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FINISHING PROCESSING OF PARTS IN A COMBINED WORKING ENVIRONMENT UNDER THE ACTION OF OSCILLATIONS. PHYSICAL PHENOMENA AND DYNAMICS OF CONTACT INTERACTION

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ФІНІШНА ОБРОБКА ДЕТАЛЕЙ КОМБІНОВАНИМ РОБОЧИМ СЕРЕДОВИЩЕМ ПІД ДІЄЮ КОЛИВАНЬ. ФІЗИЧНІ ЯВИЩА ТА ДИНАМІКА КОНТАКТНОЇ ВЗАЄМОДІЇ

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This article analyzes finishing processes using a combined abrasive medium under the action of oscillations, combining mechanical, physical, chemical, and energetic phenomena. The study investigates the physical nature of oscillation processes, the patterns of interaction between abrasive particles and the surface of workpieces, and identifies the conditions under which maximum processing efficiency is achieved. A comparative analysis of traditional finishing methods – grinding, tumble finishing, abrasive-jet machining, and vibration machining – is presented. Their advantages, disadvantages, and application limits in modern mechanical engineering are identified.

A new finishing method is proposed: machining with a combined working medium, which combines abrasive, chemical, thermal, electrical, and mechanical action. This medium consists of abrasive granules, process solutions, and process intensifiers, which, under the action of vibrations, perform a complex, deterministic circulatory motion, creating numerous micro-impacts on the surface of the workpiece. This enables cleaning, grinding, polishing, surface layer strengthening, residual stress removal, adhesion enhancement, and surface preparation for coating application. Like traditional methods, this method enables the simultaneous processing of a large number of parts, while its integrated approach allows for achieving the required surface quality in a shorter processing time.

The mechanism of contact interaction between the abrasive medium and the part surface is revealed. It is established that the process is accompanied by impact, cavitation, adhesion, wear, wave propagation, and energy dissipation. The oscillations are divided into frequency ranges, from infrasonic to ultrasonic. The effects of free, forced, parametric, and self-oscillations on the process are examined, as well as their influence on the behavior of the working medium and the workpieces.

It is shown that the machining process is a complex vibration-impact system with distributed parameters, in which the frequency, amplitude, properties of the abrasive, part geometry, and equipment operating modes play a significant role.

The dynamic properties of the working medium are examined: circulation motion, elastic impact interaction of particles, pressure wave formation, contact processes, and deformation of surface layers. The influence of process solutions on the intensity of the process is demonstrated. Mathematical relationships describing changes in contact parameters, impact energy, particle velocity, and interaction force are presented.

The proposed approach expands the capabilities of finishing machining in mechanical engineering, particularly for parts with complex geometries and high surface finish requirements, and creates the basis for further development of technologies for machining with combined abrasive media under the action of vibrations.

Key words: *finishing processing, combined working media, oscillating processes, micro-impacts, circulation motion, technological process.*

Introduction. The creation of new and modernization of existing production systems requires complex technological preparation of production. Trends in the development of modern mechanical engineering, which will remain unchanged in the future, are the production of a wide range of products while simultaneously reducing production time and economic costs. New enterprises for finishing, as a rule, use high-tech universal equipment in production.

Finishing is applied after mechanical and thermal treatment. The difficulties that arise at this stage of processing are due, on the one hand, to the wide range of parts being processed, and on the other hand, to the choice of processing method. Parts can have different parameters of mass and dimensions, have a complex shape. Processing methods also impose limitations, for example, the dimensions of the part may not allow processing or the technological capabilities of the equipment do not allow achieving the required process productivity in terms of quantitative or qualitative indicators.

Let's consider each of the relevant methods and analyze the general advantages and disadvantages.

The most common processing method today remains grinding or polishing with a fixed working tool - grinding wheels [1, 2]. Grinding belts, grinding heads, abrasive bars are also used as tools. During such processing, the tool performs only rotational motion, which is the main cutting motion, and the workpiece performs any motion. The advantages of this method are that it is sufficiently studied, and therefore, easy to use, high productivity, and the possibility of automating the process. Typical disadvantages include high wear of the grinding tool. The shape of the circle is disturbed, and accordingly, its grinding properties deteriorate. Errors in choosing an abrasive tool and processing modes can lead to surface damage. Also, like most of the methods that we will consider below, processing with grinding wheels is accompanied by the release of dust consisting of small particles of material, which requires additional efforts aimed at production safety.

Quite often, machine-building enterprises encounter equipment for processing in rotating drums - tumbling. Such equipment is quite simple in design and does not require complex adjustment, and the process itself is easily modeled and allows the use of combinations of various abrasive tools [3, 4]. Processing in tumbling drums is carried out due to the relative movement of the part and the abrasive tool when pouring the load mass (a mixture of abrasive granules, working fluid and parts to be processed). The speed of relative movements does not exceed 1 m/s, and the zone of intensive processing is only part of the load volume. The number of revolutions of the drum is chosen so that its acceleration does not exceed the acceleration of free fall. If the acceleration of the drum exceeds the acceleration of free fall, then processing in the drum will stop due to the fact that the centrifugal force will press the mass to be processed against the walls, and it will rotate with it. The limitation of the use of tumbling is the processing of thin-walled and fragile parts, which can be deformed when spilled and dropped. The inner surface of the part is also not subject to processing. This is due to the fact that the relative movement of the granule, which enters the cavity of the part, stops. As a result, the granules begin to move at the speed of the part. Also, this method excludes the possibility of simultaneous processing of parts of different dimensions and mass, since during the movement a heavy part can damage a lighter one. In addition, such equipment is characterized by a high noise level during operation and limited ability to automate the processing cycle.

Jet abrasive treatment methods are also widely used - these are surface treatment methods in which abrasive particles are directed to the surface of the product using a jet of high-speed gas or liquid [5-7]. Jet abrasive treatment allows you to work with different materials and process parts with different shapes and contours, including internal areas, holes and channels. A high-speed jet of abrasive particles allows you to achieve quick and accurate removal of contaminants, oxides and other layers from the surface of products, does not create significant thermal effects, which allows you to avoid changes in the hardness or structure of the material being processed.

Jet -abrasive processing, depending on the method of feeding the abrasive tool, is divided into sandblasting, in which abrasive fine particles under high pressure are directed to the surface of the product using a gas jet, and hydrojet (hydroabrasive), in which the movement of the abrasive is carried out using a liquid. A subtype of sandblasting can be attributed to shot blasting, in which the feed is also carried out by gas, but larger elements (shot) are used as a tool.

