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MECHANICS

Energy Aspects of Ultrasonic Intensification of Treatment of Metals

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The process of vibratory treatment of materials is investigated. The experiments on turning metals with application of ultrasonic vibrations on the cutter are simulated. To interpret the experimental dependences, the energy approach is used. An analytical solution that qualitatively agrees with the experiments is obtained.

1. Vibratory cutting of metals has been used in practice for a rather long time. Compared with conventional methods of treatment, cutting with application of ultrasound vibrations on a cutter has a series of advantages. During vibratory turning, the average force of pressure on a cutter decreases, the quality of the treated surface considerably increases, the roughness considerably decreases, and corrosion stability increases [1]. However, as the velocity of treatment (or supply of the material) increases, the difference between the vibratory and usual treatment decreases, and upon exceeding a certain critical rate, it disappears completely.

The approaches to these experimentally observed features can be conventionally separated into two types. In some works, for example [2], the drop in the average cutting force under application of ultrasonic vibrations on a cutter is associated with the appearance of resonance. However, it is unclear what just is the vibratory process with which the ultrasonic vibrations enter into the resonance. In addition, knowledge of the resonant frequency does not allow us to make any quantitative evaluations of the cutting forces in the process of the resonance. In the context of this approach, it is rather difficult to obtain the rate dependence of the cutting force during the vibratory cutting. The features of vibratory cutting are also explained via finite-element simulation [3, 4]. As usual, in these models, incorporation of the cutter into a plastic material with a previously specified propagation rate is considered; i.e., the process of rigid loading of the material, in the course of which the stress field in the sample and the force on the cutter tip are determined, is considered. When comparing the results of simulation of processes of vibratory and conventional treatment, it is possible to show a considerable decrease in the cutting force. Since the applied vibrations are in the kilohertz range, the deformation rate in the material is rather large; therefore, complex rheological models of plastic deformation with a large number of parameters are necessary.

In this work, the effects appearing during vibratory cutting are interpreted from the viewpoint of the dynamic mechanics of the fracture. Upon the application of ultrasonic vibrations on a cutter, the duration of the active phase of the effect on the treated material changes significantly. In [5], it was shown that the energy necessary to induce the threshold destructing pulse in the material strongly depends on its duration, and a characteristic minimum was observed for this dependence. Therefore, the presence of energetically profitable durations of the dynamic effect was found. This circumstance was revealed with the use of the criterion of the incubation time, which predicts well the material strength in a wide range of the effect durations. This allows us to apply it in the calculation of both static and dynamic threshold strength characteristics. Based on the above reasons, we can assume that the application of ultrasonic vibrations provides energetic optimization of the fracture effect. The energy consumption to the fracture of the material considerably decreases, which leads to a considerable decrease in the pressure force on the cutter. In addition, the supply of energy minimally necessary for the fracture provides the absence of undesired side effects, namely, excess heating and large plastic deformations of the cutting region, which provides for low roughness of the treated surface and, consequently, increased corrosion stability.

2. To interpret the decrease of the cutting force during vibratory turning, let us consider a single cycle

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of vibrations of a cutter, during which the cutter moves for a certain characteristic distance inside the treated metal. In [5], the dependence of the energy necessary to induce the threshold disturbing pulse on its duration was obtained:

$$\varepsilon = \alpha \frac{t_0^3 \sigma_{max}^{13/2}}{\rho^{3/2} E^4}, \tag{1}$$

where $a = \frac{2}{3}\frac{\pi^2}{(2.94)^3}\left(\frac{5(1-\nu^2)}{4}\right)^4\left(\frac{6}{5(1-2\nu)}\right)^{13/2}$ is a dimensionless coefficient, t_0 and σ_{max} are the duration and threshold amplitude of the disturbing pulse, ν and E are the elastic constants of the medium, and parameter ρ depends on the cutting depth (shaving thickness). When obtaining this dependence, we considered the Hertz problem on the contact interaction of a spherical particle with the surrounding medium as a way of supplying energy in the material. The experiments show that the effects appearing in the course of vibratory cutting are virtually independent of the geometry of the cutter tip [1]. Therefore, we can consider that the method of supplying the energy into the fracture region is not of basic value.

Let us consider that the cutting force consists of two components, namely, a certain constant force necessary for moving the cutter, and the dynamic component, the work of which on the fracture equals the energy consumed to induce the disturbing pulse. We can assume that this process of getting the fracture is commensurable with the amplitude of ultrasonic vibrations. Thus, the force on the cutter is calculated by the following formula:

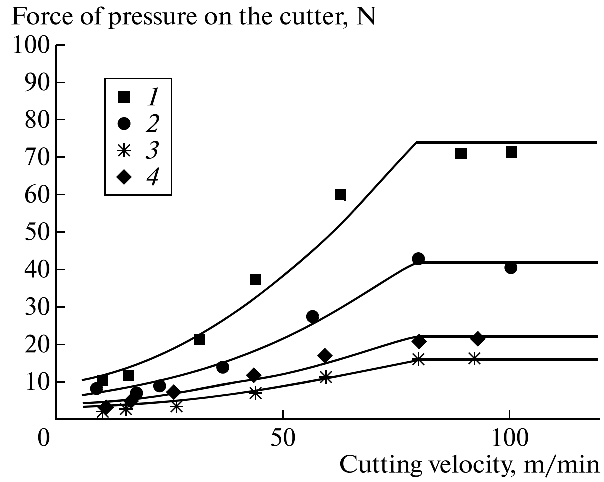
$$F = \frac{\varepsilon}{\lambda} + F_0, \tag{2}$$

where λ is the amplitude of vibrations and F_0 is the constant component.

As the velocity of the supply of the material increases, the time of contact of the cutter with the sample increases and, correspondingly, the duration of the effect increases. Consequently, as a certain critical velocity ω_c is attained, the duration of the disturbing pulse achieves a certain value t_0^*, upon exceeding which, the material perceives the load as quasi-static. Therefore, at velocities exceeding the critical one, the behavior of the material is the same as during the usual treatment. To describe the dependence of the disturbing pulse on the velocity of supply of the material at velocities lower than the critical one, we can use the linear dependence

$$t_0 = \frac{1}{2\nu} + \frac{\omega}{\omega_c}\left(t_0^* - \frac{1}{2\nu}\right). \tag{3}$$

Using the dependence of energy on duration (1) and expressions (2) and (3), let us construct the plot of the dependence of the cutting force on the velocity of treatment of the metal (Fig. 1).



Dependence of cutting force on the treatment velocity during vibratory cutting of aluminum; $\upsilon = 20$ kHz, $\lambda = 10$ μm, and $F_0 = 3$ N. Cutting depth is (*1*) 0.10, (*2*) 0.06, (*3*) 0.03, and (*4*) 0.02 mm (points correspond to experimental data of Kumabe [1], and solid lines are the calculated curves).

3. Using the methods of dynamic mechanics of the fracture, we were able to qualitatively explain the behavior of the cutting force during the vibratory treatment of materials. Applying the criterion of the incubation time, we were able to show the most energetically favorable modes of fracture of metals, which are determined by the time characteristics of the process of fracture of this material. The existence of energetically optimal durations of the threshold pulsed effect allows us to explain the considerable drop of the cutting force in the case of the vibratory treatment of metals as well as its dependence on the supply velocity of the material.

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