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FRICTION IN LINEAR ORTHOGONAL CUTTING OF BEECH WOOD (*FAGUS SYLVATICA*) CONSIDERING PLOUGHING EFFECT FORCES DUE TO CUTTING TOOL TIP BLUNTNESS

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ASTRACT

The paper presents the calculation of the coefficient of friction between the cutting tool and the chip in case of linear orthogonal cutting in the direction of 90-0°. Beech wood was cut with HSS cutting-tool at the cutting speed of 0.03 $m.s^{-1}$. Rake angles were 16, 22, 31 and 42°, and the depths of cut were 0.3, 0.25, 0.2, 0.15 and 0.1 mm. A type II chip according to Franz was formed at the angles of 16 and 22°, and a type I chip was formed at the angles of 31 and 42°. The force resulting from the ploughing effect due to cutting tool tip bluntness was subtracted from the forces measured perpendicularly to the direction of cutting F_y, while the force resulting from the ploughing effect and the fracture force for creation of new surfaces were subtracted from the forces measured in the direction of cutting F_x. The coefficient of friction at all rake angles and depths of cut, calculated from the difference of forces, was 0.46 on average with a standard deviation of 0.009. The model with subtracted forces resulting from the ploughing effect has proved to be correct; the calculated coefficient of friction at all rake angles and chip thicknesses is constant since the coefficient of friction has to be independent of the force magnitude, while in the literature found, the coefficient of friction varies with the chip thickness and rake angle.

KEYWORDS: Wood cutting, coefficient of friction, ploughing effect, cutting tool tip bluntness.

INTRODUCTION

In wood cutting it is important that the resulting machined surfaces are of appropriate quality and that the least possible amount of energy is used. The quality of machined surfaces and the cutting forces depend on various parameters such as cutting-tool tip radius, rake angle, friction between the cutting tool and the work piece or chip, and on the mechanical properties of wood. Cutting-tool manufacturers wish the friction or coefficient of friction between work piece and cutting tool to be as low as possible. The normal force acting on the rake face of the cutting tool causes the emergence of a friction force which acts in parallel with the cutting-tool rake face. The greater the friction force the more heat energy is created. Since wood is a poor conductor of heat, the material from which the cutting tool is made must have good thermal conductivity or the lowest possible coefficient of friction. As the coefficient of friction increases so does the cutting tool wear and consequently the life of the cutting tool is reduced. Linear orthogonal cutting in the direction of 90-0° usually forms chips of type I or II according to Franz (Koch 1985). In terms of the material that is being turned into a chip, a type I chip is discontinued, and type II chip continued (Merhar and Bučar 2012, Atkins 2004). The type of chip is also influenced by the coefficient of friction since the force of friction delays lifting of the newly formed chip. The normal force on the cutting tool rake surface is greater at smaller rake angles, and due to the coefficient of friction also the force acting in parallel with the cutting tool rake face increases and slows down the chip lifting during the process of cutting.

To determine the coefficient of friction during cutting is of essential significance since the value of friction coefficient determined in a conventional manner, i.e., by measuring the force created when two specimens are rubbed against each other, is not always representative. During cutting, the cutting-tool rake surfaces are polished to some extent, and in the case of a conventional test this is difficult to prepare accurately.

Numerous researchers have dealt with friction in cutting. McKenzie (1967) was among the first who determined the coefficient of friction between cutting tool and chips at various feed rates, rake angles, wood moisture contents, and different cutting-tool surfaces. He found that the coefficient could vary considerably between 0.1 and 0.6 for various combinations of wood moisture content, cutting-tool rake face roughness and feed rate. The author states that the coefficient of friction changes insignificantly with the type of wood, but it depends on the cutting-tool tip radius. He found that in the case of linear orthogonal cutting using a very sharp cutting-tool results in a coefficient of friction is practically equal to the coefficient of friction of 0.5 which he determined by a direct measurement.

The coefficient of friction was also measured by Klamecki (1976), who tried to model friction with the contact surface between cutting-tool and chip. The influence of wood density on the coefficient of friction was studied by Ivanovskij and Goronok (1978). They found that the coefficient of friction decreased with the density of wood and increased with the moisture content and temperature of the wood.

Huang and Hayashi (1973) mentioned various coefficients of friction obtained when cutting birch wood under various rake angles. At very small rake angles, they obtained a value of friction of around 0.5, while at the 50° angle the coefficient of friction was 0.5 at the cut depth of 0.8 mm, and 0.8 when the depth of cut was 0.1 mm.

