Annals of Warsaw University of Life Sciences – SGGW
Forestry and Wood Technology No 105, 2019: 12-19
(Ann. WULS-SGGW, Forestry and Wood Technology 105, 2019)

Decomposition of cutting forces in quasi-orthogonal CNC milling

ZDENĚK KOPECKÝ, LUĎKA HLÁSKOVÁ, MIROSLAV ROUSEK
Mendel University in Brno, Faculty of Forestry and Wood Technology

Abstract: *Decomposition of cutting forces in quasi-orthogonal CNC milling.* The paper is focused on the analysis of cutting forces in milling of MDF boards on the CNC machine called SCM Tech 99 L. The Kistler 9257 B is top-of-the-line dynamometer with DynoWare software used to measure power and analyse data. The forces were examined and analysed using quasi-orthogonal milling with a single-edged blade. The resulting force values were compared with each other depending on the conventional and climb milling of the edge of the MDF board at various feed speeds.

Keywords: Cutting forces, Ernst Merchant theory, CNC milling, MDF board, Kistler

INTRODUCTION

Machining of agglomerated wood-based materials using CNC milling machines has been one of the most common operations in the production of furniture. A suitable design, equipment operating heads, power estimation of the machine unit and finally to choose the appropriate tool is often necessary in selection of a CNC woodworking centre. In this perspective, it is advantageous, among other things, to know the parameters of the theoretical model to determine the cutting forces and the power of the machining itself.

Analysis and modelling of cutting forces are the basis of machining theory. The cutting force of machining wood and wood-based materials is not constant in fact but it varies depending on the chip cross-section, cutting speed, material removal, tool edge damping etc. In wood and wood-based materials, there is another problem that they are actually composites proving different properties in different directions.

Quasi-orthogonal milling of the edge of a board is considered as a relatively simple technology on a CNC milling machine. Moving from the endless planning knife radius to orthogonal cutting, a different chip formation and machined surface area are created on a particular cutter radius. The machined surface is not flat but formed by cycloid curl. In this context, we can speak of quasi-orthogonal cutting.

MATERIAL AND METHODOLOGY

In the climb and conventional milling kinematics, the chip thickness is changing (Siklienka et al., 2017) therefore it is necessary to realize the calculation at the place of the half angle of engagement (*ψ/2)*, in which the average thickness of the chip (h_m) and the average power of the cutting forces can be expected.
The angle of engagement is calculated according to the equation (1).

$$\boldsymbol{\psi = \arccos\psi = \frac{r-e}{r} = 1 - \frac{e}{r}} \qquad (°) \qquad (1)$$

where: r … radius cutter,
e … depth of cut (thickness of the milled surface)

As already mentioned, the average chip thickness (h_m) is operated in the calculation models

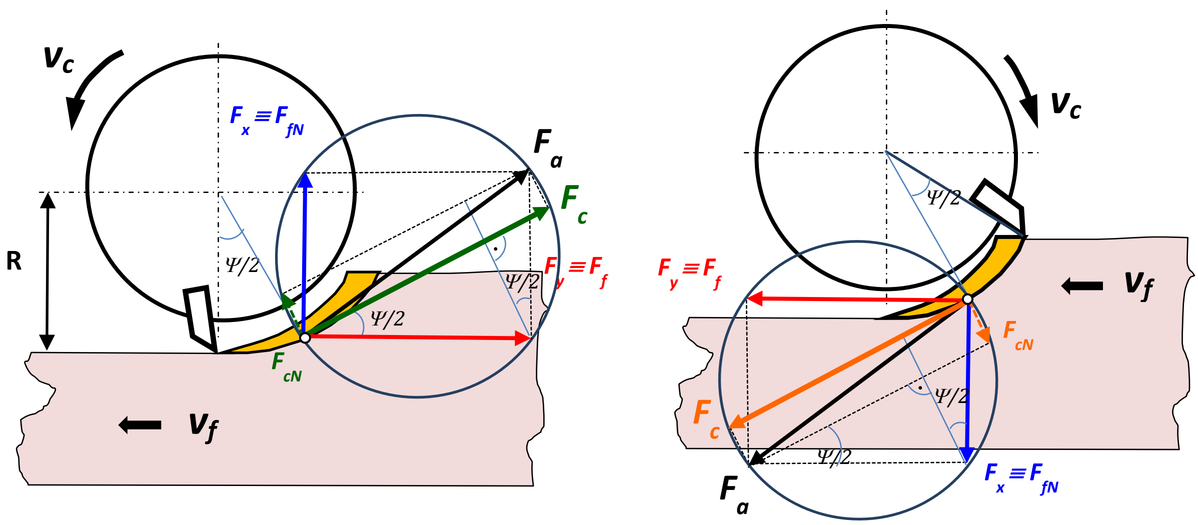
$$h_m = f_z \cdot \sin\frac{\psi}{2} \qquad \text{(m)} \qquad (2)$$

