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DETERMINATION OF CUTTING TOOL WEAR AND SURFACE ROUGHNESS OF STRAIGHT MILLED ASPEN WOOD

Andis ĀBELE
Mg.sc.eng. – Latvia University of Agriculture – Department of Wood Processing
Address: Dobeles iela 41, Jelgava, Latvia, LV-3001
E-mail: Andis.Abele@llu.lv

Ulvis MIONČINSKIS
Mg.sc.eng. – Latvia University of Agriculture – Department of Wood Processing
Address: Dobeles iela 41, Jelgava, Latvia, LV-3001
E-mail: mioncinskis@inbox.lv

Henn TUHERM
Prof.Dr.habil.sc.eng, Dr.h.c.silv. – Latvia University of Agriculture – Department of Wood Processing
Address: Dobeles iela 41, Jelgava, Latvia, LV-3001
E-mail: Henn.Tuherm@llu.lv

Abstract:
Changes of roughness of the processed surface were determined to prove usefulness of experimental method for evaluation of wear build-up on the cutter and influence of the rake angle on wear of the cutter. To characterize the wearing process values of roundup radius of cutting edge were used too, and these values were obtained by cutting edge replicating into a lead sheet. The cutting process was carried out by a computer numerical control milling machine and cutter heads. The rake angle of the cutter was 10°, 20° and 30°. Cutter knives were prepared from high-alloy tool steel X150CrMo12. Aspen (Populus tremula L.) wood samples were used for the experiments. The maximum length of the cutting trajectory varied from 110000 up to 300000 meters. Results for duration of wear phases in aspen wood straight milling process were obtained, as well as equations to describe forecasting of wear build-up. It was concluded that methodology of the experiment can be used and wear of the cutter depends on value of the rake angle. Increasing the rake angle increases duration of monotone wear phase, i.e. duration of use of the tool is higher.

Key words: *wear; milling; aspen; roughness; rake angle.*

INTRODUCTION

Various alloy steel and cemented-carbide composition cutters were investigated in several researches and conclusions about their resistance to wear and wear inducing factors were made (Porankiewicz *et al*. 2005, Szwajka and Górski 2006, Rodríguez *et al*. 2012). Cutting tools made from high speed steel were also investigated (Porankiewicz *et al*. 2006, Keturakis and Lisauskas 2010) including cutting of wood with high moisture content because it has been proved that in these circumstances resistance to wear of high speed steel and cemented-carbide composition tools was very similar (Nordström and Bergström 2005). It can be concluded that these investigations about wood cutting processes are mainly related to recognizing causes of wear of cutting tools and usually in cutting process wood of conifers and hard deciduous trees have been used. However, investigations, carried out to determine changes in wear during exploitation time of cutting tools and processing of wood of soft deciduous trees are not enough. Possibly it can be explained by the fact that in earlier investigations characteristics of changes of cutter wear have already been proved (Billatos *et al*. 1986), and that is why investigations in this interpretation have been out of focus. Three wear periods can be noticed in these characteristics, each of them has another intensity of wear. Initially the wear builds up very fast because cutting edge after sharpening is very sharp, it becomes round rapidly and parts of tool material break off inducing an increase in roughness of the processed surface. Rapid wear of the cutting tool in the initial phase can be explained also by tearing of instrument material surface layers – the cause for this is surface with defects that have emerged during production or re-sharpening of the instrument (Astakhov and Davim 2008). After that there is a monotone wear period that is characterized by a moderate increase of wear. During start of this period roundness of the cutting edge has increased, that is why under influence of cutting load less material of tool is torn from the surface of the tool. Wood extractives and minerals, contained in composition of wood, have effect on tool wear (Okai *et al*. 2006, Darmawan *et al*. 2012); and the effect becomes more noticeable in this period. Besides, extractives create corrosive environment with greater impact on wear versus mechanical load (Gauvent *et al*. 2006, Winkelmann *et al*. 2009). When length of cutting trajectory reaches a particular distance, wear of the cutter starts to increase rapidly once again indicating start of critical wear period. During the critical wear period roundness of the cutting edge has reached such a value that causes significant deformations for the processed wood surface and increase of cutting power, so that the cutting process becomes ineffective. Similar cutter wear characteristics have also been shown in other references (Astakhov and Davim 2008, Milner and Roth 2010). However, in each of them ratios of different parameters have been used. In one case – wear of the cutter expressed by radius of roundness of the cutting edge in relation to length of the cutting trajectory, in another case – wear of the cutter characterized by loss of cutter's mass or width of worn cutter surface in relation to cutting time. In addition in most cases that gives only general overview about changes of wear of cutting tools during their exploitation time, as neither duration of separate wear periods, nor characterization of technological parameters and processed material is given. In the paper where influence of angular parameters on milling of aspen wood has been investigated, the wear phases are given just at the rake angle of 10° (Ābele and Miončinskis 2012). That is why there is a need of researches, according to which it would be possible to determine wear periods because they would give an opportunity to develop optimal cycles of sharpening of wood processing tools that is the most important indicator of processing economics.