In their work, Strehler et al. (2012) present a cutting tool made of ceramic Si_3N_4/SiC. Among the mechanical properties of this material they also indicate the coefficient of friction between cutting-tools and wood determined by pulling the ceramic over the wood. The indicated coefficient of friction values are 0.58 for beech wood and 0.55 for MDF. In their research of the DLC material for cutting-tool coating, Tillmann et al. (2009) indicate coefficient of friction values of 0.1 for cutting in dry conditions and 0.2 for humid conditions.

Based on the found studies in which the researchers determine the coefficient of friction between cutting-tools and work piece by measuring the forces of linear orthogonal cutting, the forces resulting from the ploughing effect due to cutting-tool tip radius were disregarded. The ploughing effect causes a part of the material under the hypothetical cutting plane to be permanently plastically deformed. If, in the calculation of the coefficient of friction from the forces measured in the direction of cutting and perpendicularly to the direction of cutting, the force resulting from the ploughing effect is not subtracted, the results in the case of greater cutting-tool tip radiuses and smaller cut depths show considerable deviations of the coefficient value from real values.

McKenzie (1967) thus stated that the coefficient of friction in the case of very sharp cutting-tool edge equals the coefficient of friction obtained in the conventional manner, which proves that in the case of very sharp cutting-tool edge the error due to disregarding the force resulting from the ploughing effect is minimal, but this is not true in case of large radiuses.

The objective of the present paper is to determine the coefficient of friction between the cutting tool and the chip in case of linear orthogonal cutting. In the calculation, the force resulting from the ploughing effect due to the cutting tool tip bluntness will be considered in contrast to the previously mentioned researches.

MATERIAL AND METHODS

Beech (*Fagus sylvatica*) specimens, 130 mm long and 10 mm thick, were cut. The specimen was longitudinally oriented, with tangential texture, moisture content of (9 ± 5) % and density of 630 kg.m^{-3}.

The specimen was fixed onto a Kistler four-component dynamometer type 9272, as shown in Fig. 1. The speed of cutting was set to 0.03 m.s^{-1}, and a hydraulic cylinder was used for feeding. The HSS cutting tool with 30° edge angle was used for cutting. Linear orthogonal cutting in the direction of 90 - 0° was used. Rake angles were 16, 22, 31 and 42°, and the chip thickness was 0.3, 0.25, 0.2, 0.15 and 0.1 mm. Three cuts were made for each chip thickness. If the measured forces differed too much, additional cuts were made until a representative recording for a certain chip thickness was obtained. Forces were measured in the direction of cutting (F_x) and perpendicularly to the direction of cutting (F_y) at the sampling frequency of 20 kHz. Data were captured by an AT-MIO 16-E1 measurement card by National Instruments and LabView software. Force resolution in the direction of cutting was 0.488 N, and perpendicularly to the direction of cutting it was 0.0488 N, which was adequate to meet our needs.

The measured forces in the direction of cutting and perpendicularly to the direction of cutting were filtered by means of the LabView software. A lowpass Bessel filter was used. The lowpass frequency was set at 200 Hz, and the filter order was 4. The frequency was determined on the basis of frequency spectrum of the force measured in the direction of and perpendicularly to the direction of cutting and the frequency spectra of dynamometer's natural vibration in both directions. Since the frequencies occurring during cutting ranged from 0 to 100 Hz, and individual frequencies were higher than 250 Hz as a consequence of the dynamometer's natural vibration, the filtration limit was set to 200 Hz.

The model of cutting is shown in Fig. 2. Average values of the measured force F_x in the direction of cutting and force F_y perpendicular to the direction of cutting were calculated and shown in a graph, depending on the chip thicknesses for all rake angles. Since three measurements were made for each chip thickness, common average values were calculated. It was assumed that force measured in the y direction depends linearly on the chip thickness. The extrapolation of a regression curve of forces in the y direction depending on the chip thickness to the value of chip thickness of 0 mm yielded the value of the ploughing force F_{ply} in the y direction.

The same procedure was used for forces in the x direction. The extrapolated value of force in the direction of cutting at the chip thickness of 0 mm, however, in addition to the ploughing force F_{plx} in the x direction also contains the fracture force F_f for creation of new surfaces.