The feed per tooth (f_z) can be expressed according to the relationship

$$f_z = \frac{v_f}{n \cdot z} \qquad \text{(m)} \qquad (3)$$

where: v_f… feed speed,
n … number of the rotation,
z … number of teeth cutter.

Dynamic analysis is based on the Ernst-Merchant force diagram (Fig. 1). In measuring of forces on the workpiece using a three-axis dynamometer, the axial component in the Z-direction reaches zero due to the used straight edge cutter.



a) Conventional milling b) Climb milling

Figure 1. Scheme of milling and orientation of forces.

The total active force of the cutting process (F_a) (Javorek 2017) can be calculated using the Pythagoras theorem from the measured forces in the X and Y direction (the F_x force is perpendicular to the feed direction and the F_y force is equal to the force in the direction of feed $F_y \equiv F_f$).

$$F_a = \sqrt{F_x^2 + F_y^2} \qquad \text{(N)} \qquad (4)$$

The cutting force (F_c) in the direction of the main movement of the tool can be calculated by components of the (F_x) and (F_y) forces in the direction of the cutting force (F_c) and using the trigonometric functions of the ($\psi/2$) half angle of engagement (*Fig. 1*).

$$F_c = F_x \cdot \sin\frac{\psi}{2} + F_y \cdot \cos\frac{\psi}{2} \qquad \text{(N)} \qquad (5)$$

The aim of the experiment was to accurately determine the cutting forces in the conventional and climb quasi-orthogonal CNC milling of the MDF fibreboard. During the experiment, the main cutting parameter was methodically changed: feed per tooth. Depth of cut for conventional and climb milling was selected: e = 2.0 mm. The values of the cutting and feeding forces were measured and calculated from the used cutters and milling methods by which the parameters of the calculation model were determined.

- speed spindle motor power: 6,6 kW
- max. spindle speed: 24,000 rpm
- X–Y axis travel speed: 67,5 m·min^{-1}
- Z axe linear travel speed: 22,5 m·min^{-1}

Figure 2. CNC Centre SCM Tech 99 L.

Single-handed left-handed shank type cutter called S12L with replaceable cutting insert of IGM N010 (HW 453)

- diameter: 12 mm
- length: 77 mm
- max rotation speed: 24,000 rpm
- blade geometry: α=35°,β=36°,γ=19°
- radius of the edge: ρ = 11 µm

Figure 3. Cutter S 12L.

Workpiece: Medium density fibreboard (MDF)
- proportions: 500 x 500 x 18 mm (L x W x T)
- density: 684 kg·m^{-3}
- moisture: 3% at 25 °C

Cutting conditions:
- rotation of cutter: n = 15 000 rpm;
- feed speed: v_f = 1.5; 2.25; 3; 3,75; 4.5 m·min^{-1};
- feed per tooth: f_z = 0.1; 0.15; 0.2; 0.25; 0.3 mm;
- type of milling: conventional and climb milling

Measuring equipment:

The measurement of the forces was realized by a three-axis piezoelectric dynamometer called 9257B Kistler. The connection of the measuring device is schematically illustrated in Figure 4. In the order from left to right, the notebook with the DynoWare evaluation software, the DAQ system-bus data type of 5697A DAQ, the 5070A multi-channel amplifier, and the Kistler 9257 B piezoelectric three-axis dynamometer were used.

