Influence of Heat Treatment Duration on the Machinability of Beech Wood (*Fagus sylvatica* L.) by Planing

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The comparative behavior of heat-treated and untreated beech wood (*Fagus sylvatica* L.) were studied in response to planing. Beech wood samples were heat-treated in an electric oven without air circulation, at atmospheric pressure, at 200 °C for 1, 2, 3, 4, 5, or 6 h. After conditioning, both the heat-treated samples and the untreated controls were planed at a rotation speed (*n*) of 4567 rpm and a feed speed (*u*) of 10 m/min *via* a "silent power" cylindrical cutter. The cutting power was measured during machining by a Vellemann DAQ board. After processing, the surface quality was measured along and across the cutting direction with a stylus MarSurf XT20 instrument, and the processing roughness was assessed by the roughness parameter *Rk*. The influence of the heat-treating duration upon the cutting power and the processing roughness were analyzed and correlated to the mass loss after the heat treatment. Linear regression functions were generated for both of the correlations.

Keywords: Beech wood; Heat-treatment duration; Planing; Cutting power; Processing roughness

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INTRODUCTION

The machinability of wood refers to the wood behavior during its mechanical processing (by sawing, milling, planing, drilling, turning, sanding), as well as to the resulting surface quality. Therefore, the machinability through any of the above-mentioned mechanical operations can be expressed by two main parameters: the cutting power (P), which represents the amount of energy consumed to process the material, and the surface quality expressed by the roughness parameters recommended in most common standards such as ISO 4287 (1997) and ISO 13565-2 (1996). The cutting power (P) is calculated according to Eq. 1,

$$P = P_t - P_0 \ \text{[kW]} \tag{1}$$

where P_t is the total power consumed by the electric motor during processing (kW), and P_0 is the power consumed by the electric motor during the idle run (kW).

The cutting power depends on the characteristics of the processed material (species, density, moisture content, direction of the cutting plane relative to the wood grain), on the geometrical characteristics of the tool (tool diameter, number of cutting teeth), and also on the cutting parameters (rotation speed of the working shaft, cutting speed, feed speed, and cutting depth). The tools and the cutting conditions are typically chosen according to the processed species and their density, cutting direction relative to the wood grain, and also, by considering the quality requirements of the processed surface.

As mentioned above, the machining of a wood surface is also characterized by the surface quality, which is generally analyzed by the surface roughness resulting from the interaction between the tool and the wood surface. The surface quality of the processed material can be measured with optical non-contact measuring instruments, such as a laser or a stylus contact method. The latter provides more repeatable results and seems more reliable for wood (Gurau *et al.* 2005), whereas the laser seems less accurate (Sandak and Tanaka 2003). Measuring implies a correct selection of the evaluation length as well as of the lateral resolution (the distance between two consecutive data points in the direction of measuring). The measured surface or profile is filtered to obtain only those high frequency irregularities characterized as roughness. The filter selection is crucial because wood roughness is distorted by common Gaussian filters (Krisch and Csiha 1999). A robust Gaussian regression filter (RGRF) that is applied iteratively to a data set gives reliable results and with no distortion to the wood roughness data. This filter was tested while it was still in a draft version. It is useful for wood surfaces because it is more robust than the simple Gaussian filter, and it does not introduce bias related to wood anatomy (Fujiwara *et al.* 2004; Gurau 2004; Gurau *et al.* 2006). Due to the need for a robust filter for the analysis of wood surfaces, the RGRF was also proposed by more recent research from Tan *et al.* (2012) and Piratelli-Filho *et al.* (2012). However, no previous research on the surface roughness of heat-treated wood has used a robust filter; instead, a simple Gaussian filter inherent to most measuring instruments on the market has been used. After filtering, the roughness parameters can be calculated, and they are the basis for comparison between the qualities of the processed surfaces and/or wood treatment. Considering the above advantages, RGRF was the filter applied in the present research.

