Analysis of the influence of instrumental and regime factors on the quality of wood grinding

A Sergeiichev, V Kushnerev, V Sergeiichev, V Sokolova and V Onegin
Saint-Petersburg State Forest Technical University, 5 Institutskiy Lane, Saint-Petersburg, 194021, Russian Federation

E-mail: 910sav@gmail.com

Abstract. The grinding tool does not have a solid cutting edge, in most cases the front angles for abrasive grains are negative, the grains have rounded vertices and an irregular geometric shape. Grinding should be considered as a process of cutting-scratching the surface layer of wood with a large number of abrasive grains of the grinding tool. The main purpose of the grinding process is to prepare the surface for finishing by eliminating irregularities and defects of the previous processing. The effectiveness of grinding to a greater extent depends on the processing conditions, characteristics and properties of the grinding tool. Theoretical studies and analysis of the derived equations for determining the critical values of the rake angle, cut thickness and cutting speed show that all of the above parameters have a significant effect on the amount of lifting of the processed material by abrasive grain and the intensity of the appearance of contact fractures. An increase in the critical thickness of the slice leads to an increase in the deformation of the surface layers of the processed material, and, consequently, to an increase in the depth and number of contact fractures. The increase in the absolute value of the rake angle leads to the need to increase the critical cutting speed to ensure the conditions of chip formation. In general, an increase in cutting speed always has a positive effect on chip formation conditions and on the quality of the machined surface. An increase in the modulus of the rake angle leads to a deterioration in the conditions of chip formation and surface quality. An increase in the radius of curvature of the cutting edge of the grain leads to an increase in the critical thickness of the slice, which entails an increase in contact deformations and fractures.

1. Introduction
The practice of cutting and grinding gives an idea of the principal character of the influence of cutting speed, rake angle of grain, radius of curvature of the cutting edge, compressive strength and density of the processed material, the coefficient of friction of the tool material on the processed material on the conditions of chip formation [1-5], the elastic deformation of the cutting plane [6-8], the quality of the treated surface [9-10] and other output parameters of the cutting process.

However, it is important to know not only the direction in which this or that factor should be changed. It is equally important to know the critical value to which the given factor should be changed in order to achieve the desired positive effect, since changing the factor in the supercritical area will not lead to an improvement in the result and will be economically disadvantageous.
2. Methods of research

The angle that makes up the vector of the total shear stress with the cutting speed vector is called the angle of action $\psi$, and we assume that if the projection $\tau_{\text{shear}}$ on the normal plane of the cutting is directed to the material, the angle $\psi$ is negative, if this projection is directed to the grain, $\psi$ is positive. Figure 1 shows a negative angle of action.

In the case where the projection of the vector of the total shear stress $\tau_{\text{sum}}^{\text{shear}}$ arising in the material under the influence of grain is directed to the material, then the force causing the material to deform cannot lead to the formation of chips, in this case the material will be crushed by the grain.

In order for the chips to begin to form, it is necessary to change the sign of the angle $\psi$, i.e. make it positive so that the projection $\tau_{\text{shear}}^{\text{sum}}$ is upward, i.e. into the grain. This can be achieved in several ways. You can change the rake angle $\gamma$ in a positive direction, or increase $\tau_{\text{fr}}^{\text{sum}}$ by increasing the cutting speed.

Figure 2 shows a vector diagram of the stresses acting at a different cutting speeds in a material element. Provided that $v = 10 \text{–} 12 \text{ m/s}$, i.e. at cutting speeds exceeding the speed of maximum dynamic hardening, an increase in speed does not lead to growth $\sigma_{\text{din}}$, at the same time, $\tau_{\text{fr}}^{\text{sum}}$ increases with an increase in cutting speed. The length of the vectors $\tau_{\text{fr}1}^{\text{sum}}, \tau_{\text{fr}2}^{\text{sum}}$ and $\tau_{\text{fr}3}^{\text{sum}}$ corresponds to different cutting speeds, with $v_3 > v_2 > v_1$. Corresponding to an increase in cutting speed, the angle $\psi$ also increases, which leads to a change in the direction of action of the total shear stress.

