The Effect of Spiral Grain on Energy Requirement of Plane Milling of Scots Pine (*Pinus sylvestris* L.) Wood

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The effect of spiral grain angle on the cutting power was tested during plane milling of Scots pine wood. It is known that cutting resistance depends on the arrangement of grain in relation to the direction of woodworking operations. In this work, up-milling (conventional cutting) was applied, as well as two woodworking techniques: with the grain and against the grain. Tests were conducted on samples differing in their position at the stem cross-section, one located closer to the circumference with the spiral grain angle of 11.5° and the other located closer to the pith, in which the spiral grain angle was 7.5°. This analysis confirmed significant differences in cutting power recorded for different values of spiral grain angle and depending on the applied cutting techniques. Cutting power at milling with the grain was greater than at milling against the grain. For samples with a smaller spiral grain angle a lower cutting power was recorded than for samples with a greater spiral grain angle. Differences in cutting power requirement between milling with the grain and against the grain increase with an increase in spiral grain angle.

Keywords: Spiral grain; Cutting power; Plane milling; Scots pine; Grain orientation

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INTRODUCTION

Machining is a material removal process, in the course of which excess material is removed in the form of chips. The effect of grain orientation on cutting has been investigated since the 1950's. Initially researchers focused on a comparison of phenomena occurring in the course of cutting with the grain with those taking place during cutting against the grain (Kivimaa 1950; Franz 1955, 1958; McKenzie 1961; Koch 1964). At present, studies and tests are being conducted to investigate the effect of any given angle between the orientation of the grain and the feed direction on phenomena occurring in the course of cutting (Cyra and Tanaka 2000; Goli *et al.* 2002a,b; Iskra and Tanaka 2005; Aguilera *et al.* 2007; Goli *et al.* 2009a,b; Orlowski *et al.* 2013; Porankiewicz and Goli 2014). Due to the complex anatomical structure of wood, numerous useful wood species and considerable variation of wood cutting methods, the problem of the effect of spiral grain angle on phenomena occurring during cutting has not been completely clarified.

Studies on wood cutting processes generally do not take into account the occurrence of spiral grain. It is a wood defect involving an orientation of grain out of alignment to the longitudinal axis of round wood or timber (Hoadley 2000; Harris 2012). Spiral grain may be found in wood of all wood species, particularly in the circumferential zone of trees with large diameters. Among coniferous species, it is frequently found in the wood of pine (Cown *et al.* 1991) and spruce species (Säll 2002; Brännström *et al.* 2008), while among deciduous species it is observed *e.g.* in horse-chestnut (*Aesculus hippocastanum* L.) (Pyszyński 1977; Harris 2012). It is so common that it is considered a normal property of wood. Spiral grain shown in Fig. 1 is identified in debarked round wood and in tangential planes of timber based on oblique checks and the pattern of resin ducts deflecting from the log axis. A measure of spiral grain is given by the deflection of grain from the log axis per 1 m wood element length, expressed in cm/m or in degrees of angular measure. Moreover, the direction of spiral grain is defined as right-hand (RH) or left-hand (LH), respectively (Harris 2012).

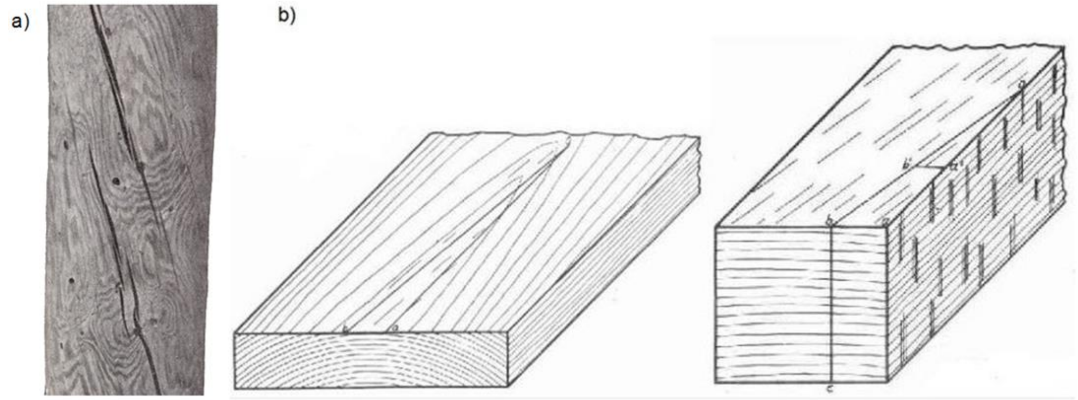

Fig. 1. Spiral grain (a) in the log (b) in the board and rectangular piece (Koehler 1955)

