CO_2 Laser–Incised Teak and Mahogany Lumber Dried by Microwave and Steam Injection

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Abstract

The aim of this study was to investigate the application of microwave and steam injection drying on CO_2 laser–incised teak (*Tectona grandis*) and mahogany (*Swietenia mahagoni*) lumber. The specimens were teak and mahogany lumber with dimensions of 60 by 120 by 600 mm. Three incising densities, 0, 1,250, and 2,500 holes per m^2, were applied to the drying specimens. The drying process was carried out by a combination of microwave and steam injection drying. Microwave irradiation had a power of 3 kW at a frequency of 2.45 GHz, while steam injection drying was done by injecting superheated steam at 105°C to 110°C through a perforated plate at 110°C to 120°C. Drying rate, moisture content (MC) distribution, and checks were observed to evaluate the quality of the drying process. The results indicate that microwave heating and steam injection drying could successfully dry incised teak and mahogany lumber. The highest drying rate was achieved in the specimens with an incising density of 2,500 holes per m^2. Interestingly, reducing the MC of teak from 46 to 20 percent required only 20 hours, while lowering the MC of mahogany from 60 to 20 percent took only 24 hours, without the formation of surface and internal checks. Laser incising, microwave heating, and the setting temperature of steam injection drying contributed considerably in creating a more uniform moisture distribution in teak and mahogany lumber, which significantly reduced surface and internal check formation.

Because awareness of energy efficiency is increasing, the wood industry has focused a number of efforts on accelerating the drying rate of lumber. Rapid drying with acceptable degradation remains important in lumber processing. Studies in wood drying have been widely directed toward the application of pretreatment processes and high temperature schedules that potentially shorten the period of drying. Previous experiments (Listyanto et al. 2013) showed that laser incising (2,500 holes per m^2) and a combination of microwave and steam injection could significantly improve the drying rate of Japanese cedar lumber (*Cryptomeria japonica* D. Don). The result emphasized the earlier research that laser incising was an effective pretreatment to provide new pathways where moisture can easily move out of lumber (Simpson 1987; Kamke and Peralta 1990; Hattori et al. 1991, 1997). Laser incising was selected to improve efficiency compared with mechanical incising, which showed difficulties in obtaining the desired depth of holes when conducted on large dimension lumber. Moreover, laser incising is preferred because it can incise through the total thickness of the board. The efficiency of laser incising increases in step with improvements in laser technology. The latest laser machine was chosen because it has several advantages, such as high beam quality ($K \geq 0.8$), low optical loss, very high thermal stability, and low running and maintenance cost. In addition, the laser-incised holes help to improve

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Forest Prod. J. 66(7/8):461–466.
doi:10.13073/FPJ-D-15-00082

the treatment, as reported by Ruddick (1991) and Morris et al. (1994).

Each species may respond differently to any drying method. For example, Kamke and Peralta (1990) reported that there was no significant difference in the drying rate between unincised and incised yellow poplar (*Liriodendron tulipifera*) lumber. On the other hand, incised lumber of loblolly pine (*Pinus taeda*) and red oak (*Quercus rubra*) showed faster drying than unincised lumber. This indicates that it is important to examine any promising drying method with other species, which have different characteristics, such as density and initial moisture content (MC). Factors that influence the drying rate include basic density and the initial MC (Berberovic and Milota 2011). Dense wood has a greater fiber wall to fiber cavity (lumen) ratio than that of low-density wood. Wood with greater fiber wall content exhibits slower movement of moisture. Subsequently, higher density lumber tends to dry slowly and is more likely to develop defects (Simpson 1991, Berberovic and Milota 2011). Teak (*Tectona grandis* L.f.) and mahogany (*Swietenia mahagoni*) wood are important hardwood species, especially in Indonesia. Teak and mahogany produce higher density lumber than Japanese cedar, and they are mostly processed into luxury products of construction, furniture, carving, and decorative components of building because of their strength, durability, and aesthetic properties (Pandey and Brown 2000). Teak and mahogany were also planted widely by Indonesia's national state company, which owns 2.5 million hectares of teak and mahogany forest plantation, and also by private Indonesian companies. Therefore, teak and mahogany were selected for this experiment. Teak and mahogany lumber measuring 80 by 120 mm were selected in this study because they are commonly used for large furniture and for construction that need more than 40 days to be dried by a conventional kiln. Reducing drying time will significantly increase economic benefit to the lumber industry. The surface color of the wood changes (surface charring) during laser incising. Because teak and mahogany lumber are preferred owing to their appearance, the incision holes must be filled and the surface charring covered with a suitable material, such as wood filler, in order to maintain the appearance of the lumber products.

