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# The microwave processing of wood using a continuous microwave belt drier

S. Vongpradubchai, P. Rattanadecho*

*Research Center of Microwave Utilization in Engineering (R.C.M.E.), Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani 12120, Thailand*

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ABSTRACT

In this study, the drying of wood by microwave energy using a continuous microwave belt drier was compared to that by conventional method. By using a continuous microwave belt drier, the microwave power was generated by means of 14 compressed air-cooled magnetrons of 800 W each that gives a maximum of 11.2 kW. The power setting could be adjusted individually in 800 W steps. Most importantly, this work focuses on the investigation of drying phenomena under microwave environment. In this analysis, the effects of the irradiation time and microwave power level on overall drying kinetics and mechanical properties were studied. 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, high energy efficiency as well as improvements in product quality. The results presented here provide a fundamental understanding of microwave-heating of various kinds of dielectric materials.



## 1. Introduction

Nowadays, the most important thing in industries, except for producing the high quality products to the markets, is to increase productivity and to reduce production cost. In general, several production processes of agricultural and industrial products are related to drying either by a natural method or using energy from other sources resulting in a low production rate or a high cost product. Microwave drying is one of the most interesting methods for drying materials. During the past decade, there are many successful examples of microwave applications including the heating and drying of foods, heating and drying of ceramics, heating and drying of concrete and vulcanizations of rubber and drying of wood. A number of analyses of the microwave heating process have appeared in the recent literature ([1–30] and [32,33]). An excellent review of the drying techniques in dielectric materials using microwave energy has been presented by Mujumdar [1], Metaxas and Meridith [2] and Schubert and Regier [3].

The drying of wood is the most energy-intensive and costly process in the forest products industry. Conventional wood dryers function under the basis of convective heat transfer from circulating hot air to the surface of wood followed by subsequent conductive heat transfer from the surface to the center of wood. These dryers require considerable amount of energy and long drying times in order to obtain high quality woods. Therefore, innovative wood drying methods have been searched and studied. Unlike the 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, reduction of the drying time, high energy efficiency, and improvements in product quality for various industrial applications [24]. Microwave drying of wood products, however, has not been used to a larger extent in wood industries mainly due to the insufficient knowledge of the complex interaction between wood and process parameters during drying as well as the higher investment expenses. Recently the development of inexpensive and reliable microwave sources has been increasing attracted to applications in wood industry.

Investigations on microwave drying of wood have been performed since the late fifties. Many authors (Antti [25], Masakasu Miura et al. [26], Oloyede and Groombridge [27], Lehne et al. [28], Turner [29] and Lee [30]) emphasize in the advantages of microwave drying over convective drying. Turner [29] points out the suitability of combined microwave and convective drying. However, there still remain obstacles to be overcome in applying microwave drying technology to wood industry. One of the difficulties is that the microwave power absorbed by moist wood depends mainly on the moisture content and it is required to move the wood for uniform power distribution with on-off type microwave system at fixed power output.

Although a number of studies have been conducted to investigate a microwave heating process, most of them were carried out using a domestic or housing microwave oven and a single or mul-

* Corresponding author. Tel.: +66 0 2564 3001 9; fax: +66 0 2564 3010.
*E-mail address:* ratphadu@engr.tu.ac.th (P. Rattanadecho).

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timode cavity with a non-movable material. Those studies showed that the result may be dependent on the method used to carry out the curing or heating process. The objective of this study is to demonstrate the applicability of microwave energy, as an energy-saving and production-cost-reducing technology. The microwave drying of wood in a continuous microwave belt drier where a series of 14 magnetrons, 800 W each with total power of 11.2 kW were installed. The experimental results from this study could help to identify some of the 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 heating-drying of dielectric materials on an industrial scale, especially in a continuous system.