OBJECTIVES

The objective of this work was to develop research methodology for wood cutting processes and to determine during of cutter's wear periods, characterized by increase of roughness of wood, depending on influence of rake angle.

MATERIALS AND METHODS

Methodology has been used, previously described in another paper (Ābele and Miončinskis 2012). Unlike in methodology mentioned earlier in this research the computer numerical control milling machine *Biesse Rover 325* was used. Its technical parameters are given in Table 1.

Table 1

Technical parameters of the computer numerical control milling machine

Characteristic	Value
Rotation frequency of shaft, min^{-1}	0…18000
Feed speed, $m \cdot min^{-1}$	0…60
Power of electromotor, kW	3.4
Maximum processing length of the x-axis direction, mm	3000
Maximum processing length of the y-axis direction, mm	900

During the cutting process only cutters of high-alloy tool steel *X150CrMo12* (according to *LVS EN 10027-1:2005*) have been used, as well as cutter heads with three different values of rake angle of

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the cutter. The cutting parameters used in the research are given in Table 2. Sharpening of the cutters was carried out in sharpening service company *Infleks Ltd*. using sharpening grinders and cutting modes that are used for sharpening of respective instruments in industry. Cubic boron nitride grinder *14F1 200 2×7×5 B126W 100 RCT* from the company *Cafro* was used in the sharpening process.

Table 2

Parameters of cutting process

Characteristic	Value
Rake angle, degree	10, 20, 30
Sharpness angle, degree	40
Clearance angle, degree	40, 30, 20
Cutting velocity, $m \cdot s^{-1}$	40
Feed speed, $m \cdot min^{-1}$	4.7
Feed per tooth, mm	0.443
Cutting depth, mm	1
Length of cutting trajectory per revolution, mm	8.95
Diameter of cutting circumference, mm	72
Rotation frequency of cutter head, min^{-1}	10610

To evaluate wear development of the cutter only roughness of the processed wood surface and cutting edge's radius of roundness was measured in this research, after reaching definite length of the cutting trajectory (according to Ābele and Mienčinskis 2012). Measuring device Perthometer M2 from company Mahr was used for measuring roughness of treated wood surface (Rz). Roughness measuring was performed perpendicularly to wooden fibres, making measurements in three different length positions of wooden samples, from which was calculated mean arithmetic value. Edge's radius of roundness was determined by using the replicating method. Lead plate was pressed on the cutting edge perpendicularly to rake face of cutter. Depth of imprints was 0.5mm. To measure the radius of roundness from imprints and to capture photos of cutters by 200 to 800 times enlargement the digital light microscope *Keyence VHX-100K* was used.