Little consideration has been given to the temperature of steam injection and the optimal incising density for providing the best possible impact on the drying rate and reduction in lumber degradation. A steam injection temperature of 110°C and a platen temperature of 120°C (Listyanto et al. 2013) can cause surface and internal checks. It is important, therefore, to set the initial temperatures of steam injection and platen lower than the final temperatures. This study used a new setting temperature for steam injection and a new platen temperature, which are different from the method reported by Listyanto et al. (2013). In this study, a steam injection temperature of 105°C and a platen temperature of 110°C were used in the first 4 hours after microwave irradiation, and then the temperature of steam injection was increased to 110°C and the temperature of the platen was increased to 120°C until finishing the drying process. Another important suggestion from the previous study was the optimum incising density. Higher incising density increases the drying rate of lumber. However, an incising density of 10,000 holes per m^2 significantly reduced modulus of rupture (Suzuki et al. 1996). Therefore, an investigation on the effect of incising density less than 10,000 holes per m^2 is in order.

The aim of this study was to determine the effect of incising density combined with microwave and steam injection drying on the drying quality of teak and mahogany lumber. This study also developed different settings of temperature for the steam injection and the platen. Drying quality was determined by observing temperature, pressure, drying rate, moisture distribution, and checks.

Materials and Methods

Three green boards (80 by 120 mm) of teak (*Tectona grandis* L.f.) and the same number of green mahogany (*Swietenia mahagoni*) with lengths of 2,100 mm were used in this experiment. Every long board was sawn into three parts with lengths of 600 mm, which were used for drying specimens (Figs. 1a and 1b). Specimens were prepared to investigate temperature and pressure profile inside the lumber (Fig. 1b). Wood sections 25 mm long were taken in between the drying specimens for measurement of initial MC (Fig. 1a). Specimens for MC measurement were sawn as shown in Figure 1c and cut into rectangular shapes with dimensions of 20 by 20 mm and with lengths of 25 mm from the entire transverse area. The MC was determined based on the ovendry method at 103°C ± 2°C

Drying specimens were incised with three incising densities: 0 (unincised), 1,250, and 2,500 holes per m^2. The laser used for this experiment was a CO_2 laser (Rofin Basel, type DC 025) with an output power of 1.5 kW. In order to incise through the thickness (120-mm depth) of the specimens, the laser irradiated each hole for 0.9 second for teak and 0.5 second for mahogany. The diameters of incised holes were approximately 2 mm at the surface and became smaller at the opposite face. The incising pattern used in this experiment was based on the observation reported by Listyanto et al. (2013) and is shown in Figure 2. For the incising density of 1,250 holes per m^2, the longitudinal distance between holes (x) was 113 mm and the lateral distance between holes (y) was 14 mm. For the incising density of 2,500 holes per m^2, $x = 80$ mm and $y = 10$ mm. Both ends of all specimens were sealed by urethane resin before drying to prevent drying from end faces.

