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# Measurement of Wood Cutting Forces during Bandsawing Using Piezoelectric Dynamometer

## Mjerenje sila rezanja piezoelektričnim dinamometrom tijekom piljenja drva tračnom pilom

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**ABSTRACT •** *Optimization of wood cutting conditions can decrease the cutting forces, which directly relates to the energy consumption. The aim of this study was to measure cutting force components in bandsaw processing of green oak and beech wood at 90°-90° cutting direction (mode A). For this purpose, a piezoelectric dynamometer (KISTLER type 9257A) mounted on the log carriage of vertical bandsaw machine (ESTERER model EB 1400) was used to measure the parallel, normal and lateral cutting forces for different cutting speeds (20, 30 and 40 m $s^{-1}$) and feed rates (20, 30 and 40 m $min^{-1}$ ). Results showed that all cutting force components change by increasing the cutting speed and feed rate over the analysed range. However, little changes were observed for lateral force. Overall, oak wood required greater cutting forces compared to beech wood. Conclusively, in the studied range, with increasing cutting speed ratio to feed rate, main cutting force and normal force were decreased.*

***Key words:*** *bandsawing, cutting forces, cutting speed, feed rate, piezoelectric dynamometer*

**SAŽETAK •** *Optimizacijom uvjeta rezanja drva mogu se smanjiti sile rezanja čija veličina izravno utječe na potrošnju energije tijekom piljenja. Cilj istraživanja bio je odrediti sastavnice sile rezanja tijekom piljenja svježe hrastovine i bukovine tračnom pilom, uz smjer rezanja 90° - 90° (mod A). U tu svrhu piezoelektrični je dinamometar (Kistler tip 9257A) montiran na posmična kolica za trupce vertikalne tračne pile (ESTERER model EB 1400) i upotrijebljen za mjerenje paralelne, okomite i bočne sile rezanja pri različitim brzinama rezanja (20, 30 i 40 $m \cdot s^{-1}$) i posmičnim brzinama (20, 30 i 40 $m \cdot min^{-1}$). Rezultati su pokazali da se sve sastavnice sile rezanja mijenjaju s povećanjem brzine rezanja i posmične brzine u istraživanom rasponu. Male promjene zabilježene su za bočnu silu. Rezultati su pokazali da su za piljenje hrastovine potrebne veće sile rezanja nego pri piljenju bukovine. Zaključno, u promatranom se rasponu brzina s povećanjem omjera brzine rezanja i posmične brzine smanjuju glavna i okomita sastavnica sile rezanja.*

***Ključne riječi:*** *piljenje tračnom pilom, sile rezanja, brzina rezanja, posmična brzina, piezoelektrični dinamometar*

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## 1 INTRODUCTION
## 1. UVOD

Optimization of wood cutting conditions can decrease the cutting forces, which directly relates to the energy consumption. The cutting speed and feed rate are the main machining parameters affecting the cutting forces. The effect of cutting speed was well reviewed by Lubkin (1957). There are some contradictory reports regarding the cutting speed and cutting force relations. Some studies indicated that the cutting speed had practically no effect on cutting forces (Franz, 1958; McKenzie, 1961; Eyma *et al*., 2005), while others showed a cutting force curve with a minimum at some speeds, or a linear change of cutting force by increasing the speed (Pahlitzsch and Dziobek, 1959; Porankiewicz *et al*., 2007). Davim (2011) mentioned that the parallel force increases with increasing cutting speed from 30 m $s^{-1}$ to 60 m $s^{-1}$ for five different coated carbide tools in wood cement board machining. Porankiewicz *et al.* (2007) reported that during milling of laurel blanco wood (*Cordia alliodora*), the parallel force increases by increasing of cutting speed over the analysed range ($10\ m{\cdot}s^{-1} < v_c < 40\ m{\cdot}s^{-1}$). Eyma *et al*. (2005) measured the cutting speed in beech (*Fagus sylvatica*) and Ipe (*Tabebuia* sp.) wood in the cutting speed range of 0.1 to 8 $m{\cdot}s^{-1}$. Their results showed that the cutting speed had no effect on cutting forces. Similar to the cutting speed, the feed rate can impact the cutting forces. Lucic *et al*. (2004) showed that the cutting force during circular rip-sawing of oak wood (*Quercus robur* L.) in transversal cutting direction (90º-90º) increases by increasing the feed rate. Heisel *et al*. (2007) indicated that parallel and normal force increases with increasing of feed rate from 20 $m{\cdot}min^{-1}$ to 55 $m{\cdot}min^{-1}$.