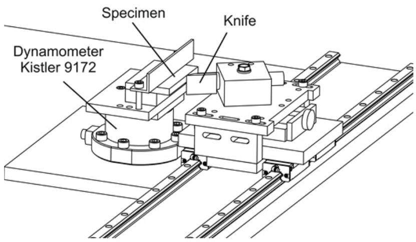

Fig. 1: Experimental system.

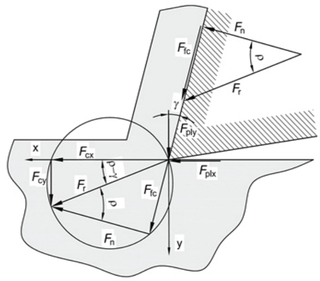

Fig. 2: Cutting model. F_{cx}, F_{cy} - cutting forces in x and y direction; F_{plx}, F_{ply} - ploughing forces due to tool tip bluntness in x in y direction; F_{fc} - friction force between chip and tool rake face; F_r - resultat force; F_n - normal force between chip and tool rake face; γ- rake angle; ρ- friction angle.

The value of force at the chip thickness of 0 mm was subtracted from the forces measured at various chip thicknesses using equation No. 1, which yielded the actual cutting forces F_{cx} in the direction of cutting and F_{cy} perpendicularly to the direction of cutting:

$$\begin{aligned} F_{cx} &= F_x - (F_{plx} + F_f) \\ F_{cy} &= F_y - F_{ply} \end{aligned} \tag{1}$$

After that, the angle ρ and coefficient of friction μ were calculated:

$$\begin{aligned} \rho &= \gamma + \arctan\frac{F_{cy}}{F_{cx}} \\ \mu &= \tan\rho \end{aligned} \tag{2}$$

RESULTS AND DISCUSSION

At the angle of 16°, the chips of type II according to Franz (Koch 1985) were formed, while at 22° type II chips with a small portion of type I prevailed. Chips formed at the rake angles of 31 and 42° were discontinuous chips of type I. The consequence of discontinuous chips were distinct variations of cutting forces in both *x* and *y* direction (Merhar and Bučar 2012).

Fig. 3 shows the measured forces of cutting the specimen in the direction of cutting (F_x) and perpendicularly to the direction of cutting (F_y) for the rake angle of 31° and chip thickness of 0.3 mm, while Fig. 4 shows individual sections of measurement together with the values filtered by the Bessel lowpass filter of 200 Hz and filter order 4. Considerable force variation both in the direction of cutting and perpendicularly to the direction of cutting can be seen in these figures. Also discernible in Fig. 4, in addition to a greater variation of force as a consequence of individual phases of cutting, is a minor harmonic oscillation imposed on the basic greater force variation. Figs. 5 and 6 show the frequency spectra of the time record from Fig. 3. Distinct peaks in the frequencies of 276 Hz, 568 Hz and some frequencies in the range from 814 to 859 Hz are discernible from the spectra. The already mentioned frequency peaks are distinctive which means that the time record of force shows the presence of harmonic oscillations with the aforementioned frequencies, which is only possible either as a forced harmonic oscillation at the mentioned frequencies or forced periodic nonharmonic oscillation at a lower frequency, while the aforementioned values represent higher harmonics or natural harmonic oscillation. No forced harmonic oscillation was possible anywhere and neither was a periodic nonharmonic oscillation, since this would mean that there were structure properties variations in even intervals.

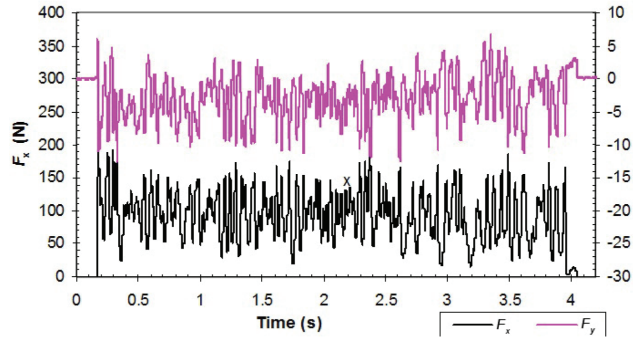

Fig. 3: The F_x and F_y force components; 31° rake angle; chip thickness of 0.3 mm.

