Fracture toughness and shear yield strength determination of steam kiln–dried wood

K.A. Orlowski [1] & M.A. Wierzbowski [2]

Abstract

Results of fracture toughness (specific work of fracture) and shear yield strength of steam kiln–dried wood simultaneously determined on the basis of cutting power measurement are presented. Wood species, namely oak (*Quercus robur* L.) and pine (*Pinus sylvestris L.*) from the northern part of Pomerania region in Poland, were subject of steam kiln–drying process in a laboratory kiln, specially designed and manufactured for the Gdansk University of Technology. While the colour changes have been observed directly after process, changes in mechanical properties have to be measured. The samples, after drying, were subject of examination during cutting tests on the modern narrow-kerf frame sawing machine PRW15M. Measurements of cutting power for steam dried and air dried samples, as a reference, allowed to reveal the effect of wood steam drying on mechanical properties of wood. It has been recognized that steam wood drying causes a decrease of the mechanical properties of the wood such as: fracture toughness and shear yield strength. Those mechanical properties were determined on the basis of the modern fracture mechanics.

1 Introduction

In the lumber manufacturing process, drying is one of the most costly consuming operation in terms of energy and time. Reduction of the energy consumption and drying processing time are currently two important objectives of timber industry. Many scientific researches have been done and are still in progress to determine the optimal drying strategy to achieve the required timber quality at minimum cost. Drying in superheated steam is economically justified because of the shorter processing time and reduced energy consumption in comparison to drying in hot air. Evaporation of free water does not change wood shape and main dimensions during process of wood drying. With the loss of water evaporation zone moves deeper into the wood. The proper conduct of the drying process allows faster extraction of water (Gard 1999, Wierzbowski et al. 2009).

The drying process was conducted in the experimental kiln of 0.55 m^3 load capacity, especially designed at the GUT (Figure 1a). There are two chimneys at the top to control pressure and environment conditions inside the kiln. The test stand is equipped with a heat exchanger, which is supplied by exhausting gases from a furnace, allowing spread water to evaporate on its surface.

[1] Professor, korlowsk@pg.gda.pl
Mechanical Engineering Faculty, Gdansk University of Technology, Poland
[2] Senior Research Fellow, rwierzbo@pg.gda.pl
Mechanical Engineering Faculty, Gdansk University of Technology, Poland

Generated steam, by the circulation fan, is distributed between wood piles. The kiln is powered by the heat from both a heat exchanger, supplied with exhaust gases from burner, and fan's engine. That kind of location allows us to minimize energy losses outside the kiln. Inside the kiln, there is a forced vapour circulation with speed adjusted up to 5.5 m/s. The fan and the heat exchanger are located in the working area of the kiln separated from the drying area by the wall. The stand is equipped with a control system, located outside the kiln. It includes 4 thermocouples for measurement of dry-bulb temperature inside the kiln and temperature of wood. The system also includes 15 moisture content sensors used to measure the value in the core of the wood and in the kiln.

The drying time in the kiln is significantly reduced, nevertheless, the wood colour is changed. Thus, this phenomenon can testify that also mechanical properties could be also varied. For that reason, the mechanical properties of wood samples before and after an accelerated drying process have to be estimated. Since, Patel et al. (2009) claim that cutting tests could be used as a substitute for fracture tests, moreover, cutting forces may be employed to determine not only toughness but also shear yield strength for a range of solids, including metals, polymers, and wood (Atkins 2005), it was decided to apply the methodology proposed by Orlowski & Atkins (2007), and also described by Orlowski & Palubicki (2009).

2 Theoretical background

Orlowski & Atkins (2007), and Orlowski & Palubicki (2009) have applied the new cutting model for the sawing process on the sash gang saw (PRW15M, Figure 1b), whereby three cutting edges of each tooth are in contact with the workpiece and take part in sawing; the process is conducted in a narrow slit.

a) b)