As it is commonly known, annual wood growth increments are seen at the stem cross-section in the form of concentric rings, the so-called annual rings. Annual growth increments are three-dimensional structures, with each successive annual increment in the stem or branch overlapping the previous one, assuming the geometric form resembling a hollow baseless cone (Sydor 2011). A board with a tangential arrangement of annual rings at its wide, *i.e.* tangential plane, comprises a series of sawn cones of individual annual rings. On the surface of such a board we may observe the wood figure in the form of curves resembling parabolas with vertexes oriented along the line. In the course of milling of such a plane, depending on the direction of cutting, we may distinguish two main mechanisms of chip formation (Goli *et al.* 2004): the so-called shear split, in accordance with the diagram in Fig. 2d, when type II chip is formed (Fig. 3a) (Franz 1958), and failure split (Fig. 2e), when type I chip is formed (Fig. 3b) (Franz 1958).

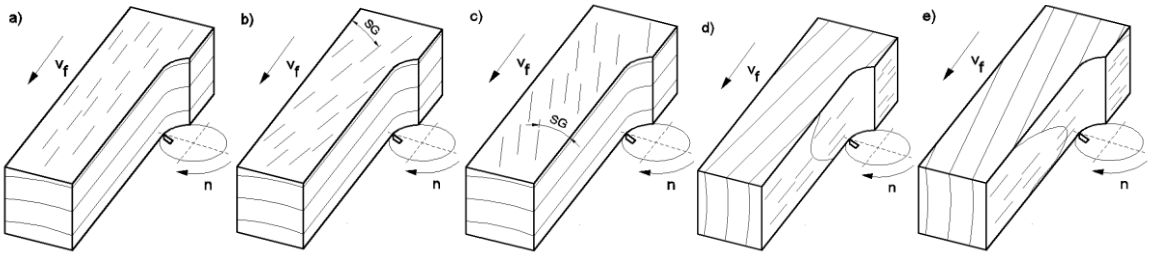

Fig. 2. Techniques of lengthwise milling according to grain orientation: (a) parallel to the grain - without spiral grain, axial arrangement of annual rings, (b) with the grain - spiral grain on the tangential surface, (c) against the grain - spiral grain on the tangential surface, (d) with annual rings - without spiral grain, unaxial arrangement of annual rings, (e) against annual rings - without spiral grain, unaxial arrangement of annual rings; v_f – feed speed, n – rotational speed, SG – spiral grain angle

In turn, in the pith board with a radial arrangement of annual rings on its tangential plane, sawn cones of annual rings are not found, while if present we may rather observe spiral grain (Figs. 2b and 2c). In the case of spiral grain in wood we may see an analogy in the process of chip formation between cases presented in Figs. 2b and 2d for cutting with the grain and for the cases in Figs. 2c and 2e for cutting against the grain.

The position of the cutting edge and the direction of feed in relation to grain orientation determine, *e.g.*, the value of specific cutting force, chip formation type, as well as smoothness of the milled surface. Disregarding the relatively common spiral grain in studies aiming at the determination of the effect of grain angle on parameters and effects of cutting may lead to inaccurate results.

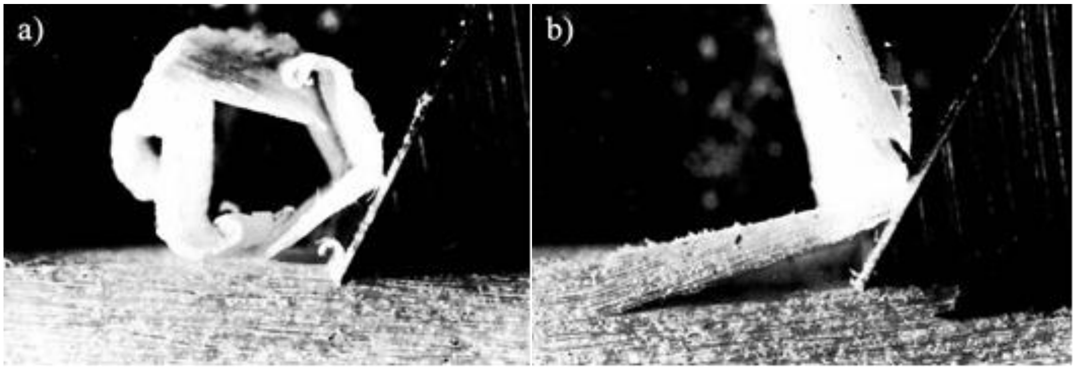

Fig. 3. Chip formation at cutting: (a) with the grain, (b) against the grain (Franz 1958)