According to the literature, the contradictory results reported about the cutting speed impact on cutting forces can be attributed to the use of different cutting speed range, wood species and machining process. However, the method of cutting force measurement cannot be neglected. The measuring of cutting forces can be carried out using various methods such as pendulum (Eyma *et al.*, 2005), strain gauge (Porankiewicz *et al.*, 2008) and piezoelectric dynamometer. The pendulum dynamometer is a good tool to measure the cutting energy, but it cannot measure the cutting force components. The strain gauge dynamometer is not suitable for high dynamic loads and high cutting speeds and its applicability is extremely limited and the results are difficult to apply to the real situation. Piezoelectric dynamometer is characterized by high sensitivity and a good response to large stresses and thus the accurate date acquisition. Up to now, the piezoelectric dynamometer has been applied to measure the cutting forces in different wood machining processes, such as routing (McKenzie, 2001; Eyma *et al.*, 2004; Goli and *et al.*, 2010), horizontal bandsawing using a single bandsaw tooth (Loehnertz and Cooz, 1998; Ko and Kim, 1999; Cooz and Mayer, 2006) and shaping (Aguilera and Martin, 2001). However, there is no information about using the piezoelectric dynamometer for measuring the cutting force components in an industrial vertical bandsaw. Hence, the aim of this study was to measure the cutting force components during bandsawing of oak and beech wood at different cutting speeds and feed rates using piezoelectric dynamometer.

## 2 MATERIALS AND METHODS
## 2. MATERIJAL I METODE

### 2.1 Specimen preparation
### 2.1. Priprema uzoraka

Beech (*Fagus sylvatica* L.), a diffuse porous species and oak (*Quercus robur* L.), a ring porous species, with mean specific gravity of 0.53 and 0.59, respectively, were selected for the study. For each species, 3 trees with the age range of 75 to 85 years old were randomly cut from the southern forests near Rosenheim in Germany. Then, straight grain lumbers with dimensions of 5000×150×150 mm were prepared. Finally, defect free samples with dimensions of 150×150×150 mm were cut from the straight grain lumbers using circular saw (OptiCut S50). After drying of wood samples inside the kiln (LAUBER TROCKNUNGSTECHNIK) to the target moisture content of about 30 %, a conditioning box was used to homogenize the wood moisture content through the specimen thickness. Three different feed rates (20, 30 and 40 $m{\cdot}min^{-1}$) and cutting speeds (20, 30 and 40 $m{\cdot}s^{-1}$) were considered for the experiments. A total of 108 specimens were prepared with 6 replications for each treatment.

### 2.2 Measuring cutting forces
### 2.2. Mjerenje sila rezanja

Cutting operation for each wood species was carried out in the sawmill laboratory of the University of Applied Sciences in Rosenheim, Germany using a vertical band saw machine (ESTERER model EB 1400) with log carriage (ESTERER model EW 1000) at 90°-90° cutting direction (Figure 1).

A new blade (ALBER SÄGEBLÄTTER) was used for cutting tests. Technical characteristics and geometry of the used bandsaw are shown in Table1.

A Piezoelectric dynamometer (KISTLER type 9257A) attached to the steel plate was firmly mounted

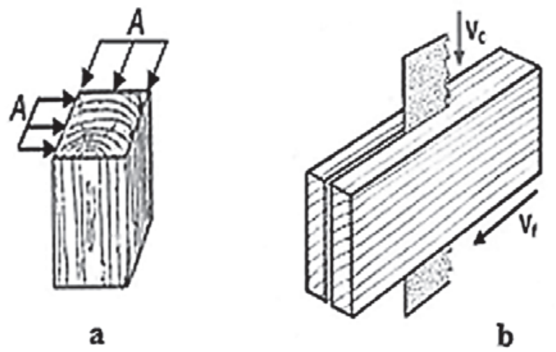


**Figure 1** (a) Definition of cutting directions: mode A= cutting direction 90°-90°(Kivimma, 1950); (b) Angle of inclination between cutting direction and grain orientation during band sawing
**Slika 1.** a) Definicija smjera rezanja: mod A – smjer rezanja 90°-90°(Kivimma, 1950.); b) kut između smjera rezanja i smjera drvnih vlakanaca tijekom piljenja tračnom pilom

