British Journal of Applied Science & Technology
14(5): 1-7, 2016, Article no.BJAST.24465
ISSN: 2231-0843, NLM ID: 101664541

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Predictions of Cutting Tool Wear of Straight Milled Aspen Wood with Taylor's Equation

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2016/24465
Editor(s):
(1) Manoj Gupta, Department of Mechanical Engineering, NUS, 9 Engineering Drive 1, Singapore 117576, Singapore.
Reviewers:
(1) Pradeep Kumar Patil, Rajeev Gandhi Technical University, Bhopal, India.
(2) T. A. O. Salau, University of Ibadan, Nigeria.
Complete Peer review History: http://sciencedomain.org/review-history/13341

Original Research Article

Received 22nd January 2016
Accepted 9th February 2016
Published 18th February 2016

ABSTRACT

Taylor's equation has proven utility for determination of the lifetime of cutting tool in machining of metal. Whereas, Taylor's equation is not widespread for prediction of wear of wood machining tools due to lack of appropriate coefficients of the equation. Therefore, aim of the study is determination of coefficients of Taylor's equation. Computer numerical control machine was used for conventional milling of aspen (*Populus tremula* L.) wood with cutter knives of high-alloy tool steel X150CrMo12 on the cutter head. Changes of the surface roughness characterized the wear phases of cutting tool at two different values of cutting velocity were obtained depending on length of the cutting trajectory. It was concluded that length of cutting trajectory is greater when cutting velocity is increasing from 20 to 40 m s^{-1} and it was obtained equation to predict length of cutting trajectory till critical wear phase of cutting tool depending on the cutting velocity.

Keywords: Tool wear; Taylor's equation; cutter head; milling; aspen.

1. INTRODUCTION

The traditional change curve of wear of a cutter describes cutting conditions under certain fixed technological parameters of the cutting process, but it may be expected that under different parameters structure of the change curve will be differ. The main technological parameter of

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cutting process affecting the wear of cutting tool is the cutting velocity [1]. Beside, by increasing the cutting velocity, the critical wear period of a cutting tool is reached earlier [2].

Based on the different curves of the wear it may be concluded that there is correlation between the cutting velocity and wear of a cutter, which is a fundamental factor for the ability to calculate the beginning time of the critical wear phase of a cutter in advance. In this regard it is possible to use the Taylor's equation which was developed in 1906 and which has been a significant factor in the development of cutting tools [3]. Even though, the Taylor's Equation was developed based on results acquired in metal processing works, it may also be applied in respect to woodworking cutting tools as the basic cutting principles for both materials are the same. The Taylor's Equation looks at the cutting tool life expectancy as a function of the cutting velocity, expressing both indicators with a natural logarithm, which results in a straight line characterizing this function and showing a certain angle in respect to the coordinate axes, when constructed in the coordinate system. It is the base of Taylor's Equation, which is as follows [4]:

$$v \cdot T^{n} = G \tag{1}$$

where

v – cutting velocity, m s^{-1};
T – duration of exploitation of cutting tool, s;
n – a constant which depends on slope of the curve which depends on tool and wood material;
G – a constant which depends on the tool and wood material and it is equal to the intercept of the curve and the ordinate.

Constant n is characterized by this equation [4]:

$$n = \tan\theta = \frac{\ln v_1 - \ln v_2}{\ln T_1 - \ln T_2} \tag{2}$$

where

θ – directional angle between function of exploitation of cutting tool and abscissa axis of coordinate system, degrees;
v_1; v_2 – different cutting velocity, m s^{-1};
T_1; T_2 – duration of exploitation of cutting tool that is corresponding to cutting velocity v_1 and v_2 respectively, s.

The constants G and n depend on type of material used in production of the cutting tool, as well as type of the treated material and wood specie [1], therefore, every combination of cutting tool and treated material has different values of these constants, which may only be found empirically by running several experiments and changing some of the affecting factors in each of them. It, however, makes it very difficult to get the values of the constants as there are several hundreds of combinations of the cutting tool materials and treated wood species, and cutting velocity is a variable factor as well in this equation. However, it is possible to limit the number of combinations by selecting the cutting tool materials and wood species which are used in practice the most often. It must be noted that in the metal processing industry constants of the Taylor's Equation may be found rather often and they are defined for most of the combinations of cutting tool material and treated material [4]. In its turn, the Taylor's Equation is almost never used for calculation of the cutting tool life expectancy in woodworking industry as it has only been mentioned only in few studies on wear of woodworking cutting tools. There are also no values of the Taylor's Equation defined which might be used in the main wood cutting techniques – sawing and milling.