The samples were dried by a combination of microwave heating for 1 hour before steam injection drying. Three replicate specimens were used for each incising density. Microwave drying was conducted in a microwave chamber, with two power sources operating at 2.45 GHz and each having specific output power at 1.5 kW. A hole with a diameter 4 mm and a depth 60 mm was made in the center point of the specimen (Fig. 1b) where a fiber-optic thermometer FT1110 (Takaoka Electric MFG. Co.) was inserted to measure the temperature during drying. Pressure was measured by creating similar depth and diameter holes near the hole for the temperature sensor (Fig. 1b). Transducers (Kyowa Electronics Instruments Co., Ltd.) connected to a data logger through a stainless steel tube (inside diameter, 0.5 mm) were used to measure pressure inside the lumber. The holes were sealed with urethane resin. Microwave drying was operated by irradiating discontinuously to set the center point temperature of the specimen between 95°C and 100°C (Listyanto et al. 2013). Steam injection drying with a steam injection press (Kitagawa Seiki Co. Ltd; VH2-1449) was conducted by injecting 105°C superheated steam through the perforated

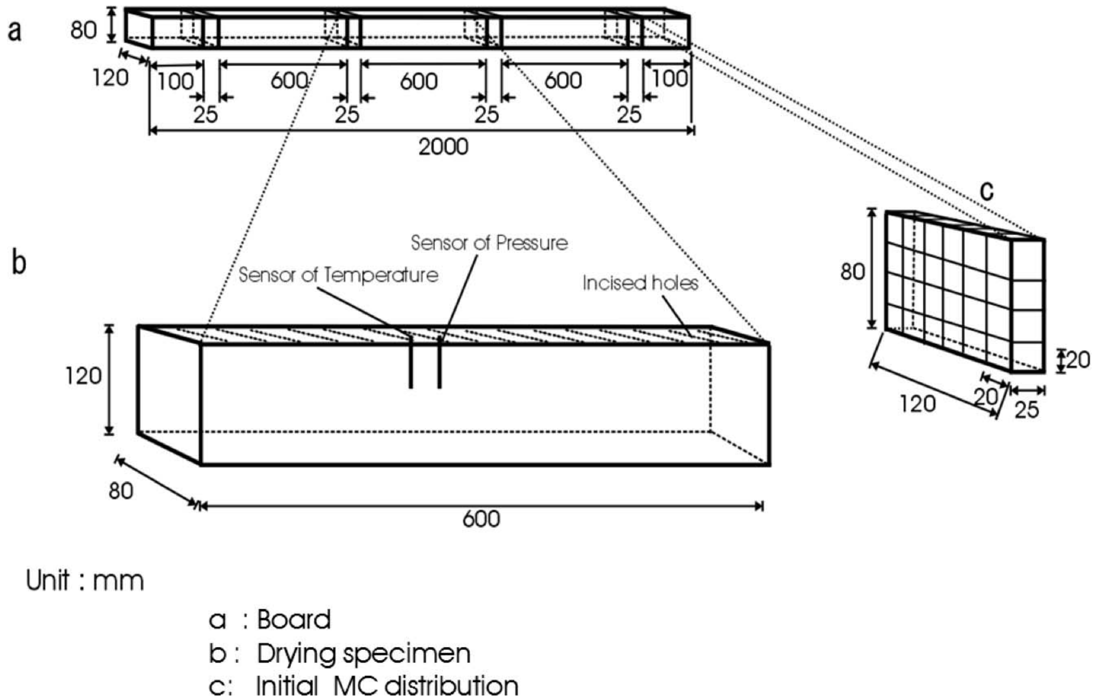

Figure 1.—Sample preparation: (a) long board used to prepare specimens, (b) drying specimen with two holes drilled for sensors inserted to measure temperature and pressure, and (c) specimen to measure moisture content (MC) across the transverse area.

plate at 110°C for 4 hours, continued by injecting 110°C superheated steam through the perforated plate at 120°C until the end of the drying process. Pressure inside the chamber was kept at 50 kPa above atmospheric pressure. In the case of unincised specimens, spacers were inserted in between the specimens to allow steam flow during injection. Temperature and pressure were recorded at 10-second intervals by the sensors inserted in the center point of the specimens. The drying process was monitored by the weight change of the samples, measured every 4 hours. The drying process was designed to reach a MC of 20 percent or less, as recommended by the Japanese Agricultural Standards Association (2007).

