Calculation of power and energy indicators of the process of materials rapture during their processing with the help of an inertial tool with a curved cutting rim

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Abstract. The article presents the research which reveals the analytical dependences for the determination of the strength and energy characteristics of the process of materials rupture during their processing with an inertial tool with a curved cutting surface. The research was performed on the basis of the laws of classical mechanics, as well as existing models of the destruction of brittle materials. The revealed dependencies reflect the interrelation of power and energy indicators of the instrument and its structural and technological parameters of work, as well as the mechanical characteristics of processed material. According to the results of a brief comparative analysis of the values of power of processing, obtained from the analytical dependence and the results of a trial experiment, the assessment of the applicability and further improvement of the obtained analytical dependencies was made.

1. Introduction
Rupture during the processing of various non-metallic materials with predominantly brittle properties, such as glass, stone, graphite, and ceramics [1-3], finds its place in mechanical engineering as well as in other industries. Thus, for example, in heat – power engineering, mechanical treatment of the internal surface of pipes of heat exchangers is widespread. The purpose of this type of treatment is rupture and removing scale deposits from heat exchange surfaces of pipes, which leads to the provision of the performance requirements of power equipment [4-6].

During the implementation of this technology, the inertial cutting tool (Figure 1) has found wide application. Important advantages of this tool are the possibility of inertial opening of working elements, which makes it possible to use it for a fairly wide range of diameters of heat exchange pipes [7].
However, the lack of methods for calculating the main power and energy indicators of tools and equipment does not allow the possibility of calculating the technological processing modes that are currently assigned according to practical processing experience, which significantly reduces technological effectiveness of the process and also complicates the design of tools and equipment.

Obviously, the decisive energy characteristics of this process are the loads influencing a tool during processing, as well as the power developed by a drive.

The application of the laws of classical mechanics and the usage of the features of the destruction of materials with brittle properties is the solution to this problem. This approach is reasoned by the fact that scale deposits on heat exchange pipes are presented by carbonate compounds of high hardness.

2. Methods and materials

In accordance with the basic mechanical laws, the power spent during the processing can be represented as

\[ N = M_\Sigma \cdot \omega, \]

where \( M_\Sigma \) – total moment of resistance forces applied to a tool, \( \omega \) – rotational speed of a tool.

During the operating stroke of a tool, each cutting plate removes a certain amount of material. In this case, the front surface of a plate is affected by the resistance force from the side of removed material, and the friction force acts on the back surface. In this regard, the value \( M_\Sigma \) can be represented as

\[ M_\Sigma = M_{fc} + M_{fr}, \]

where \( M_{fc} \) – the moment of force that causes the destruction (chipping) of material, \( M_{fr} \) – the moment of force necessary to overcome the friction forces of the working element on the surface of a deposit.

In turn, the moments of \( M_{fc} \) and \( M_{fr} \) are determined by the values of the corresponding forces of resistance to the cleavage of material deposits \( R_c \), and friction on the rear surface of the cutting plate \( F_{fr} \) (Figure 2a).

**Figure 1.** Inertial tool with curved cutting rim.

**Figure 2.** To the calculation of power parameters: a – scheme of active loads acting on a tool; b – a diagram for determining the pressing force of a working item.

Let us determine the force of resistance to a chip \( R_c \). For this purpose we consider a certain amount of material deposition at the time preceding its cleavage.
The results of the research [4] show that during the process of chipping of a material with predominantly brittle properties, it shifts at an angle $\theta$ to the surface of the applied load. Considering that we divide the cross-sectional area of the removed material $S$ into a certain number of surfaces $S_i$ (figure 3, a), then the chipping amount of material is also divided into the corresponding number of volumes (figure 3, b).

![Figure 3](image)

**Figure 3.** To the calculation of the cleavage effort: a – splitting the section into elementary surfaces; b – diagram for the determination of the elementary force of chipping resistance.

Let us assume that the force affecting the normal force on the side of the cutting plate $R_{pi}$ act on each volume. Then the shift of each element of the volume occurs at an angle $\theta$ to the surface drawn tangentially to the end of the plate, parallel to the force of $R_{pi}$.

In the shift surface, a resistance force acts, which can be defined as

$$R_{pi} = \tau_c \cdot S_u,$$

where $\tau_c$ – the value of critical tangential stresses, at which a shift element of the deposition occurs, $S_u$ is the shift area, which in turn can be expressed in terms of the element geometry (Figure 3b):

$$S_u = \frac{S_i}{\cos(90 - \theta)}.$$  \hfill (4)

Taking into account the scheme presented in Figure 3b, the equation of balance of the I-element in the projection on the direction of the shift has the following form

$$R_{pi} \cdot \cos \theta - R_{ri} = 0.$$  \hfill (5)

Then, taking into account (3) and (4), the value $R_{pi}$ (5) can be expressed as

$$R_{pi} = \frac{\tau_c \cdot S_i}{\cos(90 - \theta) \cdot \cos \theta}.$$

Considering that the product of $R_{pi} \cdot r_i$, where $r_i$ is the distance from the axis of rotation of a tool to the i-volume of material, gives the value of the elementary moment $M_{fci}$ developed by the tool when the material is removed, we express the value of $M_{fc}$, taking into account the number of working elements $n_{wc}$ as

$$M_{fc} = n_{wc} \sum M_{fci} = n_{wc} \sum \frac{\tau_c \cdot S_i \cdot r_i}{\cos(90 - \theta) \cdot \cos \theta}.$$  \hfill (6)

The value $\sum S_i \cdot r_i$ in work (6) is the value of the static moment of the cross-sectional area of the removed layer $S$ relative to the axis of rotation and therefore, it can be represented as:

$$\sum \tau_c \cdot S_i \cdot r_i = \tau_c \sum S_i \cdot r_i = \tau_c \cdot S \cdot (R_{in} - t / 2),$$

(7)

where $R_{in}$ is the internal radius of the pipe, $(R_{in} - t / 2)$ is the distance from the center of section mass of the layer of material to be removed to the axis of rotation of a tool. Considering that the cross-sectional area $S$ of the removed layer does not depend on the blade shape and is defined as the product of the thickness of the removed layer $t$ and the feed to the working element in one turnover $S = S_o \cdot t / n_{wc}$, let us rewrite expression (6), in the form (7)

$$M_{fc} = \frac{\tau_c \cdot S_o \cdot t \cdot (R_{in} - t / 2)}{\cos(90 - \theta) \cdot \cos \theta}.$$  \hfill (8)
where $S_0$ is the tool feed per one turnover.

