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FEATURES OF VIBRATION DAMPERS APPLICATION IN THE DESIGN OF VIBRATION-RESISTANT METAL CUTTING TOOLS

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Abstract. Dry and viscous friction is used as a damper of oscillation energy in the construction of metal-cutting tools. A mathematical model of a two-mass oscillatory scheme of the insert of an assembled milling cutter was developed and studied, one of the masses of which models the clamped part of the insert - a press connection with dry friction, and the other – the cantilever part, which is subject to self-oscillations that are possible in the process of metal cutting. The influence of dry friction in the press joint of the insert on the amplitude of resonant oscillations of the cutter and the part was analyzed. The possibility of reducing the magnitude of the cutter's self-oscillations is demonstrated by selecting the most suitable parameters for the press connection of inserts with the body of the assembled milling cutter. The influence of internal viscous friction in materials with a high level of energy damping on the amplitude of self-oscillations of the cutter was evaluated and the possibility of their use in the design of a vibration-resistant metal-cutting tool was considered.

Key words: self-oscillation; damping of vibration energy; structural damping; vibration amplitude; surface quality.

Introduction

Corrosion-resistant and heat-resistant steels and alloys are widely used in modern mechanical engineering, instrumentation, and shipbuilding, especially in aircraft and rocketry, as well as in chemical and energy engineering, along with polymer composite materials. The cutting process has more intense vibrations than the machining process for carbon and low-alloy structural steels under the same conditions, resulting in a decrease in the surface quality of the parts.

Problem statement

A characteristic feature of the cutting process of difficult-to-machine alloys is the tendency of the elastic technological system to intense vibrations. In the case of heat-resistant titanium alloys, this is primarily explained by the high values of the normal cutting force relative to the tangential. This is due to the low plasticity and high friction coefficients of titanium alloys. Additionally, the sharply pronounced chip element, which increases with the increase of the cut cross-section and cutting speed, as well as unstable chip buildup and seizure, serve as an additional source of excitation of parametric and forced vibrations. In the case of cutting corrosion-resistant and heat-resistant alloys, intense self-excited vibrations of technological systems occur. This is explained by both the large cutting forces and the high values of the chip shrinkage coefficient. This leads to an increase in the phase characteristic of the cutting force (lagging behind critical values) and, consequently, a sharp increase in the amplitude of self-excited vibrations.

The oscillations that occur in metal cutting machines during the processing of these materials significantly complicate the process of obtaining a quality surface of the part and reduce the stability of the tools.

Review of modern information sources on the subject of the paper

One of the main and effective methods of reducing the amplitude of forced and parametric oscillations of technological systems is to move away from resonance. The chip elementality and the chip formation process itself in the case of machining titanium alloys has a pronounced frequency component. Therefore, cutting modes are preferably chosen where possible [1]. If the use of such cutting modes is not possible, damping phenomena in the MFTW (Machine-Fixture-Tool-Workpiece) system are utilized to reduce vibration amplitudes, which can also yield positive effects, as they occur near resonance.

In the case of self-excited vibrations occurring at the resonant frequency of the cutter and workpiece, damping is the only effective method to combat this phenomenon. Damping can be active or passive. Damping should be introduced into the element of the MFTW system with the smallest mass [2]. That is, if the mass of the cutter is less than that of the workpiece, damping of cutter vibrations is necessary. One of the effective dampers of such vibrations is the hysteresis of MFTW system elements. Hysteresis can be either structural [2], occurring in stationary connections of technological system mechanisms, or internal, arising in materials with a high level of energy dissipation of vibrations [3].

Active dampers are more effective. Their action is based on the creation of an out-of-phase force to vibrations using various sources of vibrations [4]. Vibration sources can be electrical, hydraulic, and pneumatic transducers [5].

The control system of an active damper allows changing the frequency of the out-of-phase force within a fairly wide range, which can significantly expand the scope of these devices, but the use of this type of damper is limited by their excessive complexity, high cost, and increased power consumption.