Nonlinear (polynomial) regression was used for interaction's analysing between parameters of tool wear and length of the cutting trajectory. However also linear regression was used for determining of changing intensity of resultant sign in separates wear periods. According to F-test with a p-value were tested (with software IBM SPSS Statistics 19) hypotheses about the significance of the regression equations ($H_0 : \rho^2 = 0,\ H_1 : \rho^2 > 0$); but with p-value of t-test were tested hypotheses about the significance of the regression coefficients $H_0 : \beta_i = \beta_i^0 \quad (i = 1,2,3)$ (for nonlinear regression) and $H_0 : \beta_1 = \beta_1^0$ (for linear regression). P-value was compared with significance level $\alpha = 0.01$.

RESULTS

Wear of the cutter when milling at rake angle of 10°

Initial changes of surface roughness (Fig. 1) show that wear-in is occurring during which amount of irregularities of the cutting edge surface decreases and cutter's resistance against the wood increases. It can be concluded that the initial wear phase ends by approximately 8000m but the cutting time is 1.5 hours. Coefficient 0.0011*x* of the linear regression equation (Fig. 1) shows that during the initial period, as length of the cutting trajectory increases by 1m, the roughness of the processed surface increases by 0.0011μm.

After reaching length of the cutting trajectory 8000m a monotone wear period starts, and it continues until approximately 95000m with respective cutting time of 16 hours. Linear regression analysis in monotone wear phase shows that, as length of the cutting trajectory increases by 1m, roughness of the surface increases by 0.0001μm. It is 11 times less than during the initial period.

The critical wear period starts after reaching length of cutting trajectory 95000m because roughness of the surface increases rapidly. It means that re-sharpening of the cutter has to be carried out after working for 16 hours. Re-sharpening of the cutter can be done both before and after this critical point but doing so will decrease usefulness of the cutter. When performing re-sharpening of the cutter before start of the critical wear border, the potential of intermediate sharpening period of the cutter will not be used completely, but when performing re-sharpening after the critical wear point, the restoration working capacity of cutter will increase and total estimated exploitation time will decrease. So that re-sharpening of the cutter has to be done as close to the critical point as possible or at least before that but it is not acceptable to perform re-sharpening after critical wear of the cutter has already occurred.

During the critical wear period when length of the cutting trajectory increases by one meter, the roughness of the surface increases by 0.0013μm. It means that intensity of increase of cutter wear is

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13 times larger when compared to the monotone wear period and 1.2 times larger when compared to the initial wear period.

This model is statistically significant because p-value of the F-test ($1,246 \cdot 10^{-53}$) is lower than α = 0.01. P-values of the regression equation coefficients β_1, β_2, β_3 ($3.06 \cdot 10^{-17}$, $5.69 \cdot 10^{-13}$, $2.35 \cdot 10^{-14}$ respectively) are also lower than $\alpha = 0.01$.