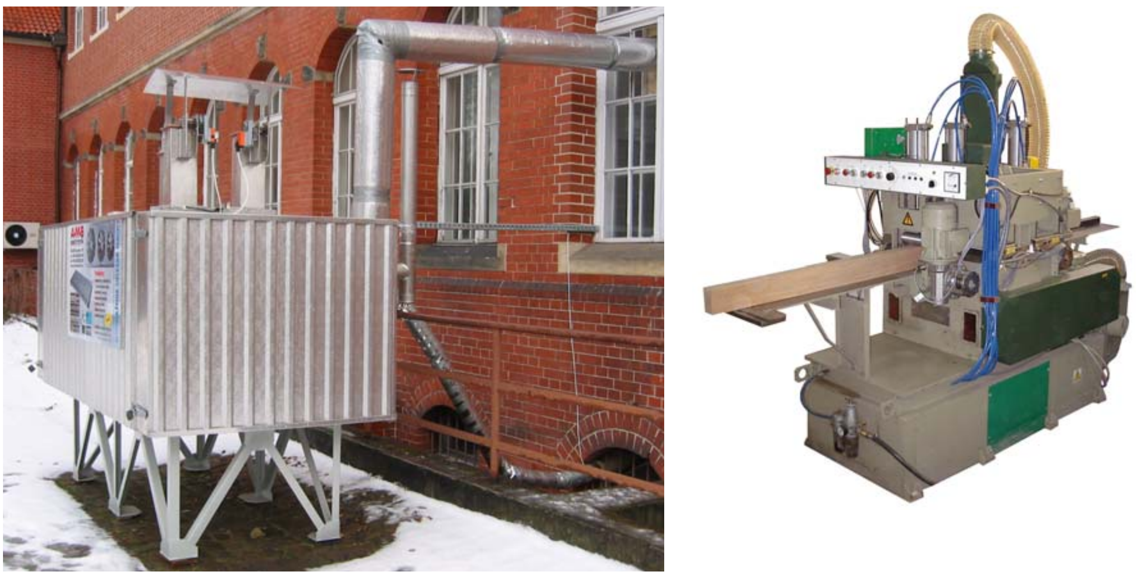

Figure 1: Experimental stands: a) Kiln, b) Narrow-kerf sash gang saw PRW15M

Since the cutting process takes place in the working stroke, therefore the cutting power in that stroke is $\overline{P}_{cw} = 2\overline{P}_c$, for one saw in the saw frame, is given by:

$$\overline{P}_{cw} = \left[\mathrm{Ent}\left(\frac{H_P}{P}\right) \cdot \frac{\tau_\gamma S_t \gamma}{Q_{shear}} v_c f_z + \mathrm{Ent}\left(\frac{H_P}{P}\right) \cdot \frac{R S_t}{Q_{shear}} v_c \right] \quad \text{Equation 1}$$

where: $\mathrm{Ent}\left(\frac{H_P}{P}\right)$ – number of teeth being in the contact with the kerf (integral), H_P is a workpiece thickness, P is a tooth pitch, S_t is an overall set (kerf), τ_γ is the shear yield stress, γ is the shear strain along the shear plane, which is given by:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi_c - \gamma_f)\sin \Phi_c} \quad \text{Equation 2}$$

f_z is feed per tooth (uncut chip thickness), v_c is cutting speed, γ_f is the rake angle, Φ_c is the shear angle which defines the orientation of the shear plane with respect to cut surface, and may be calculated for larger values of feed per tooth f_z with the Merchant’s equation (Orlowski & Atkins 2007):

$$\Phi_c = (\pi/4) - (1/2)(\beta_\mu - \gamma_f) \quad \text{Equation 3}$$

β_μ – friction angle which is given by $\tan^{-1}\mu = \beta_\mu$, with μ the coefficient of friction, Q_{shear} is the friction correction:

$$Q_{shear} = [1 - (\sin \beta_\mu \sin \Phi_c / \cos(\beta_\mu - \gamma_f)\cos(\Phi_c - \gamma_f)] \quad \text{Equation 4}$$

and R specific work of surface separation/formation (fracture toughness).

On the assumption, that every saw tooth of the plain shape is symmetrical and sharp, and may have contact with the kerf bottom only during the working stroke of the saw frame, and moreover, the feed per tooth has a uniform distribution in this stroke, the mean experimental cutting power magnitude $\overline{P}_c$ should be determined experimentally to obtain it as a function of feed per tooth in a form of a linear equation (*e.g.* Equation 1). It ought to be emphasized that the character of cutting power alterations is linear (Orlowski 2007). Toughness R is determined from the experimental ordinate intercept “*b*” ([W], the second component of Equation 1), and the friction correction in this calculation equals Q_{shear} = 1 for the largest kerf, because it can be said that the wider cutting tooth works in quasi-orthogonal conditions which are more similar to orthogonal cutting (Orlowski & Atkins 2007). In the next step, other characteristic data of the sawn material and the cutting process can be estimated according to Atkins (2005), from the coefficient value of *“a”* ([W mm^{-1}], the first component in Equation 1).