The use of this type of processing requires detailed study of the technological process, since incorrect selection of parameters may damage the surface of the part, and the processing of thin-walled or fragile parts is even more difficult and, in some cases, not advisable, as it can lead to the destruction of the part. However, the main disadvantage of this method is its environmental friendliness and harmfulness to the operator.

One of the rather “young” methods of processing with free abrasives is the processing of parts in an oscillating tank – vibration processing, which is actively used at the stage of cleaning, grinding, polishing and other operations [8, 9]. Vibration processing is the process of removing metal from the processed surfaces of parts by grains of abrasive granules of the working medium, which are communicated with vibrations. Processing occurs as a result of the sequential application of a multitude of micro-impacts to the surface of the processed parts by granules of the working medium when they collide with the parts and when they slide past each other under the influence of force pulses transmitted to the working medium from the vibration exciter of the vibrating machine. The main advantages of this processing method include, first of all, the ability to simultaneously process a large number of parts.

However, at present this method has acquired new properties. Today, finishing equipment in which a free abrasive medium is used that moves under the influence of vibrations, as a rule, has several sources of vibrations, which, depending on the needs, can operate in synchronous mode, which ensures uniform processing of parts in long containers. Additional sources can be located in other areas of the tank, for example, on the side walls or directly inside the tank and, by providing additional pulses, increase the contact interaction of the working medium and parts, or help change the direction of movement of the working medium. The frequencies and amplitudes that generate the main and additional sources of vibrations can be the same, or they can differ, for example, additional sources of vibrations cannot work constantly, but be turned on with a certain periodicity. The very first vibration processing operations were carried out only with the use of abrasive granules, but quite quickly, the need to use chemical solutions at the stages of cleaning and main processing became obvious. Today, processing without liquids is not considered, on the contrary, the use of chemical solutions has become a separate area of research. The same thing happened with abrasive tools. Today, for processing parts, not only the general type of tool of a certain size is selected, but also many of its other parameters - bond characteristics, type of abrasive grains, geometric characteristics of the granules (number of sharp edges, their relative location).

In conclusion, today it is appropriate to discuss the emergence of a new method - combined working environment processing under the influence of vibrations. In which the nature of vibrations, parameters of the abrasive tool, composition of chemical solutions, properties of the processed part, the feasibility of using thermal or electrical intensifiers are considered in a complex. This method combines classical vibration processing, vibrothermal, vibrochemical, vibroelectric, vibroshock and other vibration processing methods.

This method is used for cleaning, grinding, polishing, preparing the surfaces of parts for coating, removing and leveling or creating optimal residual stresses in the surface layers of parts.

The objective. Determination of physical properties and dynamics of contact interaction of the combined abrasive medium processing under the action of oscillations.

Research results. The general physical nature that characterizes the processes of processing parts with free working media under the influence of vibrations is quite complex and is associated with the phenomena of impact, adhesion, cavitation, wear, contact interaction of the processed parts, and wave processes. Processing parts with free abrasives subjected to vibrations is divided into 3 main groups: infrasonic vibrations (frequency up to 10 Hz), low-frequency vibrations (15 – 100 Hz) and ultrasonic vibrations (more than 1000 Hz).

The processing process is further complicated by the use of additional technologies that act as catalysts for the process. This effect is created by the additional influence of electric and magnetic fields, chemical solutions, low and high temperatures.

Let us consider the physical characteristics of the processing process with a combined abrasive medium under the influence of vibrations.

Mechanical oscillations. It is obvious that when creating pulses by a source of vibrations, mechanical vibrations arise, which are the main ones when processing with free abrasives. The processing process itself is directly related to general information about free and forced vibrations, the vibrational effect on the working environment, the interaction between the working environment (together with and separately from the processed parts) and the elements of the machine tools, the phenomena of self-oscillations and resonance, vibrations of mechanical systems [10, 11].

Oscillations are characterized as limited movements that are partially or completely repeated relative to some average position (state). Accordingly, systems that perform oscillations under certain conditions are called oscillatory systems. Oscillations are mechanical in the case of changes in only mechanical quantities (velocity, acceleration, displacement, pressure). In the case of oscillations with a relatively small amplitude and average frequency, they are usually defined as vibration. When processing parts with free abrasives, the oscillations of the working medium transmitted from the source are periodic, and as a rule they are harmonic. The variable is determined by the law [12]:

$$U(t) = A\sin(\omega t + \varphi), \quad (1)$$

where *A is* the amplitude of oscillations, ω – angular frequency, φ – the initial phase of oscillations.

The initial phase of the oscillations is the parameter φ, and the phase of the oscillations at time t is described by the expression $\omega t + \varphi$.

The period of harmonic oscillations is determined by the angular frequency:

$$T = \frac{2\pi}{\omega}, \quad (2)$$

in accordance

$$\omega = \frac{2\pi}{T} = 2\pi f. \quad (3)$$

Speed $V(t)$ and acceleration $\omega(t)$ in harmonic oscillations also change over time according to a sinusoidal law with the same frequency as the displacement $U(t)$, with the amplitudes and velocities being equal to $A\omega$ and , respectively $A\omega^2$.

The sum of two harmonic oscillations with the same frequencies will be a harmonic oscillation with the same frequency:

$$A_1 \cos\omega t + A_2 \cos(\omega t + \psi) = A\cos(\omega t + \gamma). \quad (4)$$

The amplitude A and phase γ of the resulting oscillations are equal to:

$$A = \sqrt{A_1^2 + A_2^2 + 2A_1A_2\cos\psi}, \quad (5)$$

$$tg\gamma = \frac{A_2 \sin\psi}{A_1 + A_2\cos\psi}. \quad (6)$$

Mechanical oscillations that arise from the influence of forces arising in an oscillating system are free oscillations. Free oscillations are carried out in the absence of external influence, they can occur only in autonomous systems due to accumulated energy.