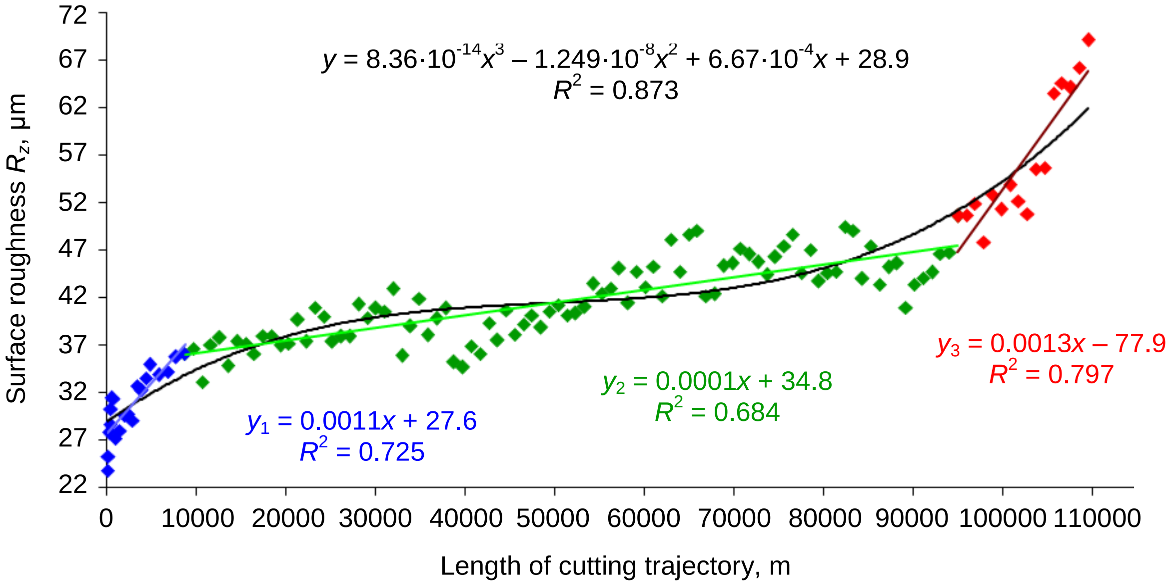

Fig. 1
Changes of surface roughness R_z respect to length of cutting trajectory when milling at rake angle of 10º.

To forecast roughness of the surface and also wear of the cutter in relation to length of the cutting trajectory when milling at the rake angle of 10º the following equation can be used:

$$R_z^{10} = 28.9 + 6.67 \cdot 10^{-4} L - 1.249 \cdot 10^{-8} L^2 + 8.36 \cdot 10^{-14} L^3 \text{ [μm]} \quad (1)$$

R_z^{10} – roughness of the processed wood when milling at rake angle of 10º, in μm;
L – length of cutting trajectory, in m.

Wear of the cutter when milling at rake angle of 20°

Increased intensity wear phase of the cutter that is characteristic and observable during start of the cutting process is for length of cutting trajectory between 0m and approximately 8000m that corresponds to cutting time interval from 0 up to 1.5 hours. When milling at the rake angle of 10º, it was exactly the same. It means that increase of the rake angle from 10º to 20º does not affect duration of the initial period. It is also confirmed by the fact that values of roughness of the surface are not significantly different because p-value of the t-test (0.751) is larger than $\alpha = 0.01$. Although changes in duration of cutter initial wear period are not observed when changing the rake angle, the initial phases shown in Fig. 1 and 2 are not completely identical. Coefficient of the linear regression function (Fig. 2) shows that roughness of the surface increases by 0.0009μm, if length of the cutting trajectory is increased by 1m. It is 1.2 times less than at the rake angle of 10º. But the difference is only 0.2μm, and it is not significant.

After reaching length of cutting trajectory of 8000m the intensity of growth of surface roughness decreases. In this moment the monotone wear period starts and it continues up to length of cutting trajectory of 200000m (cutting time 35 hours). That is a little bit more than two times larger than at the rake angle of 10º. It means that the critical wear when the rake angle is increased from 10º to 20º starts approximately two times later. It can be explained by the fact that there is a need to fold the cut chip less than at rake angle of 10º and that decreases the pressure on the front surface of the cutter and its wear.

Coefficient of the linear regression equation shows that during the monotone wear period when length of the cutting trajectory increases by 1m then roughness of the surface increases by 0.0001μm. It is 9 times less than during the initial wear period. Besides it is equal to intensity of growth of surface roughness in monotone wear phase at the rake angle of 10º.

The linear regression function of the changes in surface roughness of the processed wood that characterizes critical wear period shows that when length of the cutting trajectory increases by one meter the surface roughness increases by 0.0011µm. It means that intensity of wear of the cutter during start of the critical wear phase is 11 times larger compared to the monotone wear period and 1.2 times larger compared to the initial wear period. So that relations of intensities of wear build-up among different wear periods are similar to those that are determined when milling at the rake angle of 10º.