## 2. Related theories

With the basic knowledge of heating by microwave energy, it concerns heat dissipation and typical microwaves propagation in which the dipoles start to vibrate and rotate furiously by mean of the electric field. When the microwave energy emitted from a microwave oscillator (Pin) is irradiated inside the microwave applicator, the dielectric materials which has a dielectric loss factor absorb the energy and are heated up. which has a dielectric loss factor. Then the internal heat generation takes places. The basic equation to calculate the density of microwave power absorbed by dielectric material ($P_1$) is given by [19]:

$$P_1 = \omega \varepsilon_0 \varepsilon_r'' E^2 = 2\pi f \varepsilon_0 \varepsilon_r (\tan\,\delta) E^2 \tag{1}$$

where $E$ is electromagnetic field intensity; $f$ is microwave frequency; $\omega$ is angular velocity of microwave; $\varepsilon_r$ is relative dielectric constant; $\varepsilon_0$ is dielectric constant of air and $\tan\delta$ is dielectric loss tangent coefficient.

From Eq. (1), $P_1$ is directly proportional to the frequency of the applied electric field and dielectric loss tangent coefficient and root-mean-square value of the electric field. It means that increasing of $\tan\delta$ of specimen, energy absorption and heat generation are also increased. While $\tan\delta$ is small, microwave will penetrate into specimen without heat generation. However, the temperature increase probably depends on other factors such as specific heat, size and characteristic of specimen.

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 [23].

$$\begin{aligned} D_\mathrm{P} &= \frac{1}{(2\pi f/\upsilon)\sqrt{\left[\varepsilon_r'\left(\sqrt{1+(\varepsilon_r''/\varepsilon_r')^2}-1\right)\right]/2}} \\ &= \frac{1}{(2\pi f/\upsilon)\sqrt{\left[\varepsilon_r'(\sqrt{1+(\tan\,\delta)^2}-1)\right]/2}} \end{aligned} \tag{2}$$

where $D_\mathrm{P}$ is penetration depth $\varepsilon_r''$ is relative dielectric loss factor and $\upsilon$ 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. Furthermore, the dielectric properties of wood specimens typically show moderate lossiness depending on the actual composition of the material. With large amount of moisture content, it reveals a greater potential for absorbing microwaves. For all wood specimens, a decrease in the moisture content typically decreases $\varepsilon''$, accompanied by a slight increment in $D_\mathrm{P}$.

In the analysis, energy $P_2$ is required to heat up the dielectric material $W$(g) placed in a microwave applicator. The temperature of material is initially $T_1$ is raised to $T_2$. The energy $P_2$ can be estimated by the following calorific equation:

$$P_2\ (\mathrm{W}) = \frac{4.18 W C_\mathrm{P}\,\Delta T}{t} \tag{3}$$

where $W$ is weight of the dielectric material (g), $C_\mathrm{P}$ is specific heat of the dielectric material (Cal/gr °C), $\Delta T$ is the increment of temperature ($T_2 - T_1$) (°C), $t$ is heating time (s).

Assuming an ideal condition, all of the oscillated microwave energy ($P_\mathrm{in}$) is absorbed into the dielectric material; such internal heat generation as Eq. (1) shows takes place. In this case the relation between $P_\mathrm{in}$ and $P_2$ is shown below:

$$P_\mathrm{in}\ (\mathrm{W}) = P_2 \tag{4}$$

In a practical point of view, however, the transformation energy ($\eta$) in applicator is exists due to (1) the rate of microwave energy absorbed by means of the dielectric loss factor of the sample and (2) the energy loss in the microwave devices. Accordingly, by taking into account of this transformation efficiency, the microwave oscillation output can be calculated by the following equation:

$$P_\mathrm{in}\ (\mathrm{W}) = \frac{P_2}{\eta} \tag{5}$$

Accordingly, in order to determine the efficiency of the applicator during the microwave processing of wood using a continuous microwave belt drier, the Eqs. (3) and (5) can be manipulated as follows:

$$\eta = \frac{P_2}{P_\mathrm{in}} \tag{6}$$

where

$$P_2 = \frac{QSC_\mathrm{P}\,\Delta T 4.18}{60\eta_m \times 10^3} \tag{7}$$

where $\eta_\mathrm{m}$ (%) is efficiency of microwave devices, $Q$ (g/m) is weight per meter of dielectric material (softwood), $S$ (m/min) is a rate at which the dielectric material is put on the belt conveyer, $C_\mathrm{P}$ [Cal/gr (°C)] is specific heat of dielectric material, $\Delta T$ (°C) is heat-up range of $T_1 - T_0$.