Cutting force and cutting power depend on many factors connected with parameters of the process (Aguilera and Martin 2001) as well as morphological characteristics and physico-mechanical properties of cut wood (Chuchała *et al.* 2013, 2014). There is a lot of work investigating the energy requirements of the process of cutting wood materials (Hernández *et al.* 2014; Gürleyen and Budakçı 2015). Milling as one of the basic and common wood-working methods strongly depends on electrical energy. Annual costs of energy used in wood processing are huge (Barcík *et al.* 2010).

The aim of this study was to determine the effect of spiral grain on cutting power at milling both with and against the grain.

EXPERIMENTAL

Materials

The workpieces used were Scots pine (*Pinus sylvestris* L.) blocks, 20(R)x50(T)x250(L) mm (thickness x width x length), conditioned to a moisture content of 8% with specific gravity of 520 kg/m^3 – workpiece A and 480 kg/cm^3 – workpiece B (measured at 8% of M.C.). Location of samples within the log is given in Fig. 4.

Analyses were conducted on two samples: denoted as A – located closer to the circumference, and denoted as B – located closer to the pith. Annual rings in the samples were arranged linearly and parallel to the longitudinal axis, visible on the radial plane, and tangential to the longitudinal axis of samples visible on the tangential plane. Spiral grain angle was determined as presented in Fig. 5. The average value of spiral grain angle in sample A was 11.5°, while for sample B it was 7.5°.

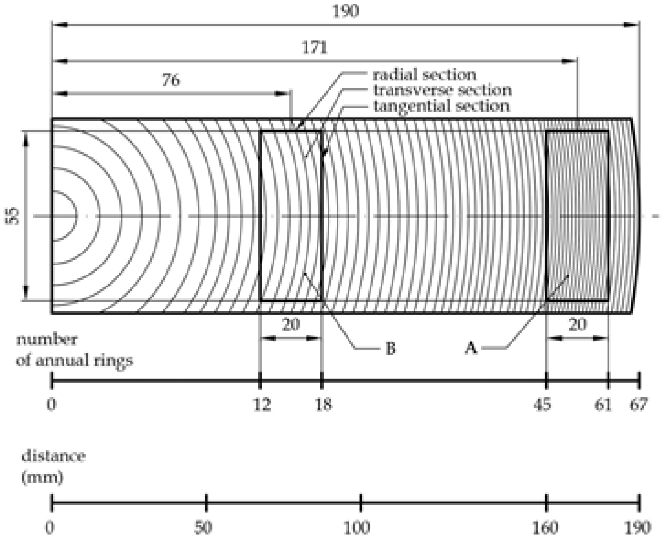

Fig. 4. Location of samples at log cross-section

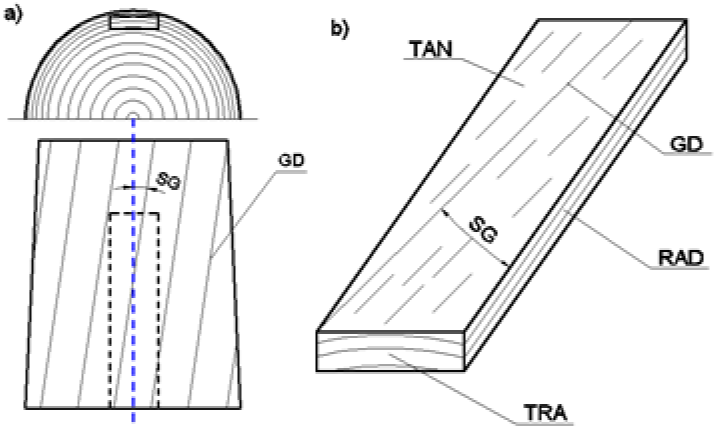

Fig. 5. Spiral grain: (a) in the log, (b) in the sample; SG –spiral grain angle, GD – grain direction, RAD – radial surface, TAN – tangential surface, TRA – transverse surface

Methods

Tests on milling were conducted using a 3-axial CNC FLA-16 CNC woodworking machine by OBRUSN (Toruń, Poland). Parameters applied during woodworking are given in Table 1.

