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FRACTURE TOUGHNESS IN MECHANICAL TESTING AND CUTTING MODELS

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Abstract

Since the concept of a surface energy necessary to separate a material was introduced in cutting theories, these theories were successfully applied to different materials, one of them wood. While the approach is convincing it is still an open question, what is the counterpart in mechanical testing. In this experimental work fracture energy from cutting experiments were compared to fracture energies from mechanical testing.

Key words: *cutting, modeling, fracture toughness*

INTRODUCTION

The study of cutting forces is of central interest for machine and tools producer to predict power requirements and loads for their products. It would be of major advantage to predict these parameters from required process parameters, e. g. depth of cut and general wood properties like density or strength. Whereas usually it is very simple to get density data from literature, e. g. from collections like [1-3] it is often a challenge to get more detailed data on strength of wood, and also to find the full set of nine elastic parameters to model wood as an orthotropic material is often impossible. Finally data on fracture toughness of different wood species is very scarce.

This general lack of data might be one of the reasons why many wood cutting models are more or less empirical [4] [5] [6] These models are often gained directly from a specific cutting process and are therefore limited in their applications. Some of these models focus on the influence of the materials to be cut, keeping the machining parameters constant. Examples of this kind of models are the works of [7] and [6]. Eyma et al. [7] analysed a peripheral milling process with a single set of process parameters and studied the influence of wood species, characterised by their densites, shear and compression behaviour. Two models predicting the measured cutting forces from a subset of parameters were presented. The best model had an R^2=0,73. A more general approach is presented by Naylor et al. [6] They used a variant of single tooth cutting process with a rake angle of 0°. Studied parameters where moisture content depth of cut and direction (along or accross the grain), wood species described by density, shear tests and three point bending tests. The correlation coefficients of the statistical models (R^2=86% across and 90% along the grain) for the cutting forces are higher than the models presented by Eyma et al. [7] and cover a broader set of parameters.

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Other studies focus on the influence of machining parameters while keeping the wood species and its physical condition constant. An example of this kind of studies is the work of Axelsson et al. [8]. They varied the cutting orientation from a rip sawing process to a milling orientation, modified the rake angle, tool radius, cutting speed and chip thickness while cutting scots pine. Beside these paramters they also changed the temperature and the moisture content. Proposed model is nonlinear in the cutting orentation, furthermore some interaction terms of moisture content with temperature and cutting orientation are included. Porankiewicz et al. [9] proposed a new non-linear statistical cutting model based on cutting orientation, tool geometry and condition, cutting speed and wood properties like density, moisture content and temperature for scots pine. The quality of approximation reached a value of $R^2=0,91$. The authors developed their model on new experimental data and verified it on data from the literature.

Beside these statistical models, which require a high number of parameters and therfore experiments to be verified, in the last years new analytical models based on energy criteria did get popular [10-13]. The developmet of this models were driven by the difficulty to measure the fracture toughness of soft materials with traditional methods. Williams [10] developed a model which assumes a chip produced by elastic and plastic bending, whereas Atkins [11; 12] proposed a model for the generation of a chip by shear in front of the tool. Both models have in common, that they use fracture toughness as an essential parameter, which describes the energy for new surface creation in cutting. The shear chip model was successfully applied to describe the wood cutting process. For example Beer et al. [14] did apply this model to describe the cutting of particle boards. Further modifications to the shear model from Atkins [12] were described by Orlowski et al. [15] in a review on cutting processes. The force model was translated into a power model and the simultaneous action of more than one tooth were described in order to be able to apply the theoretical model to practical applications of frame saw cutting. The circular sawing process could be also described [16; 17]. This cutting process made it necessary to consider the orthotropic nature of wood which was described in detail in [18].

While the cutting models, which use fracture toughness and shear strength as parameters are very powerful in predicting cutting forces and power consumption for different processes [19] the significance of the predicted parameters remain uncertain.

In order to get some insight into this open question, single-tooth cutting experiments were performed and fracture toughness was determined. These parameters were then compared with parameters from fracture mechanical testing.

MATERIALS

Four different wood species were used for the experiments, two softwoods and two tropical woods. The softwoods were larch (*Larix decidua* Mill.) and western red cedar (*Thuja plicata* D. Don) and the tropical woods were Jatoba (*Hymenaea courbaril* L.) and Wenge (*Milettia laurentii* De Wild). Before cutting, wood logs were cut into samples of ca. 3x8x3 cm^3 and stored in a climate chamber of standard environment conditions 20 °C and 65 % relative humidity until an equilibrium moisture content was reached.

METHODS

Microtome cutting and force measurement

In order to control cutting directions as well as chip thickness in a repeatable and controllable way, a modified microtome, equipped with a single cutting tooth, was used for the cutting experiments.

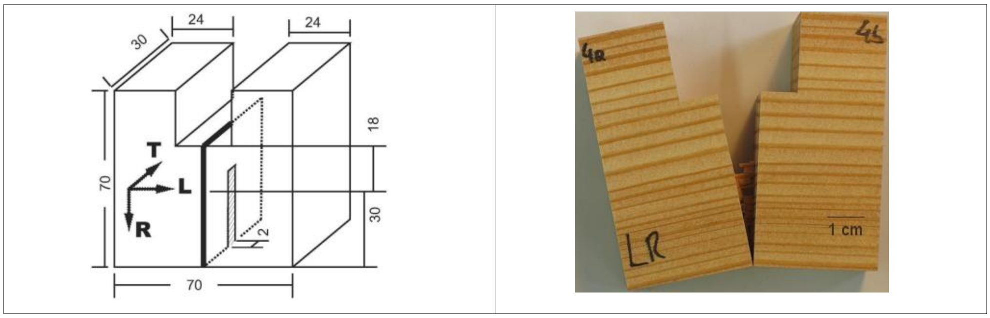
Cutting forces were measured with two 3d piezoelectric force sensors from PCB® joining the specimen holder with the gear of the microtome. Cutting tool had a rake angle of 7,6° degree and a width of 1,16 mm. Experiments were analysed using the cutting force equation 1 of Atkins [12], where $\boldsymbol{F_c}$ is cutting force, $\boldsymbol{w}$ is kerf width, $\boldsymbol{\gamma}$ shear strain and $\boldsymbol{\tau_f}$ shear strength, $\boldsymbol{f_z}$ is uncut chip thickness and $\boldsymbol{R}$ is fracture toughness. $\boldsymbol{Q_{shear}}$ is called friction correction factor and it is a factor depending on rake angle, shear angle and friction. The shear angle $\boldsymbol{\Phi}$ is a result from minimization of the cutting energy and depends on chip thickness, shear strength and toughness. The parameters are calculated by an iterative process described in [12].