Objectives and problems of research

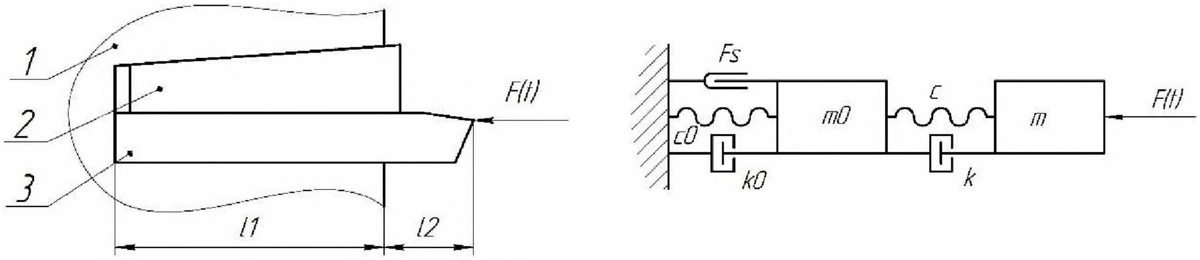
This paper considers a method for determining the damping capacity of a cutting tool – an assembled cutter insert – during its resonant oscillations and determines the limits of optimal values of the friction force in the press connection of the insert for effective damping of self-excited oscillations of the MFTW system. A promising direction of reducing the amplitudes of self-excited vibrations of the MFTW technological system, i. e., energy damping based on the use of materials with a high level of dissipation of internal energy of vibrations, is also presented.

Main material presentation

As seen in Fig. 1, *a*, insert 3 is installed in the slot of cutter 1 and secured by press connection with wedge 2. In most cases, the knives themselves are designed in the form of a wedge, however, such a structural scheme is more complex for calculations (asymmetric), therefore, we will consider a simpler scheme, as all subsequent conclusions will be valid for more complex mounting schemes as well.

As known [2], during the loading of the press connection with axial force, the deformation caused by this force will spread to a certain extent, which will be proportional to the ratio of this force to the friction force of the press connection. And if these forces are equal, then there will be a displacement of the part in the connection. In this case, part displacement will be impossible because the rear end of the insert abuts against the end of the slot in the cutter body. However, the friction force will act along the entire length of the press connection. If the magnitude of the axial force is less than the friction force, then the deformation zone will be correspondingly smaller, and the work of the friction force will also be smaller.

It is possible (and advisable) to calculate the damping in such a connection using the finite element method with moving boundaries since the size of the deformation zone will determine the stiffness and moving mass of the insert. However, this method, unfortunately, has not yet been implemented in programs such as MATLAB or SolidWorks, so its use requires serious professional qualifications in this area of theoretical research. The second disadvantage of this method is that mathematical modeling of self-oscillations of a metal-cutting machine is possible only in a discrete model, and the use of a continuum model in a discrete model is impossible.



a *b*

Fig. 1. Design (a) and calculation (b) diagrams of the press connection

To solve this problem, an attempt is made to describe the constructive scheme shown in Fig. 1, *a* by the system of differential equations (1), the calculation scheme of which is shown in Fig. 1, *b*.

As can be seen from the design scheme, the mass of the insert is conditionally replaced by two reduced masses m and m_0, and the stiffness is replaced by two stiffnesses c and c_0. Moreover, the mass of the insert cantilever m is affected only by the damper of viscous internal friction in its material, and the mass of the clamped part of the insert is also affected by the friction force.

$$\begin{aligned}
&\frac{d^2x}{dt^2}m - c(x - x_0) - k\left(\frac{dx}{dt} - \frac{dx_0}{dt}\right) + F(t) = 0\\
&\frac{d^2x_0}{dt^2}m_0 + c(x - x_0) + k\left(\frac{dx}{dt} - \frac{dx_0}{dt}\right) - cx_0 - k_0\left(\frac{dx_0}{dt}\right) - F_s = 0
\end{aligned} \qquad (1)$$

We will calculate the mathematical model for the case when the excitation force $F(t)$=0, and the initial value of the coordinate $x=1\times10^{-6}$ m, which, in combination with the stiffness of the cantilever part of the insert, will create an initial stiffness force of 2100 N (kinematic excitation of insert oscillations due to its interaction with a solid inclusion of 1 μm). The stiffness and reduced mass of the clamped part of the insert in this model depend on the ratio of stiffness and friction forces.

For the convenience of assessing the effect of dry friction on vibration damping, we exclude the influence of viscous dampers, i. e., k_0=k=0.