## 3. Research methodology

From a practical point of view, it is well known that for a given microwave system, a load (specimen) placed in different locations inside the applicator absorbs microwave differently. Furthermore, despite the high number of stimulated modes, often a non-uniform 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 non-uniform field distribution, which would result in non-uniform heating pattern, is not desired, since it is difficult to control. An undesired non-uniform 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) [3].

It is expected that the continuous microwave applicators technique will be introduced soon. The reason for this is that energy conservation, labour savings and rationalization of production are

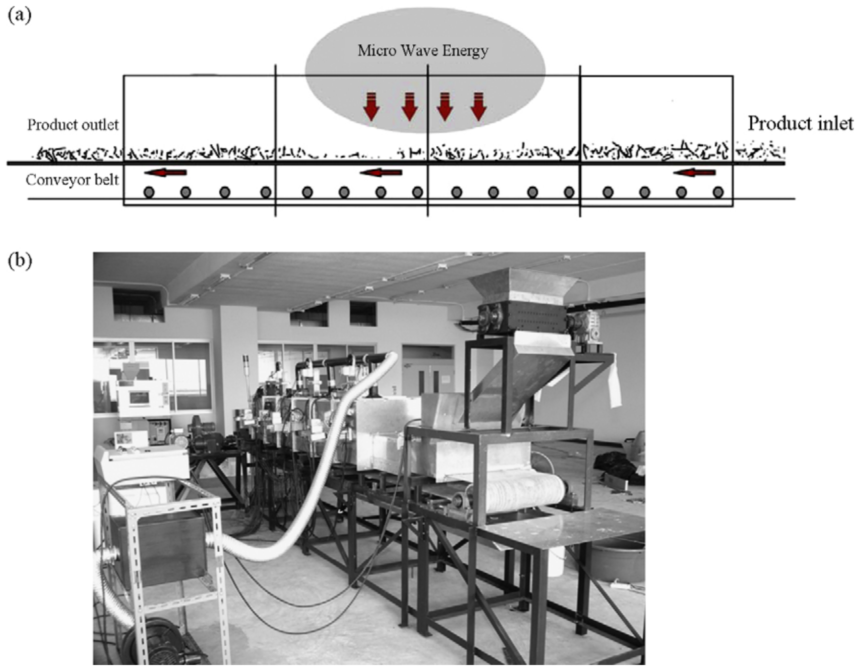


**Fig. 1.** Experimental equipment: continuous microwave belt drier.

seriously promoted in the high energy consuming wood and rubber industries. Particularly, drying and forming processes in the drying of wood products need a lot of time and energy, which results in a lack of rationality. Only the introduction of some continuous production system through the efficient use of a rational energy source can solve this problem.

## 4. Experiment procedure

Microwave heating was carried out using a microwave continuous belt drier (Fig. 1). The microwave cavity was a rectangular shape with a cross-sectional area of 94 cm × 47 cm. The drier operates at a frequency of 2.45 GHz with maximum working temperature of 200 °C. The microwave power was generated by means of 14 compressed air-cooled magnetrons. The maximum microwave capacity is 11.2 kW in frequency of 2.45 GHz. The power setting could be adjusted individually in 800 W steps. The magnetrons are fan cooled. The magnetron cover can be adjusted of furnace ventilation by an adjustment wheel. In the continuous processing equipment, two open ends are essential, through which the material to be heated up on the belt conveyer is put in and taken out. The belt conveyor system consists of a drive motor, a tension roller and a belt conveyor. During the heating process, the conveyor speed is adjustable upto 2 m/min and can be set at the potentiometer of control unit.