According to the ThermoWood handbook (FTA 2003), the most important differences between the planing of heat-treated wood *versus* untreated wood are given by the increased brittleness and the increased cupping tendency of the heat-treated material. This is probably due to the fact that the post-treatment movement of wood is very limited. Therefore, when planing a heat-treated timber piece, it should be placed with the convex face upwards, and the wide infeed roller (cylinder) should be replaced by two narrow wheels, located at the outer edges of the timber piece (FTA 2003). This arrangement forms a flat surface, while avoiding surface checking, as the piece proceeds through the planer. Because the strength of the heat-treated material is lower, the infeed rollers must be adjusted to lower pressure values to avoid cracking of the boards. Another recommendation is to decrease the infeed speed by *ca*. 20 m/min compared with the processing of untreated wood. In this case, the rotation speed of the cutters must also be decreased to avoid surface burn. No "optimal" planing regimes are given by reference literature, as they are highly dependent on the planing line and equipment. However, the close connection between the infeed roller type and pressure, the grain direction, the cutter sharpness, the infeed speed, and the rotation speed of the cutters must be carefully harmonized to obtain good results.

Scientific results concerning the machinability of heat-treated hardwoods are poorly represented in the reference literature. Previous studies concerning the cutting power during the milling of heat-treated beech wood (*Fagus sylvatica* L.) (Mandic *et al.* 2010; Kubs *et al*. 2016) did not show a clear variation in the trend of the cutting power with the rotation speed, the feed speed, the cutting depth, and the tool face angle. The only clear result obtained so far is that the cutting power involved in machining the heat-treated hardwoods is lower than in untreated wood, which is expected considering the mass loss and mechanical strengths reduction due to the heat-treatment.

The surface quality of heat-treated hardwoods was previously studied in several species, *e.g.*, oriental beech (*Fagus orientalis* L.) (Yildiz 2002; Kilic *et al.* 2008), Turkish hazel (*Corylus colurna* L.) (Korkut Sevim *et al.* 2008), hornbeam (*Carpinus betulus* L.) (Gunduz *et al.* 2009), sessile oak (*Quercus petraea* L.) (Budakci *et al.* 2013), and beech (*Fagus sylvatica* L.) (Kvietkova *et al.* 2015). Most of these studies compared the surface roughness of heat-treated and untreated wood by planing the wood samples prior to the heat treatment. However, evaluating the surface roughness of heat-treated wood after planing is more interesting because in real practice, heat treatment precedes the mechanical processing and only this way, one may see if the heat treatment intensity influences (or not) the surface roughness. This aspect is of utmost importance for further gluing and coating.

The only published report on the processing roughness after the planing of a heat-treated hardwood species assessed the surface quality of *Eucalyptus grandis* wood after planning; increased treatment temperature (up to 200 °C) caused a remarkable increase in the wetting time (De Moura and Brito 2008).

Another important machinability property of wood, strongly related to surface roughness, is the adhesion strength of varnish. Kilic (2009) performed a study with steamed beech wood (*Fagus orientalis* L.) and found that steaming increases the roughness and reduces the adhesion strength significantly. He also found that the adhesion strength of specimens with a radial surface is higher than that of the specimens with tangential surfaces, which led to the recommendation of sanding once again the material due to the increase in roughness due to the steaming.

The main aim of the present research was to investigate the influence of the heat-treating duration on the cutting power and the processing roughness after the planing of beech wood (*Fagus sylvatica* L.) compared with untreated wood. A similar study was performed with resinous wood (Scots pine) by Krauss *et al.* (2016) and Pinkowski *et al.* (2016). In addition, correlation functions between the mass loss, as main indicator of the heat treatment intensity, and the two machinability parameters were established.

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica* L.) samples with an initial density of 704.1±10.23 kg/m^3 were used in this experiment. They were cut to the dimensions of 400 mm × 50 mm × 25 mm. One group of 6 replicates remained untreated and served as controls. The other samples were heat-treated in an electric oven without air circulation, at atmospheric pressure, at 200 °C for 1, 2, 3, 4, 5, or 6 h, using a group of 6 replicates for each treatment duration.

The mass loss (*ML*) was assessed after every hour of treatment to draw the correlation function between the treating time and the mass loss.

Both the heat-treated and untreated samples were further conditioned for 4 weeks at 20 °C and 55% relative humidity (RH) until their average moisture content (MC) stabilized at 3% ± 0.2% for the heat-treated samples and at 8% ± 0.5% for the untreated controls. All samples were planed on a D963 thicknessing machine with a “silent power” cylindrical cutter head (Fig. 1) (FELDER, Absam, Austria) with helical cutters with Tungsten carbide inserts. The planing was performed at a rotation speed of 4567 rpm and a feed speed of 10 m/min. The cutting power during machining was measured by a data-acquisition board (VELLEMANN, Gavere, Belgium).