**Table 1** Technical characteristics of the used saw blade
**Tablica 1**. Tehnička obilježja upotrijebljene tračne pile

| **Properties** / *Obilježje* | **Value** *Vrijednost* | **Properties** / *Obilježje* | **Value** *Vrijednost* |
|---|---|---|---|
| Blade length, mm /*duljina lista pile,* mm | 10035 | Sharpness angle, ° /*kut oštrenja*, ° | 33 |
| Blade width, mm / *širina lista pile,* mm | 175 | Rake angle, ° / *prsni kut*, ° | 36 |
| Blade thickness, mm / *debljina lista pile,* mm | 1.5 | Clearance angle, ° / *leđni kut,* ° | 21 |
| Kerf, mm / *širina propiljka,* mm | 3.1 | Tangential clearance angle, ° *tangencijalni kut,* ° | 4 |
| Tooth pitch, mm / *korak zuba,* mm | 45 | Radial clearance angle, ° / *radijalni kut,* ° | 2 |
| Number of teeth / *broj zubi* | 223 | Gullet depth, mm / *visina pazuha,* mm | 15 |
| Tooth form / *oblik zuba* | Swage set / *stlačeni* | Wheel diameter, mm / *promjer kotača pile,* mm | 1400 |
| Tooth alloy / *legura zuba* | Stellite / *stelit* | Saw power, kW / *snaga motora,* kW | 55-90 |

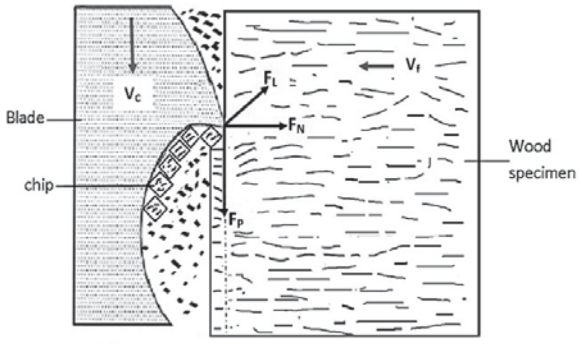


**Figure 2** Cutting force components for the applied bandsawing
**Slika 2**. Sastavnice sile rezanja pri piljenju tračnom pilom

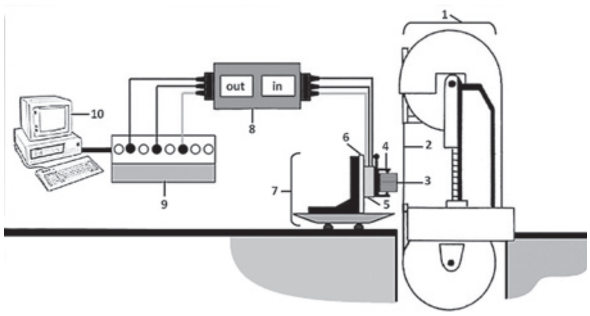


**Figure 3** Experimental set-up;1 – band saw; 2 – saw blade; 3 – wood specimen; 4 – clamp; 5 – piezoelectric gauge; 6 – steel plate; 7 – feed table; 8 – amplifier; 9 – A/D converter; 10 – computer
**Slika 3**. Shema eksperimenta: 1 – tračna pila; 2 – list pile; 3 – uzorak drva; 4 – držači; 5 –piezoelektrični mjerač; 6 – čelična ploča; 7 – posmični stol; 8 – pojačalo; 9 – A/D konverter; 10 – računalo

on the carriage of the saw machine to measure the cutting forces in the three principal axis, including the parallel, normal and lateral forces. The position of the analysed cutting force components in the parallel ($F_P$), normal ($F_N$), and lateral ($F_L$) directions in the bandsawing are defined in Figure 2.

