Wood Sci Technol (2013) 47:1323–1334
DOI 10.1007/s00226-013-0578-z

ORIGINAL

Fracture energy approach for the identification of changes in the wood caused by the drying processes

Hermann Pleschberger · Christian Hansmann ·
Ulrich Müller · Alfred Teischinger

Received: 24 July 2012 / Published online: 26 September 2013

Abstract Specific fracture energy measurements were applied to identify changes caused by wood-drying processes of solid wood. Specimen design and geometry as well as parameters and specifications for a fracture energy test were determined experimentally. The specific test set-up was applied on plantation teakwood sample sets of standard as well as alternating convection kiln dryings and one oven drying. The results show that alternating changes of the drying temperature along with the equilibrium moisture content (EMC) in a kiln schedule have a small but significant decreasing effect on the specific fracture energy in the radial/longitudinal as well as the tangential/longitudinal testing direction. Furthermore, oven drying at constant high drying temperature along with low EMC did not result in a significant change of specific fracture energy compared with standard drying, but caused greater scattering values in both transverse crack propagation systems.

Introduction

Technical kiln drying of lumber is a fundamental process to reach targeted and uniform moisture in the wood prior to any further secondary wood processing. Drying schedules typically start at low drying temperature (TEMP) and high equilibrium moisture content (EMC), which develop into the opposite during the progress of drying. TEMP as well as EMC is subjected to fluctuations from the beginning until the end of a kiln schedule due to the drying device. In order to reach

---

H. Pleschberger (✉) · C. Hansmann · U. Müller · A. Teischinger
Wood K plus, Competence Centre for Wood Composites and Wood Chemistry,
Altenberger Straße 69, 4040 Linz, Austria
e-mail: h.pleschberger@kplus-wood.at

U. Müller · A. Teischinger
Department of Material Science and Process Engineering, Institute of Wood Technology and
Renewable Resources, University of Natural Resources and Life Science, Vienna, Austria

adjusted set points of TEMP as well as EMC, values of TEMP and EMC often vary above and below their set points during a drying schedule. There is no information available on the influence of these variations in TEMP and EMC within a kiln schedule on the strength properties of wood. In order to establish solid wood in higher-grade structural applications, all undesirable changes in strength, caused by the drying processes, should be avoided and also minor changes should be detected.

The main reasons for any mechanical strength losses during wood drying are the degradation of wood components, in particular the depolymerisation of hemicelluloses and stress development (Hinterstoisser et al. 1992; Perré 2007). There is only little permanent reduction in mechanical properties of wood when TEMP does not exceed 100 °C (Smith et al. 2003). Moreover, it is not possible to determine a general critical TEMP where mechanical properties start to decrease (Oltean et al. 2007). Conventional strength properties, such as three-point-bending strength as well as modulus of elasticity in three-point-bending, impact bending strength and even tensile strength perpendicular to the grain, were not affected at TEMP up to 80 °C and 2 % EMC (Oltean et al. 2011). Fracture mechanic experiments are a means of sensitive characterisation of strength properties perpendicular to the grain (Teischinger 1992). Concepts handling with fracture energy permit a wide range of application. Experimental techniques for fracture mechanic experiments are described by Porter (1964), Mai (1975), Schniewind et al. (1982), Logemann and Schelling (1992), Tschegg et al. (2001), Stanzl-Tschegg (2006) and Majano–Majano et al. (2012). Specific fracture energy (G_f) represents the amount of energy per unit of area needed to break cohesive forces (Griffith 1921) and for the formation of a new crack surface, which is a specific value in fracture mechanics. Common theories of fracture energy are designed for homogeneous structures and their properties. In order to apply fracture energy measurements to solid wood, inhomogeneous solid wood structure has to be taken into account. Design of the specimen, particularly a large enough ligament area, which is the effective test length without initial notch, has to be considered to exclude any size effects. Furthermore, test procedure, basically the testing speed, has to be adapted to obtain comparable results in different testing directions and to fracture energy values measured on different shapes of specimen.

The target of this study was to apply a method which is able to detect possible changes caused by low-temperature kiln drying by means of G_f measurements. The possible influence of alternating changes of TEMP and EMC on G_f, which may occur by the kiln drying process, intentionally caused in this study, should be investigated in particular. This way, the knowledge of the change in fracture energy caused by the drying processes could be generated.