The dried specimens were examined to measure the number of surface and internal checks (Fig. 3). The total length of surface checks of all four sides of the dried specimens was measured by caliper, while internal checks were determined using soft X-ray with a digital camera (Softex M 60). The final MC distribution measurement was conducted from the dried specimen using a transverse section similar to the observation of the initial MC (Fig. 3c). Analyses of variance with $\alpha = 0.05$ were conducted to analyze any significant difference in the drying rate between incised and unincised teak and mahogany specimens. Tukey's honestly significant different test was used to determine the difference.

Results and Discussion

Temperature and pressure change

The time to reach a temperature of 100°C in the incised specimens under microwave irradiation was 18 minutes. There is no significant difference in the temperature increase between specimens with an incising density of 1,250 holes per m^2 and those with 2,500 holes per m^2. The advantages of microwave drying, as well as dielectric drying, are that the frequency can heat quickly within wood, which leads to higher drying rate and more uniform final MC over a shorter time period (Hattori et al. 1997, Antti and Perre 1999, Fang et al. 2001). This result was slightly slower than the temperature rise in Japanese cedar, where ca. 10 minutes was required to achieve 100°C. The lower initial MC of teak (46% ± 6%) and mahogany (60% ± 7%) may have contributed to the longer heating time. Temperature increases faster in specimens with higher MC because moist wood absorbs more energy than dry wood (Antti and Perre 1999). Therefore, the effectiveness of microwave drying declined with decreasing MC There was no significant difference in the temperature increase among different incising densities.

As temperature increased, the vapor pressure increased gradually. This condition contributed to the faster drying process of the specimens with higher incising density. The pressure dropped periodically owing to measurement of MC reduction. Pressure of the specimen after irradiating by microwave increased rapidly. This indicated that microwave irradiation generates high pressure inside the specimens.

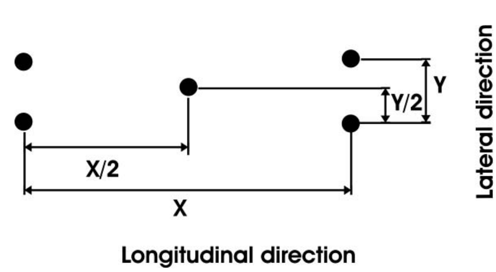

Figure 2.—Incising pattern used in this experiment. Circle holes represent position of incising holes.

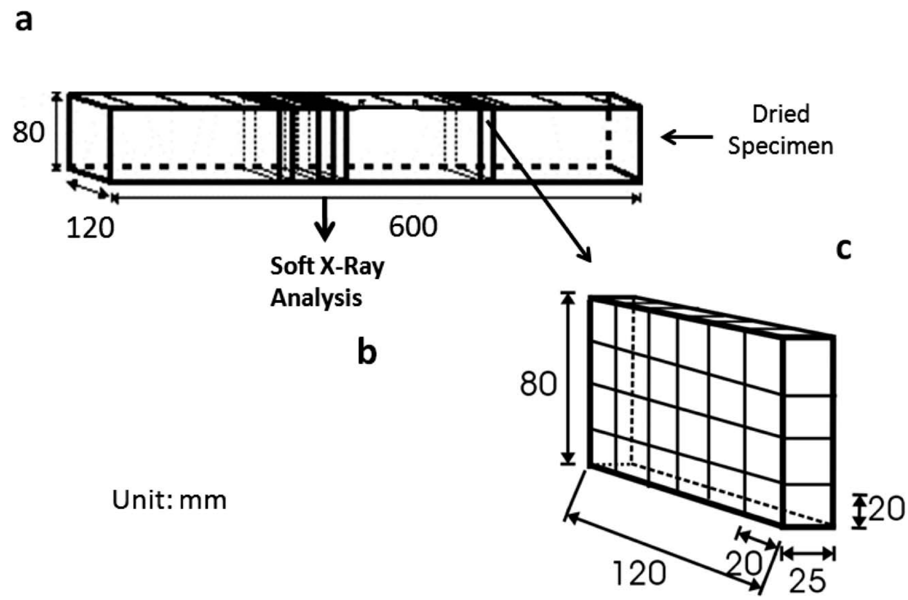

Figure 3.—Observation to measure the number of surface and internal checks and distribution of final moisture content (MC). (a) Dried specimen. (b) Internal checks were determined by using soft X-ray with digital camera (Softex M 60). (c) Final MC distribution measurement.