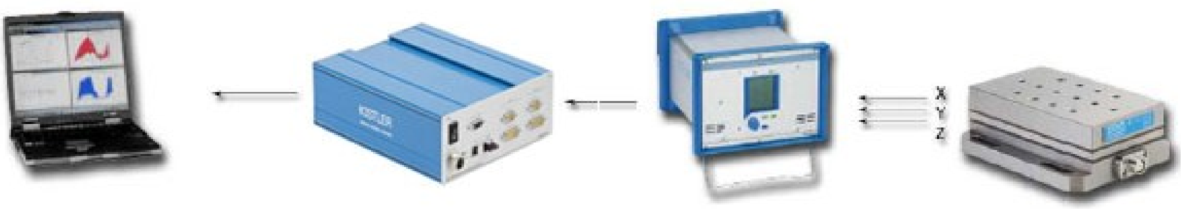


Figure 4. Measuring equipment 9257B Kistler.

An important step was the setting of the measuring time or the recording time of data during the machining before the actual experiment. In this case, the time of recording was established up to 130 seconds. This fact was due to sufficient time to record data for machining. Later, however, the time reserve for higher feed speeds proved to be superfluous and the measurement was terminated by a manual stop. The sampling frequency of the measured data record was set to 4000 Hz because of the possibility of analysing the dynamic course of forces on the cutter blade. In the DynoWare and MS Excel programs, as the value of mean, variance, standard deviation and median from 30,000 to 50,000 of data were subsequently processed and further statistically evaluated for each measurement.

The measurement was carried out first by milling the right edge of the MDF board by conventional milling, then the milling head was moved to the left edge of the workpiece and the climb milling was performed (Fig. 5). In the case of repeatability and statistical data evaluation, at least 10 measurements were carried out for individually modified cutting conditions.