There is also a definition of a pseudoelastic force, which is the cause of harmonic oscillations. Pseudoelastic forces are not elastic in nature, but their magnitude is proportional to the displacement of the body from the equilibrium position. They are always directed towards the equilibrium position. The pseudoelastic force is expressed by the expression:

$$F = -ku, \quad (7)$$

where k the coefficient of the pseudoelastic force; u – displacement, the sign indicates the opposite direction of the force and displacement vectors

It should be noted that for free oscillations, a characteristic feature is damping. Oscillations are damped if the damping is due to the simultaneous action of the pseudoelastic force and the friction force, proportional to the instantaneous velocity u:

$$F_{mp} = -ru, \quad (8)$$

In damped oscillations:

$$u = Ae^{\delta_t}\sin(\omega t + \varphi), \quad (9)$$

where δ – is the extinction coefficient; Ae^{δ_t} – is the instantaneous amplitude value; e – is the base of the natural logarithm:

$$\delta = \frac{r}{2m},\ \omega = \sqrt{\omega_0^2 - \delta^2}, \quad (10)$$

where r is the resistance coefficient; m is the mass of the oscillating body; k is the coefficient of the pseudoelastic force,

$$\omega_0^2 = \frac{k}{m}. \quad (11)$$

Oscillations are polyharmonic if they can be represented as two or more harmonic oscillations with frequencies that are in real proportion to each other.

Forced oscillations, unlike free ones, arise under the influence of an external force and are characteristic of non-autonomous systems. The process of forced oscillations is characterized by the phenomenon of resonance, which leads to a sharp increase in the amplitude of oscillations of a body or system. In industry, resonant oscillations can occur as a negative phenomenon and in this case, there are methods that allow you to get rid of them, but they are also used in various technological processes, for transporting something [13].

Oscillatory systems in which energy loss is supplemented by an internal source are called self-oscillating, respectively, self-sustained oscillations in such systems are called self-oscillations. They arise from a source of energy of a non-oscillating nature that is included in the system. The occurrence of self-oscillations is possible only in non-conservative stationary systems. Usually, the phenomenon of self-oscillations is caused by the nonlinear nature of dissipative forces (friction); in the case of weakly expressed nonlinearity, the oscillations are more similar to harmonic.

If the system satisfies the condition below, then it is linear:

$$L(a_1u_1 + a_2u_2) = a_1Lu_1 + a_2Lu_2 . \quad (12)$$

If the system does not meet this condition, it is non-linear. Note also that linear systems are characterized by the presence of the superposition principle.

If the system does not change in a certain period of time, then it is stationary, the same is true of oscillations, and vice versa, if the properties of the system change, then it is non-stationary. The processes that occur in stationary systems are described by differential equations with constant coefficients, and in non-stationary systems by differential equations with variable coefficients.

A system is conservative if its total mechanical energy remains constant during oscillations, otherwise it is non-conservative. Among non-conservative systems, there are systems with characteristic properties. A system is dissipative if its total mechanical energy of the corresponding autonomous system decreases.

The intensity of processes in oscillatory systems is characterized by the ratio between the measured value of the process parameter and some non-standard value that corresponds to the zero level. The intensity of oscillations is determined by:

$$\lambda = A\omega^2 / g . \quad (13)$$

If $\lambda = 1$, then this value is critical, because it is at this value that various vibrational effects occur. The logarithmic unit of oscillations is called the Bel, and its tenth part is the decibel (dB).

For a change in an energy quantity (energy, power, etc.), the logarithmic level can be represented as:

$$L = 10\lg V / V_0 \quad (14)$$

where V_0 is the value corresponding to the zero level.

When changing oscillatory displacement, velocity, or acceleration, the logarithmic level is equal to:

$$L = 20\lg a / a_0 \quad (15)$$

where a_0 is the initial value of the parameter a, which corresponds to zero level.

If $V = const$ and a^2, expressions 14 and 15 are equivalent. Usually, the initial value a_0 is equal to the acceleration of free fall.

Parametric oscillations occur in linear and nonlinear systems. They arise as a result of the variability of the elastic force coefficients. An example of the simplest model of parametric oscillations is a pendulum with a pivot point.

Deformation of working media under the influence of periodic oscillations occurs according to rheological laws [14]. However, the main difference in the rheology of such media is that all rheological bodies simultaneously have basic and inertial properties. The presence of inertial properties of bodies is due to changes in accelerations during periodic loads, as a result of which significant inertial forces arise.

Wave phenomena. When vibrations affect media and bodies placed in them, the phenomenon of wave processes occurs. Such processes are characterized by characteristic regularities, which include refraction, diffraction, interference, reflection, refraction and the Doppler effect. [15].

Regarding the processes under consideration, it is appropriate to clarify that in this context, waves of mechanical origin are considered, which have the usual kinematic characteristics (velocity, acceleration, displacement). The speed of wave propagation depends on the medium. The movement of waves is carried out according to the law of refraction [15, 16].

As the distance increases, the vibrations of the particles of the medium that occur during the passage of waves decrease. This occurs as a result of the absorption of wave energy by the medium. The propagation of waves depends on refraction, which is significantly affected by the heterogeneity of the medium. [15, 16].

The state of the medium in which waves propagate has a direct impact on the dynamic properties of the waves. Thus, the theory of wave propagation allows us to study changes in the nature of wave propagation depending on the properties and state of the medium and the influence of waves on changes in the state of the medium itself [15, 16].

The study of wave processes that arise during oscillatory phenomena is associated with the periodic and non-periodic influence of exciting forces. The latter characterizes shock processes, in which the action of the excitation is limited, and the oscillations generated by the shock decay over time. Such oscillations are called non-stationary [19, 21].

Special attention should be paid to wave reflection, because under certain conditions the shape of a wave propagating in an elastic medium may change. In addition, some waves propagate more easily on the surface of the body, while others propagate more easily inside the body [16, 19].

The propagation of elastic waves in long bodies, for example, in rods, the dimensions of which are larger compared to elastic displacements, and have large internal damping properties, is due to the damping of the elastic wave before it is reflected from the fixed boundary to the excitation source [18, 20]. Such waves can be called "impulsive", that is, the excitation has no time limits and manifests itself periodically. In other words, we consider special forced oscillations in which the frequency is much higher than the fundamental natural frequency of the oscillating system. In this case, the oscillation frequency is greater than all natural frequencies of the system and, accordingly, there are no forms that can fall into resonance. In the case under consideration, the induced oscillations are understood as a movement that occurs under the action of excitation, the existence of which does not depend on the possibility or not of transmitting motion to the system. That is, the excitation does not depend on the presence or absence of oscillations of the excitation system, and this excitation can be harmonic or random in nature [20].