Materials and methods

Plantation teakwood (*Tectona grandis* L.f.) from a region of the provincial site of Puntarenas on the pacific coast of Costa Rica was used in this study. Two eighteen-year-old logs, one with a diameter of 23.5 cm, an initial MC of 109 % and oven-dry density of 612 kg/m^3 and another one with a diameter of 30.5 cm, an initial MC of

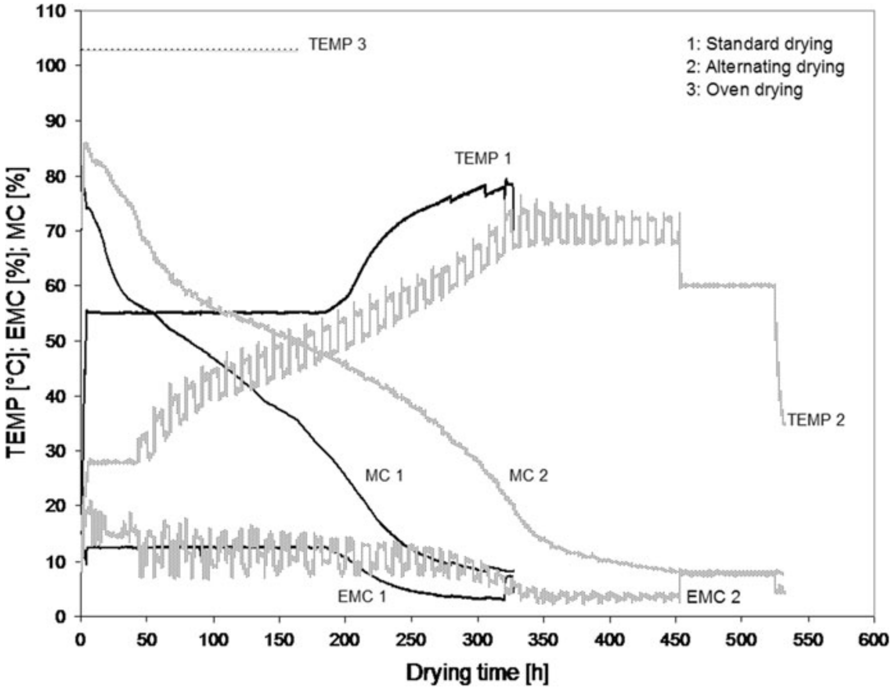


Fig. 1 Temperature (TEMP), equilibrium moisture content (EMC) and wood moisture content (MC) plotted versus drying time of analysed drying schedules *1* (standard), *2* (alternating), *3* (oven-dry)

125 % and oven-dry density of 614 kg/m^3 were selected for the drying experiments. The values of the MC and the oven-dry density are mean values and refer to the heartwood. The logs were cut by live log sawing into adjoining boards with a thickness of 30 mm using a band saw and cut to a length of 1.5 m, wrapped separately into PVC-films and stored at −10 °C to keep initial MC during storage. Before the drying experiments took place, the boards were slowly defrosted and cross-sectional areas were adhesive coated to prevent accelerated drying of board faces. Three different drying schedules were chosen in order to analyse the influence of different drying configurations, especially in regard to alternating TEMP and EMC, on the fracture energy performance of dried plantation teak. To ensure comparability of the material between all drying experiments, adjoining cut boards of the two selected logs were equally divided into three groups.

One standard and one alternating convection drying schedules as well as one oven drying schedule were compared (Fig. 1; Table 1). The standard as well as the alternating drying experiment was performed in a laboratory convection kiln dryer equipped with an electronic humidity and temperature sensor and were operated by a computer-aided process control (MB8000, Mühlböck Holztrocknungsanlagen GmbH, Austria). Each drying schedule was controlled in dependence of the wood moisture content (MC) by means of electrical resistance measured with screwed in electrodes. The oven drying was carried out in a conventional laboratory oven (Venticell 111, MMM Medcenter Einrichtungen GmbH, Germany) at 103 °C

Table 1 Settings of drying temperature (TEMP) and equilibrium moisture content (EMC) at certain moisture contents (MC) of compared drying schedules