As is well known, the frequency of damped oscillations is close to the frequency of the system's natural oscillations, so we will evaluate the damping for damped oscillations excited by the initial condition.

The damping of damped oscillations will be determined by the value of the logarithmic decrement of the dampings, which is determined by the formula

$$\delta_i = \ln\frac{A_n}{A_{n+1}}, \qquad (2)$$

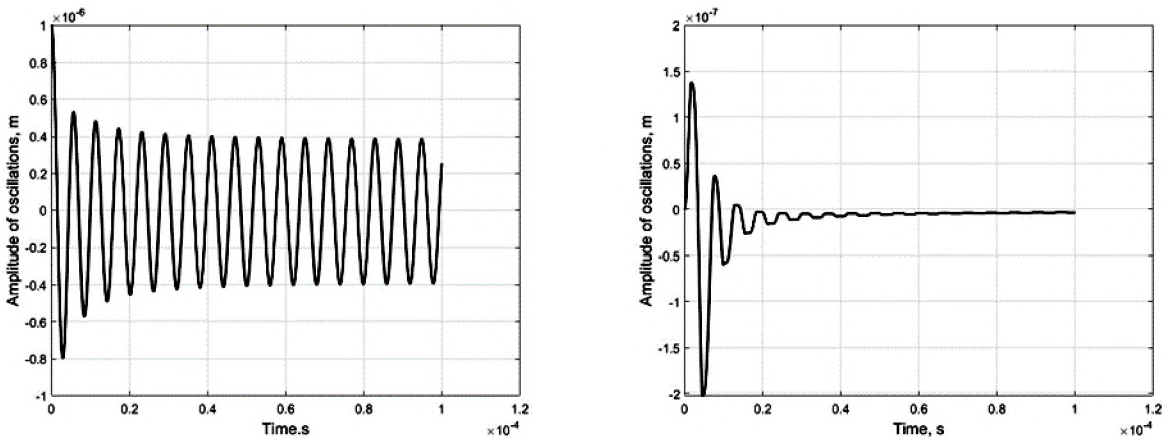
where A_n is the amplitude of the nth period of oscillations; A_{n+1} – the amplitude of the next period.

The results of the mathematical modeling performed in this way, for the case when the friction force is 800 N, are shown in Fig. 2–4.

In Fig. 2, *a* shows the amplitude of oscillations of the cantilever mass of the insert of the cutter, and Fig. 2, *b* shows the amplitude of oscillations of its clamped mass (time scans).

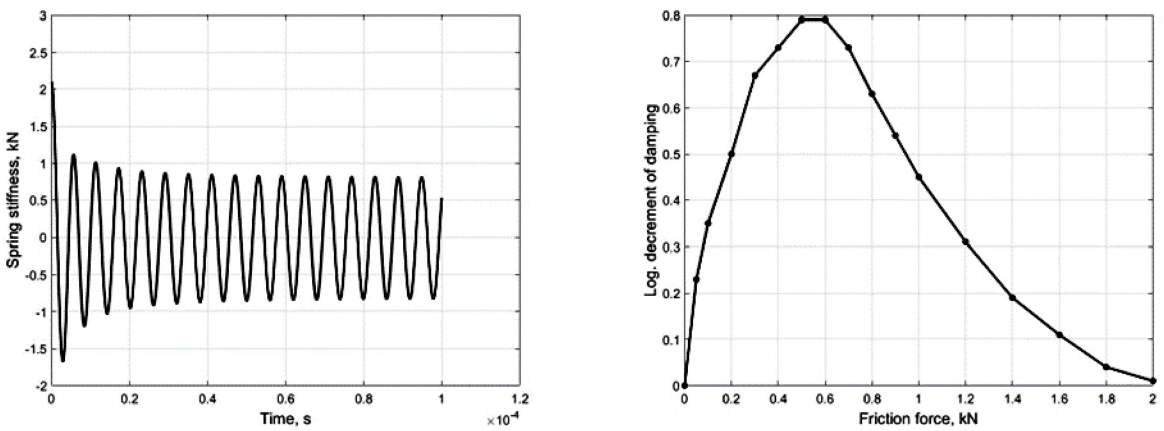
The analysis of these figures shows that the vibrations of the cantilever mass (part) of the insert dampen only up to a certain value, namely, as long as there are displacements (vibrations) in the clamped part of the insert. The absence of damping in Fig. 2, *a* is due to the absence of displacements in Fig. 2, *b*.