The efficiency of the impulse wave increases with an increase in its energy component, which occurs with high-frequency oscillations (ultrasonic oscillations) [17, 20]. As is known, the power transmitted by a wave of a given amplitude through a unit plane is proportional to the square of the frequency, therefore, by focusing the power of the ultrasonic beam, we will obtain high-frequency oscillations that cause deformation or destruction, which in turn is the basis of processing processes.

Wave processes associated with shock processes are complex, which is due to the different reaction of materials to shock loads in contrast to static ones, because such properties as the speed of wave propagation or the density of the material are of little importance for slow loads and, conversely, play a major role for shock loads [21]. The magnitude, duration and distribution of forces are largely determined by the reaction of the material and the shape of the body to which the shock load is applied. The distribution of stresses that occurs under the action of this load is both localized and mobile. The action of the load is not transmitted to the entire body instantly; at the beginning, some of its areas remain unexcited. In this case, stresses and deformations move in the body in the form of waves. In metals, this speed reaches several thousand meters per second. After the end of shock phenomena, the body can return to its original state or undergo irreversible changes (elastic or plastic impact).

Depending on whether the direction of motion of the particles of the body coincides with the direction of wave propagation or occurs perpendicularly to it, two types of elastic oscillations are distinguished: longitudinal waves (longitudinal excitation, expansion wave, primary wave), transverse waves (shear wave, secondary wave). Longitudinal waves propagate in the material by compression and stretching, and transverse waves by shear displacements [15, 16, 18].

As stated in the theory of elasticity, the speed of wave propagation depends on the elastic constants E, G and the density ρ [16, 18]. For a cylindrical rod it is determined by the formula:

$$a = \sqrt{E / \rho} \tag{16}$$

From a physical point of view, the formation and propagation of a wave in a metal rod occurs in the following order: the shock wave N instantly loads the end of the rod F; during the time dt that has passed since the moment of impact contact, only a certain layer of the rod dl will have time to compress, the rest of the rod will remain undeformed and, accordingly, without stresses. The relative reduction of the first layer will be:

$$E = \frac{du}{dl} \tag{17}$$

The formation of stress waves that arise as a result of a perfectly elastic impact, there is a separation of the impact energy into kinetic and potential forms. This applies to both compression waves and tension waves. The process of converting kinetic energy into potential energy is sequentially distributed to adjacent layers of contacting bodies, as a result of which the deformation spreads in the rod from one cross-section to another [19, 21].

For processes in which mechanical vibrations are used, the basis is the physical state of the abrasive media and the nature of the interaction between the media and the parts being processed.

Vibrations can be transmitted directly to the workpieces by external influence, for example, through special applications. Providing vibrations or movement to the workpieces allows to intensify the machining process, to ensure uniform machining and transportation of the part. Such solutions can be used to solve both a single problem and in complex solutions.

Individual vibrations with a frequency and amplitude other than the operating frequency can be transmitted directly to the working environment.

Processing with combined abrasives affects the internal structure of the part, changing its physical and mechanical properties. Under the influence of vibrations in the processed parts and the environment itself, primary deformation waves arise in the place of transmission of the primary impulse from the working body, which transmit force impulses to the subsequent layers of the working environment. The forces of friction, inertia, deformation processes of the material of the parts and the environment affect the transmission of impulses and they gradually become weaker. That is, the effect of energy dissipation is observed [20, 21].

The effect of vibrations largely depends on the characteristics of the combined abrasive medium, namely the dispersion of particles and the state of the working medium as a whole.

Dynamic properties of systems under the action of oscillations. The main characteristics of technological processes in which vibrations are used as a source of energy for the movement of combined abrasive media include: amplitude-frequency characteristics, geometric and physical parameters of the abrasive tool, machined parts and equipment [21].

The technological system of processing with a combined working material under the action of vibrations is an oscillatory-impact system with distributed parameters and impact pairs of unstable structure [20, 21].

When using combined abrasives on equipment with a classical layout scheme, the tank moves with an acceleration $A\omega^2$, the value of which is in the range of 1.5 – 2.0 *g*, while the working medium performs a circulation movement at a speed of 0.2 – 0.9 rpm in the plane of rotation of the unbalances and in the opposite direction relative to the shaft of the source of vibrations. The vibration speed of the abrasive particles consists of movements transmitted from contact with the tank and relative shock movements in the medium with a frequency of ω 0.8 – 1.0 m/s. It should be noted that the acceleration and speed indicators presented above are currently basic, and in modern equipment they can be much higher [21].

The movement of particles under the influence of vibrations transmitted from the tank is characterized by the occurrence of dissipative processes, the presence of gaps between the particles and the tank walls, and elastic-impact processes. During one oscillation cycle, the particles of the working medium simultaneously collide and move away from the tank walls, the working medium can periodically compress or expand and move together with the tank [21].

The maximum effect of vibrations transmitted to the working medium is observed directly near the walls of the tank and decreases with distance from it. Figure 1. shows the pressure distribution depending on the tank area. In this case, a diagram of classical equipment with a U-shaped tank and the location of the source of vibrations in the lower part is shown. Of course, the location of the source or sources of vibrations significantly affects the pressure distribution and, accordingly, the productivity of the processing process [22].

Considering the above diagram, it is noticeable that the working medium is conditionally divided into two layers - the first layer is in contact with the reservoir and is maximally active, and the second can only contact the parts being processed. The general rotational motion of the working medium, which consists of a combined abrasive material, parts being processed and chemical solutions, is opposite to the vector of the exciting force created by the source of vibrations.

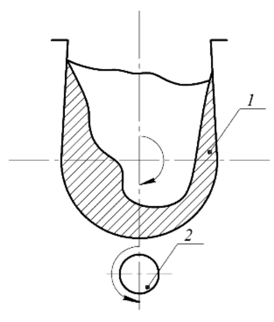

Fig. 1. Pressure distribution in the tank:
1 – zone of maximum pressure;
2 – source of oscillations

Oscillations (vibrations) and variable accelerations of abrasive particles exert a dynamic effect on the surface of the parts being processed due to the combination of micro-impacts of both individual and groups of particles.

The movement of parts in the flow of the working medium can be of a diverse nature. When loading parts into the working medium without fixing, they can change their positioning, oscillate with the working medium and perform rotational movements. The properties of the movement and the speed of movement of the processed parts depend on their geometric dimensions, shape and mass. [22].