Parameter	MC				TEMP				Drying gradient				EMC			
Schedule	1	2		3	1	2		3	1	2		3	1	2		3
Unit Programme	(%)	(%) A	(%) B	(%)	(°C)	(°C) A	(°C) B	(°C)	(–)	(–) A	(–) B	(–)	(%)	(%) A	(%) B	(%)
Heating-up	–	–	–	–	6.5 min/°C	30 min/°C	30 min/°C	103	–	Auto	Auto	–	10.6	15	15	–
Heating-through	–	–	–	–	Auto	28	28	103	–	Auto	Auto	–	10.6	15	15	–
Drying	60	70	70	–	55	26	31	103	2.4	2.1	3.3	–	12.5	14	9	–
	40	50	50	–	55	45	50	103	2.4	2.2	3.4	–	12.5	13.7	8.7	–
	30	40	40	–	55	54	59	103	2.4	2.4	3.5	–	12.5	12.6	8.6	–
	25	33	33	–	58	59	63	103	2.4	2.7	3.6	–	10.4	11.3	8.3	–
	20	26	26	–	65	64	69	103	2.6	3	4.1	–	7.7	8.6	6.4	–
	15	20	20	–	70	67	74	103	2.7	3.4	4.7	–	5.6	5.8	4.3	–
	10	13	13	–	75	68	73	103	2.7	3.3	4.2	–	3.7	3.9	3.1	–
	7	9	9	–	80	68	72	103	2.8	2.4	2.8	–	2.5	3.8	3.2	–
Conditioning	–	–	–	–	Auto	60	60	103	–	–	–	–	7.2	7.7	7.7	–

1: Standard drying

2: Alternating drying (dual system—switch from programme A to B every 6 h)

3: Oven drying

A: Programme A (lower temperature and higher EMC)

B: Programme B (higher temperature and lower EMC)

Auto: Automatic control

without control of MC. The standard drying schedule represented a conservative drying schedule for conventionally grown teakwood as commonly used in practice (Table 1). In the alternating drying schedule, a dual drying system was used, where TEMP and EMC switched periodically every 6 h from programme A to programme B during the drying stage (Fig. 1). The TEMP decreased while EMC increased in programme A and TEMP increased while EMC decreased in programme B, like the settings shown in Table 1. Parameters of compared convection kiln runs corresponding to applied industrial practice with a maximum TEMP level below 80 °C and minimal EMC of 2.5 %. The severeness of kiln schedules is expressed in the drying gradient, which indicates the ratio of MC to EMC (Table 1). Drying parameters were deliberately set at a moderate range to test the practical feasibility of the fracture energy method in situations where conventional mechanical testing detects no significant changes according to, for example, Oltean et al. (2011).

After the drying experiments, all boards were checked regarding drying defects in order to select apparently clean heartwood areas to prepare double-cantilever-beams (DCB). Specimens in form of cuboids with a dimension of 200 (longitudinal) × 20 (radial) × 20 (tangential) mm^3 were cut (Fig. 2), according to ASTM D 3433-75 (1985). Particular attention was paid to the alignment of the annual rings to cut rift shaped, clear and knotless test specimen. Different anatomical orientations of the test specimen, RL (radial/longitudinal) and TL (tangential/longitudinal), were cut side by side and in a row from each board to obtain comparable test material. In the coding of the samples, the first letter indicates the direction perpendicular to the crack propagation, and the second letter determines the direction along the crack propagation (Fig. 3). For mounting the specimen to the testing machine, holes with a diameter of 4.5 mm were drilled in each specimen above and below crack initiation (Fig. 2). Crack initiation in mode I according to Irwin (1958) was centred in the cross-sectional area and machined by a 3-mm band saw blade to a depth of 28.5 mm and finally by using a razor blade up to a depth of 30 mm. The finishing by a razor blade in the band-sawn-root was performed to ensure controlled initial