The wood samples were fixed on the dynamometer by a fixture and then calibrated. The signal from the dynamometer was amplified through the charge amplifier (KISTLER type 5007). The amplified signals were collected by means of A/D converter. Finally, the acquired data were presented on the monitor screen. For better data analysis, 10 percent of the obtained data at the beginning and end of cutting were eliminated, due to high saw balde vibration in these situations. General scheme of experimantal set up is shown in Figure 3.

The teeth number involved during bandsawing ($Z_e$) is given by:

$$Z_e = \frac{h}{p} \quad (1)$$

Where $h$ is specimen thickness (mm) and $p$ is tooth pitch (mm). Then, cutting force components ($F$) for one tooth and one millimeter of tooth thickness were determined using the following equation:

$$F = \frac{F_{ave}}{Z_e \cdot w} \left(\frac{\mathrm{N}}{\mathrm{mm}}\right) \quad (2)$$

Where $F_{ave}$ are the mean cutting forces (N) obtained in three directions and $w$ is tooth thickness (mm). Figure 4 shows the cycles of the cutting forces signal obtained during bandsawing by piezoelectric dynamometer.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

Based on statistical analysis, the effect of cutting speed and feed rate on the orthogonal cutting forces at the 90°-90° cutting direction was significant. In contrast to the lateral force, it was established that the parallel and normal forces depended on wood species. Table 2 shows the Pearson correlation coefficients for cutting speed, feed rate and cutting forces. According to Table 2, it can be noted that 60 % ($r^2$ = 0.77) of the variation in the parallel and normal forces is explained by the cutting speed and 51 % ($r^2$ = 0.71) by the feed rate. The cutting speed and feed rate had little effect on the lateral force and there was no correlation between the cutting speed and feed rate.

### 3.1 Effects of cutting speed on cutting forces
### 3.1. Utjecaj brzine rezanja na sile rezanja

Results showed that the parallel and normal forces decreased when the cutting speed increased (Figures 5-7). Overall, the parallel force for the cutting speed of 20 m·s$^{-1}$ was about 50 % greater than that for the cutting speeds of 30 and 40 m·s$^{-1}$(Figure 5). These results can probably be explained by the decreased friction between the tool and work-piece due to the increase of the cutting speed. Another positive effect of the cutting speed on the parallel force reduction can be attributed

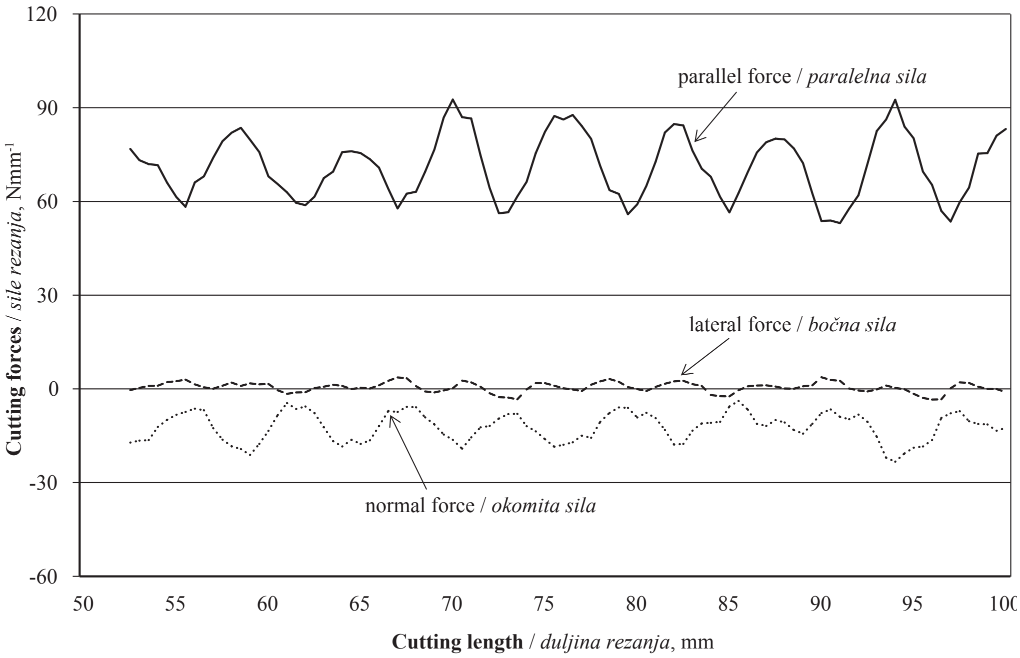


**Figure 4** The cycles of cutting forces signal obtained during bandsawing by piezoelectric dynamometer
**Slika 4**. Ciklusi signala sila rezanja dobivenih piezoelektričnim dinamometrom tijekom piljenja tračnom pilom

