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CUTTING FORCES IN QUASI-ORTHOGONAL CNC MILLING

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ABSTRACT

The paper is focused on the analysis of cutting forces in milling of MDF on the CNC machine (SCM Tech 99 L, SCM Group, Italy). The measurement of the forces was realized by a three-axis piezoelectric dynamometer Kistler 9257B (Kistler Holding AG, Switzerland). The forces were examined and analysed during quasi-orthogonal milling with a single-edged blade. The resulting forces were compared to each other depending on the conventional and climb milling of the edge of the MDF at changing feed speeds from 1.5 to 4.5 $\mathrm{m \cdot min^{-1}}$ with steps of 0.75 $\mathrm{m \cdot min^{-1}}$. The experimental values of cutting forces were also used for the first assessment of the fracture toughness and shear yield strength, main parameters of computational model based on Ernst-Merchant theory and on fracture mechanics. These values were input data for the calculation of the specific cutting resistance for CNC machining. The experimental data confirmed that the cutting force increases and the specific cutting resistance decreases with the increasing chip thickness.

KEYWORDS: Cutting forces, Ernst-Merchant theory, CNC milling, MDF board, Kistler 9257 B.

INTRODUCTION

Milling of wood and agglomerated wood-based materials using CNC machines has been one of the most common operations in the production of furniture and construction joinery. The basic trend is to use CNC machines enabling the digitization and the associated automation of manufacturing processes within the fourth industrial revolution called Industry 4.0 (Basl 2017). 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, fiber direction, etc. (Naylor et al. 2012). 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 (Costes et al. 2004). McKenzie (1961) described three basic types of orthogonal cutting of greenwood using two numbers representing the angle between the cutting edge of the tool and the cellular grain direction and the angle between the direction of cutting and the grain direction. Moving from the endless tool radius (planning knife) 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 (Chen et al. 2018).

In the conventional and climb milling kinematics, it has been known that the cutter blade moves after the cycloid due to the folded rotational motion of the tool in the direction of cutting speed (v_c) and the linear motion of the milling spindle in the direction of the feed speed (v_f), (Fig. 1). During climb milling, the tool´s axis of rotation is the same as the sample. The nominal chip thickness at the start of the cut is at its maximum and progressively decreases to zero. During conventional milling, the tool rotates against the direction of the sample feed. The cutting edge of every tooth begins to cut the chip at a minimum thickness (Siklienka et al. 2017).

Energetic effects can be theoretically calculated using conventional methods based on specific cutting resistance which is a function of many factors (Lisican 1996). Necessary coefficients are derived from the base of the experiments conducted in the 50s of the 20th century and currently therefore they are inaccurate (Porankiewicz et. al. 2007). On the other hand, the power of the cutting force can be judged according to the latest knowledge also from the point of view of fracture mechanics (Williams 1988, Atkins 2003, Laternser et al. 2003, Atkins 2009, Williams et al. 2010). With the application of the results based on fracture tests, further progress can be made by analyzing the cutting process. Based on the experiments, Atkins (2005) suggested that the forces involved in the cutting process depend not only on the geometry of the tool and on the basic properties of the material but to a large extent on the fracture-related processes. The main parameters of the theoretical calculation based on fracture mechanics are R - fracture toughness and τ_y - shear yield strength (Atkins 2005).

Cutting forces can be used to determine fracture toughness and shear stress for a wide range of solids including metals, plastics and wood Orlowski and Palubicki (2009), furthermore fracture is an important parameter in all machining processes (Atkins 2003, Atkins 2005). Kowaluk (2007) applied the results obtained during longitudinal cutting and wood milling and also fracture mechanics to chipboard machining.

Analysis of the issue

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 ($\psi /2$), 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 Eq. 1:

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

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

As already mentioned, the average chip thickness (hm) 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, (m·min^{-1})
n - number of the rotation, (min^{-1})
z - number of teeth cutter, (-).