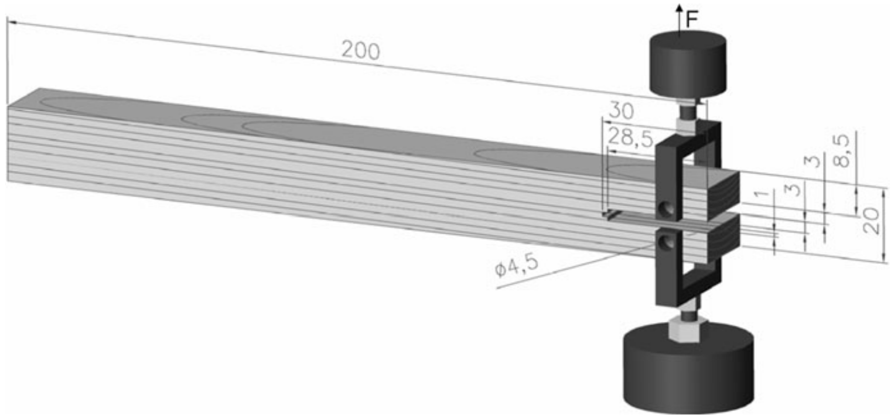
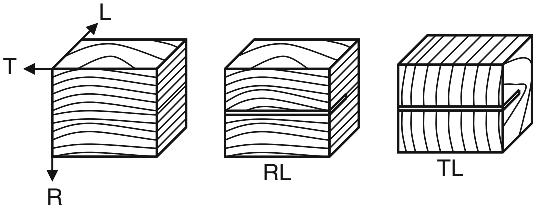


Fig. 2 Double-cantilever-beam (DCB) in view of mode I. Load application is plotted in the test orientation radial/longitudinal (RL). Dimensions are indicated in millimetres

Fig. 3 Anatomical characteristics in wood (*L* longitudinal, *R* radial, *T* tangential) and investigated crack propagation systems (*RL* radial/longitudinal and *TL* tangential/longitudinal)



cracking and a stable development of the crack process until complete separation. Dimensions of the specimen and geometry are shown in Fig. 2. Finished and marked test specimens were conditioned at 20 °C and 65 % relative humidity (RH) until constant weight before final testing was achieved.

Ligament length as well as crack tip formation and cross-sectional area data were collected before clamping specimen into the testing machine. The fracture energy tests were carried out on a universal testing machine (Zwick/Roell 100 kN) equipped with a 2.5 kN load cell. The test schedule (testXpert V11.0) was set including maximum breaking load ($F_{\max}$), energy to break until $F_{\max}$ ($W_{F_{\max}}$) and until complete separation of the test specimen W_{break}. The initial test force was adjusted to 20 N at a rate of 10 mm/min testing speed. After initial load was reached, the test specification was configured with 1 mm/min displacement velocity during real sampling time and speeded up to 10 mm/min based on a 0.002 acceleration factor. Testing was interrupted if a sudden drop in force of 50 % of $F_{\max}$ appeared, if elongation of 50 mm was exceeded or if a 5 N absolute lower shutdown threshold was achieved. In order to have comparable quality for evaluating the results after testing was completed, the fracture surface was examined regarding slope of grain in fibre direction and alignment of annual rings. The result after a mode I load cycle of tested DCB specimen is a force displacement function with a characteristic run of the curve, as shown in Fig. 4. According to Frühmann et al. (2002), the initial slope (k_{in}) of the load–displacement diagram (LDD) is a characteristic for the stiffness and elastic properties as well as for the shape and size of a specimen. $F_{\max}$ is the maximum force value in the LDD and a characteristic, comparable strength value. The G_{f} value for mode I loading is the quotient of the sum of energy absorption during crack initiation (G_{init}) and propagation (G_{prop}) divided by fracture surface (A) and characterises the resistance against fracture which is obtained according to Eq. (1). The LDD contains all necessary information in order to describe crack initiation as well as propagation and fracturing until complete separation of specimens. The G_{f} value of each sample was calculated corresponding to Eq. (1) in the RL and the TL crack propagation direction, respectively. Pretest analyses have shown that dimensions and geometry of the specimen as well as the test set-up are suitable for fracture energy testing on solid wood. Furthermore, the method was applied to different wood species such as spruce, oak, beech, ash and maple (Pleschberger et al. 2013). In the current study, a total of 80 specimens, 40 in RL and 40 in TL test direction, were tested from three drying experiments. The statistical checks were performed with a one-way analysis