For each treatment duration, three machined samples were further randomly chosen for surface quality analysis. The surface quality was measured with a stylus MarSurf XT20 instrument (MAHR GMBH, Göttingen, Germany). The instrument was endowed with a MFW 250 scanning head with a tracing arm in the range of ± 500 μm and a stylus with a 2-μm tip radius and 90° tip angle (Fig. 2). The specimens were measured at a speed of 0.5 mm/s and at a low scanning force of 0.7 mN. From each specimen, three 42 mm long profiles were scanned across the grain (across the feed direction), and three 100 mm long profiles were scanned along the grain (in the feed direction) at a lateral resolution of 5 μm so that for each treatment and scanning direction, 9 profiles were analyzed.

a.

b.

Fig. 1. (a) FELDER D963 thicknessing machine equipped with (b) a “silent power” cylindrical cutter head with helical cutters

Methods

The instrument had MARWIN XR20 software (Göttingen, Germany) installed for processing the measured data. First, the software removed the form error, and a primary profile was obtained, containing the waviness and roughness. The roughness profiles were obtained by filtering each profile with a robust RGRF filter as noted in ISO 16610-31 (2010). The 2.5 mm cut-off used was described previously (Gurau *et al.* 2006).

Fig. 2. Measuring the processing roughness by a MarSurf XT20 stylus

Wood anatomy affects the filtering process and also the evaluation of the processing roughness parameters of wood; the surface can be evaluated as rougher than it is in reality. Ideally, the processing roughness should be separated from the anatomical irregularities if the effect of the processing is to be properly evaluated. However, if anatomy is not removed from the measured profile, the R_k parameter can be used as an approximation of the processing roughness (Westkämper and Riegel 1993; Gurau 2004; Sharif and Tan 2011). The R_k is defined in ISO 13565-2 (1996) and is called the core roughness depth. It measures the core roughness of a profile and should be sensitive to wood processing and surface heat treatment. The standard calculation of R_k is based on the Abbot-curve, which is a curve where all of the data points in a profile are ranked in descending order (the curved continuous line in Fig. 3). The core data should represent the highest concentration of data points in a roughness profile and according to ISO 13565-2 (1996), this control region is defined as the 40% of the Abbot-curve whose secant has the smallest gradient. The indices of the upper and lower boundaries of the central region correspond to their rank and are shown as dotted vertical lines. A line following the gradient of the central region is extended to intersect with the upper and lower boundaries of the ranked data. The roughness core profile R_k is the difference between the y-values at these intersections, and is marked by the horizontal dashed lines.

Therefore, the roughness parameter R_k from ISO 13565-2 (1996) was calculated from data sets measured across and along the grain and for each heat treatment duration. A mean value and the standard deviation were calculated.

The analysis of variance (ANOVA) and Duncan's multiple range tests were performed to test significant differences in the R_k between the control and heat-treated samples for various treatment durations.