Processing with a combined working material is carried out without a rigid kinematic connection between the machine tool, the tool and the workpiece, due to which the working medium acquires the properties of fluidity and flexibility, which allows the tool to contact the entire surface of the part regardless of its geometric parameters.

*General characteristics of oscillatory processes***.** Oscillating processes of processing with combined working media are complex and multifactorial, but they have common characteristics for a wide range of vibrations. When processing with a combined working tool under the influence of vibrations, the frequency range is quite wide and includes both low-frequency mechanical vibrations and high-frequency vibrations, respectively, the amplitude of vibrations decreases with increasing frequency. The transfer of energy under the influence of vibrations is carried out stepwise, and has basic and driving relationships. Thus, it is advisable to consider the processes of surface processing with a combined working material under the influence of vibrations from the standpoint of classical physics and quantum mechanics [18, 20].

The characteristics of vibration systems intended for processing with a combined working medium are as follows: source(s) of vibrations; sources of additional vibrations, working medium in which the combined abrasive tool acts on the surface of the object to be processed by transferring vibration energy from the energy source to the abrasive tool; absence of rigid fastening of the abrasive tool; directly the abrasive tool, which is a combination consisting of an abrasive component(s) and a bond and has various shapes; amplitude-frequency characteristics; devices designed to orient parts, influence the pressure indicators of the working medium or the directions of its movement [18, 20].

In general, vibrational processes of combined abrasive processing are used in solving the following technological areas: the effect of vibrations on dispersed systems; immersion of vibrational elements in a continuous medium; cutting processes; grinding of materials.

This allows solving technological problems of separation of multiphase media, micro-cutting of the surface and direct cutting, changing the shape, grinding, improving the physical and mechanical properties of the surface and the interior of the material of the parts, and also allows creating a transporting effect.

It should be noted that some types of oscillations are poorly studied and their application is limited, moreover, in a number of cases they have a negative impact on the system. These include low-frequency oscillations in the range of 10 – 15 Hz, they have great destructive power, and the study of their nature is mainly aimed at finding methods for preventing and combating them. But, despite the complexity of the application, such oscillatory processes are used in the field of seismology, metallurgical and chemical industries.

Oscillating processes with a frequency range of 15 – 300 Hz have a much wider scope of application. Processing with a free abrasive tool with oscillations of this frequency is used in machine-building, instrument-making, agricultural, mining, medical and environmental sectors of the modern industrial complex [18, 20].

Subsequently, ultrasonic technologies that use vibrations with a frequency above 20,000 Hz have received significant development. This is explained by the fact that, in comparison with other frequency spectra, in the ultrasonic range it is possible to obtain directed radiation (impact), which can be focused on a specific area and obtain powerful energy pulses. Such technologies are used for cutting of superhard materials and in the medical field for cleaning [17].

The issue of using vibrations with different frequency and amplitude characteristics requires special attention. Some technological processes are sufficiently studied and allow achieving the desired result by using a combined abrasive tool and vibrations of a fixed frequency and amplitude, which in most cases is the most appropriate, since it allows obtaining high surface quality indicators at minimal economic costs. At the same time, the processing process is highly deterministic and quite simple.

At the same time, when processing complex parts of complex shapes with internal cavities, ensuring the quality of processing usually requires non-standard technological processes, and in this case the processing process can be carried out using several sources of oscillations [11, 20]. The sources of oscillations can be located in different positions and create oscillations of different frequencies and amplitudes, some of them can operate continuously and in-phase, while others create oscillations of a different nature (with a larger amplitude and a lower frequency or vice versa), thus providing, for example, a local change in the direction of movement of the working medium, or a temporary decrease or increase in the speed of movement of the entire load mass. In some cases, it is advisable to create a single high-amplitude pulse after a certain period of time, for example, to change the orientation of parts in the working medium.

Mechanics of interaction of combined working environments and parts. The process of machining with a working tool without a rigid kinematic connection is characterized by many mechanical and chemical phenomena, which are due to the variety of abrasive tools, characteristics of the parts being machined, equipment modes, and chemicals [23, 24]. Also present are processes of plastic deformation, friction, thermal and chemical phenomena, processes of adhesion and chemical interaction, and the action of electric and magnetic fields [23].

Analysis of the interaction of the abrasive medium and the processed parts allowed us to determine the technological properties of the processing process under the influence of vibrations of various nature. Special attention is required to study the process of contact interaction between the elements of the combined abrasive medium and the processing objects, which includes point (local) contacts and their integral manifestation, the consequences of micro-cutting and deformation processes, the characteristics of the abrasive itself and the processed material [24].

The interaction of the elements of an abrasive tool as a single medium under the action of vibrations is a dynamic process with the corresponding parameters of displacements and force actions. The abrasive medium together with the processed parts under the action of external vibrations, which are created by sources with imbalances and transmitted from the walls of the working chamber, performs a complex circulatory movement, during which the movement of both the abrasive medium and the parts in it occurs, oscillations of both the entire load mass and individual elements, relative displacements, angular rotations and impact processes [23, 24]. The interaction of single and many repeatedly damped collisions determines the level and nature of the dynamic impact on the formation of the surface being processed and on the processing process as a whole.

In general, the process of processing with combined abrasives has many common features with the process of grinding by vibration, and some process patterns, such as circulation movement and design features of the equipment, are of the same nature and are valid for both processes.

The movement of the working medium is circular and is characterized by angular velocity φ, linear velocity v and cycle velocity, direction of circulation. Such a movement process is deterministic and ensures uniform contact interaction of the particles of the working medium with the surface of the processing object, which is due to the non-coincidence of the coordinates of separation and contact of the medium with the walls of the working chamber, which oscillates from cycle to cycle. The time of movement with separation (per oscillation period T) increases with increasing oscillatory accelerations $A\omega^2 > g$, and $A\omega^2 > (8-10)g$ is equal to $t_0 = (0,8-0,9)T$. At the same time, the time of joint movement of the medium and the walls of the working chamber decreases from $t_0 = T$ (provided $A\omega^2 > g$) to $t_0 = (0,1-0,2)T$ (provided $A\omega^2 > (8-10)g$). With increasing $A\omega^2 > g$ the difference in the coordinates of separation and contact also increases. The slippage of particles of the abrasive medium at the moment of contact with the walls of the working chamber is less than the value of the cycle movement, S_T which is determined by the difference in the phase angles of separation φ_0 and contact φ_τ:

$$S_T = A \cdot (\cos\varphi_0 - \cos\varphi_\tau) \cdot \frac{\lambda}{2-\lambda} \cdot \frac{1-R^*}{1+R^*} \tag{18}$$

where A – amplitude of oscillations of the working chamber; $R^* = (0.15-025)$ – coefficient of recovery upon collision of a column of medium particles with the wall of the working chamber; λ – coefficient of viscous impact friction. Linear circulation velocity $V_C = S_T \cdot \omega$, angular velocity $\varphi = \dfrac{S_T \cdot \omega}{R_C}$, where R_C – radius of the circulation surface.