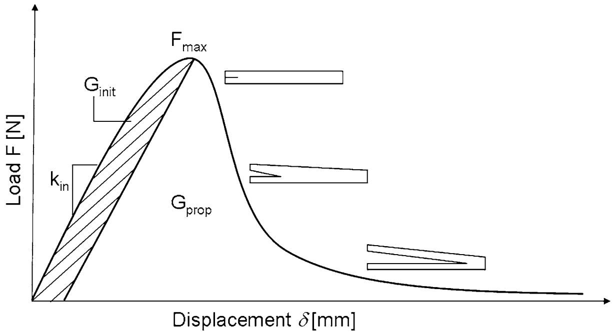


Fig. 4 Schematic share of energy during individual stages of specimen fracturing and characteristic values (corresponding to Ehart et al. 1996; Frühmann et al. 2002; Stanzl-Tschegg 2006)

of variance (ANOVA) at a 5 % significance level using superior performing software system (SPSS 15.0).

$$G_{\mathrm{f}} = \frac{1}{A} \int_{0}^{\delta\max} F_{\mathrm{H}}(\delta)\, d(\delta) \quad (1)$$

G_{f}-specific fracture energy (J/m^2), A fracture surface (m^2), F_{H} horizontal load (N), d displacement (mm), δ differential quotient.

Results

Different settings of the applied drying schedules led to different drying times. The drying time of the standard drying was 62 % of the drying time of the alternating drying, even though the drying gradient of the alternating drying was almost constantly higher than in the standard drying. A comparison of the different drying schedules is shown in Fig. 1, with regard to characteristics of MC, EMC and TEMP in dependence of the drying time. The parameters of each drying schedule are shown in Table 1. The progress in the drying schedules for the standard and alternating drying were based on actual MC. During the drying processes, TEMP and EMC were adapted automatically by the process control when the end of a predefined moisture step was reached. For the calculation of the governing MC, the median value (instead of mean value) of the measurements of the activated electrodes was used to prevent possible high influences of outliers and to comply with current industrial practice. Oven drying was performed at constant TEMP (103 °C) without any control of the EMC. All dryings, in particular convection kiln dryings, showed apparently high drying quality according to standards and recommendations (EN 14298:2004; Welling 1996). A conventional evaluation of the drying quality by means of cracks, bows, crooks, twists and uniform distribution of MC resulted in the best grading. Consequently, apparently defect-free specimens could be obtained from the material out of all drying trails.

Figure 5 shows box plots of the G_f values of samples of the standard, alternating as well as oven drying method in the RL and the TL crack propagation direction. The results in Table 2 denote the corresponding medians, means and standard deviations (SD) for the compared drying schedules. Significant differences in G_f values in the RL as well as the TL crack propagation system were found for the alternating drying schedule compared with the standard drying schedule as well as to the oven drying schedule. The G_f values measured in the RL crack propagation system were lower than the values measured in the TL direction within each drying experiment. The G_f values scattered much more determinedly in the standard drying schedule than the G_f values in the alternating drying schedule. However, most scattering was observed in the oven drying schedule. Furthermore G_f values in the TL crack propagation system showed a larger variation than in the RL system in all investigated drying experiments.

Fig. 5 Specific fracture energy (G_f) values after different drying schedules in radial/longitudinal (RL) and tangential/longitudinal (TL) crack propagation system

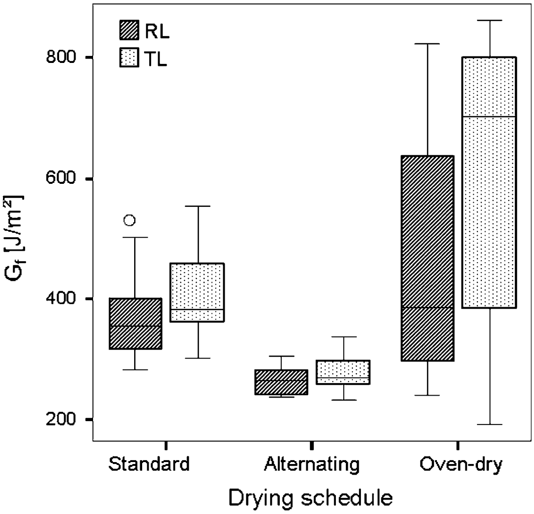


Table 2 Medians, means and standard deviations of specific fracture energy (G_f) values in radial/longitudinal (RL) and tangential/longitudinal (TL) crack propagation after different drying schedules