In one of the studies is processed solid wood and engineering wood workpieces of rubber wood (*Hevea Brasiliensis*) by using a computer numerical controlled milling machine and shank router cutter with tungsten carbide cutters [5]. However, the aim of this study was more to find out efficiency of the respective wood species in production of furniture. Therefore, it does not focuses on providing the values of constant in obvious and usable way. However, it may be concluded from the study that the constant G of the Taylor's Equation may be used to compare abrasiveness of the treated material, which causes loss of the mass of the cutting tool as the material is tearing down from the cutting edge. It is related to the feature of the Taylor's Equation where the value of constant G, given that the duration of exploitation of the cutter T is one minute, is equal to the cutting velocity. Thus, the constant G describes the cutting velocity at which equal wear of the cutter is reached after one minute long cutting. Thus, by comparing the values of G calculated in this way it is possible to determine how different treated materials affect wear of the cutter.

The other study, which included use of the Taylor's Equation to modelling wear of woodworking cutting tools, was carried out by drilling medium density fiberboard [6]. In addition to the cutting velocity, this study also showed how the hardiness of the cutter affects wear of cutting tools. The study provides values of constants of the Taylor's Equation which may be used in practice to forecast the beginning time of the critical-wear phase of cutters at different cutting velocity and different hardiness values of the cutting tools. However, this equation may be applied only under the same cutting conditions and mode as used in the study, by processing medium density fiberboards, and other cutting conditions required their own equations for wear of the cutting tools.

It is expected that the Taylor's Equation for forecasting of life of straight milling cutting tool expectancy would provide more accurate results. Therefore, aim of the study is determination of coefficients G and n of Taylor's equation in limited range of the cutting velocity.

2. MATERIALS AND METHODS

A multifunctional computer numerical control (CNC) machine with separate drive mechanism for cutter heads "Biese Rover 325" was used in this study. A unique cutter head has been design for the experimental work. The cutter head was produced by a cutting tool producer "Frezite". Knives of the cutter head was made of high-alloy tool steel X150CrMo12 (according to [7]) and its chemical composition is following: C = 1.40 to 1.65%, Cr = 11.00 to 13.00%, Mo = 0.40 to 1.20%, Fe = 83.35 to 86.40% other chemical elements = 0.80%. The parameters of the cutting regime are indicated in the Table 1. This cutter head consists only of a knife and one balancing plate that are located on the opposite circumference points of the cutter head. Therefore, it takes less time to reach the prescribed load capacity for the tool cutter comparing to cutter heads with many knives.

Samples of aspen (*Populus tremula* L.) wood with a moisture content of 8 to 10%, thickness of 20 mm, length of 480 mm and variable width were used during the experiment work of the study. Conventional milling was carried out by creating longitudinal cuts next to each other on the sides of the wood samples. Cutting was performed in depth of 1 mm what gives 8.95 mm long length of the cutting trajectory for every rotation of the cutter head. For the calculating of the length of the cutting trajectory at one rotation of the cutter head the following equation was used [8]:

$$l = \frac{10^3 \cdot u}{N \cdot z} + \frac{\pi \cdot D}{360} \arccos\left(1 - \frac{2 \cdot H}{D}\right) \qquad (3)$$

where

l – length of the cutting trajectory at one rotation of the cutter head, mm;
u – feed speed, m min^{-1};
N – rotation frequency of cutter head, min^{-1};
z – number of knives of the cutter head;
π – the constant ($\pi = 3.14$);
D – diameter of cutting circumference, mm;
H – cutting depth, mm.