In this equipment, leakage of microwaves is prevented by the countermeasure in double with a combination of mechanical blocking filter and microwave absorber zone filter is provided at each of the open ends. The microwave leakage was controlled under the DHHS (US Department of Health and Human Services) standard of 5 mW/cm$^2$. The multiple magnetrons were installed in an asymmetrical position around the rectangular cavity (Fig. 1). The microwave power was then directed into the drier by using waveguides. An infrared camera was used to measure the temperature of the specimens (accurate to ±0.5 °C).

The specimen selected for drying test was a softwood with dimensions of 3 cm × 3 cm × 10 cm which had the initial moisture content of 80% (dry basis) and the initial temperature of 28 °C.

The mechanical characteristics of wood specimens before dried was undergone bending testing, following the BSI, London [31]. While fifteen of the specimens were microwave dried. The microwave dried specimens were weighed before and after they were transferred to the microwave cavity via belt conveyer. The specimens to be dried passed through the drier on an air-permeable microwave transparent conveyor belt. After a certain time, microwave power was applied for a specified period of time. During the heating process, microwaves penetrated the specimen, heating the water until it diffused to the surface. The humid air was then drawn out of the cavity by a suction system. While the drying process proceeded, temperature variations of specimens were measured by using an infrared camera for a specified period of time. The dried specimens left the cavity through another opening for further characterization. The twelve specimens were then removed from the cavity and weighted again to determine the moisture loss. The moisture content of microwave-dried specimen can be calculated based on dry basis from the weight loss of wood specimens before and after microwave drying in order to determine the weight loss. A plastic sheet was wrapped around the specimens to prevent further moisture loss. The other three specimens were capped for bending testing. The 15 conventional dried specimens are covered with plastic sheets after being chopped, removed from the controlled room after one day, and dried in oven at 100 °C, to establish reference strength against which microwave dried specimens can be compared. Finally, the quality of dried specimen was done by SEM (scanning electron microscope).

The dielectric properties for wood specimens were measured at 28 °C using a portable dielectric measurement (network analyzer) over a frequency band ranging from 1.5 to 2.6 GHz as shown in Fig. 2. The portable dielectric measurement kit allows for measurements of the complex permittivity over a wide range of solid, semi-solid, granular and liquid materials. It performs all of the necessary control functions, treatment of the microwave signals, calculation, data processing, and result representation. The software controls the microwave reflectometer to measure the complex reflection coefficient of the material under test (MUT). Then it detects the cavity resonant frequency and quality factor and converts the information into the complex permittivity of the MUT. Finally, the measurement

**Table 1**
Dielectric properties of wood and penetration depth.

| | Data | | | $D_P$ (m) |
|---|---|---|---|---|
| | Dielectric constant ($\varepsilon'$) | Dielectric loss factor ($\varepsilon''$) | Loss tangent coefficient ($\tan\delta$) | |
| Present study | 1.591 | 0.033 | 0.021 | 1.470 |
| Lehne et al. [28] | 2.419 | 0.036 | 0.015 | 1.669 |
| Datta and Anantheswaran [4] | 1.5–4 | 0.015–0.04 | 0.01 | 1.946–3.178 |
| Buffer [32] | 1.2–5 | 0.02–0.5 | 0.017–0.417 | 0.174–2.090 |