Test value	Specific fracture energy (J/m^2)					
Crack propagation	RL			TL		
Drying schedule	Median	Mean	SD	Median	Mean	SD
Standard drying	354	365	(66.9)	381	405	(68.5)
Alternating drying	265	265	(23.7)	269	277	(36.3)
Oven drying	386	460	(200)	702	587	(250)

RL: Radial/longitudinal test direction

TL: Tangential/longitudinal test direction

SD: Standard deviation

Discussion

The results in Fig. 5 and Table 2 show that the applied method determines differences in G_f of the alternating drying to the standard drying as well as to the oven drying used. Kiln schedules, in particular one standard and one alternating convection drying, controlled by TEMP (<80 °C) and EMC (>2.5 %), as shown in Table 1, can be distinguished clearly by means of G_f in RL as well as TL testing direction (Fig. 5).

In the studies by Reiterer (2001) and Stanzl-Tschegg et al. (1994), a decrease in G_f values in the RL orientation after increased TEMP drying was found, but the test methods as well as the drying methods and the wood species were different to this study. Reiterer (2001) measured decreasing G_f values in the RL orientation for spruce and beech after increasing microwave drying at increasing TEMP at 20, 40, 60 and 80 °C according to the wedge splitting test by Stanzl-Tschegg et al. (1995). Reiterer (2001) attributed the reduced fracture energy, in particular by increasing TEMP from 60 to 80 °C, to a weakened hemicelluloses and lignin matrix. Stanzl-Tschegg et al. (1994) measured decreasing G_f values for spruce in the RL orientation and increasing G_f values in the TL orientation after different drying methods with increasing temperature levels. Wedge splitting specimens, according to Stanzl-Tschegg et al. (1995), after prefreezing at −20 °C for one month and further air drying at 20 °C showed the highest G_f values in the RL orientation compared with fresh air drying at 20 °C and kiln drying at 50–60 °C for 650 h as well as high-temperature drying at 100–110 °C for 145 h. The fracture behaviour in the TL orientation after the different drying methods showed the opposite; the highest G_f values were obtained for the high-temperature drying and the lowest after the prefreezing and further air drying method. The differences in G_f between kiln drying and high-temperature drying in both testing directions were not as clear as in comparison with the prefreezing combined with air drying as well as the fresh air drying. The TEMP used in the kiln drying and the high-temperature drying in the study by Stanzl-Tschegg et al. (1994) are comparable with the TEMP of the standard drying and the oven drying of this study. Furthermore, the results by Stanzl-Tschegg et al. (1994) are in accordance with the findings of this study, where values in TL are higher than in RL and the high level of statistical scattering. Different crack paths seemed to be responsible for the differing results in RL and TL orientation; in particular in TL orientation, a very rough fracture surface and edges were observed by Stanzl-Tschegg et al. (1994). Further, from TEMP above 100 °C remarkable chemical deterioration could be responsible for the scattering of the values without measurable significant decrease in comparison with standard kiln drying. Temperature-related hydrolysis causes a reduction in monosaccharides, which are the main constituents of the hemicellulosic part of the cell wall, which in turn acts as a kind of coupling agent between cellulose and lignin and is very important for the strength properties of wood (Hinterstoisser et al. 1992). Moreover, in high-temperature dried wood EMC is reduced due to this chemical deterioration. EMC of the standard as well as alternating drying at 20 °C and 65 % RH should be at the same level due to their maximum TEMP, but not so for the oven drying (Fig. 1; Table 1) in this study. In view of that, if the test material is not conditioned carefully to a moisture content below fibre saturation point, reductions in G_f may not be significant but the variance can increase by a significant amount (Smith and Chui 1994). Oltean et al. (2011) found no significant influence on the tensile strength perpendicular to the grain of spruce after different dryings at 45, 55, 65 and 80 °C each at EMC of 2 %. The kind of loading of the tensile test perpendicular to the grain is comparable with the G_f characterisation in the RL crack propagation system, but probably less sensitive. Summing up, a consistent influence of the TEMP on the fracture behaviour in RL as well as in TL crack propagation is not reported in literature (e.g. Stanzl-Tschegg et al. 1994; Reiterer 2001; Oltean et al. 2011), which is in accordance with the findings of the present study.