3 Material and methods

Samples were dried in the experimental kiln, in which the drying process consists of three phases. In the first phase wood material temperature was increased up to 95°C with scheduled progress, and water is supplied to the kiln to maintain proper humidity inside the kiln. This phase was not a really drying phase. Temperature was measured and used by the control system to switch to the next phase. In the second phase wood was dried to the final MC. After the drying phase timber was cooled down and conditioned at the programmed temperature. At this temperature MC-sensors can be used to confirm that the final MC was achieved. Those three phases comprised the drying schedule. The duration of those phases depends on the wood species and its thickness. For pine (*Pinus sylvestris* L.) the third phase was the longest while for oak (*Quercus robur* L.) the second phase lasted the longest. The oak samples were dried in three different patterns: air, steam with a manual control and steam with an automatic control (Table 1). Pine lumber was dried only with an automatic control in cases of both prisms and boards.

Table 1: Drying patterns, initial and final MC for oak and pine samples

Type of wood and drying pattern	Drying time	Initial MC [%]	Final MC in kiln [%]	Final MC before sawing [%]	Comments
Oak / air	Appr. 3 months	58	-	9.7	
Oak/ system control	4 weeks	58	13	10.2	Water nozzles directed on wood
Oak/ manual control	31 hours	47	7	6.8	Water nozzles directed on exchanger
Pine / air	Appr. 2 months	25	-	6.5–9.8	
Pine prism / system control	58 hours	24	13	9.5–10.3	Water nozzles directed on exchanger
Pine board / system control	72 hours	25	12	7.2–9.4	Water nozzles directed on exchanger

In the sawing experiments the frame sawing machine applied: PRW15M (Figure 1b), which works with a kinematic system having an elliptical trajectory of the teeth movement. The driving system is dynamically balanced and it guarantees that no contact of the saw teeth with the kerf bottom occurs (Wasielewski & Orlowski 2002). Specifications of the machine tool: number of the saw frame strokes $n_F = 685$ rpm, stroke of the saw frame H_F = 162 mm, feed speed at two levels $v_f \approx 0.2$ m min^{-1} and $v_f \approx 1.0$ m min^{-1}, m = 5 number of saws in the gang, and average cutting speed v_c = 3.69 m s^{-1}. Data of saw blades with stellite tipped teeth which were employed in the tests: overall set (kerf) S_t = 2 mm, saw blade thickness s = 0.9 mm, a free length of the saw blade L_0 = 318 mm, saw blade tension stresses σ_N = 300 MPa, blade width b = 30 mm, tooth pitch P = 13 mm, tool side rake angle γ_f = 9°, tool side clearance angle α_f = 14°. Blocks and lumber (a set of 3 pieces) stacks made of pine (*Pinus sylvestris* L.) of H_p = 70 mm in height, with MC as in Table 1 were cut. Prisms made of oak (*Quercus robur* L.) of H_p = 70 mm in height, with MC as in Table 1 were sawed. The above mentioned data was the set of input values and the average value of the cutting power $\overline{P}_c$ was the output value. The mean value of total power $\overline{P}_{cT}$ and the idling power $\overline{P}_i$ of the main driving system were measured with a power transducer. The latter was determined directly before each cutting test.

In computation of fracture toughness (specific work of fracture) and shear yield strength it was assumed that in case of oak μ = 0.8 (according to Beer 2002) and for pine μ = 0.6 (Beer 2002).

4 Results and discussion

Figure 2 shows the comparison of fracture toughness R of pine and oak for both methods of drying: natural and accelerated in the kiln. For both species it is observed a decrease in fracture toughness as a result of accelerated drying.