The total length of the cutting trajectory related to the one cutting knife was calculated by the following equation [8]:

$$L = \frac{l \cdot N \cdot l_p}{10^6 \cdot u} \cdot m_{ie} \cdot m_p \qquad (4)$$

where

L – total length of the cutting trajectory, m;
l_p – length of the wood sample ($l_p = 480$), mm;
m_{ie} – number of cutting strokes in the one wood sample;
m_p – number of wood samples.

Roughness R_z of the processed wood surface was measured with measuring device Perthometer M2 from company Mahr to evaluate wear development of the cutting knives. Initially measurements of roughness were made after each 10 milling strokes, which correspond approximately 100 m of cutting trajectory. When 60 strokes were reached in total, determination of roughness was performed after each 20 continuous milling strokes. When 100 strokes were reached in total, measurements of roughness were performed after each 50 continuously made milling strokes. Whereas determination of roughness was performed after each 100 continuously realized milling strokes in range of milling strokes from 500 up to final number of strokes.

Regression was used for interaction's analysing between surface roughness and length of the cutting trajectory because it is suitable for cutting processes models [9]. 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 $H_0 : \beta_i = 0 \; (i = 1, 2, \cdots, m)$, $H_1 : \beta_i \neq 0 \; (i = 1, 2, \cdots, m)$. P-value was compared with significance level $\alpha = .01$.

Table 1. Parameters of the cutting regime

Characteristic	Value
Diameter of cutting circumference, mm	72
Clearance angle, degree	40
Sharpness angle, degree	40
Rake angle, degree	10
Cutting velocity, m s^{-1}	20 and 40
Feed speed, m min^{-1}	2.35 and 4.70
Rotation frequency, min^{-1}	5305 and 10610
Feed per tooth, mm	0.443
Cutting depth, mm	1
Cutting width, mm	20

3. RESULTS AND DISCUSSION

Initial changes of surface roughness at cutting velocity 20 m s^{-1} (Fig. 1) indicate that the wear-in of cutter is happening. During this period surface roughness of cutting tool decrease but resistance of cutting tool to load increase. Consequently, initial wear phase is in range of cutting trajectory from 0 m to approximately 10000 m, which comply with cutting time 4 hours. Afterwards the intensity of processed wooden surface roughness decreases. It shows beginning of monotone wear phase of cutter, which continuous up to reaching approximately 45000 m length of cutting trajectory with corresponding cutting time 16 hours. After end of monotone cutter's wear phase, surface roughness R_z sharply increases again, showing beginning of critical wear phase of cutter.

Whereas, curve of surface roughness at cutting velocity 40 m s^{-1} (Fig. 2) indicate that initial wear phase is in range of cutting trajectory from 0 m to approximately 8000 m, but corresponding cutting time is 1.5 hours. Afterwards begins monotone wear phase, which continuous up to reaching approximately 96000 m length of cutting trajectory with corresponding cutting time 16 hours. Critical wear phase begins after reaching approximately 96000 m length of cutting trajectory of cutter because surface roughness sharply increases.

Both models are statistically significant because $P<.001$ for F-test and regression equation coefficients β_1, β_2, β_3.

Even though the tendency towards changes in the surface roughness in relative to length of the cutting trajectory is very alike, when comparing both characteristic curves differs the length of the cutting trajectory after which the critical wear phase initiates. The beginning values of the critical wear phase differ almost twice, which is a very significant variance. This is due to difference in some specific mode parameters, such as the cutting velocity and feed speed. The main parameter that should be taken into consideration as a result changing factor is the cutting velocity because it is impacting the wear