No significant differences regarding G_f were found between standard and oven drying in the present study. The TEMP of the standard and the alternating schedule were below 80 °C and significant differences in G_f were still detected in this study. The maximum TEMP of the standard and the alternating schedule showed only minimal differences, which cannot be responsible for the degradation (Table 1). Oven-dry specimens showed no significant differences in G_f values compared with the standard dried specimen in the RL as well as in the TL orientation, but showed greater scattering of the measured values (Fig. 5; Table 2). The greater scattering of the G_f values after oven drying may be attributed to chemical deterioration (Hinterstoisser et al. 1992) combined with the reduction in EMC, microcracks in cell walls caused by high TEMP (e.g. Stanzl-Tschegg et al. 1994) and commencing embrittlement of the fracture process (Kifetew et al. 1998). High TEMP in association with extremely low EMC seems to cause higher scattering of G_f values, partly shown by Reiterer et al. (2001) and Stanzl-Tschegg et al. (1994) with other fracture energy testing methods.

The alternation of the TEMP and the EMC in the present study seemed to be much more influential on the decrease in G_f than a high temperature level, as used in oven drying. The periodical change of the TEMP as well as the EMC and the higher-drying gradient of the alternating drying, in particular programme B (Table 1), compared with standard and oven drying reduce G_f but also the scattering of G_f. The G_f values and the scattering of the alternating drying schedule were lower compared with the standard drying and even to the oven drying, which was not expected. Gerhards (1986) compared conventional drying at 82 °C with high-temperature drying at 116 °C and found no appreciable effect on static strength, but mentioned that high-temperature drying has a deteriorating effect on many hardwood species and that the effect is less severe for lumber than for small clear specimens. According to Hillis (1984), the effects of the drying temperatures and time of application on the stability and strength have not been defined completely. Conventional and plantation teak tend to low swelling and shrinkage due to the low content of hydrolysable hemicelluloses (Burmester 1975; Bhat et al. 2001; Posch et al. 2004), which could be responsible for the good drying quality in this study after oven drying. Cracks, casehardening, warp or discolouration are parameters, which define drying quality in general on a macroscopic level. For the fracture energy investigations in this study, clear specimens were prepared and obvious macroscopic defects, particularly drying defects, were excluded. In view of that, high-temperature drying has to be applied in consideration of the individual wood species as well as constant oven drying at 103 °C, which is not applicable to dry lumber, even if no significant deterioration was found in this study. The fracture energy test used seemed to be very sensitive on a microscopic level, in particular to periodic alternating changes of TEMP and EMC during convection kiln drying, which was the focus in the current study. The results of this study show significant differences between a continuous and an alternating drying schedule at the same temperature level in G_f characterisation in RL as well as the TL crack propagation system.

Conclusion

The specific fracture energy method applied in the radial/longitudinal and tangential/longitudinal crack propagation system for drying quality assessment of solid wood reacts sensitively to deterioration by alternating convection kiln drying process. The periodic alternation of the drying temperature along with the periodic alternation of the EMC reduce the specific fracture energy and the scattering of the values compared with continuously increasing drying temperature along with continuously decreasing EMC within the same range and also compared with drying at constant higher-drying temperature along with constant extremely low EMC. According to this, periodically alternating process control affects the specific fracture energy more than a comparable continuously one and even more than drying at constant higher-drying temperatures along with extremely low EMCs by far longer drying time in comparison with the continuously standard process control.