With an increase in the angle $\psi$ from $-\psi$ to $0$, the voltage $\tau_{\text{shear}}^{\text{sum}}$ will reach a critical value, and the vector $\tau_{\text{shear}}^{\text{sum}}$ will occupy a position parallel to the cutting speed vector. In figure 2 the critical position of the vector of the total shear stress, i.e. the position at which chip formation begins is indicated $\tau_{\text{shear}}^{\text{cr}}$. In this case (at $\psi = 0$) the angle $\varphi_{\text{fr}}^{\text{sum}}$ will become equal in absolute value to the front corner.

Consequently, the chips will begin to be removed at the moment when the angle $\psi = 0$, and the angle $\varphi_{\text{fr}}^{\text{sum}}$ becomes equal in absolute value to the front corner. Or, with variable $\gamma$ and constant $\varphi_{\text{fr}}^{\text{sum}}$, the chips will be removed provided that $\gamma$ is modulo equal to or smaller than the angle $\varphi_{\text{fr}}^{\text{sum}}$. We call this value of the angle $\gamma$ critical.

Given the above, we can write down the condition of chip formation relative to the rake angle

$$\gamma_{\text{cr}} = \varphi_{\text{fr,cr}}^{\text{sum}}$$

or

$$\gamma_{\text{cr}} = \varphi_{\text{fr,cr}}^{\text{sum}}$$

Figure 1. Static and dynamic loads acting on abrasive grain during cutting.
Figure 2. The design scheme for determining the angle of action of the total shear stress depending on the cutting speed.

Substituting the value $\tau_{\text{shear}}^{\text{sum}}$ into formula (2), we determine the critical value of the rake angle at which the transition from shearing to chip formation occurs

$$\gamma_{\text{cr}} = -\arctg \frac{\tau_{\text{shear}}^{\text{sum}}}{\sigma_{\text{st}}^{\text{str}}}$$

(2)

For given values of the factors included in the expression on the right side, chip formation is possible only if the rake angle $\gamma > \gamma_{\text{cr}}$. When $\gamma > \gamma_{\text{cr}}$ chip formation cannot occur. It can be seen from formula (3) that the critical value of the rake angle is influenced by the static and dynamic strength of the processed material, the coefficient of friction of the grain material over the material of the workpiece, the density of the processed material, and the cutting speed. Moreover, the cutting speed is included in the equation in the second degree, therefore, its influence is maximum.

On the right side of expression (3), all factors, except the cutting speed, are constant for a given pair: abrasive - processed material. The cutting speed may vary. Therefore, by changing the cutting speed, you can change the critical value of the rake angle. It also follows from (3) that with an increase in cutting speed, the absolute value of the critical value of the rake angle increases, i.e. at higher cutting speeds, the chips can be removed when cutting with large negative rake angles.

If the material is cut with an absolutely smooth cutter at an infinitely low cutting speed, then in the root-root expression of formula (3), the second and third terms will turn to zero. In this case $\gamma_{\text{cr}} = -\pi/4$ i.e. when exposed to the material with an absolutely smooth cutter with an infinitely low speed, the chip will be removed only at values of the rake angle $\gamma_{\text{cr}} > -\pi/4$.

Separating the cutting speed from equation (3), we can obtain the condition of chip formation relative to the cutting speed at negative rake angles.
Formula (4) can be simplified by reducing the numerator and denominator by $f \cdot \rho/2$. In this case we will get

$$v_{cr} = \sqrt{\frac{\frac{2\sigma_{str}}{\rho} - \frac{\rho f}{2} \sqrt{\left(\frac{\sigma_{str}}{\rho} \right)^2 - 4\left(-\frac{\rho f^2}{4} - \left(\sigma_{st}^2 + (\sigma_{str}^2)^2\right)\right)}}{\rho f}}$$

where $v_{cr}$ is critical cutting speed, which is the condition for the start of chip formation at a given value of the rake angle and other factors.

It should be noted that formula (5) is valid only for $\gamma < 0$. It can be seen from the formula that since $\tan|\gamma|$ enters the expression to the second degree and with a positive sign, the critical value of the cutting speed increases with decreasing $\gamma$ (with increasing $|\gamma|$). Increasing the density of the processed material leads to a drop in the critical cutting speed, since $\rho$ is in the denominator.