The used tool was an end mill with one cutting knife, with a tool blade of cemented carbide HW - producer: TIGRA GmbH (Oberndorf, Germany), trade name T02SMG - group of application K01. The rake angle was 20°, the wedge angle was 55° and the clearance angle was 15°.

Cutting power was measured using an N13 3-phase network parameter meter by Lumel (Zielona Góra, Poland) with a RS-485 digital interface. Analyses were conducted using a PD10 converter by Lumel (Zielona Góra, Poland). During the measurements of cutting power the sampling frequency was 8 Hz.

Active energy of the woodworking machine running idle and the total active energy consumed by the woodworking machine during milling were recorded. Cutting power of wood was assumed to be active energy calculated as a difference in the energy during cutting and active energy of the idle mode.

The down-milling process is presented in fig. 6. Radial surface of pine wood samples with spiral grain were milled.

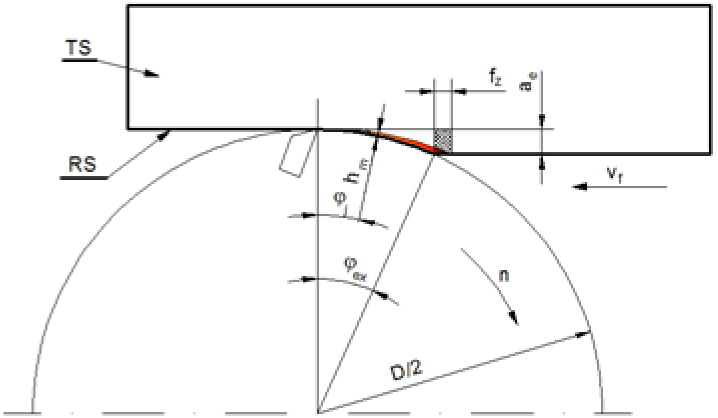

Fig. 6. A scheme of plain milling with conventional cutting, where: *D* – tool diameter, f_z – feed per tooth, a_e – working engagement, v_f – feed speed, *n* – rotational speed, h_m – average uncut chip thickness, φ - angular cutting edge position, *RS* – radial surface, *TS* – tangential surface

Milling was performed with the grain and against the grain, as presented in the diagram given in Figs. 2b and 2c. Two samples were worked, performing three milling operations for each wood-working method. Identical woodworking parameters were applied for all cutting tests, thus guaranteeing comparability of the results.

Table 1. Woodworking Parameters Applied in the Tests

Parameter	Value
Tool diameter *D* (mm)	16
Working engagement a_e (mm)	1
Feed speed v_f (m·min^{-1})	1
Number of cutter *z* (pcs)	1
Rotational speed *n* (min^{-1})	18000

In order to determine the dependence between the analysed factors, *i.e.* milling method and sample type, the analysis of variance was conducted assuming the significance level P<0.05. This is a widely method of analysis used in research in the field of woodworking (Barcík *et al.* 2010; Budakçı *et al.* 2013; Hernández *et al.* 2014). Statistical analysis was performed using the STATISTICA 12 software (StatSoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Results of cutting power measurements in both described directions are presented jointly in Table 2 and in Fig. 8. Table 3 presents results of the analysis of variance for cutting power. These results indicate that at the assumed significance level (P<0.05) there were significant differences in the recorded cutting power values depending on sample type (A vs. B) and woodworking technique (with the grain and against the grain). An example of cutting power fluctuations for sample A milled against the grain is presented in Fig. 7.