**Table 2** The Pearson correlation coefficients between cutting speed, feed rate and cutting forces
**Tablica 2**. Pearsonov koeficijent korelacije između brzine rezanja, posmične brzine i sila rezanja

| **Variable** Varijabla | **Cutting speed** *Brzina rezanja* | **Feed rate** *Posmična brzina* | **Parallel force** *Paralelna sila* | **Normal force** *Okomita sila* | **Lateral force** *Bočna sila* |
|---|---|---|---|---|---|
| Cutting speed / *brzina rezanja* | 1 | 0.0 | -0.77** | 0.78** | -0.42* |
| Feed rate / *posmična brzina* | | 1 | 0.71** | -0.71** | 0.40* |
| Parallel force / *paralelna sila* | | | 1 | -0.90** | 0.55** |
| Normal force / *okomita sila* | | | | 1 | -0.63** |
| Lateral force / *bočna sila* | | | | | 1 |

** Correlation is significant at the 0.01 level / *korelacija je signifikantna pri 0.01*; * Correlation is significant at the 0.05 level / *korelacija je signifikantna pri 0,05*

to the temperature increase in the cutting zone up to 700 °C and wood strength reduction due to softening of wood lignin (Blackwell and Walker, 2006; Iskra *et al.*, 2005). According to the results, with increasing ratio of the cutting speed to feed rate, parallel force decreases gradually (Figure 6). The value of normal force at different cutting speeds for both wood species was negative (Figure 7). Negative normal force occurs at larger rake angles (Koch, 1964). Negative normal force can also be attributed to wood machining defect, such as raised grains that could increase friction force and the ratio of tool cutting edge radius to chip thickness, pushing the tool out (Palmqvist, 2003). Our finding is in agreement with some previous researches (Pahlitzsch and Dziobek, 1959) and in contrast to other researches (Porankiewicz *et al.*, 2007; Eyma *et al.*, 2005).

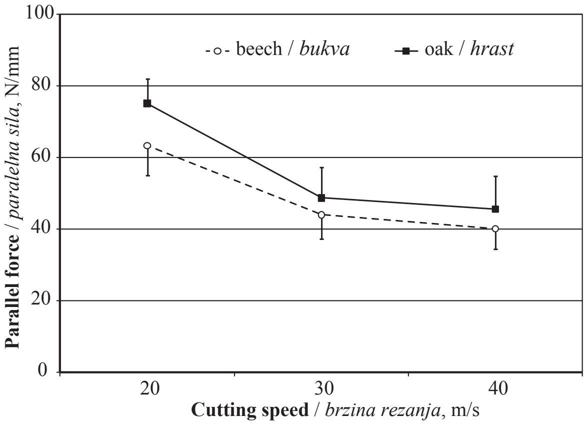


**Figure 5** Relationship between parallel force and cutting speed
**Slika 5**. Odnos između paralelne sile rezanja i brzine rezanja

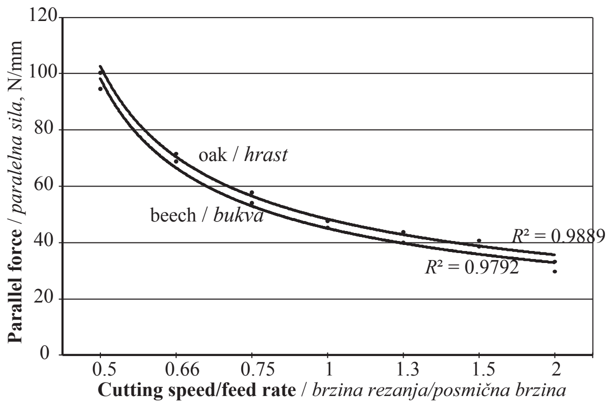


**Figure 6** Relationship between ratios of cutting speed /feed rate on parallel force
**Slika 6**. Odnos između paralelne sile rezanja i omjera brzine rezanja i posmične brzine