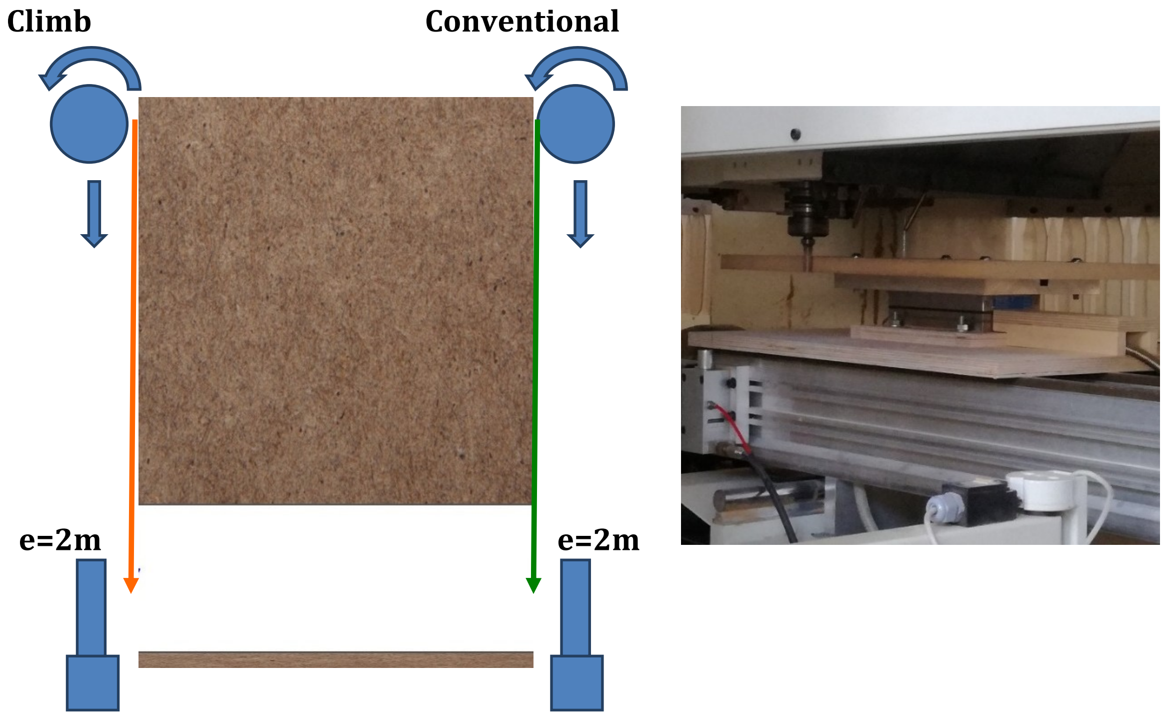


Figure 5. Milling scheme.

RESULTS AND DISCUSSION

Recording of measured data in DynoWare software after the filtration and compensation drift is shown in Fig. 6. In the first half of the record, the values of F_x and F_y are for conventional milling, in which the F_y feed force acts against the intended feed rate of the workpiece and proves a positive value. In climb milling, the feed force has the opposite direction and acts in the direction of the intended feed rate of the workpiece and shows a negative value. The output values are the time value and the corresponding measured value. The median and other statistical data can also be determined from the optional value range.

After exporting the data to the MS Excel software and their statistical processing for each values of feed per tooth (chip thickness) and depth of cut (*e = 2 mm*), the graphs of the forces in the direction of feed $F_y \equiv F_f$ and the F_x force in the direction perpendicular to the feed speed of the tool were assembled.