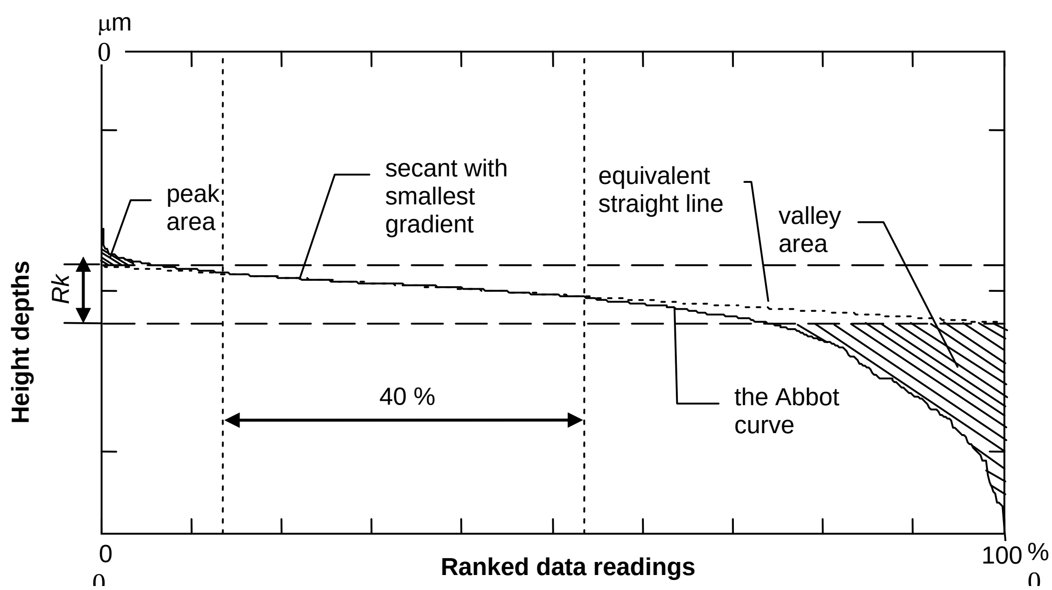


Fig. 3. The calculation of R_k parameter from ISO 13565-2 (1996) (Gurau 2004)

RESULTS AND DISCUSSION

Mass Loss

Mass loss (*ML*) is closely related to the thermal degradation of wood during a heat treatment and appears to be the main indicator of the treatment intensity (Allegretti *et al.* 2012). The mass loss and the heat treatment duration of beech wood (*Fagus sylvatica* L.) at 200 °C were correlated, as represented in Fig. 4. There was a linear increase in ML with increased treatment duration ($R^2 = 0.99$).

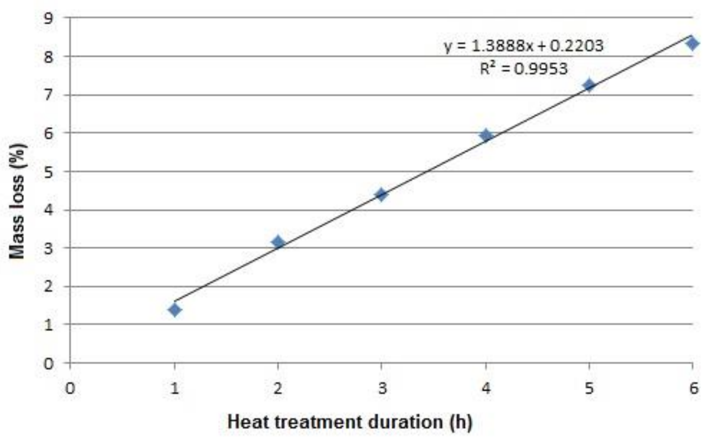


Fig. 4. Mass loss caused by heat treatment in air at atmospheric pressure and 200 °C *versus* process duration; the continuous line represents the regression function

Cutting Power

Table 1 presents the results regarding the cutting power for untreated and heat-treated wood as a function of the treatment duration. All power values recorded during the processing of the heat-treated wood were lower than in the untreated controls, which was expected considering the mass loss (and related strength reduction) due to the heat treatment, especially at treating durations above 3 h. The linear correlation between the active cutting power and the mass loss is represented in Fig. 5; it shows a linear decreasing function with $R^2 = 0.98$.

Table 1. Cutting Power as a Function of Heat Treatment Duration

Heat Treatment at 200 °C (h)	Cutting Power (kW) (Mean Value ± Standard Deviation)
Untreated	0.767 ± 0.08
1	0.510 ± 0.07
2	0.493 ± 0.08
3	0.468 ± 0.08
4	0.455 ± 0.08
5	0.423 ± 0.06
6	0.410 ± 0.07

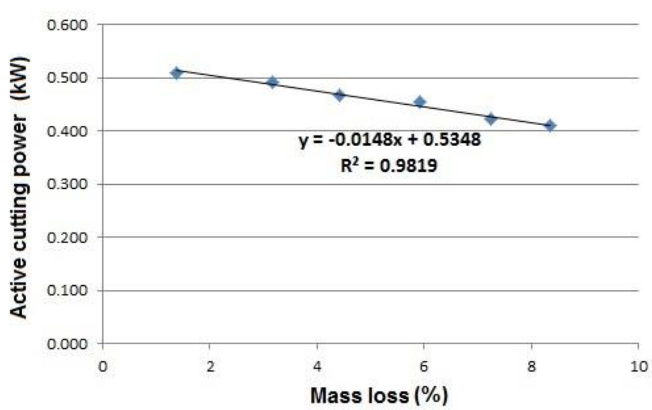


Fig. 5. Variation of active cutting power as a function of mass loss; the continuous line represents the regression function

Surface Quality- Roughness Parameters

The mean values and their standard deviations for the R_k parameter measured across and along the grain are included in Table 2 and Figs. 6 and 7. Table 2 also contains the statistical analysis *via* Duncan's multiple range test.