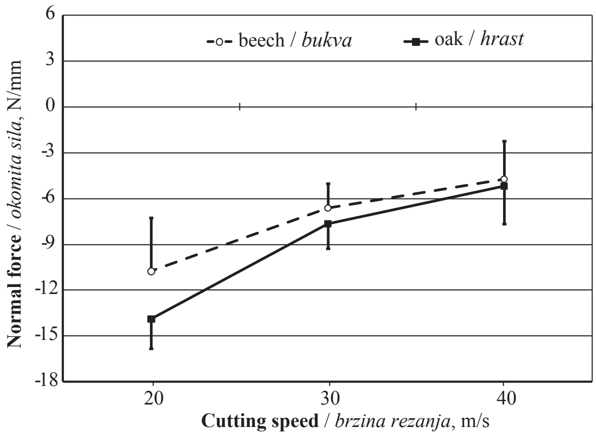


**Figure 7** Relationship between normal force and cutting speed
**Slika 7**. Odnos između okomite sile i brzine rezanja

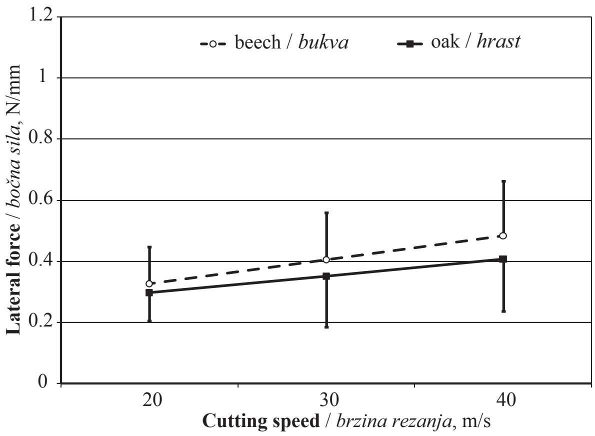


**Figure 8** Relationship between lateral force and cutting speed
**Slika 8**. Odnos između bočne sile i brzine rezanja

Result also revealed that oak wood required more cutting force than beech wood, which can be due to the higher specific gravity of oak wood (SG ≈ 0.53 for beech wood and SG ≈ 0.59 for oak wood). The greatest and lowest parallel and normal forces were observed for oak wood with the cutting speed of 20 m·s$^{-1}$ and for beech wood with the cutting speed of 40 m·s$^{-1}$, respectively.

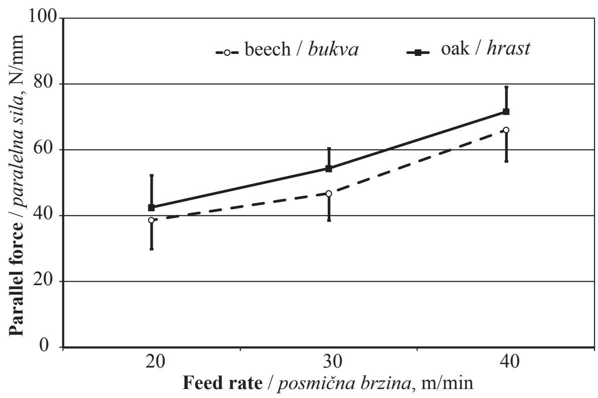


**Figure 9** Behaviour of parallel force during bandsawing at different feed rates
**Slika 9**. Promjene paralelne sile tijekom piljenja tračnom pilom pri različitim posmičnim brzinama

Results indicated that the lateral force for beech wood was a little higher than that of oak wood (Figure 8). Due to the symmetric shape of the teeth, the lateral force was expected to be zero. This means that readings deviating from zero can be attributed to irregular disturbances as a result of inhomogeneity, increasing of friction between saw tooth and chips, poor ground teeth or blade vibrations as indicated by Loehnertz and Cooz (1998). The greatest lateral force value was observed for beech wood at the cutting speed of 40 m·s$^{-1}$, and the lowest one was observed for oak wood at the cutting speed of 20 m·s$^{-1}$