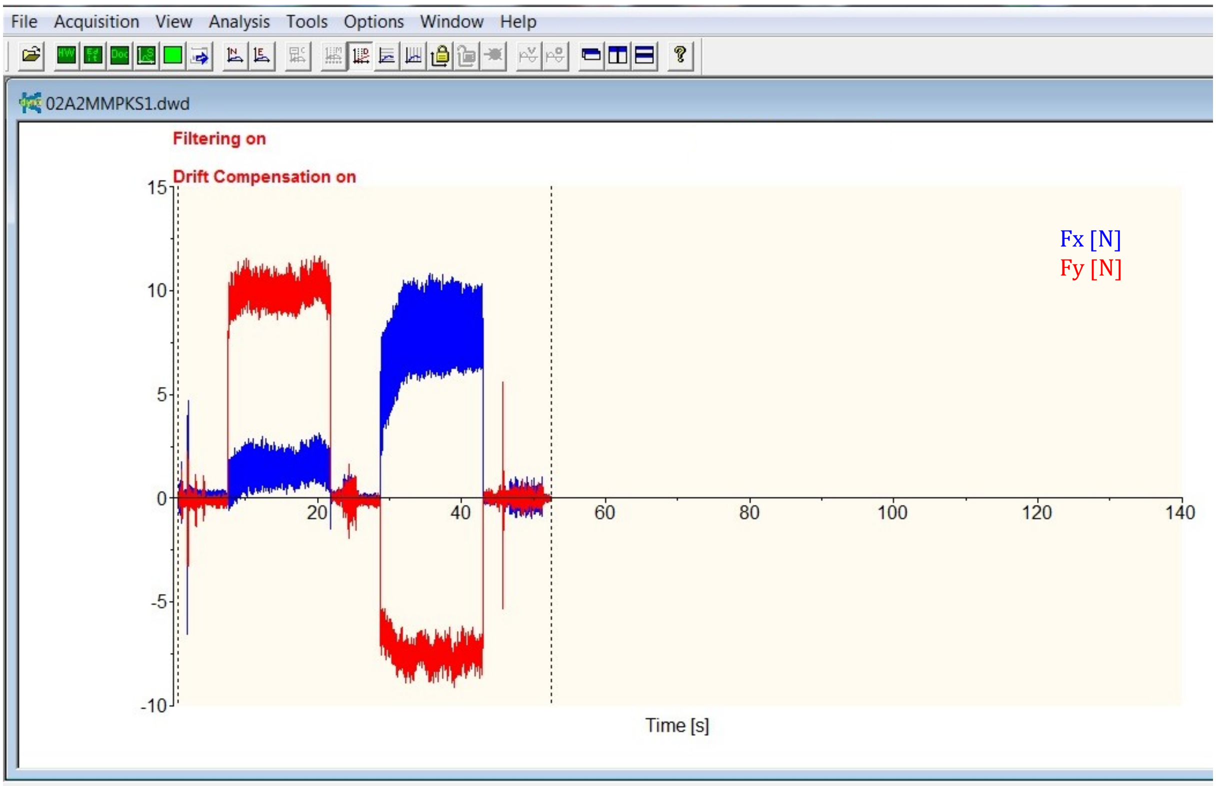


Figure 6. The record of data for feed per tooth 0.2 mm.

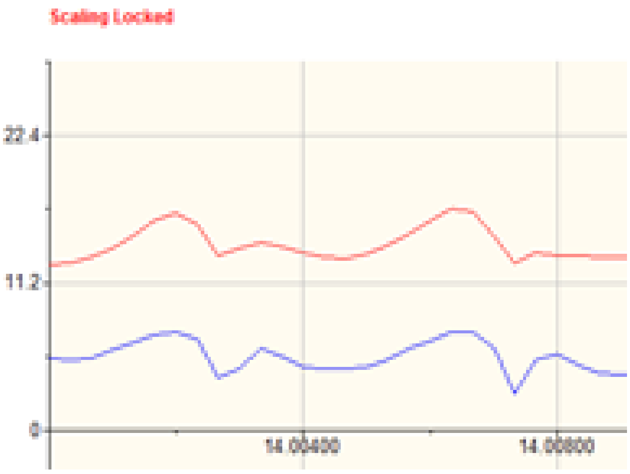


Figure 7. Dynamics of the change of forces.

It is possible to examine the dynamics of the change of forces during machining using the zoom function. The graph (Fig. 7) shows the repetitive frequency of the force increase in the machining of the chip by a single-handed shank type cutter. The period of the repetitive frequency is the range of 0.004 seconds. This corresponds to the milling speed of the cutter n = 15 000 rpm (f = 250 Hz, t = 1/250 = 0.004 s).

The graph of Fig. 8 shows a different effect of delivery forces. The F_y feed force in the climb milling is negative and therefore the resultant force that means the F_a active force (see Fig. 1) works in the feed direction of the workpiece. This is a relatively familiar phenomenon in practice, and consequently the climb milling of the manual workpiece feed rate is inadmissible in terms of safety.