References

ASTM D 3433-75 (1985) Standard practice for fracture strength in cleavage of adhesives in bonded joints. American Society for Testing and Materials, Philadelphia

Bhat MK, Priya BP, Rugmini P (2001) Characterisation of juvenile wood in teak. Wood Sci Technol 34:517–532

Burmester A (1975) Zur Dimensionsstabilisierung von Holz. Holz Roh-Werkst 33:333–335

Ehart AJR, Stanzl-Tschegg SE, Tschegg EK (1996) Characterization of crack propagation in particleboard. Wood Sci Technol 30:307–321

EN 14298 (2004) Sawn timber—assessment of drying quality. European Standard, Brussels

Frühmann K, Tschegg EK, Dai C, Stanzl-Tschegg SE (2002) Fracture behaviour of laminated veneer lumber under mode I and III loading. Wood Sci Technol 36:319–334

Gerhards CC (1986) High-temperature drying of southern pine 2 by 4's: effects on strength and load duration in bending. Wood Sci Technol 20:349–360

Griffith AA (1921) The Phenomena of Rupture and Flow in Solids. Philos Trans R Soc Lond A 221:163–198

Hillis WE (1984) High temperature and chemical effects on wood stability. Part 1: general considerations. Wood Sci Technol 18:281–293

Hinterstoisser B, Weingärtner J, Praznik W (1992) Influence of wood drying processes on the carbohydrate matrix of wood of picea abies. In: Proceedings of 3rd IUFRO International Conference. Vienna, pp 217–221

Irwin RG (1958) Fracture. Encyclopedia of Physics, Berlin

Kifetew G, Thuvander F, Berglund L, Lindberg H (1998) The effect of drying on wood fracture surfaces form specimens loaded in wet condition. Wood Sci Technol 32:83–94

Logemann M, Schelling W (1992) Die Bruchzähigkeit von Fichte und ihre wesentlichen Einflußparameter—Untersuchung im mode-1. Holz Roh-Werkst 20:47–52

Mai YW (1975) On the velocity-dependent fracture toughness of wood. Wood Sci 8(1):364–367

Majano–Majano A, Hughes M, Fernandez-Cabo JL (2012) The fracture toughness and properties of thermally modified beech and ash at different moisture contents. Wood Sci Technol 46:5–21

Oltean L, Teischinger A, Hansmann C (2007) Influence of temperature on cracking and mechanical properties of wood during wood drying—a review. Bioresources 2(4):789–811

Oltean L, Teischinger A, Hansmann C (2011) Influence of low and moderate temperature kiln drying schedules on specific mechanical properties of Norway spruce wood. Eur J Wood Wood Prod 69(3):451–457

Perré P (2007) Fundamentals of wood drying. COST, A.R.BO.LOR, European COST, France

Pleschberger H, Teischinger A, Müller U, Hansmann C (2013) Mechanical characterization of lumber of small-diameter hardwood species after different drying schedules. Dry Technol 31(9):1056–1062

Porter AW (1964) On the mechanics of fracture in wood. For Prod J 14(2):325–331

Posch B, Wegener G, Grosser D, Wagner L (2004) Physikalische und mechanische Untersuchungen an Teakholz (*Tectona grandis* L.f.) aus Plantagen in Panamá. Holz Roh-Werkst 62:31–35

Reiterer A (2001) The influence of temperature on the mode I fracture behaviour of wood. J Mater Sci 20:1905–1907

Schniewind AP, Ohgama T, Aoki T, Yamada T (1982) Effect of specific gravity, moisture content, and temperature on fracture toughness of wood. Wood Sci 15(2):101–109

Smith I, Chui YH (1994) Factors affecting mode I fracture energy of plantation-grown red pine. Wood Sci Technol 28:147–157

Smith I, Landis E, Gong M (2003) Fracture and fatigue in wood. Wiley, Chichester

Stanzl-Tschegg SE (2006) Microstructure and fracture mechanical response of wood. Int J Fracture 139:495–508

Stanzl-Tschegg SE, Tschegg E, Teischinger A (1994) Fracture energy of spruce wood after different drying procedures. Wood Fiber Sci 24(4):467–478

Stanzl-Tschegg SE, Tan MD, Teschegg EK (1995) New splitting method for wood fracture characterization. Wood Sci Technol 29:31–55

Teischinger A (1992) Effect of different drying temperatures on selected physical wood properties. In: Proceedings of 3rd IUFRO International Conference. Vienna, pp 211–216

Tschegg EK, Frühmann K, Stanzl-Tschegg ES (2001) Damage and fracture mechanisms during mode I and III loading of wood. Holzforschung 55:525–533

Welling J (1996) Zur Ermittlung der Trocknungsqualität von Schnittholz. Holz Roh-Werkst 54:307–311