If we analyze the relationship between the damping of oscillations of the cantilever part of the insert and the force of its stiffness, i. e., the force of interaction between the cantilever part of the insert and the clamped part (Fig. 3, *a*), it becomes obvious that the ratio of stiffness and friction forces influences the presence of displacements. In this case, the value of the friction force in the clamped part of the insert is 800 N and, as can be seen from Fig. 2, *b*, displacements in the clamped part of the insert are observed only when the value of the elastic force is greater than 800 N.



a *b*

Fig. 2. Oscillations of the cantilever (a) and clamped (b) parts of the cutter



a *b*

Fig. 3. Effect of the stiffness force on the clamped part of the cutter insert (a), and the logarithmic coefficient of vibration damping (b)

Since the work of the friction force is the product of this force on the displacement in the clamped part of the milling cutter insert, and we cannot directly control the value of this displacement, let us analyze the influence of the friction force in the clamped part of the milling cutter insert on the damping of the oscillations of the cantilevered part.

Fig. 3, *b* shows the dependence of the logarithmic decrement of oscillations on the value of the friction force in the press connection of the insert of the milling cutter. The logarithmic decrement of damping was determined from the graphical dependence (Fig. 2, *a*) according to the formula (2), which was plotted for different values of the friction force in the press connection of the cantilevered part of the insert. Since the values of the decrement of damping for each period of oscillations were different (decreasing), the value of the first period was taken as the basis. As seen from the figure, this dependence has a pronounced optimum, which qualitatively coincides with [2].

Therefore, the optimal value of the contact pressure in the press connection of the inserts of the assembled milling cutter can significantly reduce the amplitude of self-oscillations of the MFTW system, and the proposed computational scheme, the essence of which lies in replacing a single-mass scheme with a two-mass scheme, adequately describes the oscillations of the inserts and can be used in mathematical modeling of self-oscillations vibrations in metal cutting machines.

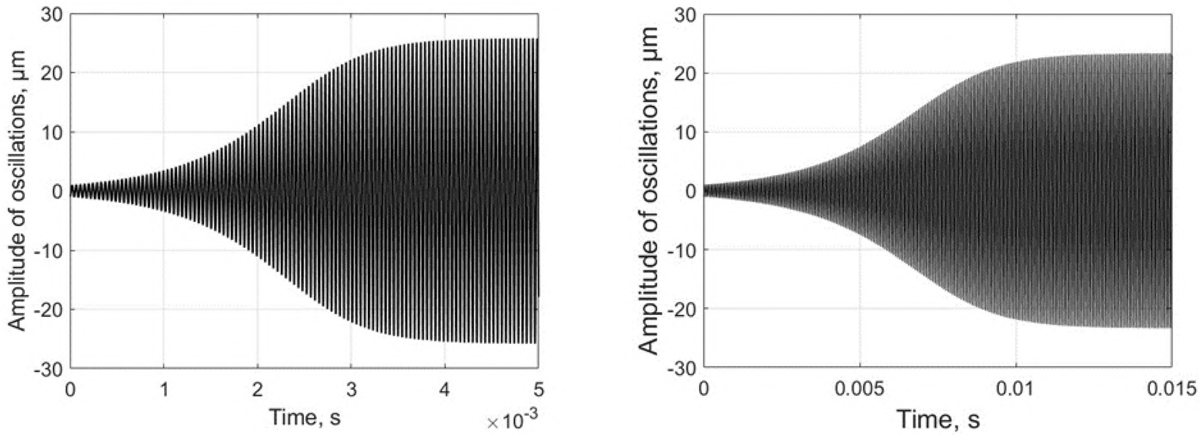
The use of a tool with increased internal dissipative properties also makes it possible to reduce the amplitude of self-oscillations in the machine tool technological system that occur during the cutting of difficult-to-machine steels and alloys.

In this regard, the direction of creating universal holders for cutters with the mechanical fastening of polyhedral inserts that can be made of high-damping alloys [3], which are widely used in industry for the manufacture of housing parts of diesel internal combustion engines, frame support structures, elastic supports for precision machine tools, gears, steam and gas turbine edges to reduce their acoustic and vibration activity, as well as increase fatigue strength, is promising.