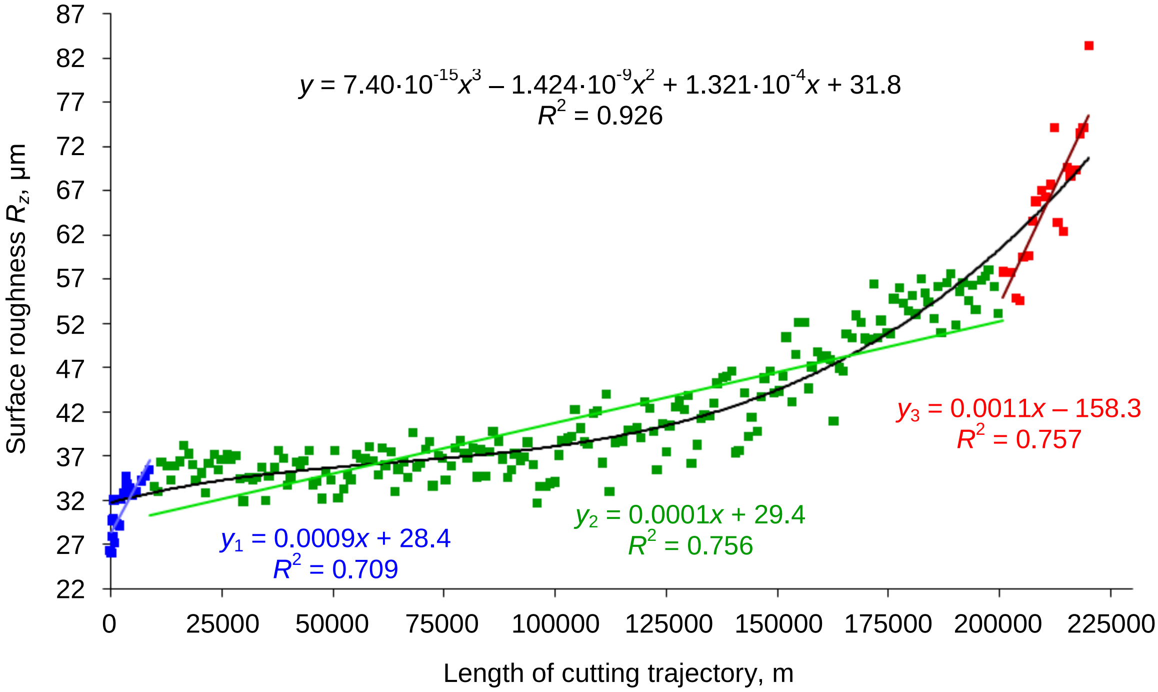

Fig. 2
Changes of surface roughness R_z respect to length of cutting trajectory when milling at rake angle of 20º.

P-value ($2.28 \cdot 10^{-131}$) of F-test of the regression model (Fig. 2) is lower than α = 0.01. P-values of the regression equation coefficients β_1, β_2, β_3 ($2.84 \cdot 10^{-7}$, $6.00 \cdot 10^{-7}$, $6.07 \cdot 10^{-16}$ respectively) are lower than α = 0.01. To forecast roughness of the surface and also wear of the cutter in relation to length of the cutting trajectory when milling at the rake angle of 20º the following equation can be used:

$$R_z^{20} = 31.8 + 1.321 \cdot 10^{-4} L - 1.424 \cdot 10^{-9} L^2 + 7.40 \cdot 10^{-15} L^3, \text{ [µm]} \quad (2)$$

R_z^{20} – roughness of the processed wood when milling at rake angle of 20º, in µm;
L – length of cutting trajectory, in m.

The second parameter that characterizes wear of the cutter and that has been used in this research is radius of roundness of the cutter's cutting edge. It was concluded that at the start of cutting process it was 5...10µm but at the end of the experiment – 20...30µm. The values observed at the start of the cutting process are completely consistent with other papers. However the values observed at the end of the experiment are just partly consistent because radius of roundness of worn cutting edges is up to 60µm (Siklienka and Mišura 2008).