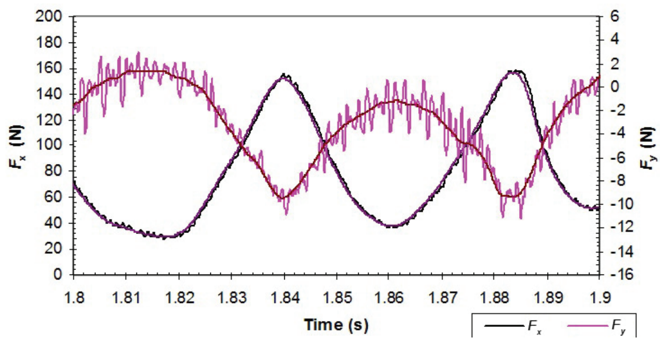

Fig. 4: The F_x and F_y force components together with the filtered values.; 31° rake angle; chip thickness of 0.3 mm.

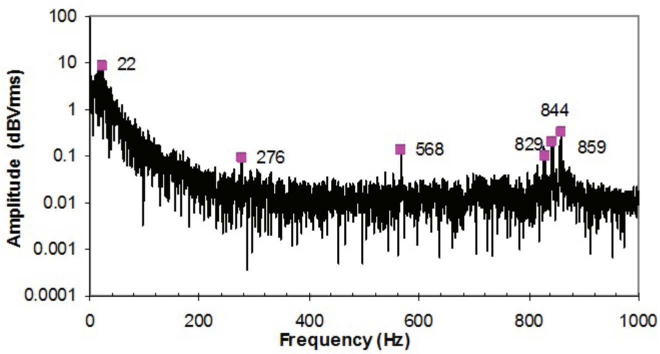

Fig. 5: The spectrum of forces in the x direction; rake angle of 31°; chip thickness of 0.3 mm.

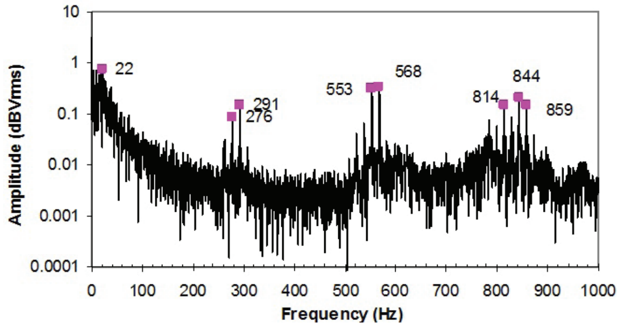

Fig. 6: The spectrum of forces in the y direction; rake angle of 31°; chip thickness of 0.3 mm.

Only the dynamometer's natural vibration resulting from excitation by the cutting force remains. To facilitate further analysis, all the measurements were filtered with Bessel lowpass filter.

Fig. 7 shows the calculated average values for the resulting cutting forces F_y in the y direction, and Fig. 8 shows F_x in the x direction. The figure demonstrates a linear dependence of cutting force in the y direction on the thickness of removed material. The average value of extrapolated values in the y direction to the chip thickness of 0 mm is 5.5 N (F_{ply}), while the average value in the x direction including the ploughing force and the fracture force for creation of new surfaces is 21.9 N ($F_{plx} + F_f$).

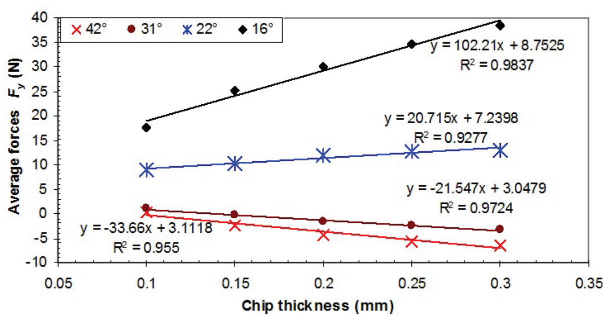

Fig. 7: Average values of the measured forces in the y direction together with linear regression.

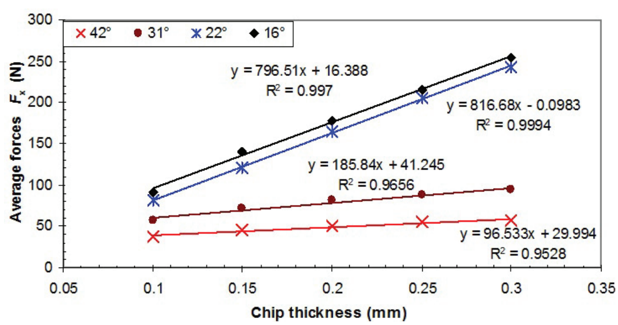

Fig. 8: Average values of the measured forces in the x direction together with linear regression.