However, it is also determined by other equally important properties, namely stiffness (modulus of elasticity of the material) and resistance of damping parameters to temperature.

First and foremost, we should mention the manganese alloy NES 780, which contains 75 % manganese and 25 % copper and is industrial. The reason for the high energy damping in this group of alloys is structural defects. The logarithmic attenuation coefficient of the alloy δ is 0.15 at a strain amplitude of $\gamma = 0.75\times10^{-3}$ and $\delta = 0.075$ at $\gamma = 0.05\times10^{-3}$. For comparison, the logarithmic attenuation coefficient of steel 45 is in the range of 0.006 to 0.009, which is less than an order of magnitude. However, the modulus of elasticity of this alloy is 2 to 2.5 times lower than that of steel, which significantly affects the rigidity of the cutter. As for the strength, it is approximately in the same range as non-hardened steel 45. The relative elongation is even better (18–25 % of the alloy versus 14–16 % of steel).

Theoretical studies of the vibration resistance of cutter holders made of steel 45 and Alloy NES 780 were carried out on the mathematical model of self-oscillations of the MFTW system [3], and the results of the studies are presented in Fig. 4.



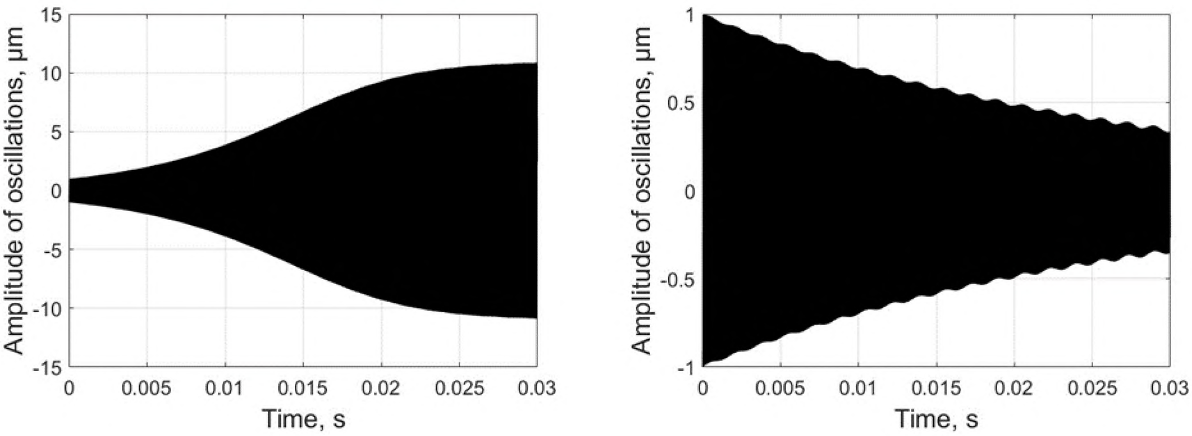
a *b*

Fig. 4. Results of theoretical studies: *a* – δ=0.01, E=2×10^{11} Pa; *b* – δ=0.075, E=0.8×10^{11} Pa

Fig. 4, *a* shows the time scan of self-oscillations of a cutter whose holder is made of steel 45, and Fig. 4, *b* is the same, but the material of the holder is alloy NES 780. As can be seen from the comparison of the results, an almost eightfold increase in the damping of vibration energy did not give positive results; on the contrary, the amplitude of self-oscillations of the cutter with a holder made of alloy NES 780 is 10 % lower. The reason for this is a 2.5-fold decrease in the elastic modulus, i. e., the stiffness of the cutter, which led to a decrease in the vibration frequency from 22.6 kHz to 14.3 kHz. A further increase in stiffness leads to an increase in frequency and a decrease in the amplitude of self-oscillations. Thus, with a 1.5-

fold increase in stiffness (Fig. 5, *a*), the amplitude of self-oscillations decreases to 11 μm, and with a further increase in the cutter stiffness (similar to E=1.,6×10^{11} Pa, Fig. 5, *b*), self-oscillations disappear completely.