Drying rate

The drying process in this experiment was started from an MC in the range of 40 to 57 percent to the desired final MC of 20 percent or less. Graphs of the drying rate of teak and mahogany under three incising densities are shown in Figure 4. Statistical analysis confirmed that there was a significant difference ($P < 0.05$) in the drying rate among specimens with three kinds of incising densities. The highest drying rate was found in the mahogany specimens with the incising density of 2,500 holes per m^2, which was 1.68 percent per h (±0.1%/h). The second fastest drying rate was for mahogany specimens with an incising density of 1,250 holes per m^2, where the drying rate was 1.1 percent per h (±0.1%/h). On the other hand, the drying rate of unincised mahogany specimens was only 0.58 percent per h (±0.1%/h). Comparable data were found for teak (Fig. 4). Teak specimens with an incising density of 2,500 holes per m^2 showed the highest rank, which was 1.31 percent per h (±0.2%/h). This result was followed by teak specimens with an incising density of 1,250 holes per m^2 and the unincised teak specimens, which were 0.95 percent per h (±0.1%/h) and 0.41 percent per h (±0.1%/h), respectively. It can be said that an incising density of 2,500 holes per m^2 could accelerate the drying of specimens up to three times compared with that of unincised samples. This indicates that laser incising is required for high speed MC reduction of the specimens. Interestingly, reducing MC of teak from 46 to 20 percent required only 20 hours, while reducing the MC of mahogany from 60 to 20 percent required only 24 hours. This process was 10 to 15 times faster than conventional drying, without severe defects. Faster drying in the specimens with the higher incising density is caused by greater surface area in which moisture can flow out easily.

Moisture distribution

There was a considerable difference in MC gradient among different incising densities of teak and mahogany lumber in this experiment. The final MC distributions of all specimens for each drying method are shown in Figure 5. It is clear from Figures 5a and 5d that unincised specimens showed the steepest MC gradient. This steep moisture gradient will also cause surface and internal checks to occur on unincised specimens during drying. Incising seemed to positively contribute to decreasing the MC gradient, as can be seen from Figures 5b, 5c, 5e, and 5f. This result is consistent with an earlier study reported by Listyanto et al. (2013). The incised holes are important in providing better porosity, which allows moisture from the inside region to move easily to the nearest incised surface rather than external surface of the lumber. Therefore, incised holes support rapid drying and increase uniformity of MC distribution.

Surface and internal checks

Interestingly, no surface and internal checks were found in the laser-incised specimens dried by microwave heating

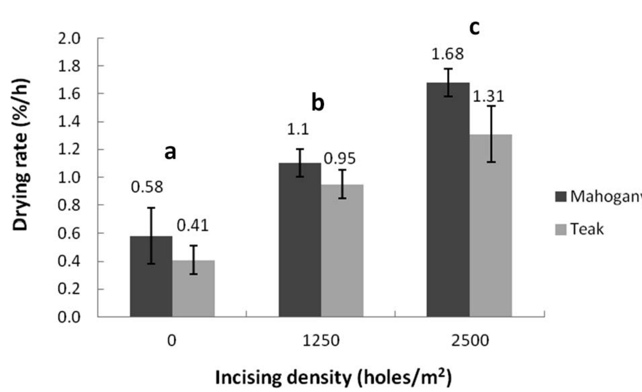

Figure 4.—Drying rate of the unincised and incised teak and mahogany, dried by a combination of microwave heating for 1 hour and steam injection drying.