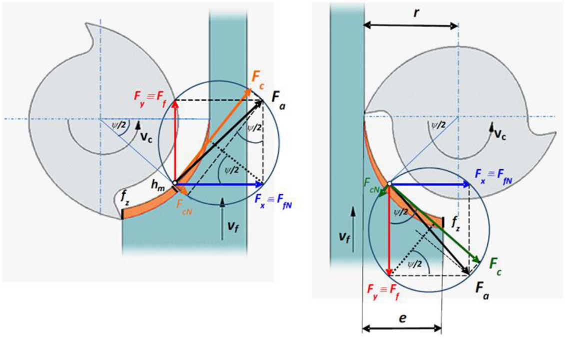


Fig. 1: Scheme of milling and orientation of forces.

Dynamic analysis is based on the Ernst-Merchant force diagram (Fig. 1). In measuring of forces on the sample using a three-axis dynamometer, the axial component in the Z-direction reaches zero due to the used straight edge cutter. The total active force of the cutting process (F_a) (Csaba et al. 2019) 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 (ψ/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 parameters of the calculation model based on the fracture properties of the sample material with the elaboration of the Ernst-Merchant theory can be determined from the knowledge of the course of cutting and feed forces depending on the chip thickness (Kopecky et al. 2014, Hlaskova 2017).

According to the latest theoretical findings with the use of fracture mechanics methods (Atkins 2003, 2009) and (Orlowski 2010, Orlowski et al. 2013), a mathematical model of power when cutting by saw blades can be expressed in the following form:

$$\overline{P}_{av} = F_c \cdot v_c + P_a = \left[z_a \cdot \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \cdot h_m \cdot v_c + z_a \cdot \frac{R \cdot b}{Q_{shear}} \cdot v_c \right] + \dot{m} \cdot v_c^2 \qquad \text{(W)} \tag{6}$$

where: z_a - number of simultaneously cutting teeth, (-)
τ_γ - shear yield strength, (MPa)
b - saw kerf width, (mm)
g - shear strain along the shear plane, (-)
h_m - mean uncut chip thickness, (mm)
v_c - cutting speed, ($m \cdot s^{-1}$)
R - specific work of surface separation (fracture toughness), ($J \cdot m^{-2}$)
Q_{shear} - friction correction coefficient (-)
$\dot{m}$ - mass flow of chips, ($kg \times s^{-1}$).

The first equation member expresses the power necessary for shearing and subsequent removal of the chip, the second member expresses the power for overcoming friction between the sample and the tool edge, including the formation of a new surface, and the third member expresses the power necessary for the chip acceleration and its sweep out of the point of cutting. However, the third member does not express force ratios at the chip separation (no effect on cutting resistance), but expresses kinetic energy for carrying chips (sawing) out of the cut by the saw blade. This means that it only affects the total consumed saw power (Orlowski et al. 2013). The following is applied for the mass flow of chips:

$$\dot{m} = \frac{b \cdot l \cdot v_f \cdot \rho}{2} \qquad (kg \times s^{-1}) \tag{7}$$

Under the theory which uses fracture mechanics, the cutting force, related to one blade tooth, is expressed by the slope of the line in the form y=(k)×x+(q) (Orlowski and Palubicki 2009, Orlowski 2010):

$$F_c^{1z} = \left(\frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \right) \cdot h_m + \left(\frac{R \cdot b}{Q_{shear}} \right) \qquad \text{(N)} \tag{8}$$

Shearing strain along the shear plane is possible to obtain from the formula (Atkins 2003):

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi - \gamma_f) \cdot \sin \Phi} \qquad (-) \tag{9}$$

where: γ_f - tooth rake angle, (°)
Φ - shear angle, (°).

For large uncut chip thicknesses, the Ernst-Merchant's equation can serve as the basis (for large uncut chip thickness values, the shear plane angle (Φ) is constant):

$$\Phi = \left(\frac{\pi}{4} \right) - \left(\frac{1}{2} \right) \cdot \left(\beta_\mu - \gamma_f \right) \qquad (°) \tag{10}$$

where: β_μ - friction angle obtained from $tan^{-1}\mu = \beta_\mu$ (μ is friction coefficient), (°)
π *[rad]* - 180°.