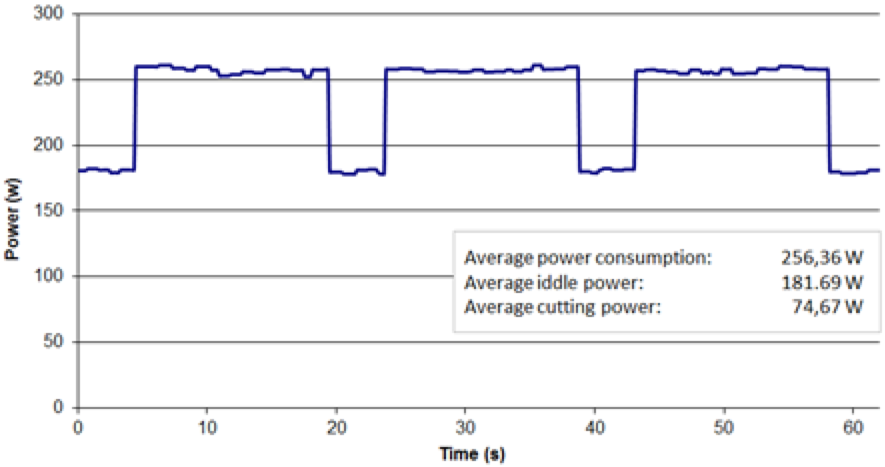

Fig. 7. An example graph of cutting power for sample A milled against the grain

Table 2 gives mean values of density and spiral grain of tested wood as well as cutting power and specific cutting force at milling with and against the grain.

Table 2. A Summary of Testing Results

Sample	Density at 8% M.C. (kg/m^3)	Spiral Grain Angle (°)	Cutting Power^1 (W)		Cutting Power Difference^2 (%)	Specific Cutting Power^3 (W·cm^3/g)		Specific Cutting Power Difference^4 (%)
			With the Grain	Against the Grain		With the Grain	Against the Grain	
A	520	11.5	82.19 0.19 2.70 7.28	74.67 0.21 3.39 11.46	10	158	144	8
B	480	7.5	69.35 0.26 3.46 11.94	66.31 0.20 3.25 10.59	5	144	138	4

Note: $^{1)}$ mean, standard error, standard deviation, variance

$^{2)}$ Difference in energy requirement at milling with and against the grain, expressed in percentage of energy requirement at milling against the grain

$^{3)}$ Cutting power referred to a unit of wood density

$^{4)}$ Difference of specific cutting power at milling with and against the grain, expressed in percentage of specific cutting power at milling against the grain

Table 3. Results of Analysis of Variance ANOVA for Cutting Power

Factor	Sum of Squares	Degrees of Freedom	Mean Squares	Fisher's F-Test	*P*-value
Intercept	4651540	1	4651540	448685.6	0.00
Sample (a)	24446	1	24446	2358.1	0.00
Cutting technique (b)	6068	1	6068	585.3	0.00
a x b	1091	1	1091	105.3	0.00
Error	9258	893	10		

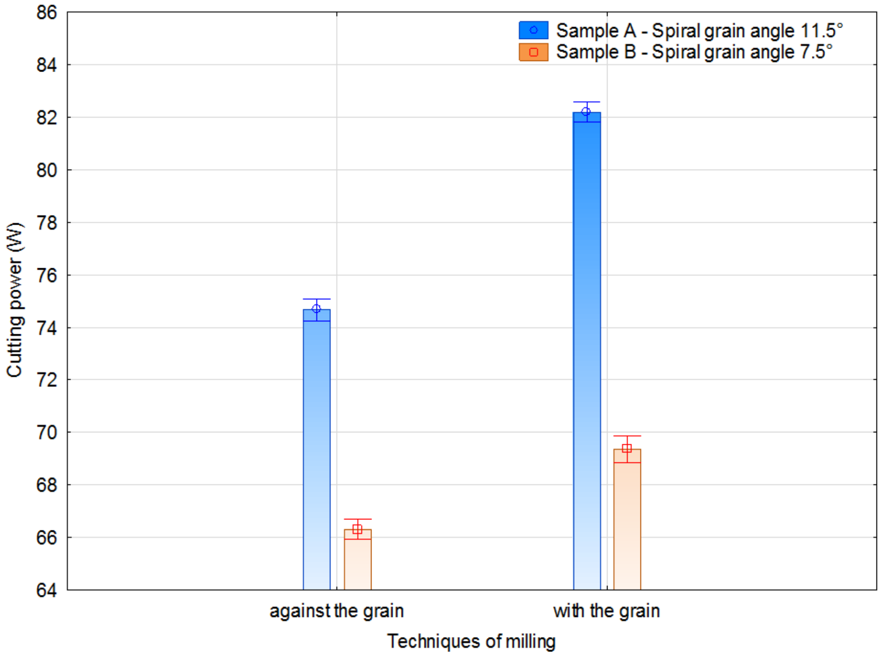

Fig. 8. The influence of the techniques of milling and spiral grain angles on the cutting power. Values are depicted as the mean and the associated 95% confidence interval