$$\frac{F_c}{w} = \frac{1}{Q_{shear}}(\gamma \tau f_z + R) \qquad \text{(Equation 1)}$$

The optimization procedure fits the normalized cutting force as a function of the uncut chip thickness $\boldsymbol{f_z}$ and delivers fracture toughness $\boldsymbol{R}$, shear strength $\boldsymbol{\tau_f}$ and shear angle $\boldsymbol{\Phi}$.

Fracture mechanical testing

Wedge splitting experiments were designed to measure fracture energy and fracture toughness of wood [20; 21]. Grooves were cut on the side of the specimens to reduce the loaded area and guide the crack, since the strength of wood in fiber direction is very strong for the LR-specimens (see figure 1 for specimen shape and dimensions). Specimens were loaded in mode I, i. e. crack opening mode, and LR-crack propagation system. The first letter L indicates the anatomical direction, where loading is applied, and the second letter indicates the direction of crack propagation. Specific fracture energies $\boldsymbol{G_f}$ were evaluated from load displacement curves.



a) b)

Figure 1: Wedge splitting specimen for the LR-crack propagation system with side grooves: a) sketch and b) picture of fractured larch sample

RESULTS

Results of density measurements are summarized in table 1. The densities span a range of 368 to 937 kg/m³
The cutting forces showed linear dependence on chip thickness as predicted by the model. Fracture toughness, shear strength a swell as shear angle were evaluated according to equation 1, results are summarized in table 1:

Table 1: density and cutting parameters: fracture toughness $\boldsymbol{R}$, shear strength $\boldsymbol{\tau_f}$ and shear angle $\boldsymbol{\Phi}$ from least squares fitting of equation 1.

	western red cedar	larch	Jatoba	Wenge
density, (kg/m³)	367,7±3,3	594,5±5,8	937,2±5,6	840,3±1,9
R, (J/m²)	2315	1423	1564	1808
τ, (MPa)	24,6	16,5	68,3	57,4
Φ, (°)	27,6	27,9	31,3	30,7

The results from wedge splitting experiments are shown in figure 2, only the specific fracture energy, I. e. the energy per broken area, was evaluated.

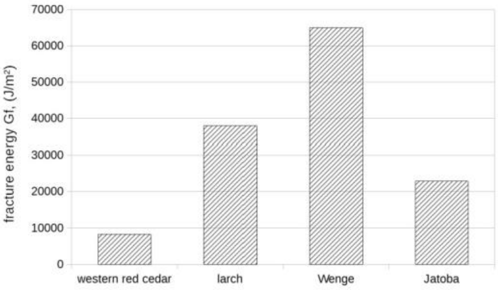


Figure 2: specific fracture energy for all investigated wood species

DISCUSSION

Analysis of data showed that shear strength from cutting correlated very well with density (R^2=0,95), whereas the correlation between fracture toughness from cutting with density was lower (R=0,73).
The correlation between energy from splitting and fracture toughness from cutting is low (R^2=0,59) (see fig. 3). The reason might be in the different crack growth mechanisms. In cutting the crack growth is limited to a very small region in front of the tool where loading reaches strength of the material, whereas in splitting a much larger volume is affected. Pull out of fibers on a very rough broken area was a commonly observed phenomena.

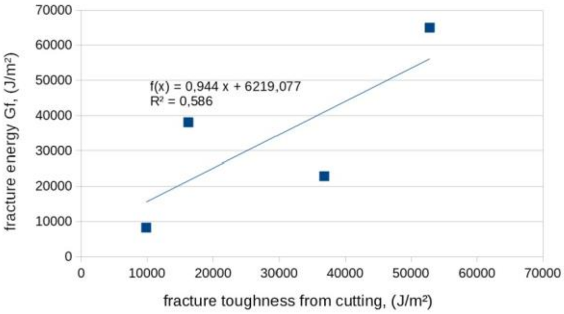


Figure 3: fracture energy G_f from splitting experiments as a function of fracture toughness R from cutting.

Due to the side grooves the fracture tests are non standard methodology for fracture testing and an additional influence of depth and size of the specimen might be expected in determining the fracture energy. Nevertheless the regression line from figure 3 has a slope of approx. 1, which shows, that the parameters follow the same trend. The non-zero axis intercept might have its origin in the different volumes involved in cutting and splitting as described before.

CONCLUSIONS

Fracture mechanical tests as well as cutting experiments were performed in order to get more insight into the parameters involved. Fracture toughness from cutting did correlate to fracture energy from splitting but the correlation coefficient found was low. Further investigations and improvements in methodology as well as theoretical models might be necessary to close the gap between fracture parameters from cutting and from independent mechanical testing. A close correlation of mechanical parameters to cutting parameters would give the possibility to predict cutting forces from mechanical testing and therefore from independent material tests.

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