The greatest height of the circulating movement of the working medium is determined taking into account the pushing force from the vibration transport force:

$$F_C = \frac{\lambda}{2-\lambda} \cdot \frac{1-R^*}{1+R^*} \cdot \frac{m \cdot l \cdot a \cdot g}{D^2} \cdot ctg\beta \tag{19}$$

where m, D is the mass and diameter of the medium particle; l, a is the length and width of the transporting layer of the working medium; β is the angle of onset of slipping of the medium particles relative to the working chamber during oblique collision.

The pushing force is capable of lifting a column of particles with a total mass of:

$$G_\Sigma \le F_C \qquad (20)$$

to the height H_C.

Number of particles in the column:

$$i = \frac{h}{D} \text{ and } i = \frac{G_\Sigma}{m};$$
$$H_C = \frac{\lambda}{2-\lambda} \cdot \frac{1-R^*}{1+R^*} \cdot \frac{m \cdot l \cdot a \cdot g}{D^2 \cdot G_\tau} \cdot ctg\beta \qquad (21)$$

where G_τ is the mass of the working medium particle.

The periodic transfer movement of the working medium is accompanied by periodic collision with the frequency ω and is characterized by the displacement angle φ, the angles of collision with the processing object φ_k and the working chamber φ_g and provides its energy properties.

The multiplicity of particle oscillations is equal to unity, with an increase in the intensity of accelerations, $A\omega^2 > 1g$ the value of the phase angle of collision of the working medium with the walls of the working chamber φ_τ increases from 90 to 340 and reaches maximum values at $A\omega^2 > (8-10)g$. It should be noted that in this range, larger values φ_τ correspond to smaller values of oscillation frequencies. With an increase, $A\omega^2 > 1g$ the phase angle of separation φ_0 gradually decreases from 90 to 20 - 30 and reaches minimum values at $A\omega^2 > (8-10)g$. The interval of movement of the working medium between φ_τ and φ_0 reflects the duration of the separation movement:

$$t_0 = \frac{T \cdot (\varphi_\tau - \varphi_0)}{360^\circ} \qquad (22)$$

The duration of the joint movement determines the ratio:

$$t_0 = T \cdot \left(1 - \frac{(\varphi_\tau - \varphi_0)}{360^\circ}\right) \qquad (23)$$

The phase angle of contact of the medium with the surface of the working chamber can be represented in the following form:

$$\varphi_\tau = \theta + \left[\arcsin\left(\frac{z^*}{\sqrt{1+\Phi\omega}}\right) - arctg\Phi\omega\right] \qquad (24)$$

,

In this case, the phase angle of separation of the working medium layer from the chamber surface will take the form:

$$\varphi_\tau = (180+\theta)^\circ + \left[\arcsin\left(\frac{z^*}{\sqrt{1+\Phi\omega}}\right) - arctg\Phi\omega\right], \qquad (25)$$

where $\theta < z^* < 1$ is the value of the dynamic gap, Φ is the functional that takes into account the oscillatory mobility of the medium; θ is the position angle at which the circulation is measured.

When increasing $A\omega^2$ from 1 to 10 *g*, the range of change is $\approx \pi$, the range of change φ_τ is $\approx 3\pi$, which is explained by the influence of counter-oscillations of the working environment.

Relative movements of particles of the working medium under the action of vibrations occur with a personal frequency ω_0 and characterize its mobility, ensuring dynamic contact of the particle with the surface of the part or parts being processed.

The behavior of a system of particles of a working medium under the action of vibrations can be partially described using the theory of semi-plastic collision with repeatedly decaying co-collision. The value of the equivalent coefficient of recovery of the co-collision velocity (taking into account the added mass) for some types of media is equal to [23]:

$$R_E = (0,1-0,25)R \qquad (26)$$

This value reflects the ratio of the velocities of the centers of mass of the boundary layer of a group of abrasive particles before and after the collision. With a small thickness of the boundary layer, this ratio may be violated due to the fact that the velocity after the collision of the particle and its subsequent separation, for example from another particle or part, may be higher than its velocity before the collision.

The thickness of the boundary layer, in which repeated, decaying collisions between particles occur in an active form during the collision cycle before the start of joint motion with the processing object, is characterized by the number of particle layers and is determined by the following expression:

$$n = A\omega \cos \varepsilon_\tau \left[0,5D \cdot (P-1)\right]^{-1} \quad (27)$$

If $R = 0,8 - 0,9$ the duration of the collision cycle significantly exceeds the collision time of a single particle.

$$t_\tau = \frac{V_g - \lambda V_c}{2g\lambda} \quad (28)$$

The vibrational mobility of individual particles is determined by their individual vibrational frequency ω_0 and the probable value of their amplitude of vibrational displacements a_1 before collision:

$$a_1 = 0,25D \cdot \omega_0^2 \frac{P-1}{g}, \quad (29)$$

where D is the particle diameter.

In a real system, there are always contact impacts of particles of the medium with the workpiece and with each other which repeat and subside.

In the absence of rotational velocity, single contacts of particles with the surface of the part create elastic-plastic deformation [23, 24]. The nature of such interaction can be described by the following types of mutual displacements: partial displacement of bodies upon contact, particle repulsion, particle failure with sliding without or with rotation.

Deformation processes. Processing with a combined working medium is intended to obtain a strengthening or stabilizing effect, which is carried out mainly in the environment of metal and hard alloy bodies [25]. Obtaining the specified technological effect, the ability to control the process are determined by the state of the processing medium and its properties, which include the value of the equivalent mass of the medium under the action of vibrations, the recovery coefficient, the parameters of the force connection, the dynamic gap between the particles of the medium, dissipative and elastic properties [25, 26].