The Atkins's model, which includes the fracture toughness (R) (see Eq. 6), can help to derive a relationship for the calculation of specific cutting resistance k_c.

$$k_c = \frac{\tau_\gamma \cdot \gamma}{Q_{shear}} + \frac{R}{Q_{shear} \cdot h_m} \qquad \text{(Pa)} \qquad (11)$$

The formula for the calculation of specific cutting resistance shows that the specific cutting resistance will increase sharply with a small chip thickness). The friction correction coefficient (Q_{shear}) depends substantially on the orientation of the shear plane towards the worked surface (Atkins 2003, 2009). When shear angle (Φ) equals zero (the tool cuts off no chips), the friction correction coefficient (Q_{shear}) equals one, see Eq. 12 (Orlowski and Palubicki 2009, Orlowski 2010):

$$Q_{shear} = \left[1 - \sin\beta_\mu \cdot \sin\Phi / \cos(\beta_\mu - \gamma_f) \cdot \cos(\Phi - \gamma_f)\right] \qquad (-) \qquad (12)$$

MATERIALS AND METHODS

Machine

The machining was performed by CNC milling machine (SCM Tech 99 L, SCM Group, Italy). The aim of the experiment was to accurately determine the cutting forces in the conventional and climb quasi-orthogonal milling of the MDF fibreboard.

During the experiment, the main cutting parameter was methodically changed: feed per tooth. The values of the cutting and feed forces were measured and calculated from the used cutters and milling methods by which the parameters of the calculation model were determined.

Tool

Single-handed left-handed shank type cutter called S12L (Habilis Tools, s.r.o) with replaceable cutting insert of IGM N010 (HW 453)

- diameter:	12 mm
- length:	77 mm
- max rotation speed:	24.000 rpm
- blade geometry:	a =35°, β = 36°, γ = 19°
- cutting edge radius:	r = 11 μm.

Sample and cutting conditions

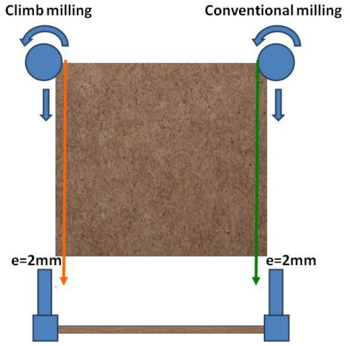


Fig. 2: Milling scheme.

Sample: Medium density fibreboard (MDF) proportions –

500 x 500 x 18mm (L x W x T),

density - 684 kg×m^{-3},

moisture - 3% at 25°C.

<u>Cutting conditions:</u>

rotation of cutter – n = 15.000 rpm,

feed speed - v_f = 1.5; 2.25; 3; 3,75, 4.5 m·min^{-1},

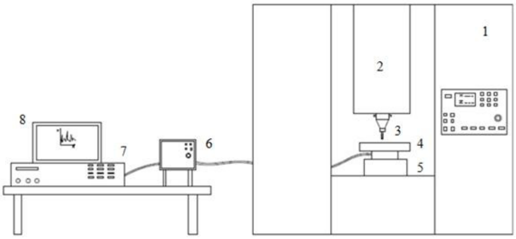
feed per tooth - f_z = 0.1; 0.15; 0.2; 0.25; 0.3 mm,

depth of cut – e = 2 mm,

type of milling - conventional and climb milling.

Measuring equipment

The measurement of the forces was realized by a three-axis piezoelectric dynamometer (Kistler 9257B, Kistler Holding AG, Switzerland). The connection of the measuring device is schematically illustrated in Fig. 3. 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.



1 - CNC milling machine SCM Tech 99 L, 2 - spindle milling machine, 3 – milling cutter S12L, 4 – sample (MDF), 5 – Fx, Fy, Fz dynamometer Kistler 9257B, 6 – multi-channel amplifier 5070A, 7 – DAQ system-bus 5697A, 8 – notebook with the DynoWare software.

Fig. 3: The scheme of the experimental device.

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 sec. 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 sample and the climb milling was performed (Fig. 2). In the case of repeatability and statistical data evaluation, at least 10 measurements were carried out for individually modified cutting conditions.

RESULTS AND DISCUSSIONS

Recording of measured data in DynoWare software (Kistler Holding AG, Switzerland) after the filtration and compensation drift is shown in Fig. 4. 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 sample 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 sample 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 and their statistical processing for each 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 rate of the tool were assembled.