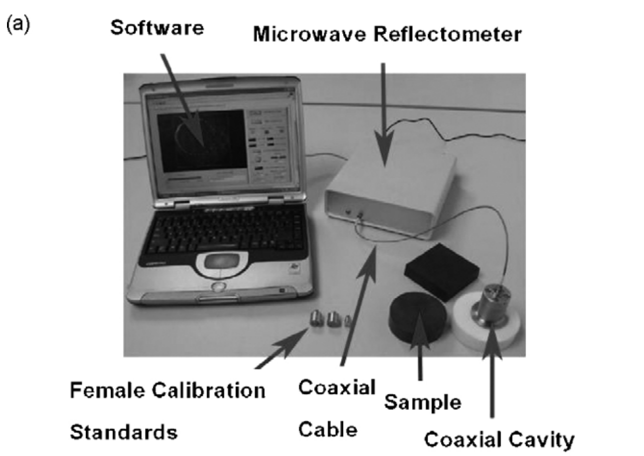


**Fig. 2.** Portable dielectric measurement (network analyzer).

results are displayed in a variety of graphical formats, or saved to disk. The dielectric properties of wood and its penetration depth obtained from present study and relevant literatures are summarized in Table 1.

## 5. Results and discussion

Experimental data were analyzed for the drying kinetics for different drying methods and conditions.

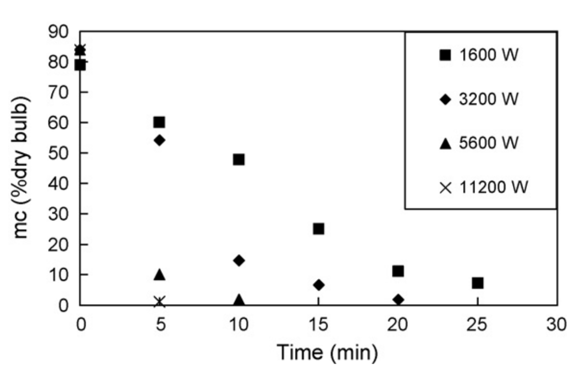


**Fig. 3.** Moisture profile versus elapsed times for different microwave power levels.

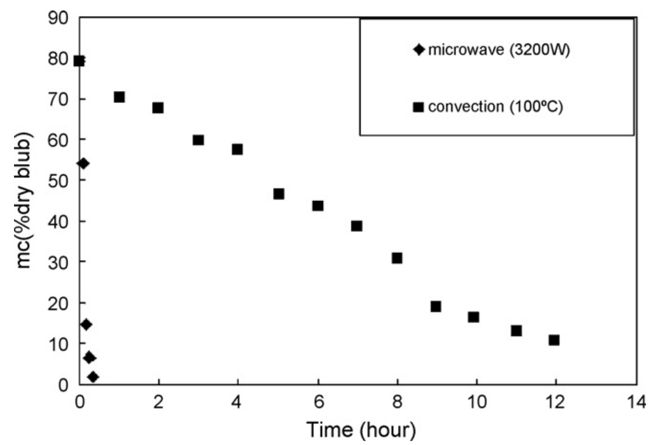


**Fig. 4.** Comparison of moisture profiles for different drying methods.

Fig. 3 shows moisture profiles with respect to elapsed times for different microwave power levels with constant initial moisture content of 80% (dry basis). It is found that at a high microwave power level the moisture profile of the specimens continuously decreases faster than that in the case of low microwave power level. This is because in the case of higher microwave power level the bulk of this specimen receives the largest amount of microwave energy absorbed. This phenomenon corresponds to the level of absorbed energy in specimens as described in Eq. (1). Furthermore, near the end stage of drying process as the moisture content inside the specimen is reduced, this decreases the microwave energy absorbed. Thus, equilibrium is reached between microwave drying and convective losses by lowering specimen temperature.

Fig. 4 shows the comparison of moisture profiles with respect to elapsed times for different drying methods. It can be observed from Fig. 4 that for microwave drying the specimen dries quickly throughout without the shrinkage phenomena that arises due to uniform heating. It is clear that drying times are drastically reduced compared to conventional drying, from 12 h to less than 1 h. The results show that microwave drying, i.e., microwave continuous belt drier can yield a considerable gain in drying time by a factor of ten or more. In case of conventional drying, as the surface is dried while the interior is still wet the dry layer offered a resistance to the heat transport resulting in a reduction of the evaporation rate as well as drying rate, causing non-uniform shrinkage.