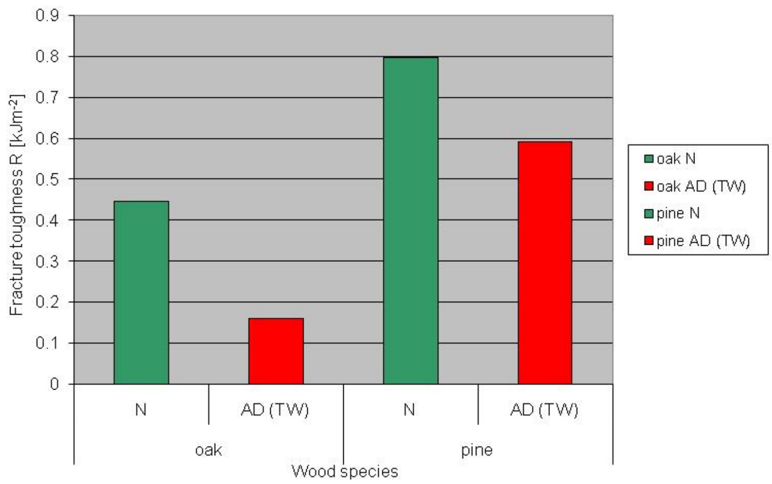

Figure 2: Comparison of fracture toughness R of oak and pine, where: N – natural drying in air, AD – accelerated drying in the kiln

The comparison of shear yield strength of pine and oak for both methods of drying: natural and accelerated in the kiln is presented in Figure 3. For both species it is observed a decrease in shear yield strength caused by the accelerated drying method.

As a result of mechanical properties decreasing after accelerated drying in the experimental kiln it was observed also a reduction in the specific cutting resistance k_c (Figure 4).

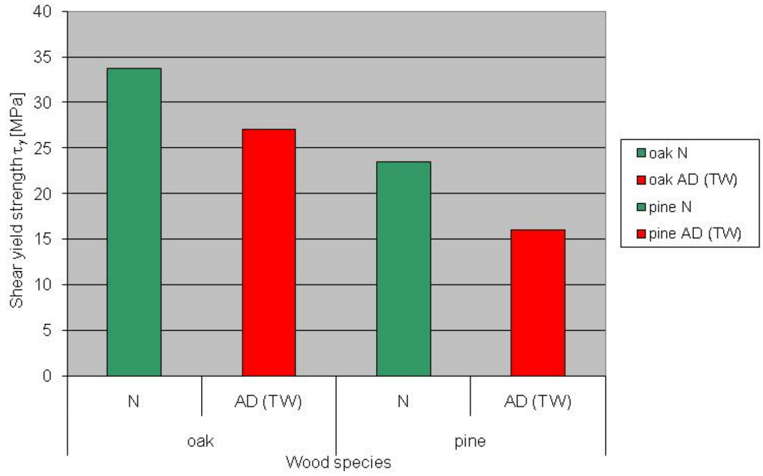

Figure 3: Comparison of shear yield strength of pine and oak for both methods of drying: natural (N) and accelerated (AD) in the kiln

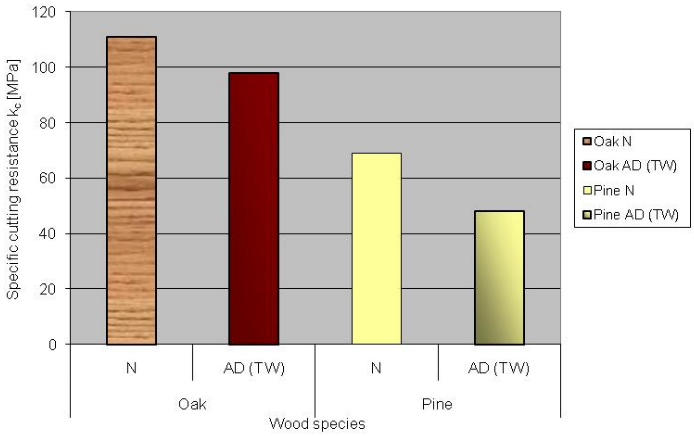

Figure 4: Comparison of specific cutting resistance of pine and oak for both methods of drying: natural (N) and accelerated (AD) in the kiln (values are valid for feed per tooth equal to f_z = 0.2 mm)

5 Conclusions

Although the sawing process is not a pure example of orthogonal cutting, the application of the results obtained by experimental cutting allows the determination of the toughness (specific work of fracture) and shear yield strength of the sawn wood. Obtained results revealed that accelerated drying of pine and oak conducted in the experimental kiln, according to the drying patterns as is shown in Table 1, caused a decrease of wood mechanical properties such as fracture toughness and shear yield strength. Moreover, these phenomena caused also a reduction in the specific cutting resistance. Thus, mechanical properties of wood dried using described schedule may decrease up to 30% of reference value.

6 Acknowledgement

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