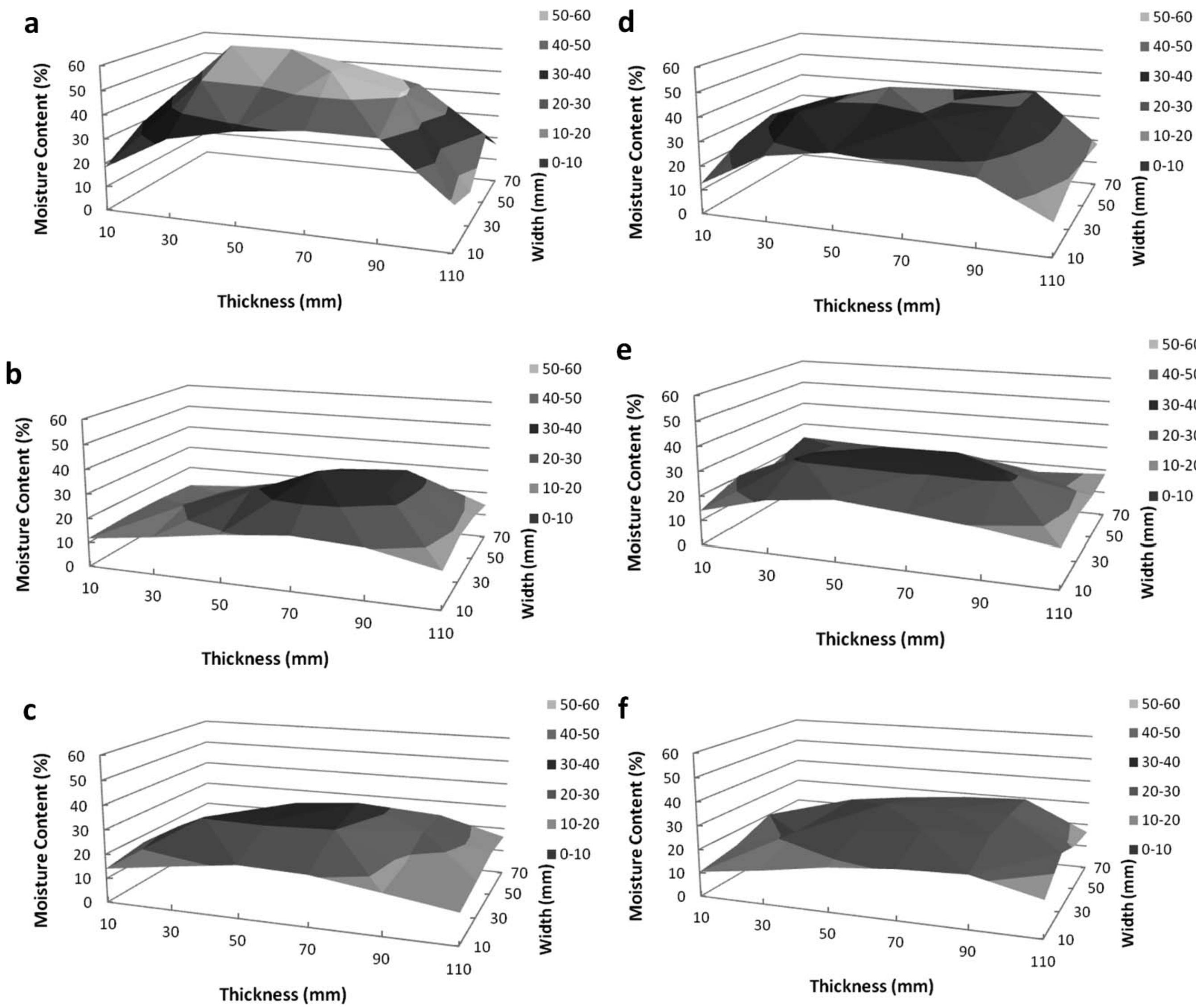

Figure 5.—Final moisture content distribution across the transverse area: (a) unincised mahogany, (b) incised 1,250 holes per m^2 of mahogany, (c) incised 2,500 holes per m^2 of mahogany, (d) unincised teak, (e) incised 1,250 holes per m^2 of teak, and (f) incised 2,500 holes per m^2 of teak.

and steam injection drying. The most severe surface checking was found in unincised specimens for both teak and mahogany lumber (Table 1). Observation with soft X-ray also showed that internal checks occurred extensively in unincised specimens (Fig. 6). Rapid drying and a steep moisture gradient between the surface and the inner region in the early stages of drying seemed to contribute to surface

Table 1.—Total length of surface checks of the unincised teak and mahogany samples dried by a combination of microwave heating (1 h) followed by steam injection drying. No surface checks were observed for any of the incised samples.