Wear of the cutter when milling at rake angle of 30°

The initial wear period in this case is in interval of length of cutting trajectory from 0m up to approximately 8000m (Fig. 3). Again the same as milling at the rake angle of 10º and 20º. It proves the previously proposed assumption that changes of rake angle of the cutter do not significantly affect duration of the cutter's initial wear period. It is because at the rake angle of 30º, when length of the cutting trajectory increases by one meter surface roughness increases by 0.0011µm – the same as when milling at the rake angle of 10º. So length of the cutting trajectory during the initial wear period is too small to express differences between rake angles.

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The monotone wear phase lasts 267000 meters – from 8000 up to 275000 meters of length of the cutting trajectory (cutting time is 48 hours). It is 1.4 times more than at the rake angle of 20º and even 3 times more than at 10º. So that as the rake angle increases the critical wear border is reached later. This conclusion corresponds to the information given in references (Simonin *et al*. 2009). It says that when the rake angle of the cutter is increased wear of the cutter decreases because such changes of angular parameters decreases the load on the cutter during cutting process.

The start borders of critical wear period that have been determined by this research are relatively high, if they are compared to the practice where duration of re-sharpening cycle is usually approximately 4...8 hours. If 16 hours cutting time up to start of the critical wear is an achievable result then to save capacity up to 48 hours is very limited when using steel cutters. Significant differences between cutting time determined in the research and time in practice until start of the critical wear period can be explained by different working conditions. Samples without wood defects (for example branches) were used in the research. These defects when coming in contact with cutting tools induce impact loads because their density and stiffness is significantly different from the rest part of the wood. In practice it is impossible to avoid these wood defects and it is also not necessary but it accelerates wear build-up of the cutter. Besides quite often there are mineral substances on surfaces to be processed, for example sand that increase roughness of cutting edge of the cutter and wear. The wood surface samples used in the research were carefully cleaned from possible mineral substances that are why using time of the cutter has increased.

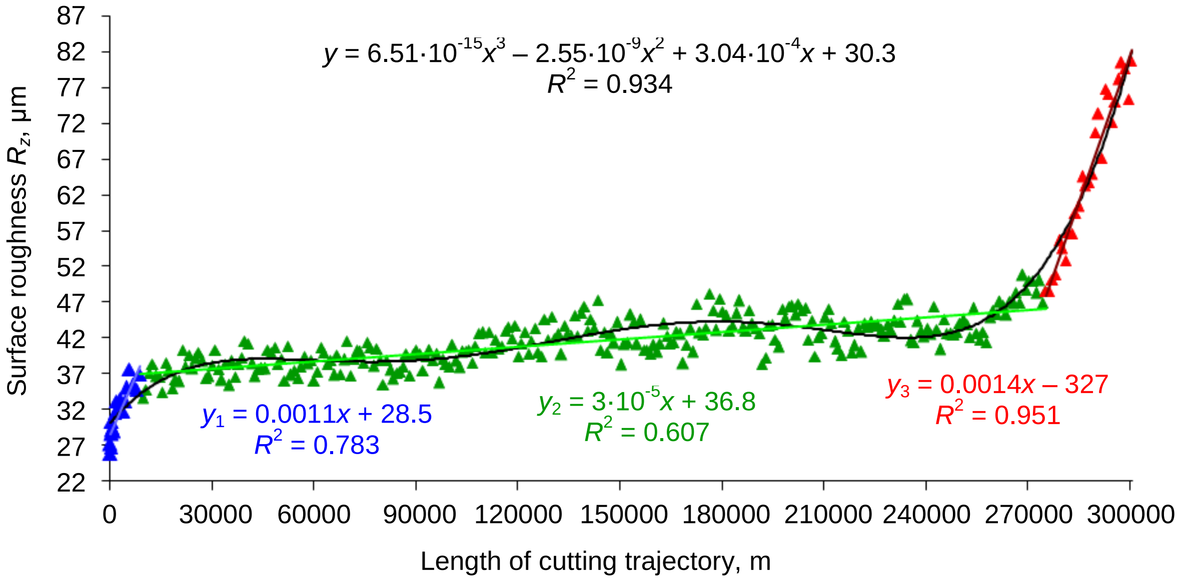


Fig. 3
Changes of surface roughness R_z respect to length of cutting trajectory when milling at rake angle of 30º.

