Investigation of cutting process and process of surface quality formation during machining of fragile components

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Abstract. This article presents the process of the material destruction and formation of roughness during the edge cutting machining of brittle materials. Also, this article presents the theoretical equations of macro-chips and micro-chips formation, as well as equations of relationship of processing conditions with the surface quality parameters, which allow providing the desired roughness of parts.

1. Introduction
One of the most urgent tasks of engineering production is to increase the efficiency of processing methods, which means to provide the required quality of parts at minimal cost. Graphite parts (inserts, bearings, electrodes, crucibles, etc.) are widely used in engineering production. A production process of brittle materials is different from that of other structural materials because of specific properties (low hardness, lack of plasticity, high brittleness, and porosity). Reference books do not contain data on possible edge cutting machining to provide perfection factors of the surface made of brittle materials and to reduce their production costs. That is why, it is very urgent to study the ways to increase the efficiency of edge cutting machining of brittle parts.

The aim of this paper is to provide the efficiency of parts made of brittle materials with minimum production costs during edge cutting machining.

2. Theoretical description of the chip formation process in cutting edge machining of brittle materials
The process of cutting brittle materials (graphite, glass, ceramics, etc.) compared to the cutting of plastic materials has a number of features due to their properties. This leads to the cyclical nature of chip formation, which is accompanied by the formation of macro-chipping (pulverized) and microchipping (fracture) (Figure 1). When we move the blade of the tool from position I, in which microchipping I was formed, towards the work piece cut layer of zone 2, there will be normal (σ) and shear loads (Figure 1b), the magnitude of which will increase up to σ material, which will inevitably lead to the contact destruction under compression with the formation of small dust-like shavings. This process will continue until the contact area on the blade front surface increases to a certain critical value, at which again there will be spall and microchipping formation (tool blade position II (Figure 1a)).
Having considered the treatment process (Figure 1) and making the assumption that a force acts on the material from the tool that causes shear and normal stresses, we obtain the following equation of forces acting on the cut layer:

\[ \tau \cdot b \cdot L_2 = \sigma \cdot b \cdot L_1, \]

where \( b \) is the width of the area, which is under the influence of shear stresses and normal stresses; \( L_1 \) is the length of the area, which is under the influence of normal compressive stresses; \( L_2 \) is the length of the area which is under the influence of shear stresses.

\[ L_2 = \frac{(a - H)}{\sin F}, \]

where \( a \) – the slice thickness; \( N \) – the value of the brittle fracture layer with a radius of rounding the cutting edge; \( f \) – conditional shear angle \( (F = \arctg \frac{\sigma}{\tau}). \)

If shear stresses exceed ultimate shearing strength \([\tau]\), it will spall; if not — it will be brittle fracture with the formation of dust-like chips due to exceeding temporary strength by normal stresses \( \sigma \).

Considering all mentioned above, we get the conditions of the chip formation when machining brittle blade materials:

\[ L_1 \leq \frac{[\tau](a - H)}{\sigma \sin F} - \text{the conditions for microchipping formation;} \]

\[ L_1 > \frac{[\tau](a - H)}{\sigma \sin F} - \text{the conditions for macrochipping formation.} \]

Defining the nature of chipping formation with processing blade, one can create a theoretical picture of roughness formation during edge cutting machining of brittle materials.

3. Theoretical description of the part surface quality formation made of brittle materials with a processing blade

When manufacturing parts, their quality is assessed by accuracy of dimensions and the quality of the surface layer. From the quality parameters set of the surface layer [1-4], only roughness parameters are standardized. Therefore, in many cases, the surface layer quality is estimated according to their size.

To predict the magnitude of high-rise roughness parameters is possible by the dependence [3]:

\[ R_z = h_1 + h_2 + h_3 + h_4, \]
where $h_1$ is a component of the surface roughness caused by the geometry of the working part of the tool (blade) and its working motion kinematics relative to the treated surface; $h_2$ is a component of the surface roughness caused by oscillatory movements of the tool relative to the treated surface; $h_3$ is a component of the surface roughness caused by plastic deformation of the workpiece material in the zone of contact with the working tool; $h_4$ is a component of the surface roughness caused by roughness of the working part of the tool.

However, this linear connection is valid for the plastic materials, during the processing of which the plastic edging of the material is possible by means of the auxiliary cutting edge [5, 6, 10].

And during processing of fragile materials the pattern of surface roughness formation will be different. Its formation (as well as during the machining of plastic materials) will be determined by the geometry and movement kinematics of working parts of the tool relative to the treated surface ($h_1$) by means of tool oscillations ($h_2$). However, the component $h_1$ is partially reduced due to the cut of the roughness tip during the shift of the material by means of the secondary cutting edge by value $h_3$ (Figure 2). It is natural that plastic edging of the material caused by its brittleness during the formation of roughness will not occur during the processing.

The roughness of the cutting edge at the top of the cutter will further increase formed roughness up to value $h_4=R_z$.