Under the action of vibrations, the behavior of the working medium can be considered as the behavior of a rheological body. When a load is applied to such a body, a deformation occurs, which decreases to zero in its absence, while the stresses decrease over a certain period of time t_{with} [25]. Separately, one should consider the type of collision in which there is a flow around the source of momentum by the working medium. With this type of contact interaction, during the collision time period, there is a large number of particles that perform many repeated damped collisions with each other and with the surface of the part [25, 26]. The collision time for a single particle of the medium is $\tau = 0,001 - 0,005$ s, while the coefficient of velocity recovery during collision is equal to $R = 0,6 - 0,8$. Over time, when the strength of the treated surface increases, the value τ decreases, and R vice versa increases. The duration of repeatedly damped collisions of a group of particles with the surface of the part is 10-20 times greater and is 20 – 40% of the oscillation period [25], such a significant duration is explained by the fact that a large number of particles participate in the collision. Analysis of the impulse effect in such a collision shows that at a collision speed of $V > 0,7$ m/s and moderate loosening, $1,0 < K_W < 1,2$ an intensive increase in the force impulse and the development of the impact are observed, characteristic of a viscoelastic body [25, 27]. At small values of loosening $V < 0,5$ and at significant loosening, $K_W < 1,2$ the force impulse increases slowly, and the nature of the dependence $F(t)$ acquires a character that corresponds to the dependence *(t)* for an elastic-plastic body.

During a collision, the development of the force impulse is delayed; when the deforming load is removed, the medium is completely restored, and the stresses

are extinguished in several oscillation periods and collision cycles [25, 26, 28]. The numerical value of the damping coefficient for a viscoelastic system can be represented by the following expression:

$$b = \alpha_+ (2\sqrt{mG_+})^{-1} \quad (30)$$

A mentioned above, the working medium under the action of vibrations performs circulation and translational periodic movements. In this case, the particles in the medium perform relative oscillatory movements, and the technological fluid - circulation and pulsation in the gaps between the particles [25, 26]. The angular rotation of the particles as a result of collisions at an angle decreases to zero until the next collision cycle due to the absence of gaps between the particles

In the process of interaction of the medium with the workpiece under the action of vibrations, there are both instantaneous properties of the collision of individual particles and integral properties of the particle system [25, 27]. Relative movements of particles in the working medium occur with a frequency ω_0, ensuring its mobility and contact with all elements of the machining surface [26]. Circulating and pulsating movement of the technological fluid between particles of the working medium helps to reduce friction forces in the contact zone with the machined surface and ensures the removal of wear products (particles of the medium and the workpiece) [26, 28]. The duration of the separation and joint motion of the medium can be determined using the following expressions (respectively):

$$t_S = \frac{T \cdot (\varphi_\tau - \varphi_0)}{360^\circ}, \tag{31}$$

$$t_C = T \cdot \left(1 - \frac{\varphi_\tau - \varphi_0}{360^\circ}\right). \tag{32}$$

The behavior of a spatial system of vibrating particles under the action of oscillations can be described by the theory of pseudo-plastic impact with repeated damping collisions [25, 27]. In this case, the velocity recovery coefficient will be equal to [27]:

$$R^* = \frac{(\mu R - 1)^2 + \mu \cdot (1 + R^2) \cdot \cos \tau_{-3}}{(1+\mu)^2}, \tag{33}$$

Where

$$\mu = \frac{m_1}{M_2} + \frac{m_1}{M_3} + \frac{m_1^2}{m_2 M}; \qquad \cos \tau_{-1} = \frac{1 + \mu R}{1 + R} \tag{34}$$

The thickness of the boundary layer, in which re-quenching collisions between particles are actively realized during the collision cycle before the beginning of the stage of their joint movement, is characterized by the number of particle layers [25, 26], which is determined by the ratio:

$$n = A\omega \cos \varepsilon_\tau t \left[0,5D \cdot (P-1)\right]^{-1} \tag{35}$$

Under the conditions $R = 0,6 - 0,8$, $R^* \approx 0,1 - 0,2$, the duration of the collision cycle is found by expression (41) to significantly exceed the collision time of one particle.

$$t_\tau = \frac{V_g - \lambda V_{-2}}{2g\pi} \tag{36}$$

Within the oscillation period, the particles of the working medium are alternately in two states - in dense and loose packing, while the total porosity of the medium is 26%, and the area of the gaps in the cross section is 9,3% [25]. The coefficients of porosity and gaps are 0,26 and 0.093, respectively. The coefficients for the medium in the dynamic state are calculated by the formula:

$$K_{Por} = 0,259(P-1), \qquad K_{Gap} = 0,2093(P-1) \tag{37}$$

A technological solution periodically flows through the working medium in a pulsating flow with an oscillation frequency at a speed of:

$$V_{TP} = \frac{\Delta P D^2 C}{l \mu}, \tag{38}$$

where ΔP – pressure drop; μ – dynamic viscosity of the liquid; l – filtration length; – C Slichter index for the cross-section of the gaps. For steel balls with a diameter of 5–6 mm, the vibrational viscosity at $A\omega^2(8-10)g$, is equal to $\mu = (3-4)$, and at $A\omega^2 = 4g$ is equal to $\mu = (7-10)$. The Reynolds number for the medium under the action of vibrations at $A\omega^2 > (6-10)g$ is determined by the formula (44) and varies in the range 25 – 100.

$$R_1 = \frac{3\pi A\omega D^2 \rho}{\alpha}, \tag{39}$$

where D, ρ is the diameter and density of the working medium particles; α is the resistance coefficient of the medium. The movement of the technological solution through the gaps of the working medium reduces the vibrational mobility of particles by up to 30% [25, 27].