Analysis of data given in Table 2 shows that cutting power of sample A in the course of milling in both tested directions was greater than that of sample B. A greater energy requirement for sample A may be explained by its greater density (520 *vs.* 480 kg/m^3). However, it needs to be stressed that cutting power of sample A at milling with the grain (82.2 W) was greater than that of sample B (69.3 W) by as much as 19% and greater by 13% at milling against the grain (74.7 W vs. 66.3 W), while the difference in density was only 8%.

Analysis of specific cutting power, *i.e.* cutting power referred to a unit of wood density, shows that also the specific cutting power of sample A was greater than that of sample B. This indicates the contribution of other factors than wood density, connected with wood structure and determining the energy requirement of cutting power.

A lower energy requirement at milling against the grain in comparison to milling with the grain indicates analogies with cutting against annual rings and with annual rings. Recorded results showed that in the case of milling against the grain a gap appears and failure split occurs at chip formation, similarly as in cutting (against the annual rings). A lesser energy requirement at milling against the grain may thus be explained by different mechanics of chip formation caused by the direction of the grain in relation to the direction of tool movement.

CONCLUSIONS

1. Cutting power during milling with the grain was greater than during milling against the grain. For the sample from the circumferential zone of the stem characterised by a greater density and a greater spiral grain, this difference was 10%, while for the sample from the pith zone with a lower density and lesser spiral grain angle it was 5%, while on average this difference was 7.5%.

2. Specific cutting power was also greater at milling with the grain in comparison to milling against the grain. This difference for the sample from the circumferential zone of the stem was 8%, while for the sample from the pith zone it was 4%.
3. Energy requirement depends not only on wood density and the direction of the machining operation, but also on the location of samples in the log (the distance from the pith).
4. The difference in energy requirement between milling with the grain and against the grain increases with an increase in the spiral grain angle.

REFERENCES CITED

Aguilera, A., and Martin, P. (2001). “Machining qualification of solid wood of *Fagus sylvatica* L. and *Picea excelsa* L.: Cutting forces, power requirements and surface roughness,” *Holz Als Roh- Werkst* 59, 483-488. DOI: 10.1007/s001070100243

Aguilera, A., Vega, M., and Méausoone, P-J. (2007). “Effects of grain angle on the amplitudes of acoustic emission and surface roughness in wood machining,” *Wood Sci Technol* 41, 373-381. DOI: 10.1007/s00226-006-0117-2

Barcík, Š., Kminiak, R., Řehák, T., and Kvietková, M. (2010). “The influence of selected factors on energy requirements for plain milling of beech wood,” *J. For. Sci.* 56, 243-250.

Brännström, M., Manninen, J., and Oja, J. (2008). “Predicting the strength of sawn wood by tracheid laser scattering,” *BioResources* 3, 437-451.

Budakçı, M., İlçe, A. C., Gürleyen, T., and Utar, M. (2013). “Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine,” *BioResources* 8, 3189-3199. DOI: 10.15376/biores.8.3.3189-3199.

Chuchała, D., Orlowski, K. A., Sandak, A., Sandak, J., Pauliny, D., and Barański, J. (2014). “The effect of wood provenance and density on cutting forces while sawing Scots pine (*Pinus sylvestris* L.),” *BioResources* 9, 5349-5361.

Chuchała, D., Orłowski, K., Sandak, A., and Sandak, J. (2013). “The differential impact of a density of Polish pine wood on cutting forces with its origin region taken into consideration,” *Ann WULS - SGGW For. Wood Technol.* 82, 122-126.

Cown, D., Young, G., and Kimberley, M. (1991). “Spiral grain patterns in plantation-grown *Pinus radiata*,” *N Z J. For. Sci.* 21, 206-216.

Cyra, G., and Tanaka, C. (2000). “The effects of wood-fiber directions on acoustic emission in routing,” *Wood Sci. Technol.* 34, 237-252. DOI: 10.1007/s002260000043

Franz, N. C. (1958). *An Analysis of the Wood-cutting Process*, PhD Thesis, University of Michigan Press, Ann Arbor, USA.

Franz, N. C. (1955). "An analysis of chip formation in wood machining," *Forest Products Journal* 10, 332-336.