Table 2. Roughness Parameter Measured Across and Along the Grain for Heat-treated and Untreated Planed Beech Wood

Heat Treatment at 200 °C (h)	Roughness Parameter R_k (µm) (Mean Value ± Standard Deviation)	
	Across the grain	Along the grain
Untreated	9.2 ± 0.63 A	9.5 ± 3.08 A
1	9.3 ± 1.23 A	11.5 ± 1.61 AB
2	9.5 ± 1.86 A	11.4 ± 2.98 AB
3	10.6 ± 1.73 AB	13.2 ± 2.67 AB
4	10.6 ± 1.68 AB	13 ± 2.06 AB
5	12.3 ± 2.65 B	12.6 ± 2.84 AB
6	12.3 ± 2.63 B	14.6 ± 4.03 B

Note: Groups with the same letters in columns indicate that there was no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range test.

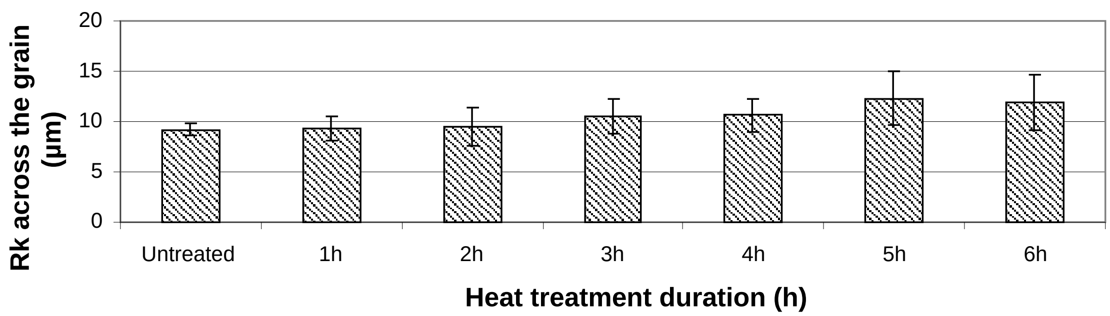


Fig. 6. Variation of the processing roughness (approximated by R_k parameter), with the heat treatment duration; measurements were taken across the grain (across the feed direction) on planed beech surfaces

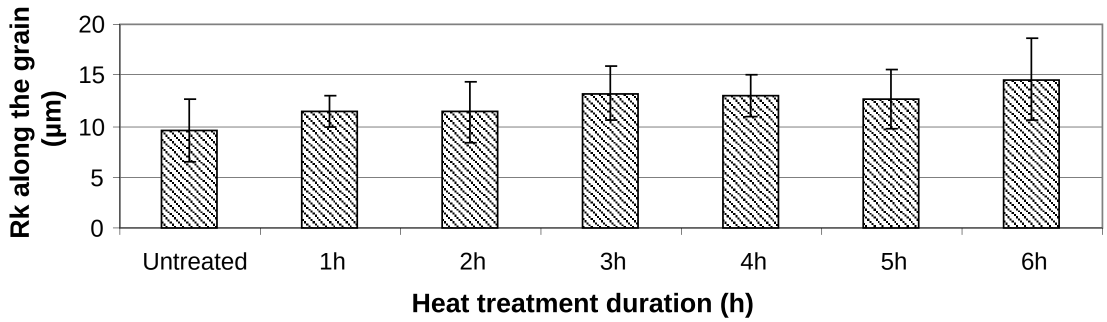


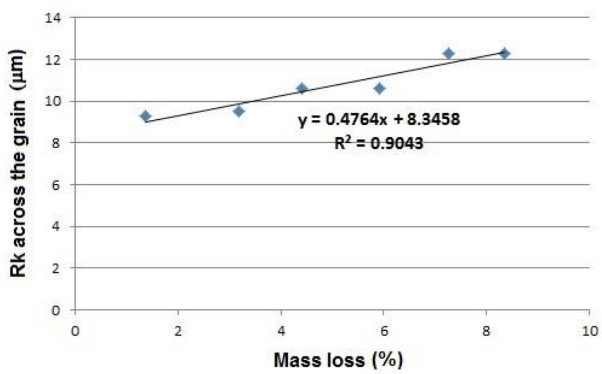
Fig. 7. Variation of the processing roughness (approximated by R_k parameter), with the heat treatment duration; measurements were taken along the grain (in feed direction) on planed beech surfaces