Incising density (holes/m^2)	Total length of surface checks (cm)	
	Mahogany	Teak
0	25	45
1,250	0	0
2,500	0	0

and internal checks, as described in the previous section. This result corresponded to the investigations by Dedic and Zlatanovic (2001) and Listyanto et al. (2013) that microwave drying can enhance the quality of dried lumber by degree of checking.

In industrial operations, we have to make several incisions at the same time with higher efficiency to reduce time for laser incising. It is necessary to investigate the relative merits of incising to a lesser depth from each face rather than completely from one face to the other. There is also an additional labor cost to restoring the appearance of wood damaged by laser incising.

Conclusions

Specimens of teak and mahogany with high incising density provided more significant pathways for steam to heat the whole specimen faster. The highest drying rate was achieved in the specimens with an incising density of 2,500 holes per m^2. Interestingly, the time required to reduce the

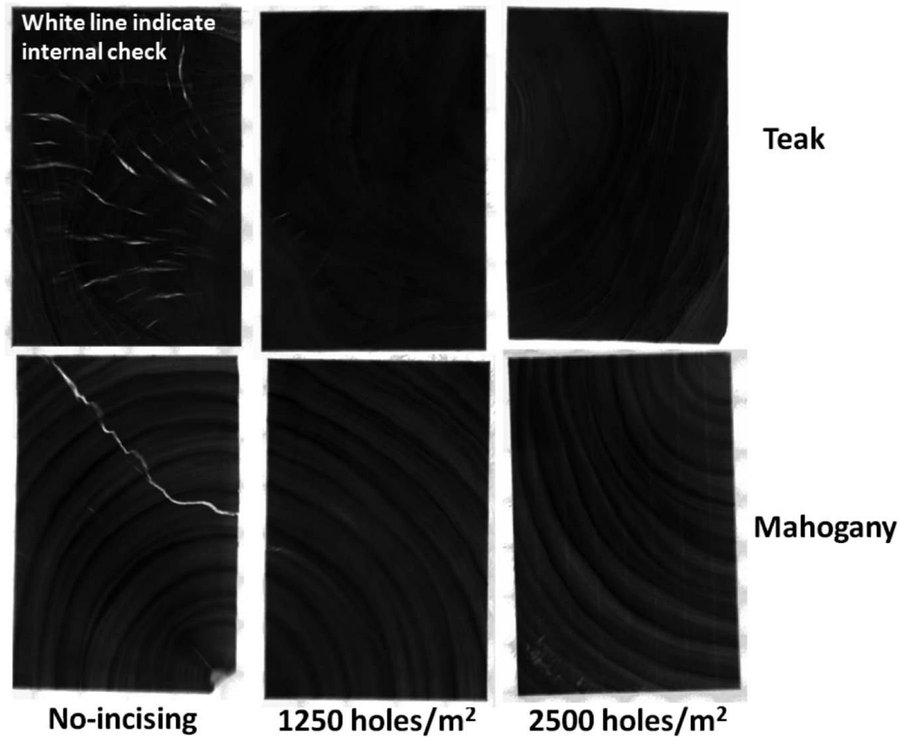

Figure 6.—Image of internal checks of the unincised and incised teak and mahogany dried by a combination of microwave heating for 1 hour and steam injection drying, obtained using soft X-ray with digital camera (Softex M 60).

MC of teak from 46 to 20 percent was only 20 hours, while the time to reduce the MC of mahogany from 60 to 20 percent was only 24 hours. Laser incising, microwave heating, and setting temperature of steam injection drying contributed considerably to creating more uniform moisture distribution of teak and mahogany lumber, which significantly reduced surface and internal checks.

Acknowledgments

This project was supported by IMHERE PROJECT funded by the Ministry of Education of Republik Indonesia and JSPS Grants-in-Aid for Scientific Research (A) No. 22248019.

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