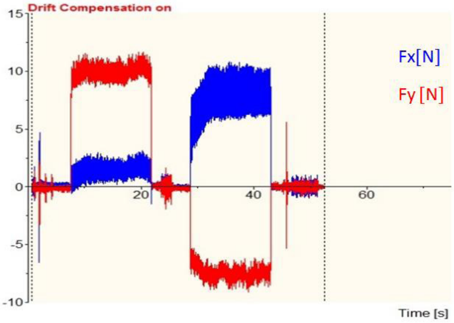


Fig. 4: The record of data for feed per tooth of 0.2 mm.

The graph of Fig. 5 shows a different effect of delivery forces. The $F_y \equiv F_f$ feed force in the climb milling is negative and therefore the resultant force that means the Fa active force (Fig. 1) works in the feed direction of the sample. This is a relatively familiar phenomenon in practice, and consequently the climb milling of the manual sample feed rate is inadmissible in terms of safety.

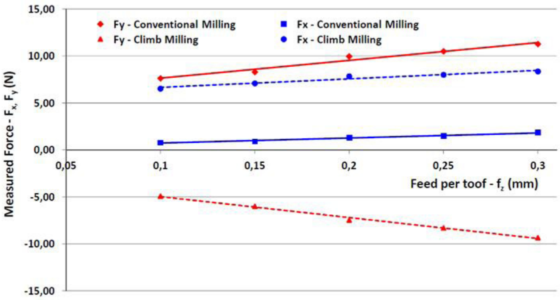


Fig. 5: Measured forces depending on feed per tooth.

The F_c cutting force (Fig. 6) 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 (Eq. 5 and Fig. 1).

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.

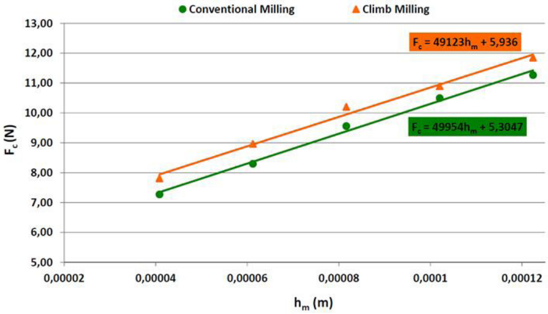


Fig. 6: Cutting forces depending on the average chip thickness.

On the other hand, the cutter edges prove higher loading at the beginning of the engagement in cutting the chip of the largest thickness. This phenomenon is also applied to the increasing amount of feed per tooth (chip thickness). The cutting force is always increasing with increasing depth of cut (*e*).

The angle of the shear plane (Φ) (angle between the force vector of (F_s) shear plane and the vector of cutting force (F_c), the shear deformation of the chip (g), the coefficient of friction (μ) and the angle of friction (β_μ) (angle between the active force of the F_a cutting process and the normal force in the $F_{\gamma N}$ shear plane) was calculated with the elaboration of the Ernst-Merchant theory (Hlaskova 2017).

The cutting force (F_c) grows linearly with the increase in the chip thickness (hm), the linear course is characterized by the coefficient of determination (R^2 = 0.993) for the conventional milling and by the coefficient of determination (R^2 = 0.9904) for the climb milling. The average size of the cutting force relative to one tooth can be expressed in a straight line shape:

Conventional milling: $F_c^{1z} = 49.954\ h_m + 5.3047$
Climb milling: $F_c^{1z} = 49.123\ h_m + 5.936$

Fracture toughness *R* (for $\varphi_2 = 24.09°$) was determined by the offset of the line (conventional milling: $q = 5.3047\ N$; climb milling: $q = 5.936\ N$) and shear yield strength τ_γ from its directive (conventional milling: k = 49.954 N·m^{-1}; climb milling: k = 49.123 N·m^{-1}).

On the basis of the performed experiments, the main parameters entering the newly designed model for the conventional and climb milling method (Tab. 1) were calculated. These values were input data for the calculation of the specific cutting resistance for CNC machining.

Tab. 1: Main parameters entering the newly designed model.