The critical section thickness depends on the rake angle. When cutting with ball-shaped grain, the rake angle is variable and depends on the radius of the grain and the penetration depth into the material. We define it based on geometric constructions, figure 3.

$$\sin \gamma = \frac{OB}{OL} = \frac{r-a_z}{r} = 1 - \frac{a_z}{r}$$

where $r$ — grain radius; $a_z$ — grain penetration depth.

$$\cos \gamma = \frac{BA}{OL} = \sqrt{\frac{2OL-a_z^2}{OL^2}}$$

**Figure 3.** The design scheme for determining the rake angle of an abrasive grain having the shape of a ball, depending on the depth of its introduction into the material.
\[
\cos\gamma = \sqrt{2 \frac{a_Z}{r} - \frac{a_Z^2}{r^2}} \tag{8}
\]

In view of (6) and (8), we can write

\[
\tan\gamma = \frac{\cos\gamma}{\sin\gamma} = \frac{1 - \frac{a_Z}{r}}{\sqrt{\frac{2a_Z}{r} - \frac{a_Z^2}{r^2}}} \tag{9}
\]

or

\[
\gamma = \arctan \frac{1 - \frac{a_Z}{r}}{\sqrt{\frac{2a_Z}{r} - \frac{a_Z^2}{r^2}}} \tag{10}
\]

Equating the first parts (2) and (10), we obtain

\[
\frac{\tau_{fr}}{\sigma_{str}} = \frac{1 - \frac{a_Z}{r}}{\sqrt{\frac{2a_Z}{r} - \frac{a_Z^2}{r^2}}} \tag{11}
\]

or

\[
\sqrt{\left(\sigma_{str}^2 + \left(\sigma_{din}^2 f + \frac{r f v^2}{2}\right)^2\right)} \left(\sigma_{str}^2\right)^{-1} = \frac{1 - \frac{a_Z}{r}}{\sqrt{\frac{2a_Z}{r} - \frac{a_Z^2}{r^2}}} \tag{12}
\]

Squaring both sides of equation (12), we obtain

\[
\left(\sigma_{str}^2\right)^2 + \left(\sigma_{din}^2 f + \frac{r f v^2}{2}\right)^2 \left(\sigma_{str}^2\right)^{-1} = 1 - 2 \frac{a_Z}{r} + \frac{a_Z^2}{r^2} \tag{13}
\]

or

\[
\left(\sigma_{str}^2\right)^2 + \left(\sigma_{din}^2 f + \frac{r f v^2}{2}\right)^2 \left(2 \frac{a_Z}{r} - \frac{a_Z^2}{r^2}\right) = \left(\sigma_{str}^2\right)^2 \cdot \left(1 - 2 \frac{a_Z}{r} + \frac{a_Z^2}{r^2}\right) \tag{14}
\]

Opening the brackets and equating to zero, we get

\[
\frac{2(\sigma_{str}^2)^2}{r} - \frac{(\sigma_{str}^2)^2 \cdot a_Z}{r^2} + \frac{(\sigma_{din}^2 f + \frac{r f v^2}{2})^2 \cdot a_Z}{r} + \frac{(\sigma_{str}^2 \cdot f + \frac{r f v^2}{2})^2 \cdot a_Z}{r^2} = 0 \tag{15}
\]

After multiplying the numerator and denominator by \(r^2\) and grouping the terms containing \(a_Z^2\) and \(a_Z\), (15) will take the form
\[ \left( \sigma_{\text{din}}^{\text{str}} \cdot f + \frac{\rho \cdot f \cdot v^2}{2} \right)^2 + 2(\sigma_{\text{st}}^{\text{str}})^2 \right) a_Z^2 - 2r \left( \sigma_{\text{din}}^{\text{str}} \cdot f + \frac{\rho \cdot f \cdot v^2}{2} \right)^2 + 2(\sigma_{\text{st}}^{\text{str}})^2 r^2 = 0 \quad (16) \]

We will introduce the notation

\[ m = \left( \sigma_{\text{din}}^{\text{str}} \cdot f + \frac{\rho \cdot f \cdot v^2}{2} \right)^2 + 2(\sigma_{\text{st}}^{\text{str}})^2 \quad (17) \]

In view of (17), we will have

\[ ma_Z^2 - 2rma_Z + (\sigma_{\text{st}}^{\text{str}})^2 r^2 = 0 \quad (18) \]

This is a quadratic equation with an argument \( a_Z \),

its roots

\[ a_{Z1,2} = \frac{2r \pm \sqrt{(-2rm)^2 - 4m(\sigma_{\text{st}}^{\text{str}})^2}}{2m} \quad (19) \]

or

\[ a_{Z1,2} = \frac{2r \pm \sqrt{4r^2m^2 - 4m^2(\sigma_{\text{st}}^{\text{str}})^2}}{2m} \quad (20) \]