## 3.2 Effects of feed rate on cutting forces
### 3.2. Utjecaj posmične brzine na sile rezanja

Results showed that parallel force increased by more than 65 % as a result of feed rate increasing from 20 to 40 m·min$^{-1}$ (Figure 9). A greater cutting force is required for pulling thicker chips. Normal forces were negative with an increasing trend in the studied conditions (Figure 10). The effect of feed rate on lateral force was insignificant (Figure 11). Our results are in agreement with some previous findings (Pahlitzsch and Dziobek, 1959; Lucic *et al.*, 2004). The greatest and lowest cutting forces were observed for oak wood with the feed rate of 40 m·min$^{-1}$ and for beech wood with the feed rate of 40 m·min$^{-1}$, respectively.

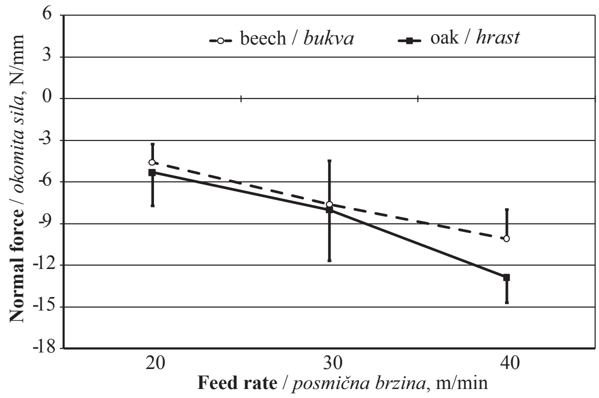


**Figure 10** Behaviour of normal force during bandsawing at different feed rates
**Slika 10**. Promjene okomite sile tijekom piljenja tračnom pilom pri različitim posmičnim brzinama

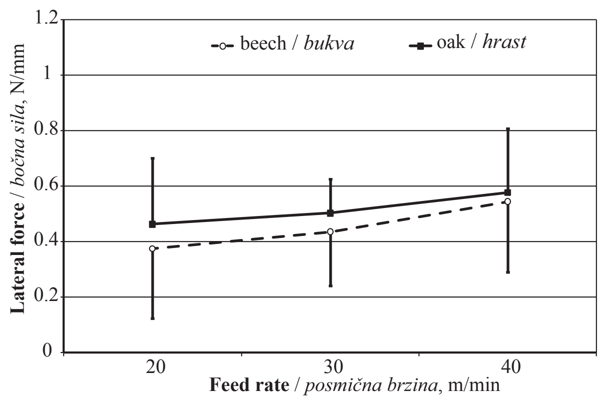


**Figure 11** Behaviour of lateral force during bandsawing at different feed rates
**Slika 11**. Promjene bočne sile tijekom piljenja tračnom pilom pri različitim posmičnim brzinama

## 4 CONCLUSION
## 4. ZAKLJUČAK

The main purpose of the present research was to accurately measure the orthogonal wood cutting forces, including lateral, normal and parallel ones for different cutting speeds (20, 30 and 40 m·s$^{-1}$) and feed rates (20, 30 and 40 m·min$^{-1}$ ) using piezoelectric dynamometer. On the whole, it was established that all cutting forces depended on the cutting speed and feed rate over the analysed range. However, little dependence was observed for lateral force.The forces increased with the increase of the feed rate. Both parallel and normal forces decreased when the cutting speed increased. Overall, oak wood required more cutting forces compared to beech wood. Higher cutting speeds are usually used during wood bandsawing to achieve higher productivity and cutting efficiency. Therefore, further study of higher cutting speeds is recommended to better understand the impact of the cutting speed on the cutting force components. Another suggestion for additional research can be to simultaneously use another method for measuring cutting forces, such as strain gauge dynamometer to make comparison with piezoelectric dynamometer method.

