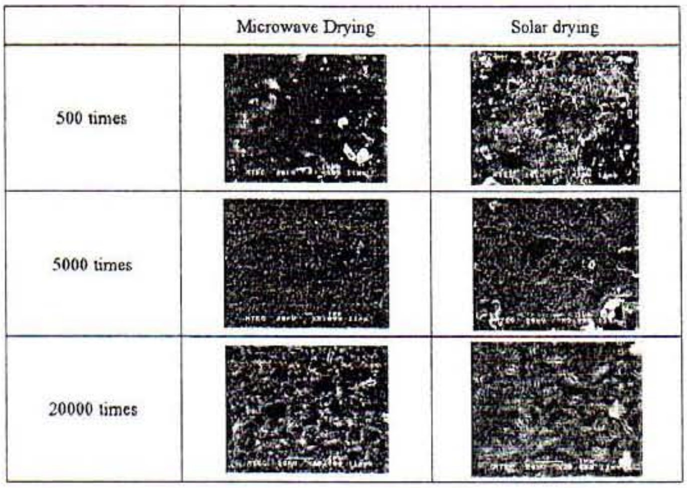

Fig. 11 Microstructure of natural rubber after drying

there is an accumulation of vapor pressure inside the samples migrating the moisture more quickly to the surrounding than in case of having fewer magnetrons.

Figure 8 shows the temperature profile with respect to elapsed times as a parameter of sample thickness with fixed microwave power level. It is found that thin samples had higher surface temperatures than thicker ones. This is because heat could be more quickly transferred from inside to outside of thinner samples. Another reason was that thin samples had less moisture content inside, making less heat of vaporization. Therefore, the surface temperature of a thin sample is higher at the beginning of drying time. However, the temperatures of samples with respect to elapsed times having different thickness had the same tendency because the factor of heat loss within the samples was over. Furthermore, the analysis of dielectric properties found that the increase of drying time could make the moisture content value near equilibrium and dielectric loss factor decreased. Then, microwave energy absorbed is decreased. This could be explained in Eq. (1).

Figure 9 shows the temperature profile with respect to elapsed times as a parameter of microwave power level with fixed sample thickness. It is found that at a high microwave power level the temperature profile within the sample continuously rises faster than that in the case of low microwave power level. Nevertheless, near the end stage of drying, as the moisture content inside the sample is reduced, this decreases the microwave energy absorbed. Thus, equilibrium is reached between microwave drying and convective losses by lowering the product temperature. Figures 9 and 10 show the wavy-temperature profiles with respect to elapsed times. It would correlate to microwave energy absorbed, which depends on the changing of the configuration of the electromagnetic field in the sample due to the variation of moisture content [8]. Besides, considering the same number of magnetrons, and other similar test circumstances, a different direction of transmitted wave from a different magnetron made for a different level of temperature of samples. This is because of the influence of the wave penetration capability shown in Eq. (2) and its wave interference, which, as explained above, could make a different level of absorbed energy in samples.

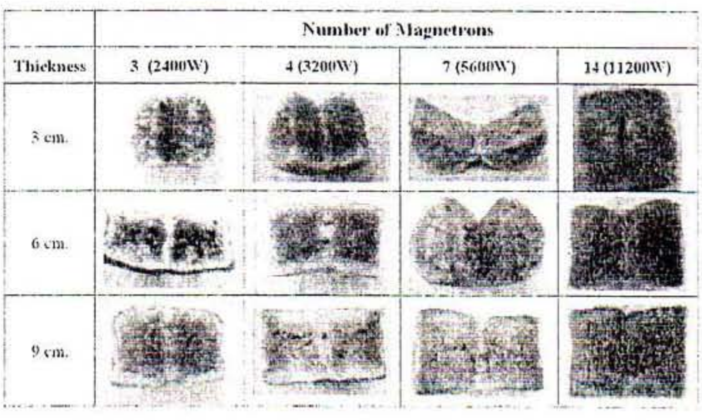

Fig. 10 Heating pattern in natural rubber

In addition, it is observed that, at longer drying times, a slight change of microwave power causes the temperature to increase rapidly to the melting point of rubber. This is due to the characteristic of dielectric loss factor, which comes to dominate microwave drying at low moisture contents. This phenomenon is commonly referred to as thermal runaway. During this stage, poor product quality and sample cracking are often exhibited if temperature levels cannot be controlled. Understanding, prediction, and preventing or controlling thermal runaway present a major challenge to the development of microwave processing.

From Fig. 11, microwave has a good penetration. It can be observed from the color of the product. Product colors at different conditions are darker in the middle of samples than at its surfaces. This is because microwaves uniformly radiated heat from the inside and there is more absorption of the microwave energy at the center of the product, causing temperature at the center to be higher than other areas. Then, the liquid in the sample could be quickly evaporated, resulting in vapor pressure high enough to migrate the moisture, which was condensed to cover all of the surface. This phenomenon could protect the surface from being burnt compared to the conventional heating processes such as smoking or exposing to the sun.

Figure 11 shows the results detected from scanning electron microscopy (SEM). It is confirmed that microwave dried products had a better microstructure arrangement because of uniform energy absorption and less shrinkage. This leads to the mechanical properties of dried products. This could be further confirmed by co-research with a polymer expert in the next research.

The next steps in research in this problem will be to develop the mathematical model to verify the experimental data.

Conclusion

In the case of microwave demolding of tableware products, 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 savings, by a factor of 2 or more. In addition, the quality and mechanical properties, i.e., strength of microwave-dried products, seem to be approved. 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.

In the case of microwave drying of rubber products, since microwaves have a good penetration and uniformly radiate heat from the inside, it is possible to perform drying of rubber products in a few minutes. The SEM results demonstrated that microwave-dried products had a better microstructure arrangement because of uniform energy absorption, and heat and moisture distribution, and offered better mechanical properties and product quality than those conventional methods.

Overall, when handling a microwave continuous belt drier 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 penetrating further into the multiplane of material,
3. immediately ready for operation and control of heat capacity without delay,
4. no heat storage losses, and
5. low specific energy consumption.

Acknowledgment

The authors gratefully acknowledge Thailand Research Fund (TRF) for supporting this research project. The authors also acknowledge Linn High Term GmbH, Germany for support equipment.

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