Fig. 5 shows the temperature profile with respect to elapsed times as a parameter of temperature measuring positions with fixed the microwave power level. During the very first period of heating, most of the microwave energy supplied is used to heat the specimen. Wood specimen temperature is raised rapidly up to 100 °C in a few minutes. It is found that only minor temperature differences are observed when microwave energy is applied. This is because an undesired non-uniform heating pattern can be prevented by changing the field configuration either by moving the product on a conveyer belt through the cavity where microwave could be fed at several positions. Besides, considering the multiple magnetron system, the different directions of transmitted wave from different

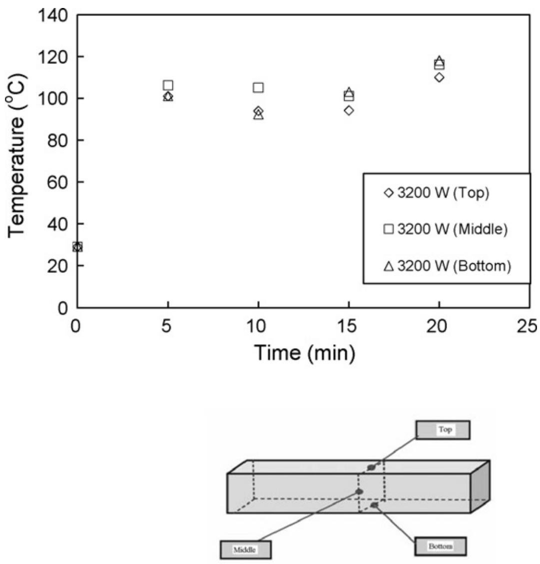


**Fig. 5.** Temperature variations versus elapsed times for different positions.

magnetron make the uniformity of temperature inside the specimens. This is because of its wave interference and the influence of the wave penetration capability shown in Eq. (2) and Table 1.

Fig. 6 shows the estimation of the efficiency of the applicator (refer to Eq. (6)) where the temperature data used in calculation (averaged value) were directly taken from temperature profile in Fig. 5. It is found that at the same microwave power level ($P_{in}$) the efficiency of the applicator continuously drops with elapsed times. This is due to the variation of moisture content inside the bulk of specimens (Fig. 4) that results in the variation of microwave absorbed energy. It would correlate to microwave energy absorbed which depends on the change of the configuration of electromagnetic field in the specimens due to the variation of moisture content [19]. Furthermore, near the end stage of drying process as the moisture content inside the bulk of specimens is reduced, the microwave energy absorbed is decreased. Thus, the efficiency of the applicator is reduced. We can conclude again that the heating efficiency largely varies with moisture content inside the bulk of specimens or quantity of dielectric load in microwave applicator. If the moisture content or quantity of dielectric load is decreased, to the contrary, the efficiency rapidly drops. Then, microwaves which could not be absorbed in dielectric load or specimens counterflow to the magnetrons as reflected power and strike its antenna dome. This will largely shorten the life of the magnetrons, and electric discharge may break the magnetron.

As mentioned in the previous work, especially by the authors [22], indicated obviously that the energy consumption by using