When processing by a multi-point tool such as a milling cutter, the runout of the teeth will affect formed roughness $h_5=\Delta\te$. Possible porosity of the material $h_6$ can also influence the roughness height in the machining process.

Thus, in the general case, the average height of the roughness profile will be determined by the equation with the blade machining brittle materials:

$$R_z = h_1 + h_2 - h_3 + h_4 + h_5 + h_6.$$

The roughness profile formation when processing single-lip cutters is presented in Figure 2. The dependence (1) for accuracy takes the following form:

$$R_z = h_1 + h_2 - h_3 + h_4 + h_6.$$

Components $h_1$, $h_2$ can be calculated according to known dependences [1, 2]. The formation of component $h_3$ will be influenced by compressive stress and shear stress. The equilibrium condition will be as follows:

$$\sigma \cdot b \cdot c = \sigma \cdot \sin \chi_1 \cdot c \cdot \l_{AB},$$

where $c$ is the width of the area, which is under the influence of compressive stress and shear stress; $b$ is the length of the area, which is under the influence of shear stress; $\l_{AB} = \rho \cdot F$ is the length of the area, which is under the influence of compressive stress, where $\rho$ is the radius of the cutting edge rounding, and $F$ is the phase angle; $\chi_1$ is the contact angle of the blade top with processed surface along the auxiliary cutting edge (Figure 2).

The following condition must be met in order to ensure the cut at the roughness tip:

$$b < \frac{\sigma}{\tau} \sin \chi_1 \cdot \rho \cdot F,$$

and this dependence must substitute the following values of $\chi_1$:

1) when $\varphi > \arcsin \frac{S}{2r}$ and $\varphi_1 > \arcsin \frac{S}{2r}$, $\chi_1 = \arcsin \frac{S}{2r}$;

2) when $\varphi > \arcsin \frac{S}{2r}$ and $\varphi_1 < \arcsin \frac{S}{2r}$, $\chi_1 = \varphi_1$ (auxiliary angle of the tool);

3) when $\varphi < \arcsin \frac{S}{2r}$ and $\varphi_1 < \arcsin \frac{S}{2r}$, $\chi_1 = \varphi_1$. 
Figure 2. The formation of the roughness profile with the blade machining brittle materials.

Correlation equations for \( b \) and \( h_3 \) values, which are the sides of the triangle chip ridge, can be obtained under the following processing conditions:

1) when \( \varphi \geq \arcsin \frac{S}{2r} \) and \( \varphi_1 \geq \arcsin \frac{S}{2r} \) (Figure 3a)

\[
h_3 = \frac{b \tan \chi}{2} \quad \left( \chi = \chi_1 = \arcsin \frac{S}{2r} \right),
\]

where \( \chi \) – the contact angle of the blade top with a machined surface on the main cutting edge;

2) when \( \varphi \geq \arcsin \frac{S}{2r} \) and \( \varphi_1 < \arcsin \frac{S}{2r} \) (Figure 3b)

\[
h_3 = \frac{b}{\frac{1}{\tan \chi_1} + \frac{1}{\tan \chi}} \quad \left( \chi_1 = \varphi_1, \chi = \arcsin \frac{S}{2r} \right);
\]

3) when \( \varphi < \arcsin \frac{S}{2r} \) and \( \varphi_1 < \arcsin \frac{S}{2r} \) (Figure 3c)

\[
h_3 = \frac{b}{\frac{1}{\tan \chi_1} + \frac{1}{\tan \chi}}, \quad \left( \chi_1 = \varphi_1, \chi = \varphi \right).
\]
Figure 3. The scheme for calculating the chip height ($h_3$) when forming a profile: 
a – by the radial part of the tool blade; b – by the radial part of the blade and support cutting edge of the tool; c – by the radial part of the blade, the main and auxiliary cutting edges of the tool.

The proposed model was tested in machining graphite (grade MG1) on the machine model ‘16K20’ by a cutter with brazed plate WK8. Given that the magnitude of cutting force fluctuation $\Delta P_y$ in processing graphite is much less than in processing structural steel, we can neglect this value, thus, $h_2=0$. Thus, equation (2) in case of turning graphite will be as follows:

$$R_z = h_1 - h_3 + h_4 + h_6.$$

4. Conclusion

Taken surface profilograms confirm the roughness formation picture (Figure 4), so the derived dependence can be used to predict the cutting process and to define high-rise parameters of roughness parts made of brittle materials [5, 7-9]. The purpose of the processing modes by the proposed dependencies will improve the performance and reduce the cost of manufacturing parts due to the absence of test moves and reducing the number of defective parts.
Figure 4. The surface profilograms treated by machining (top radius $r = 0.4$ mm, cutting depth $t = 1$ mm, cutting speed $V = 200$ m/min, feed $s_0 = 0.7$ mm/rev, angles $\varphi = \varphi_1 = 45^\circ$).

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