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## 5 REFERENCES
## 5. LITERATURA

1. Aguilera, A.; Martin, P., 2001: Machining qualification of solid wood of *Fagus silvatica* L. And *Picea excels* L.: cutting forces, power requirements and surface roughness. Holz als roh- und Werkstoff, 59 (6): 483-488 http://dx.doi.org/10.1007/s001070100243.
2. Beljo Lučić, R..; Goglia, V.; Pervan, S.; Đukić, I.; Risović, S., 2004: The influence of wood moisture content on the process of circular rip sawing. Part I: Power requirements and specific cutting forces. Wood Research, 49: 41-49.
3. Blackwell, P.; Walker, J., 2006: Primary Wood Processing- Principles and Practice. In: Sawmilling. Walker, J., Springer, pp. 203-250.
4. Cooz, V.; Mayer, R. W., 2006: Cutting forces for tension and normal wood of maple. Forest Product Journal, 56 (4): 26-34.
5. Davim, J. P., 2011. Wood Machining. First ed. ISTE Ltd and John Wiley & Sons, Inc. Great Britain and the United States, pp. 275 http://dx.doi.org/10.1002/9781118602713.
6. Eyma, F.; Méausoone, P. J.; Martin, P., 2004: Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B. Ann. For. Sci, 62: 441-447 http://dx.doi.org/10.1051/forest:2003084.
7. Eyma, F.; Méausoone, P. J.; Martin, P.; Marchal, R., 2005: Utilization of a dynamometric pendulum to estimate cutting forces involved during routing, Comparison with actual calculated values. Ann. For. Sci, 61: 55-64. http://dx.doi.org/10.1051/forest:2005040.
8. Franz, N. C., 1958: An analysis of the wood cutting process. PhD. Thesis. Ann Arbor, University of Michigan.
9. Goli, G.; Fioravanti, M.; Marchal, R.; Uzielli, L.; Busoni, S., 2010: Up milling and down milling wood with different grain orientations- the cutting force behaviour. Eur. J. Wood Prod, 68 (4): 385-395. http://dx.doi.org/ 10.1007/s00107-009-0374-5
10. Heisel, U.; Martynenko, S.; Schneider, M., 2007: Influence of chip space filling on cutting forces in high-speed milling of wood and derived timber products. In: Proceeding of third international symposium on wood machining. Lausanne, Switzerland, pp. 51-59.
11. Iskra, P.; Tanaka, C.; Ohtani, T., 2005: Energy balance of the orthogonal cutting process. Holz als roh- und Werkstoff, 63: 358-364. http://dx.doi.org/10.1007/s00107-005-0021-8.
12. Kivimaa, E., 1950. Cutting force in wood working. State Institute for Technical Research, Helsinki, pp.101.
13. Ko, T. J.; Kim. H. S., 1999: Mechanistic cutting force model in bandsawing. International Journal of Machine Tool &Manufacture, 39: 1185-1197. http://dx.doi.org/10.1016/S0890-6955(98)00087-X
14. Koch, P., 1964: Wood machining process. Ronald Press, New York, pp. 530
15. Loehnertz, S. P.; Cooz, I. V., 1998: Saw tooth forces in cutting tropical hardwoods native to South America. Res. Pap. FPL-RP- 567.
16. Lubkin, J. L., 1957: A status report on research in the circular sawing of wood. Volume 1. Res. Lab. Amer. Mach. & Foundry Co. Stamford, Conn. pp.193.
17. McKenzie, W. M., 1961: Fundamental analysis of the wood cutting process. PhD. Thesis. Ann Arbor,University of Michigan.
18. McKenzie, W. M.; Ko, P.; Cvitković, R.; Ringler, M., 2001: Toward a model predicting cutting forces and surface quality in routing layered boards. Wood Science and Technology, 35: 563-569 http://dx.doi.org/10.1007/s002260100115.
19. Pahlitzsch, G.; Dziobek, K., 1959: Untersuchungen an einer horizontalen Blockbandsage (Investigations on a Horizontal Log Band Saw). Holz als roh- und Werkstoff, 17: 364-376 http://dx.doi.org/10.1007/BF02611196.
20. Palmqvist, J., 2003: Parallel and normal cutting forces in peripheral milling of wood. Holz als roh- und Werkstoff, 61: 409-415 http://dx.doi.org/10.1007/s00107-003-0427-0.
21. Porankiewicz, B.; Bermudez, J.; Tanaka, C., 2007: Cutting forces by peripheral cutting of low density wood species. BioResources, 2: 671-681.
22. Porankiewicz, B.; Dolata, A.; Grzegorz, W., 2008: Cutting forces during the turning of wood from black locust. BioResources, 3 (3): 745-757.

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