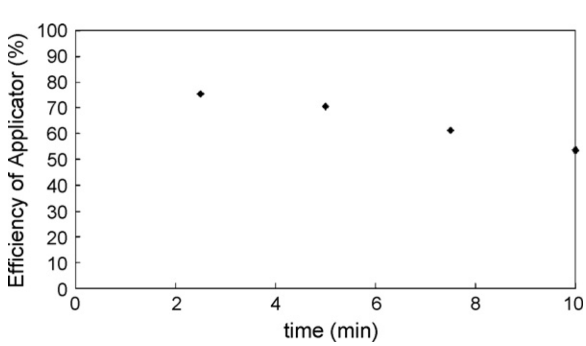


**Fig. 6.** The estimation of the efficiency of the applicator versus elapsed times.

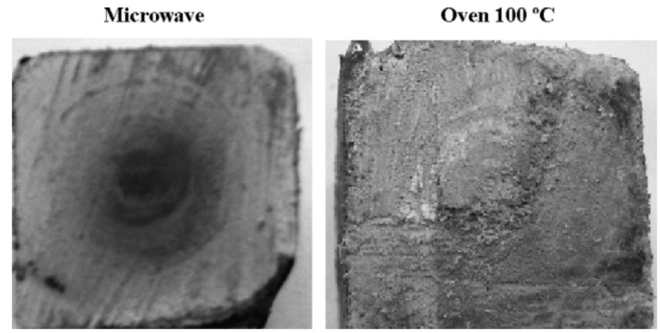


**Fig. 7.** Comparison of heat pattern in the specimens dried by microwave and oven at 100 °C.

microwave energy can potentially be reduced, Compared to the conventional drying.

Fig. 7 shows a cross section of a wood block after 5 min of microwave irradiation. No significant changes on the surface area were observed after microwave irradiation. The center of wood, however, change to black, indicating that the temperature at the wood core was higher than that at the surface. This is because microwave uniformly irradiated heat from the inside and there is more absorption of the microwave energy at the center of the wood, resulting in temperature at the center being higher than other area. Then, liquid in specimen could be evaporated quickly causing vapor pressure high enough to migrate the moisture which was condensed to cover the entire surface. This phenomenon which does not occur in the conventional drying process could protect the surface to be burnt comparing to the conventional drying process.

In Fig. 8, the quality of specimens dried by microwave is observed to be better than that of conventional dried specimen. The color of specimens dried by microwave remains, whereas the color of the convectional-dried specimen deteriorates.

In the following discussion, the internal structures of wood specimen are investigated base on an analysis of the mechanical properties after drying. Fig. 9 shows the texture overview of the wood specimens under various dried processes by using SEM technique. It is found that the dried specimens in all cases seem to have a similar micro structure arrangement. However, the microwave dried specimen has a better micro structure arrangement because of uniform energy absorption and less shrinkage. This leads to offer


(a) (b)

**Fig. 8.** Comparison of the quality of specimens dried by microwave (a) and oven at 100 °C (b).

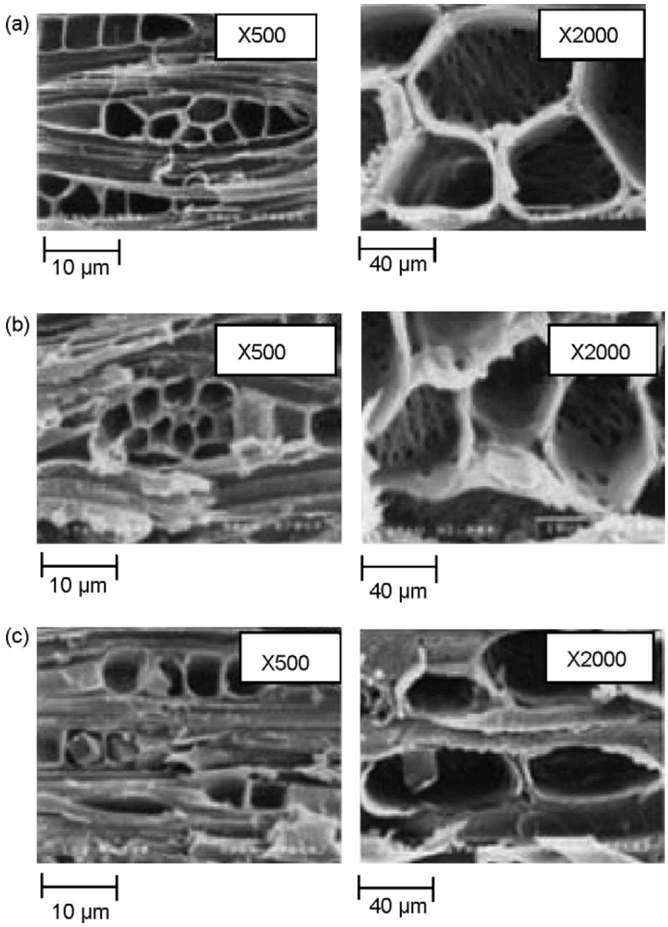


**Fig. 9.** Microstructure of specimen dried by different methods and conditions: (a) dried by microwave at 3200 W; (b) dried by microwave at 5600 W and (c) dried by oven at 100 °C.

the mechanical properties of dried products. This could be further confirmed by the co-research with material science expert in the following research.