Let us determine the friction force $F_{fr}$ on the back surface of the plate. From the course of classical mechanics it is known that the friction force is determined by $F_{fr} = f \cdot N_p$, where $f$ is the coefficient of friction, $N_p$ - the reaction force of the surface, which in its turn depends on the force of pressing the working element of the tool to the surface.

Taking into account that the operation of the tool occurs at a sufficiently high angular velocity ($n = 2000 \ldots 2500$ turnover per minute), it can be assumed that the pressing force of the working element to the surface is determined mainly by the normal inertial force $F_n$.

Then using the principle of Jean le Rond d’Alembert, and taking into account the power scheme presented on figure 2, b, we make the equation of the moments of forces relative to the axis of attachment of the working element:

$$M_N + M_F = N_p \cdot l_p - m \cdot \omega^2 \cdot R_c \cdot l_c = 0,$$

where $M_N$, $M_F$ are the moments of force $N_p$ and the normal inertial force $F_n = m \cdot \omega^2 \cdot R_c$ relative to the point O, $m$ is the mass of the working element of the tool, $l_c, l_p, R_c$, are geometric parameters that can be determined by measuring, for example, if we have a graphical model of the tool (Fig. 2, b).

Expressing with the help of equation (9) $N_p$, and taking into account the number of working elements $n_{pe}$ and the radius of application of the load $R_m$, we obtain the dependence for $M_f$ in the form

$$M_f = f \cdot N_p \cdot R_m \cdot n_{pe} = \frac{f \cdot m \cdot \omega^2 \cdot R \cdot l}{l_p} \cdot R_m \cdot n_{we}.$$

Substituting (8) and (10) in (1), we obtain equation for determining the power spent on processing:

$$N = \frac{r \cdot S_0 \cdot \omega \cdot (R_m - t/2) \cdot \omega}{\cos(90^\circ - \theta) \cdot \cos \theta} + \frac{f \cdot m \cdot \omega^3 \cdot R \cdot l}{l_p} \cdot R_m \cdot n_{we}.$$

In order to analyze the results, the cutting power was calculated using the obtained analytical dependence, which was subsequently compared with the measured power value obtained during the verification experiment.

The object of the experiment was presented by the inertial tool shown on the figure 1. As a tool drive, an asynchronous electric motor with a power of 1.5 kW and the efficiency of (η) of 78.5% and a nominal frequency of 2850 t/m was used. The registration of power consumption, as well as the speed of rotation of the tool drive was carried out with the help of DELTA frequency converter VFD-037E of 3.7 kW, with the ability to control the output current frequency in the range from 0 to 50 Hz. In the course of the experiment, a pipe was processed with an internal diameter of 52 mm, with a material thickness of 4 mm.

3. Results and discussion
The results of the calculations of the main power consumed by the drive in expression (11) and obtained as a result of a verification experiment, as well as the calculation of criteria for comparative evaluation of the results are shown in Table 1.

A relative error determined by the expression was used as a criterion for the compliance of the calculated and experimental data

$$\delta_N = \frac{|N_{calc} - N_e|}{N_e} \cdot 100\%,$$

where $N_{calc}$ is the calculated value of the processing power according to (11); $N_e$ is the power value obtained during the experiment.
Table 1. Comparative results of the determination of processing power

| Values                     | The value of processing power, kW; | The discrepancy between the calculated and experimental results |
|----------------------------|-------------------------------------|---------------------------------------------------------------|
| $\omega = 261.7 \text{ s}^{-1}$ | $\eta = 0.785$                     | Analytical                                                  |
| $S_0 = 0.2 \text{ mm/t}$     | $R_{in} = 26 \text{ mm}$            | Experimental                                               |
| $m = 0.03 \text{ kg}$        | $t = 4 \text{ mm}$                 | $|\Delta|$                                                 |
| $l_c = 27 \text{ mm}$        | $\tau_c = 2 \text{ MPa}$           | $\%$                                                       |
| $l_p = 18 \text{ mm}$        | $f = 0.4$                           |                                                             |
| $R_c = 21 \text{ mm}$        | $\theta = 25$                      |                                                             |
|                            |                                     | 0.773                                                      |
|                            |                                     | 0.85                                                       |
|                            |                                     | 0.077                                                      |
|                            |                                     | 9.06                                                       |

The data presented in table 1 shows the discrepancy between the amount of processing power calculated using the equitation (11) and the resulting experiment 9.06%, which shows a fairly good agreement of the results.

4. Conclusion
In conclusion, it is necessary to note that analytical equitation obtained in this work for the determination of the power and energy parameters characterizing the materials rupture during the processing can be used in calculating the mechanical modes of materials with predominantly brittle properties, and can also find application in the design of tools and equipment.

A further stage of work will be presented by the conduct of full-scale experimental studies aimed at obtaining a greater amount of experimental data, which will later be used to clarify the theoretical positions obtained, as well as to increase the efficiency of the mechanical process.

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