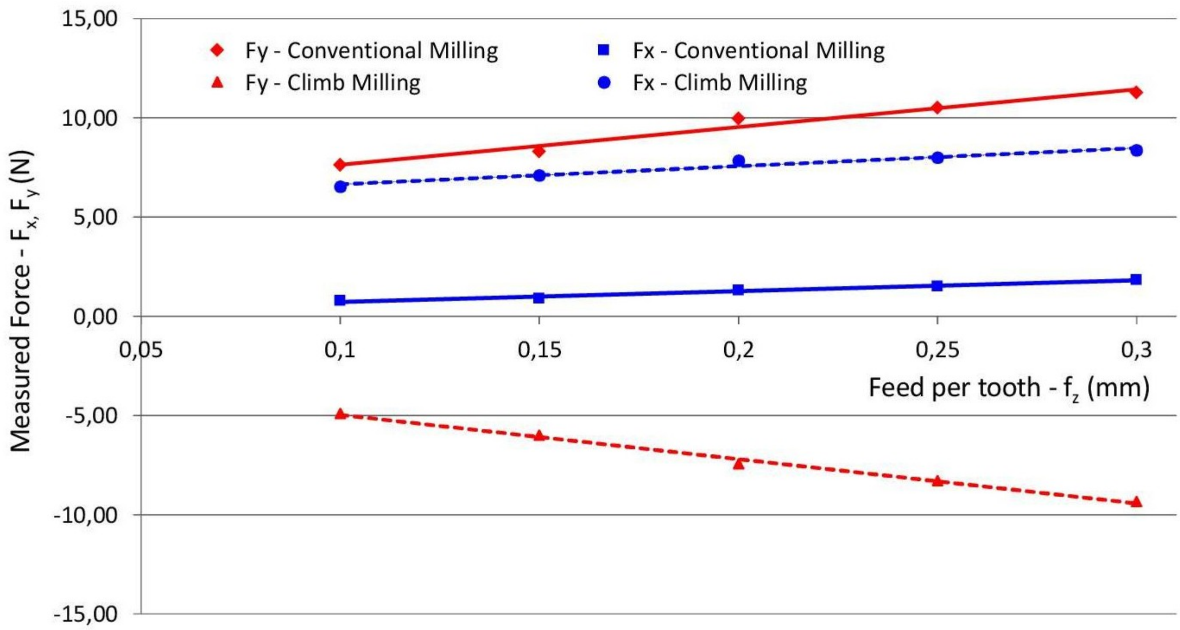


Figure 8. Measured forces depending on feed per tooth.

The F_c cutting force in the direction of the main feed rate of the tool was calculated as the vector sum of the force components in the direction of feed rate $F_y \equiv F_f$ and the force perpendicular to the feed direction $F_x \equiv F_f$ (see Equation 5 and Fig. 1).

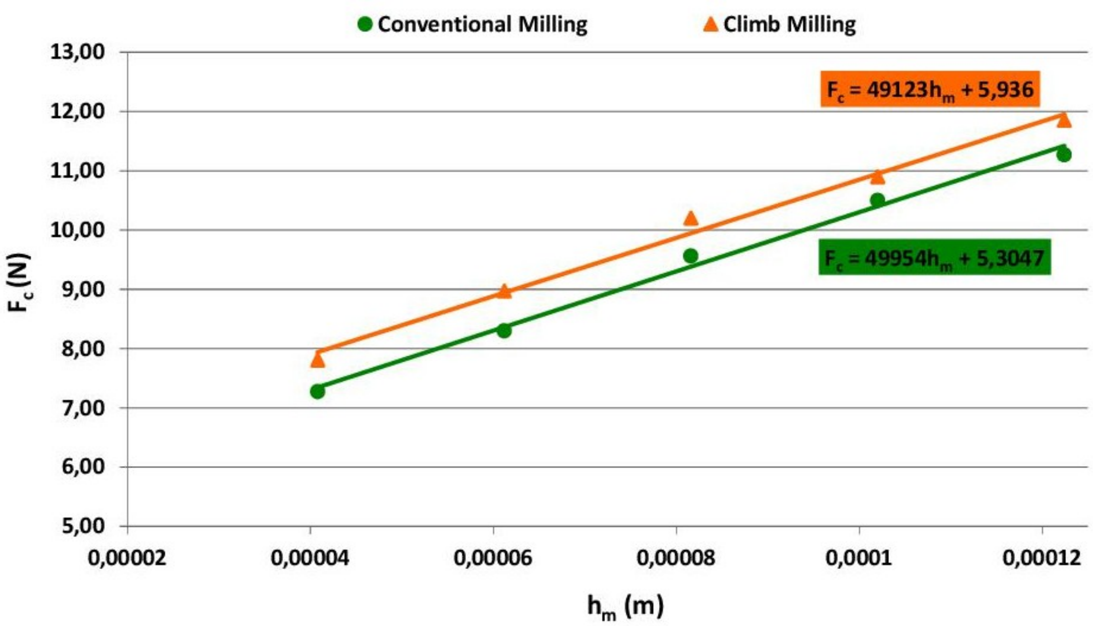


Figure 9. Cutting forces depending on the average chip thickness.

In the comparison of the experimentally measured forces, we can notice higher values of the resulting cutting forces in the climb milling process. The resultant cutting force is directed to "material" reducing clamping forces while decreasing machine susceptibility to vibrations, and it is possible to increase the feed per tooth (f_z) while maintaining a good quality machined surface.