	μ	β_μ (°)	Φ (°)	γ	Q	τγ (MPa)	R (J·m^{-2})
CONV	0.542	28.452	40.274	1.569	0.656	1.1757	294.706
CLIMB	0.628	32.145	38.428	1.613	0.630	1.0826	329.778

Fig. 7 shows modelling of the functional relationship of the specific cutting resistance and chip thickness. In evaluating the values of the specific cutting resistance, it is possible to notice the trend in which the value of the coefficient of specific cutting resistance decreases with increasing chip thickness.

According to Prokes (1978), the various authors agree that the cutting force increases and the specific cutting resistance decreases with the increasing chip thickness and at the same time increasing the feed per tooth. This statement is also applied to different geometry of the cutting edge. A higher increase can be from (hm < 0.1 mm) in the specific cutting resistance. Therefore, some computational models of cutting resistance and forces use a mathematical apparatus for a chip thickness of less than 0.1 mm and a chip thickness greater than 0.1 mm.

It can also be seen from the graph in Fig. 7 that the values of the specific cutting resistance of the climb milling are always slightly higher than the values of conventional milling.

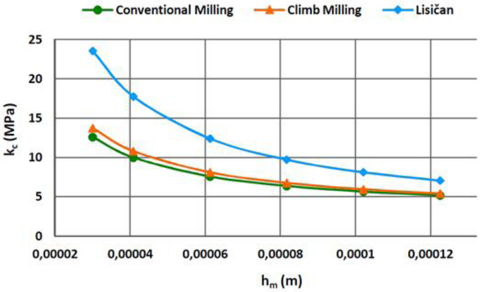


Fig. 7: Specific cutting resistance depending on the average chip thickness

The theory says that a significant force of resistance against feed rate can be in conventional milling. At the beginning of the process, the chip proves a zero value and increases toward the end of the cut. The cutting forces thus force apart the milling cutter and the sample. On the other hand, the feed resistance against feed rate is smaller in climb milling than that in conventional milling. In climb milling, the resistance gradually decreases in cutter circuit from the beginning of the chip thickness cut. At the end of the cut, the chip reaches zero.

To compare the experimental data with theory from available literature, a modified Technological-Statistical Method was used which was based on the research by Cukanov and Amalicky in Lisican (1996). It is important to note that there are currently not many publications dealing with milling (relatively new) wood-fibre materials. Most publications focus on wood or to a lesser extent on chipboard materials.

The comparatively large difference in the course of the specific cutting resistance between the newly designed model based on Ernst-Merchant theory (Hlaskova 2017) and the method of Cukanov and Amalicky according to Lisican (1996) is particularly caused in the difference in the determination and accuracy of the measurement of individual forces. In addition, the Cukanov and Amalicky method was primarily used in connection with the machining of DTD chipboards.

CONCLUSIONS

1. The measurement of the force components in the X and Y directions using a Kistler dynamometer made it possible to calculate exactly according to the proposed equation using the Ernst-merchant circle diagram. The cutting force (F_c) in the direction of the main movement of the tool was 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 (Eq. 5 and Fig. 6)

2. Measured and calculated data of cutting forces for conventional and climb milling has allowed us to determine fracture toughness and shear yield strength of milling wood for the axial-perpendicular model of milling by a cylindrical cutter with the elaboration of the Ernst-Merchant theory (Hlaskova 2017).
3. The Ernst-Merchant theory (Eq. 10) helped to calculate the orientation of the shear plane in respect to the worked surface $\Phi = 40.274°$ for conventional milling and $\Phi = 38.428°$ for climb milling, and the shearing strain along the shear plane $\gamma_{conv} = 1.569$ ($\gamma_{climb} = 1.613$) for MDF. These values are the input data when calculating the specific cutting resistance.
4. When we compare of the specific cutting resistance (Fig. 7), we can state that in areas of very low chip thickness there are large difference between the newly designed model, based on Ernst-Merchant theory and the old modified Technologically-statistical method of Cukanov and Amalicky, which was focused only on the determination of specific cutting resistance in chipboard (DTD) machining.
5. The presented methodology can be, after slight adaptations, applied for wide range of materials (wood based materials and modified materials) during processing on other machines with similar cutting kinematics, such as circular saw blades, circular cutter, etc. The model is available not only for woodworking engineers dealing with woodworking processes, but also for the designers when designing new cylindrical cutter or milling machines.

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