During the monotone wear period roughness of the surface increases by 0.00003µm when length of the cutting trajectory increases by one meter. It means that if the rake angle is increased from 10º to 30º, duration of the monotone wear period increases 3 times.

During the critical wear phase roughness of surface increases by 0.0014µm, if length of the cutting trajectory increases by one meter. In opposition to the initial wear period of the cutter, during the critical wear period wear intensity is 1.2 times larger but when comparing to the monotone wear phase – 46 times larger.

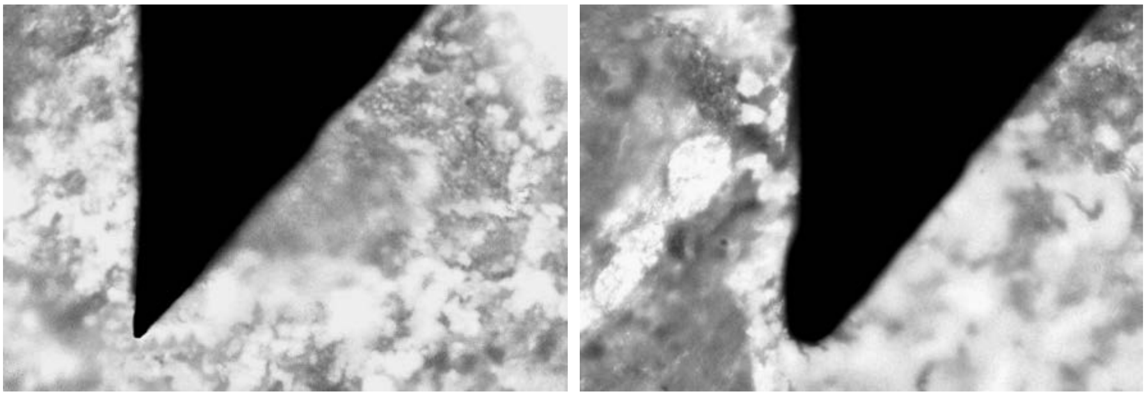
This model is also statistically significant because p-value ($5.60\cdot10^{-104}$) of the F-test is less than $\alpha = 0.01$ and p-values of the regression equation coefficients β_1, β_2, β_3 ($2.10\cdot10^{-33}$, $1.344\cdot10^{-35}$, $3.20\cdot10^{-43}$ respectively) are also less than $\alpha = 0.01$.

To forecast roughness of the surface and also wear of the cutter in relation to length of the cutting trajectory when milling at the rake angle of 30º the following equation can be used:

$$R_z^{30} = 30.3 + 3.04\cdot10^{-4}L - 2.55\cdot10^{-9}L^2 + 6.51\cdot10^{-15}L^3,\ [\mu m] \quad (3)$$

R_z^{30} – roughness of the processed wood when milling at rake angle of 30º, in µm;
L – length of cutting trajectory, in m.