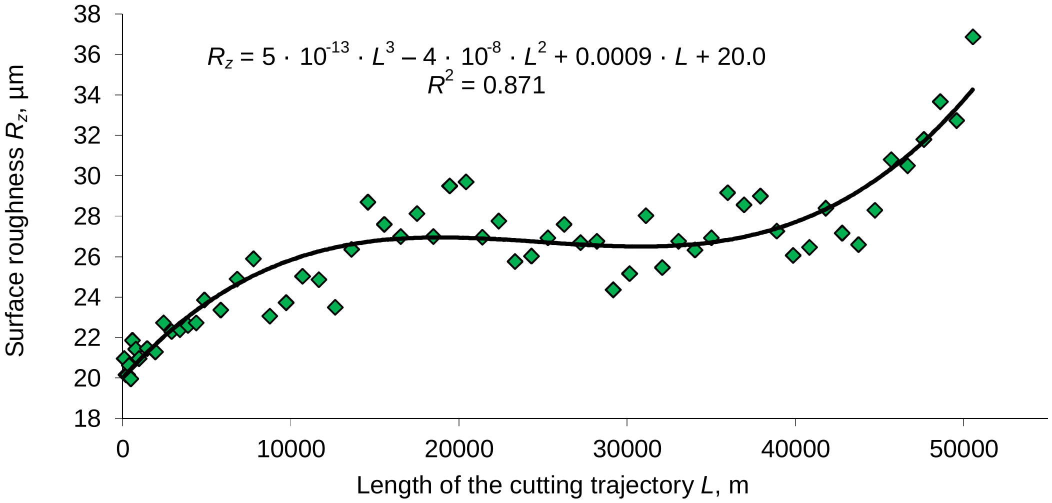

Fig. 1. Surface roughness relative to length of the cutting trajectory at cutting velocity 20 m s^{-1}

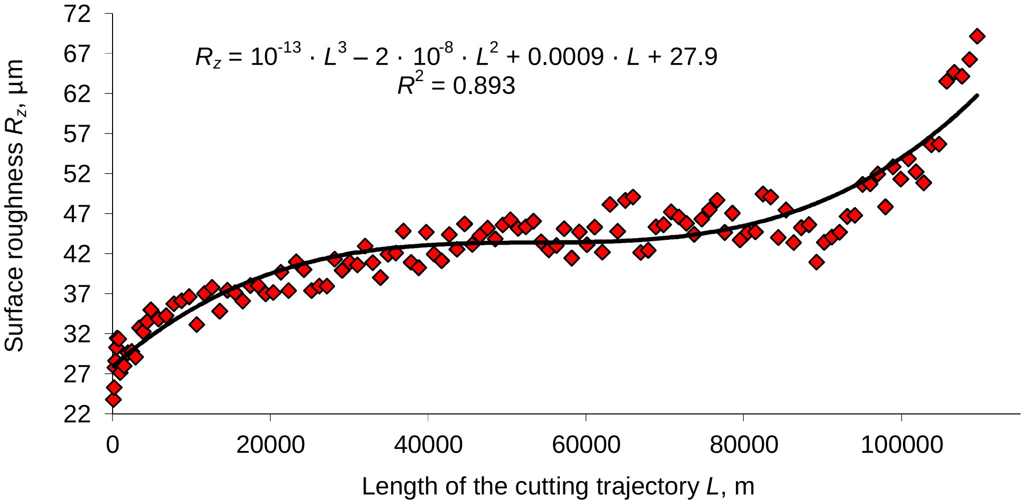

Fig. 2. Surface roughness relative to length of the cutting trajectory at cutting velocity 40 m s^{-1}

of the cutter the most [1]. The feed speed in this case is not as important because the feed per tooth has remained unchanged throughout both of the experiments. Therefore, it may be assumed that when the cutting velocity has been increased from 20 to 40 m s^{-1}, it takes twice as long length of the cutting trajectory to initiate the critical phase of wear for the cutter. However, it also has been ascertained by other authors that by increasing the cutting velocity, the critical wear phase of the cutter is being reach sooner [2,5]. The contrasting results can be explained by the fact that the wear of the cutter in various cutting velocities has always been expressed in respect to the cutting time by the other authors. Though, the feed speed, rather than the cutting velocity, is usually the factor that impacts the cutting time the most, other authors have chosen to use it as a constant, while changing the cutting velocity. In contrary, the parameters characterizing the cutter's wear are expressed in respect to the length of the cutting trajectory in this study, and the feed speed is being changed along with the cutting velocity. In addition, the cutting time, when the critical wear phase of the cutter initiates is equivalent to 16 hours for both experiments, when milling with a cutting velocity of 20 and 40 m s^{-1}. For example, if the cutting velocity increases twice and the feed speed remains the same, the cutter comes into contact with the wood twice as much in the same unit of time, chipping off twice as much wood, and as a result is subjected to a higher level of friction. Consequently, the length value of the cutting trajectory will be twice as big at the same cutting time. Whereas, for example, if both the cutting velocity and the feed speed increases twice, the length of the cutting trajectory remains the same but cutting time is two times less. Consequently, the same cutting time means that length of the cutting trajectory is two times greater, as it can be observable in this study. Thus, the specific cutting force affecting the tool wear is not increases because thickness of chip is the same. Another study indicates that by increasing the cutting velocity, the feed per tooth decreases, and therefore also decreases the amount of wood chipped off, which all results in an increase of the cutting power because a higher cutting resistance is being created [10]. Furthermore, it has been ascertained that the resistance of wood, along with the cutting power, increases more when the cutting velocity is being increased from 45 to 60 m s^{-1}, comparing to the observation of velocity increase from 30 to 45 m s^{-1}. This confirms the observation that the cutting force and thus the cutter wear increases when cutting speed is above 40 ... 50 m s^{-1}. On the contrary, if the cutting speed increases from 0 to 40 ... 50 m s^{-1}, the cutting force and thus the cutter wear decreases.