The coefficient of friction calculated according to equation 2 for the rake angle of 16° and chip thickness of 0.3 mm is shown in Fig. 9, and that for the rake angle of 31° is shown in Fig. 10. In the case of 22° rake angle the force variation and the coefficient of friction are similar to those in Fig. 9, since a continuous chip of type II has been formed at both angles, while in the case of 42° rake angle the force variation and the coefficient of friction are similar to those in Fig. 10 where a segmented chip of type I has been formed in both cases. In Fig. 9, the calculated coefficients vary slightly as the consequence of varying ploughing force which is in turn the consequence of the local wood tissue structure variability. To calculate F_{cx} and F_{cy}, a constant value of ploughing force was taken into account, i.e., 5.5 N in the y direction and 21.9 N in the x direction.

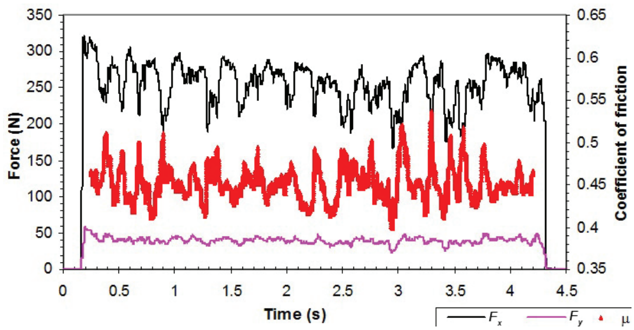

Fig. 9: Coefficient of friction at the rake angle of 16° and chip thickness of 0.3 mm.

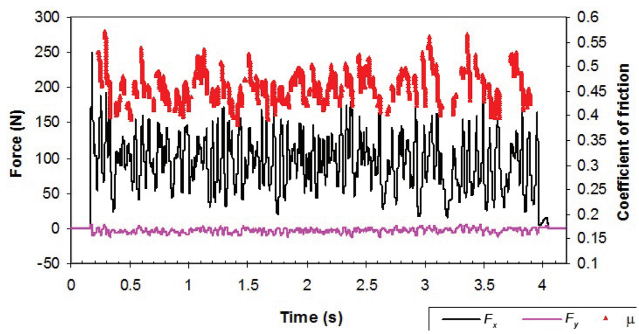

Fig. 10: Coefficient of friction at the rake angle of 31° and chip thickness of 0.3 mm.

The calculation for the rake angle of 16° was made on the basis of all cutting force data in directions x and y, while in the x direction only those cutting forces which were greater than F_{lim} = 95 N were taken into account in the calculation for the rake angle of 31° and chip thickness of 0.3 mm. At the rake angle of 16°, the cutting tool tip is always in contact with the material under the plane of cutting where continuous ploughing occurs. If all the values of cutting force were also taken into account in the calculation of the coefficient of friction at the rake angle of 31°, smaller values of the cutting force would yield variable values of the coefficient of friction up to negative values. The reason for such values is not an actual variation of the coefficient of friction but rather the variation of cutting force values. When the chip presses onto the rake face, this gives rise to friction between the chip and rake face of the cutting tool. When the chip exerts no pressure on the rake face, cutting forces F_{cx} and F_{cy} should be equal to zero. In our case, however, F_{cx} and F_{cy} can be less than zero when the crack initiated under the chip propagates not in the plane of cutting but under the plane. In this case no ploughing effect can develop since the material is under the level of cutting. To calculate F_{cx} and F_{cy}, the force created by the ploughing effect was subtracted from the resulting component of cutting force both in the *x* direction and in the *y* direction. Since in reality there is no ploughing, the x and y components of the calculated cutting force F_{cx} in F_{cy} are incorrect and so is the coefficient of friction. In the event of greater values of forces, when the cutting tool tip penetrates wood and the crack has not propagated yet, there is actual ploughing and consequently real cutting forces. For this reason, only values of cutting forces higher than F_{lim} were taken into consideration, where F_{lim} represents the average cutting force for specific rake angle and depth of cut.

Tab. 1 shows average values of friction coefficients at various rake angles and depths of cut. The coefficient of friction calculated from cutting forces F_{cx} and F_{cy} where cutting forces in the direction of cutting are greater than F_{lim} is marked μ_1. The coefficient of friction calculated from all values of forces F_x and F_y without any subtraction of force resulting from the ploughing effect is marked μ_2. All values of cutting forces F_{cx} and F_{cy} were taken into account in the calculation of $\mu 1$ at the rake angles of 16 and 22°, while only cutting forces F_{cx} and F_{cy} where F_{cx} was greater than F_{lim} were taken into account in the case of 31 and 42° rake angles.