The mechanical characteristics of wood specimens after bending testing based on the BSI, London (Fig. 10) with different drying conditions is shown in Table 1. It is found that the microwave-dried specimens under the conditions presented here seem to have higher strength than those dried at 100 °C in a conventional oven. This is because microwave dried specimens exhibit less shrinkage corresponding to a better micro structure arrangement (Fig. 9). The average strength of microwave and conventional-dried products obtained are 50.73 and 45.90 MPa, respectively (Table 2).

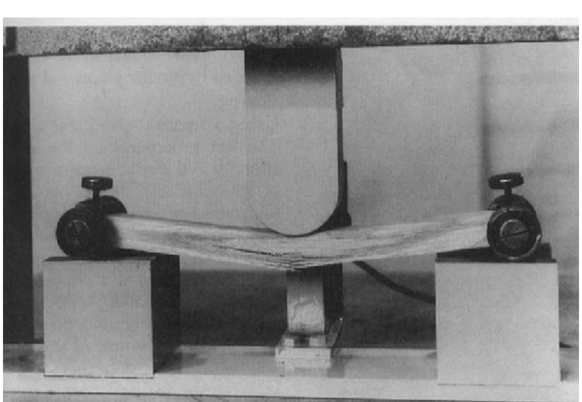

**Fig. 10.** BSI Standard of static bending test of specimen [31].

**Table 2**
Comparison of mechanical characteristics (static bending) between specimens dried by microwave and by oven at 100 °C.

| Specimen status | Modulus value (MPa) | Stress (MPa) | Toughness (MPa) |
|---|---|---|---|
| Before drying[a] | 3112.25 | 37.23 | 0.115 |
| Dried by microwave[b] | 4464.71 | 50.73 | 0.065 |
| Dried by oven at 100 °C[b] | 3766.64 | 45.90 | 0.064 |

[a] 80% moisture content (dry basis).
[b] 12–15% moisture content (dry basis).

In addition, considering thermal runaway effect, it is well known that the temperature dependence of the dielectric properties that varies according to the material is often very complex and is still unclear. The values of these properties may increase with temperature of decrease with temperature. At room temperature, the wood specimens, 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 whose the moisture content is close to bone dry or where dried out areas that occur in the product, microwave heating may not be feasible. Understanding, prediction, and preventing or controlling the thermal runaway present a major challenge to the development of microwave processing.

## 6. Conclusion

Microwave heating using a continuous belt drier provides relatively deeper penetration and displays more uniform heated pattern, compared to that achieved using other simple microwave drying systems or a conventional drying system. The SEM results demonstrated that microwave dried specimens has a better micro structure arrangement because of uniform energy absorption, heat and moisture distribution. In addition, the microwave heating offers better mechanical properties with high strength and little deterioration in its long term performance with higher quality than conventional method do.

Furthermore, in overall, when handling a microwave continuous belt drier correctly, we can conclude the following advantages, over the other heating systems:

(1) Faster, reproducible and more homogeneous heating (high product quality),
(2) Faster heating of thicker layers because the multiple magnetrons are arranged around the cavity, thus the microwaves can penetrate further into the multi-plane of material,
(3) Microwave energy can accelerate the hydration of cement, resulting in rapid strength development of wood in an early period,
(4) Immediately ready for operation and control of heat capacity without delay,
(5) No heat storage losses,
(6) Low specific energy consumption.

The next steps of the research in this problem will be to develop the control system and optimal drying schedules for combined microwave and hot air drying of wood in a microwave continuous belt drier.

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