Taking out the expression \( 2rm \) for the sign of the radical and reducing it with the denominator, we will obtain

\[ a_{Z1,2} = r \pm r \sqrt{1 - \left( \frac{\sigma_{\text{st}}^{\text{str}}}{m} \right)^2} \quad (21) \]

Substituting the value of \( m \) from (17) into (21) and taking into account the fact that when grinding the chips are always less than the radius of curvature of the grain top and the root with the sign (+) is insignificant, we will finally obtain

\[ a_{Z} = r - r \sqrt{1 - \left( \frac{\sigma_{\text{st}}^{\text{str}}}{m} \right)^2} \quad (22) \]

A similar expression can be reached in another way

\[ a_{Z} = r - r \sin |\gamma_{\text{cr}}| \quad (23) \]

Given that according to trigonometric dependencies

\[ \sin |\gamma_{\text{cr}}| = \frac{\theta_{\text{cr}}|\gamma_{\text{cr}}|}{\sqrt{(1 + \tan^2 \theta_{\text{cr}})}} \quad (24) \]

and bearing in mind (3), we will obtain
which, after appropriate transformations, will lead us to expression (22).

3. Results and Discussion

Thus, a dependence is obtained that allows one to determine to what depth an abrasive grain having the shape of a ball of radius $r$ must be embedded in order for it to start removing chips.

Physically, the quantity $a_z$ represents the thickness of the raised part of the material, not only when plunging, i.e. shatterless deformation, but also in the process of removing chips.

Analyzing formula (22), we can conclude that with an increase in cutting speed, density of the processed material and its friction coefficient over the grain material, the critical section thickness decreases, since the listed values are included in the denominator of the expression. The right-hand side of the root expression in this case tends to zero, the whole root-based expression tends to unity, therefore, $r$ also tends to zero.

If we take $r = 0$ in equation (22), which is a necessary and sufficient condition for absolutely sharp grain, then $a_{z,c}$ will also turn into zero. This means that in the presence of an absolutely sharp cutter, the condition for the existence or absence of chip formation does not depend on the depth of grain penetration into the material, and if chip formation is possible with the specified cutting conditions and geometric characteristics of the grain, it begins immediately after the contact of the absolutely sharp cutter with the material being processed. In this case (when cutting with absolutely sharp grain), the material is not lifted by the grain when it is introduced into the material, therefore, the cutting surface will be without contact damage.

However, even when cutting with an absolutely sharp cutter, chip formation is not always possible. The limiting condition in this case is the critical value of the rake angle, which depends on the cutting speed, density, static and dynamic strength of the processed material and its friction coefficient on the grain material. To determine the critical value of the rake angle, we derived formula (3).

Substituting numerical values into formulas (3) and (22), it is possible to construct graphical dependences of the critical values of the cut thickness and rake angle on the cutting speed, static and dynamic strength and density of the processed material, as well as its friction coefficient over the grain material. The critical thickness of the slice is mainly affected by the radius of curvature of the grain top. Formula (5), taking into account (9), makes it possible to evaluate the nature of the influence of the grain radius, the depth of its penetration into the material, the strength and density of the processed material, and its friction coefficient over the grain material on the critical cutting speed.

The value $v$ included in the above formulas is actually the rate of deformation of the material and it does not always coincide with the value of the cutting speed. Such a coincidence is observed only at the beginning of chip separation and only along the line of chip formation, because it can be shown that below the chip line, the deformation rate of the material is less than the cutting speed, and above this line the deformation rate is greater than the cutting speed, since here the chip descent is also vectorially summed with the last. Therefore, when calculating critical values, it is legitimate to substitute the cutting speed instead of the deformation rate, since in this case they coincide.

4. Conclusions

The obtained dependences for determining the critical values of the cutting speed, rake angle, and cut thickness are of important theoretical and practical value. They allow one to theoretically determine the conditions for the existence of chip formation, that is, to determine whether chip cutting is possible under the given conditions, or when grain is introduced into the material, only the latter will crumple.
and contact destruction of the surface layers during grinding of brittle surfaces will occur. Using the obtained dependencies, it is possible to determine in which direction and, which is especially important, to which value one or another factor of the cutting mode should be changed to ensure stable chip formation and reduce crushing of the processed material.

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