Tab. 1: The coefficient of friction at various rake angles and chip thicknesses. μ_1– coefficient of friction, calculated from cutting forces F_{cx} and F_{cy}; μ_2 - coefficient of friction, disregarding the force resulting from the ploughing effect; F_{lim} – the values of boundary forces taken into account in the calculation of μ_1.

Chip thick.	**Rake angle**									
	16°		**22°**		**31°**			**42°**		
(mm)	μ_1	μ_2	μ_1	μ_2	μ_1	μ_2	F_{lim}	μ_1	μ_2	F_{lim}
0.30	0.45	0.46	0.44	0.47	0.46	0.55	95	0.46	0.72	57
0.25	0.46	0.47	0.45	0.48	0.46	0.57	91	0.47	0.74	55
0.20	0.46	0.48	0.46	0.49	0.46	0.58	81	0.47	0.75	51
0.15	0.47	0.49	0.46	0.51	0.46	0.60	70	0.50	0.83	44
0.10	0.48	0.51	0.47	0.54	0.46	0.64	56	0.53	0.92	37

The table clearly shows a constant coefficient of friction μ_1 for various rake angles and depths of cut, confirming the correctness of the calculation, since the coefficient of friction has to be independent of rake angle and chip thickness. If the value of friction coefficient at the rake angle of 42° and chip thicknesses of 0.1 and 0.15 mm, is disregarded, the result is the average value of 0.46 with a standard deviation of 0.009. In Tab. 1, μ_2 marks the coefficient of friction calculated from all the measured forces F_x and F_y. The table shows that μ_2 varies considerably with the rake angle and chip thickness ranging from 0.44 through to 0.92, which is completely incorrect since the coefficient of friction – as it has already been mentioned – must be completely independent from the rake angle and chip thickness.

If the force resulting from the ploughing effect is disregarded, μ_2 increases with decreasing chip thickness, similarly to the findings of McKenzie (1967) and McKenzie and Karpovich (1968), who obtained friction coefficients from 0.2 up to 0.7. In the already mentioned works, the authors mention no force resulting from the ploughing effect, and therefore it can be concluded that no such forces were taken into account in their calculation. Likewise, Huang and Hayashi (1973) indicate smaller coefficients of friction at greater chip thicknesses compared to smaller chip thicknesses where they obtained greater values of the coefficient of friction.

CONCLUSIONS

When calculating the coefficient of friction in the linear orthogonal cutting with HSS cutting tool in the direction of 90-0° an average value of 0.46 was obtained for all chip thicknesses and rake angles. In the calculation, the force resulting from the ploughing effect due to tool tip bluntness in the y direction and the value of force resulting from the ploughing effect and the force for creation of new surfaces in the x direction were subtracted from the measured cutting forces. At rake angles of 16 and 22°, where chip type II was formed according to Franz (Koch 1985), all the measured values with a subtracted force of ploughing were taken into account in the calculation, since the cutting tool tip was constantly in contact with the work piece. However, at the rake angles of 31 and 42° only the greater values of forces were taken into account in the calculation. In case of greater angles forming chip type I, the cutting tool tip is not constantly in contact with the work piece because wood splits under the hypothetic cutting plane, and for this reason ploughing is not always present either. If, however, there is no ploughing, the values of forces for the calculation may be incorrect since the value resulting from the ploughing effect has been subtracted from the measured values. In the event of greater cutting forces when the cutting tool penetrates the still uncracked part of wood, ploughing of the tip of the cutting tool actually occurs. The model used has proved to be correct, since it yielded a constant coefficient of friction.

In the case when the force resulting from the ploughing effect is disregarded, the obtained friction coefficients vary considerably at different chip thicknesses and rake angles, but this is incorrect since the coefficient of friction has to be constant. Numerous researchers previously mentioned also obtained different coefficients of friction for different chip thicknesses and rake angles, because they failed to subtract the force resulting from the ploughing effect from the measured values.

The model of calculating the coefficient of friction from cutting forces proved to be correct. It is of great importance for determining the coefficient of friction between cutting tool and chip during the process of cutting. Also, by using this model real values of the coefficient of friction for specific types of material and rake face of the cutting tool are obtained.

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