Length of the cutting trajectory is more appropriate for forecasting of tool wear compared to time of cutting because the time depends on the feed speed. Consequently, duration of exploitation of cutting tool can be replaced with length of the cutting trajectory in the Taylor's Equation (equation 1):

$$v \cdot L^n = G \tag{5}$$

or

$$\ln v + n \cdot \ln L = \ln G \tag{6}$$

Whereas, constant n can be characterized by this equation inasmuch as changes of the tool wear are inverse to the classical Taylor's Equation in range of cutting velocity inspected in the research:

$$n = -1 \cdot \frac{\ln v_1 - \ln v_2}{\ln L_1 - \ln L_2} \tag{7}$$

Results of the research indicate that the permissible length of the cutting trajectory till critical wear phase $L_1 = 95989$ m when cutting velocity $v_1 = 40$ m s^{-1} and the permissible length of the cutting trajectory till critical wear phase $L_2 = 44712$ m when cutting velocity $v_2 = 20$ m s^{-1} (Figs. 1 and 2). Consequently, constant n is following (equation 7):

$$n = -1 \cdot \frac{\ln 40 - \ln 20}{\ln 95989 - \ln 44712} = -0.907 \tag{8}$$

By inserting results in equation 6, it is possible to obtain:

$$\ln 40 + (-0.907) \cdot \ln 95989 = \ln G, \tag{9}$$

$$\ln 20 + (-0.907) \cdot \ln 44712 = \ln G, \tag{10}$$

Calculating equations 9 and 10, it is possible to obtain that constant $G = 1.207 \cdot 10^{-3}$. Consequently, the Taylor Equation (equation 5), corresponding to the range of the research is following:

$$v \cdot L^{-0.907} = 1.207 \cdot 10^{-3} \tag{11}$$

By expressing L from the equation 5, it is possible to get a coherence which may be directly used to calculate the length of the cutting trajectory when critical wear phase is starting:

$$L = G^{\frac{1}{n}} \cdot v^{\frac{-1}{n}} \tag{12}$$

$$L = \left(1.207 \cdot 10^{-3}\right)^{\frac{1}{-0.907}} \cdot v^{\frac{-1}{-0.907}} = 1646 \cdot v^{1.1022} \tag{13}$$

4. CONCLUSIONS

Length of the cutting trajectory till critical wear phase is increasing two times when cutting velocity is increasing from 20 to 40 m s^{-1}.

Constant of Taylor's Equation $n = -0.907$, but constant $G = 1.207 \cdot 10^{-3}$ if cutting velocity is in the range of 20 to 40 m s^{-1} and feed per tooth is 0.443 mm in straight milling of aspen wood.

Length of the cutting trajectory till critical wear phase depending on the cutting velocity can be calculated by the following equation: $L = 1646 \cdot v^{1.1022}$, if cutting velocity is in the range of 20 to 40 m s^{-1} and feed per tooth is 0.443 mm in straight milling of aspen wood.

ACKNOWLEDGEMENTS

Research was performed within the National Research Program„ Forest and earth entrails resources: Research and sustainable utilization – new products and technologies" (*ResProd*) *2014-2017*.

RESPROD

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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