Of course, in practice, we cannot increase the stiffness by changing the modulus of elasticity, but only by increasing the moment of inertia of the holder, i. e., to reduce self-oscillations, we will have to use a holder made of NES 780 grade with increased cross-sectional dimensions (if possible), or use combined holders, the main structure of which is made of steel 45 and the damper of alloy NES 780.



a *b*

Fig. 5. Results of theoretical research: *a* – δ=0.075, E=1.25×10^{11} Pa; *b* – δ=0.075, E=1.6×10^{11} Pa

Another problem with the use of high-damping alloys as a material for cutter holders is the dependence of the logarithmic decrement of the attenuation of these alloys on temperature. The high damping capacity of the NES 780 is maintained up to 100 °C [2], then (up to 150 °C) it decreases by about 5 times and then (after 150 °C) remains unchanged. That is, at a holder temperature of 200 °C, the damping capacity of this alloy is only twice as high as steel 45. However, taking into account the fact that damping depends on stress, which means it occurs in a place close to the clamping of the holder in the toolholder, it is quite possible to ensure the temperature in this place of the cutter holder, especially when cutting metal with lubricating and cooling fluid.

Other industrial high-damping alloys whose physical and mechanical properties allow them to be used as cutter holders are cobalt-nickel-based alloys, the reason for their high energy attenuation being ferromagnetism [2]. Of these alloys, the first to be noted is the alloy with the conventional name NIVCO (Westinghouse) contains about 72 % cobalt, 23 % nickel, 1.1 % zirconium, 1.8 % titanium, 0.2 % aluminum, 1 % iron, and other alloying elements. The alloy was developed as a material for gas and steam turbine edges. The alloy's high physical and mechanical characteristics (better than hardened steel 45) and high logarithmic decay factor (δ=0.125) combined with a high modulus of elasticity (close to alloy steels) and weak temperature dependence of damping make it unique for use as a vibration-resistant cutter holder. Among the disadvantages is the high cost of the alloy. Also promising are industrial alloys with a slightly lower cobalt content, which were created as a material for elastic elements with high damping. The logarithmic decrement of the attenuation of the alloys is 0.06, which is quite significant, combined with high strength, stiffness, and weak dependence of damping on temperature.

Another promising material for manufacturing vibration-resistant cutter holders is lamellar graphite cast iron [2], the reason for the high energy damping is the microplastic deformation of the metal matrix and graphite inclusions. Because of this, the damping in cast irons with globular graphite is much lower, and the damping in white cast iron is close to steel. Although the physical and mechanical characteristics of cast iron are somewhat inferior to those of stainless steel 45, in most cases they are quite sufficient for use as a holder material, especially given the fact that the logarithmic attenuation coefficient in cast iron increases with temperature (as in steels). It should also be noted that the logarithmic decrement of cast irons is highly dependent on the stress value, i.e., the damping increases with the stress in the holder material.

Therefore, the manufacture of universal cutter holders and mandrels from high-damping alloys can increase the vibration resistance of the tool when cutting corrosion-resistant and heat-resistant chromium-nickel steels and alloys.

Conclusions

1. The optimal value of the contact pressure in the press connection of the inserts of a prefabricated cutter can significantly reduce the amplitude of self-oscillations of the MFTW system, and materials with high internal damping, although they have lower values of the damping decrement, have wider range. A prefabricated metalworking tool with high values of logarithmic decay can only be used successfully for efficient cutting of difficult-to-cut materials if it is optimally adjusted to a certain cutting force value, which must be taken into account when designing it. For greater flexibility in the use of the tooling, it is advisable to provide for the possibility of adjustment and, if possible, readjustment in the design.

2. When using materials with high internal damping as holders and mandrels, preference should be given to materials with the highest possible values of the elastic modulus and/or compensate for the loss of rigidity by increasing their geometric parameters accordingly.

3. Metal cutting tools with high internal damping materials in their design, although they absorb less vibration energy, do not have a pronounced optimum, which provides greater flexibility in their use, especially as tools for finishing.

4. In general, the use of a metal-cutting tool with the ability to dampen vibration energy for machining parts made of difficult-to-machine alloys that are subject to intense vibrations of an elastic technological system can be an effective solution to problems associated with the productivity and quality of manufacturing parts made of difficult-to-machine steels and alloys.

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