CONCLUSION

The application of the obtained results enabled to accurately determine the values of the forces working in the interaction of work-tool-depth of cut. The research into mechanical phenomena in the climb and the conventional milling zone of MDF boards and other agglomerated materials can help to improve technical and technological conditions to reduce energy consumption and improve product quality. The assembled mathematical model is one of the tools, for example, for technicians and technologists dealing with tool design or CNC engineering and machining of MDF boards in furniture production.

Acknowledgments: This article is based on research sponsored by the Internal Grant Agency FFWT of Mendel University in Brno. The authors are grateful for the support of the project „ LDF_TP_2019008, „Application of progressive technologies which deal with unconventional material machining“.

REFERENCES

1. AFANASEV, P., S., 1961. Derevoobrabatyvayuschie stanki (Woodworking machinery), Moskva.
2. AGAPOV, A., I., 1983. Dinamika processa pilenija drevesiny na lesopilnych ramach (Dynamics of wood sawing on frame sawing machines). Kirovskij Politechničeskij Institut, Izdanije GGU, Gorkij.
3. BOGDAMOV, F., A., OSTROUMOV, I., P., 1986. Podgotovka i ekspluatacija ramnych pil. Lesnaja Promyšlennost, Moskva.
4. KOPECKÝ, Z., HLASKOVA, L., AND ORLOWSKI, K. (2014). “An innovative approach to prediction energetic effects of wood cutting process with circular-saw blades,” *Wood Res*earch 59(5), 827-834.
5. LATERNSER, R., GÄNSER, H., P., TAENZER, L., HARTMAIER, A., 2003. Chip formation in cellular materials, Journal of Engineering Materials and Technology 125(1), 44-49.
6. LISIČAN J., 1996. Teória a technika spracovania dreva vyd. Zvolen: Matcentrum, 625 s. ISBN 80-967315-6-4.
7. ORLICZ, T. (1988). *Obróbka drewna narzędziami tnącymi*. (In Polish: *Wood machining with cutting tools*), Skrypty SGGW-AR w Warszawie, Wydawnictwo SGGW-AR, Warszawa.
8. ORLOWSKI, K. A., and PAŁUBICKI, B. (2009). “Recent progress in research on the cutting process of wood. A review COST Action E35 2004-2008: Wood machining-Micromechanics and fracture,” *Holzforschung* 63(2), 181-185. DOI: 10.1515/HF.2009.015
9. ORLOWSKI, K. A. (2010). *The Fundamentals of Narrow-Kerf Sawing: The Mechanics and Quality of Cutting*, Publishing House of the Technical University in Zvolen, Technical University in Zvolen
10. PORANKIEWICZ, B., BERMUDEZ, J., C., TANAKA, C., 2007. Cutting force, low density wood, BioResources 2(4), 671-681.
11. PROKEŠ, S., 1978. Obrábění dřeva a nových hmot ze dřeva. Státní nakladatelství technické literatury Praha, 583 s.
12. SIKLIENKA, M., KMINIAK, R., ŠUSTEK, J., JANKECH, A., 2017. Delenie a obrábanie dreva. 1. vyd. Zvolen: Technická univerzita vo Zvolene, 332s, ISBN 978-80-228-2845-1.

Streszczenie: *Rozkład sił skrawających w quasi-prostopadłym frezowaniu CNC*. W pracy przeanalizowano siły skrawania podczas frezowania płyt MDF na obrabiarce CNC SCM Tech 99 L. Do pomiaru mocy i analizy danych wykorzystano dynamometr Kistler 9257 B z oprogramowaniem DynoWare. Pomiaru sił dokonano w trakcie quasi-prostopadłego frezowania przy wykorzystaniu pojedynczego ostrza. Uzyskane wartości sił porównano ze sobą w zależności sposobu skarawania płyty MDF (przeciwbieżne i współbieżne) przy różnych prędkościach posuwu.

Corresponding author:

doc. Ing. Zdeněk Kopecký, CSc.
Zemědělská 3,
61300, Brno, Czech Republic,
email: kopecky@mendelu.cz
phone: +420545134527

ORCID ID:

Kopecký Zdeněk 0000-0002-7076-1628