Treating beech for 1 h and 2 h had a negligible effect on the processing roughness measured by the R_k across the grain, which gradually increased by 15% for 3 h and 4 h of treatment and with approximately 33% for beech heat-treated for 5 h and 6 h. The significance of those results was tested and confirmed by ANOVA and Duncan's multiple range test at a $p < 0.05$ significance level (Table 2). The variation in R_k, as measured by the standard deviation values, increased with the heat treatment duration.

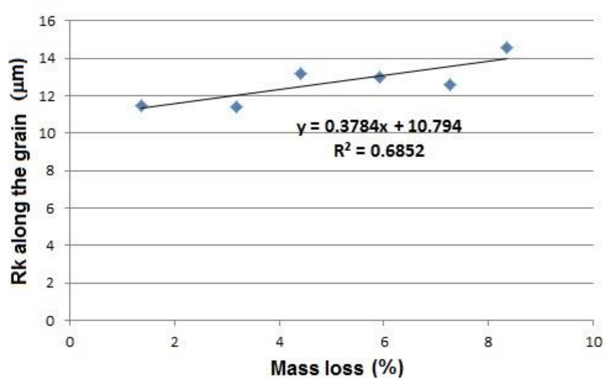
For measurements taken along the grain, compared with the untreated wood, after 6 h of heat treatment, the R_k was increased significantly by 53% according to figures in Table 2 and Duncan's test.

The correlation between the processing roughness after planing and the mass loss resulting from heat treatment durations are presented in Fig. 8.

The R_k measured across the planing direction had a strong correlation with the mass loss (R^2 = 0.9) compared with the same parameter measured along the grain (R^2 = 0.68). This confirmed that measurements taken across the planing direction were more sensitive to changes caused by the duration of the heat treatment. Also, the increased mass loss, which was associated with a decreased density, had a direct effect on the processing roughness, which increased. Thus, the cutting tool left deeper marks on less dense wood. This observation was in agreement with previous work from Gurau *et al.* (2012), who observed that species density played a much more important role in the surface roughness than species anatomy, and the R_k parameter had a strong correlation with the material density. These findings indicated that R_k is a useful expression of the processing roughness after planing wood that was heat-treated at different treatment durations.



a.



b.

Fig. 8. Variation of R_k roughness parameter measured across the grain (a), and along the grain (b), as a function of the mass loss due to heat treatment

CONCLUSIONS

1. The influence of different heat treatment durations at 200 °C on the power consumed during planing and the resulting processing roughness compared with untreated beech (*Fagus sylvatica* L.) was investigated.
2. The mass loss increased linearly with the heat treatment duration, ranging between 1.37% (after 1 h of treatment) and 8.34% (after 6 h).
3. The cutting power decreased with increased heat treatment duration. The cutting power was 47% lower when the processing wood was heat-treated for 6 h at 200 °C than for untreated wood.
4. A negative linear regression function (R^2 = 0.98) was found between the cutting power during planing and the mass loss suffered by the wooden material, due to the heat treatment at 200 °C for 1 h to 6 h.
5. Heat-treating beech for 1 h and 2 h had a negligible effect on the processing roughness after planning, measured across the grain by R_k. However, the R_k increased by 15% for 3 h and 4 h of treatment and with approximately 33% for treating the beech for 5 h and 6 h.
6. Along the grain, the R_k increased with the length of the heat treatment up to 53% (after 6 h of treatment).
7. The processing roughness evaluated by R_k was directly proportional with the mass loss caused by the length of the heat treatment and had a strong R^2 correlation (R^2 = 0.90) for measurements taken across the grain. The correlation was weaker for measurements made along the grain (R^2 = 0.68). Deeper tool marks are expected for a less dense material.

ACKNOWLEDGEMENTS

The authors acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used in this work.

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Article submitted: November 25, 2016; Peer review completed: January 2, 2017; Revised version received: January 15, 2017; Accepted: January 19, 2017; Published: February 23, 2017.
DOI: 10.15376/biores.12.2.2780-2791