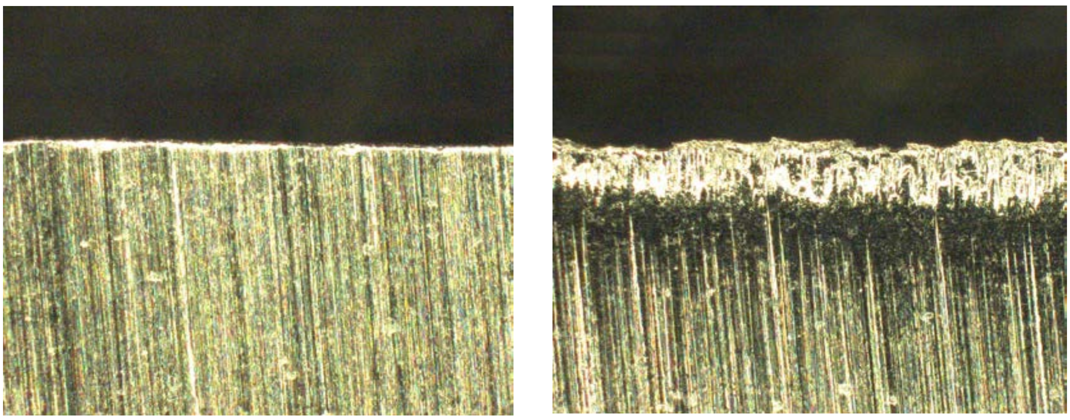
The profile imprints of the cutters in this case (Fig. 4) show that before start of the cutting experiment rounding of cutting edge was 4...5μm, but at the end of the experiment – 25...35μm. So that radius of roundness of the cutter's cutting edge has increased by approximately 5...7 times. Similar results are obtained also in experiments at the rake angle of 10º and 20º. It means that when milling aspen wood with milling knives made of high-alloy tool steel *X150CrMo12* and using such cutting mode parameters that have been used in this research quality of the processed wood surface significantly decreases when radius of roundness of the cutter's cutting edge exceeds approximately 30μm.



a b

Fig. 4
Imprints of profile of cutting edge at rake angle of 30º (magnification 800 times)
a - before cutting process; b - after cutting process.

During milling wear of the cutter forms not just on the cutting edge but on the rake face as well because the cut chippings are slipping along the surface. Before start of the cutting process only sharpening grinder imprints can be seen on the rake surface of the cutter and all rake surface of the cutter has the same texture, and the cutter's cutting edge is relatively straight and level (Fig. 5a) However, at the end of the experiment clear wear signs can be seen on the rake surface of the cutter. In addition two wear areas can be distinguished that in Fig. 5b can be seen as lighter and darker colours in direct vicinity of the cutting edge. In the lighter area, whose width is approximately 250μm, wear of the cutter is most intensive and when going closer to the cutting edge it gradually becomes a part of the roundness area of the cutting edge because there is no explicit transition between them. Whereas in the darker coloured area, whose width is approximately 200μm, wear intensity of the cutter is comparatively smaller, and there can observe more definite borders with other zones of the rake surface (the lighter coloured intensive wear area and area without wear).



a b

Fig. 5
Rake face of cutter at rake angle of 30º (magnification 200 times)
a - before cutting process; b - after cutting process.

When comparing Fig. 5b and 5a it can be seen that contour line of the cutting edge is a lot more uneven because as a result of the cutter's wear holes with depth of 10...40μm have turned up. Aspen wood is comparatively soft, so that such irregularities of the cutting edge significantly increase roughness of the processed surface. It means that increase in roughness of the wood surface is more affected by increase in roughness of the cutting edge surface, not increase of radius of roundness of the cutting edge that by the start of the critical wear is still quite small – approximately 30μm. As mentioned before, the radius of roundness indicated in references is 60μm (Siklienka and Mišura 2008) but these indicators have not been obtained milling wood of soft deciduous trees. That's why when processing aspen wood the radius of roundness of the cutter's cutting edge by which the critical wear starts is important and the values obtained in this paper are 30...35μm.

CONCLUSIONS

1. The developed methodology of investigation of cutting processes can be used to analyze regularities of the wood milling process and it is recommended to use the developed methodology to carry out research in wood cutting process field by changing cutting mode parameters and processing different species of wood.

2. Increasing the rake angle from 10° to 30° increases duration of monotone wear phase approximately three times and beginning of critical wear phase is after 95000m and 275000m respectively. It is mean that duration of use of the tool is higher at rake angle of 30° and It is recommended to use cutting tools with larger value of the rake angle in aspen wood straight milling process if roughness of the processed surface is not the main factor.

3. Duration of the cutter's initial wear period does not significantly depend on the value of the rake angle.

4. When milling aspen wood, radius of roundness of the cutting edge by which the critical wear of the cutter starts is 30...35μm.

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