Goli, G., Bleron, L., Marchal, R., Uzielli, L., and Negri, M. (2002a). “Measurement of cutting forces, in moulding wood at various grain angles. Initials results with Douglas Fir,” in: *Proceedings of the Wood Science and Engineering in the Third Millennium 2002*, Brasov, RO.

Goli, G., Bleron, L., Marchal, R., Uzielli, L., and Negri, M. (2002b). “Surfaces formation and quality in moulding wood at various grain angles. Initial results with Douglas fir and Oak,” in: *Proceedings of the IUFRO Symposium: Wood Structure and Properties*

2002, Zvolen, SK.

Goli, G., Fioravanti, M., Marchal, R., Uzielli, L., and Busoni, S. (2009a). "Up-milling and down-milling wood with different grain orientations – The cutting forces behave-iour," *Eur. J. Wood Wood Prod.* 68, 385-395. DOI: 10.1007/s00107-009-0374-5

Goli, G., Fioravanti, M., Marchal, R., and Uzielli, L. (2009b). "Up-milling and down-milling wood with different grain orientations – Theoretical background and general appearance of the chips," *Eur. J. Wood Wood Prod.* 67, 257-263. DOI: 10.1007/s00107-009-0323-3

Goli, G., Marchal, R., and Uzielli, L. (2004). "Classification of wood surface defects according to their mechanical formation during machining," in: *Proc 2nd Int. Symp. Wood Machin.*, BOKU, Vienna, Austria, pp. 315-324.

Gürleyen, L., and Budakçı, M. (2015). "Determination of machinery and knife strains in the planing of wood-based panels," *J. Wood Sci*. 61, 391-400. DOI: 10.1007/s10086-015-1481-z.

Harris, J. M. (2012). *Spiral Grain and Wave Phenomena in Wood Formation*. Springer, Berlin, Germany. DOI: 10.1007/978-3-642-73779-4

Hernández, R. E., Llavé, A. M., and Koubaa, A. (2014). "Effects of cutting parameters on cutting forces and surface quality of black spruce cants," *European Journal of Wood and Wood Products* 72, 107-116. DOI 10.1007/s00107-013-0762-8

Hoadley, R. B. (2000). *Understanding Wood: A Craftsman's Guide to Wood Technology*, The Taunton Press, Newtown, USA.

Iskra, P., and Tanaka, C. (2005). "The influence of wood fiber direction, feed rate, and cutting width on sound intensity during routing," *Holz Als Roh- Werkst* 63, 167-172. DOI: 10.1007/s00107-004-0541-7

Kivimaa, E. (1950). *The Cutting Force in Woodworking*, Rep. No. 18, The State Institute for Technical Research, Helsinki, Finland.

Koch, P. (1964). *Wood Machining Processes*, Ronald Press Co., USA.

Koehler, A. (1955). *Guide to Determining Slope of Grain in Lumber and Veneer*, US Department of Agriculture, Forest Service, Forest Prod. Lab., Univ. Wisconsin, USA

McKenzie, W. M. (1961). *Fundamental Analysis of the Wood Cutting Process*, Dept. of Wood Technology, School of Natural Resources, Univ. Michigan, Ann Arbor, USA.

Orlowski, K. A., Ochrymiuk, T., Atkins, A., and Chuchala, D. (2013). "Application of fracture mechanics for energetic effects predictions while wood sawing," *Wood Sci. Technol.* 47, 949-963. DOI: 10.1007/s00226-013-0551-x

Porankiewicz, B., and Goli, G. (2014). "Cutting forces by oak and Douglas fir machining," *Maderas Cienc. Tecnol.* 16, 199-216. DOI: 10.4067/S0718-221X2014005000016

Pyszyński, W. (1977). "Mechanism of formation of spiral grain in *Aesculus* stems: Dissymmetry of deformation of stems caused by cyclic torsion," *Acta Soc. Bot. Pol.* 46, 501-522. DOI: 10.5586/asbp.1977.040

Säll, H. (2002). "Spiral grain in Norway spruce," *Acta Wexionensia* 22/2002:1-171.

Sydor, M. (2011). *Drewno w budowie maszyn: historia najważniejszego tworzywa [Wood in mechanical engineering: the story of the most important material]*, Wydawnictwo Uniwersytetu Przyrodniczego w Poznaniu, Poznań, Poland.

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