As noted earlier, under the action of vibrations, the medium contacts the surface of the workpiece and periodically, upon contact with it, forms

on the surface there are many traces of processing, which over time as a result of repeated superposition and overlap form a new surface. The spatial model of the system that implements the processing process can be represented as a chain of concentrated masses m_n, which contain elastic-viscous and intermediate elements C_T, α and δ, which for a period T sequentially and alternately contact the surface of the part and the tank. The decisive role in the process of surface formation is played by the collision itself, the circulatory movement of the working medium does not have a significant effect on the magnitude of the collision [25, 26]. The equation for determining the maximum collision force [29]:

$$F_{\max} = \frac{m_n \omega_{02}^2 X_3 K_\beta \sqrt{1-n_2^2}}{e^{-n_2\omega_{02}t_\tau} \sin(\omega_{02} t_\tau \sqrt{1-n_2^2})}; \qquad (40)$$

The duration of the collision cycle is equal to

$$t_\tau = \frac{\pi}{\omega_{02}\sqrt{m_n c_2})}; \qquad (41)$$

At the same time

$$\omega_{02} = \sqrt{\frac{m_n}{c_2}}; \; n_2 = \frac{\alpha_2}{2\sqrt{m_n c_2}}, \qquad (42)$$

where K_β is the coefficient of the viscoelastic model.

When studying the features of the formation of the surface layer of the medium, an important role belongs to contact phenomena in the collision zone of both individual particles and their groups, and circulation movement is also taken into account. In this case, the effect of oscillatory transportation occurs, which causes circulation movement of the boundary layers of the working medium, which is determined from the expression [29]:

$$F_{CM} = \frac{\lambda}{2-\lambda} \cdot \frac{1-R^*}{1+R^*} \cdot \frac{m \cdot l \cdot d \cdot g}{D^2} \cdot ctg\alpha, \qquad (43)$$

where R^* is the velocity recovery coefficient for a group of particles.

Gravitational forces affecting the working environment during oscillatory movement:

$$Q = p \cdot g \cdot h \cdot s \qquad (44)$$

The force of resistance to the relative motion of the working medium

$$T = \alpha^* V, \qquad (45)$$

where ρ – bulk density of the working medium; h, s – height and cross-sectional area; α^* – coefficient of internal resistance of the working medium when using steel balls with a diameter of 5 – 6 mm as an abrasive filler.

If $A\omega^2 > (6-10)g$ $\alpha^* = 0{,}1-0{,}2$. The initial oscillatory displacement is determined by the average velocity of oscillatory transport:

$$S_T = A(\cos\varepsilon_0 - \cos\varepsilon_\tau) \cdot \frac{\lambda}{2-\lambda} \cdot \frac{1-R^*}{1+R^*} \cdot ctg\alpha \qquad (46)$$

,

where ε_0 and ε_τ are the phase angles of separation and collision.

The momentum of the force upon collision of a part (M) and a particle of the medium (mass of the particle m_2) is equal to:

$$I_2 = \frac{2m_2 A\omega\cos\varepsilon_2}{0{,}5-\psi(T)-\psi(0{,}5T)-2(R+1)}, \qquad (47)$$

where ε_τ – the phase angle of collision, which is determined by the expression

$$\varepsilon_2 = \arcsin\frac{\delta}{2AV1-\Phi\omega} - arctg\Phi\omega + \pi, \qquad (48)$$

where Φ – the function of the vibrational mobility of particles, which is equal to

$$\Phi = \frac{\psi(T)+\psi(0{,}5T)-\psi(0{,}25T)}{0{,}5-\psi(T)-\psi(0{,}5T)-2(R+1)}, \qquad (49)$$

where m_τ is the mass of particles that participates in repetitively decaying collisions during the collision cycle.

The path of movement of the part during the collision:

$$S_g = V_0, \qquad (50)$$

Number of particles in the collision group:

$$n = K_n V t_\tau \left[0{,}5D(P-1)\right]^{-1}, \qquad (51)$$

where K_n – the number of granule particles that collide with the part; t_τ – the collision cycle time;

P dynamic loosening of the medium; D – the diameter of the particle (granule).

$$m_\tau = 4 \cdot V \cdot \tau^2 (G \cdot \tau + \alpha) \cdot \left[R \cdot D(P-10) \right]^{-1}. \quad (52)$$

Let's take into account the mass of technological solutions m_{ts}:

$$m_{ts} = \frac{n \cdot \rho \cdot \pi \cdot D^3}{g(P-1)}, \quad (53)$$

after which we get

$$m_E = m + \frac{\rho \cdot D^2 V \cdot \tau}{g(P-1)} \cdot \frac{4 \cdot V \cdot \tau^2 (G \cdot \tau + \alpha)}{R \cdot D \cdot (P-1)}, \quad (54)$$

where m and D are the mass and diameter of the particle; ρ is the density of the technological solution; V – collision speed.

A significant factor in shaping the surface of the workpiece is the energy index of the collision of the workpiece with the working medium (E), which is determined by the formula:

$$E = \frac{m(A \cdot \omega \cdot \cos \varepsilon)^2 \cdot (1 - R^2)}{0{,}5 - \psi(T) - \psi(0{,}5T)}, \quad (55)$$

Taking into account the collision energy indicator, the following equations are used to calculate the quality of the surface layer of the part [25, 26, 29]:

microrelief height

$$R_z = \left[R_z - \sqrt{\frac{23}{\pi DHM}} \right] R_z(n); \quad (56)$$

Hardness

$$HV = \left[\sqrt[4]{\frac{32E}{\pi D^3 HM}} \cdot 100\% \right] HV(n); \quad (57)$$

Depth

$$h_\mu = \left[1{,}5 \cdot \sqrt[4]{\frac{32ED}{\pi HM}} \cdot (1{,}54 - 10^{-3}) \right] h_{HV}(n) \quad (58)$$

;

Average value of normal compre sive stresses

$$\sigma = \left[0{,}481 \left(\frac{E}{(r^*)^3} \right) \right] K_{\mu D}^{0,8} \cdot \sigma(n); \quad (59)$$

$$K_{\mu E} = \left(\frac{1-\mu_d^2}{E_d^2} \right) + \left(\frac{1-\mu_g^2}{E_g^2} \right), \quad (60)$$

where D – particle (granule) diameter; HB, – HM Brinell and Mayer hardness of the material; $R_z(n)$, $HV(n)$, $hHV(n)$, $\sigma(n)$ – functionals of the initial change in the corresponding parameters due to repeated many times combined plastic impressions; $r^* = r_d \cdot r_g / (r_d + r_g)$ – radius of contacting surfaces; R_z^* – basic surface roughness; μ_d, E_d – Poisson's ratio and Young's modulus of the part; μ_g, E_g – Poisson's ratio and Young's modulus of the granule.

The parameters of the collision of particles of the medium with the processed parts can be determined in another way [25, 27], for example, the velocity of a particle (granule) of the medium is equal to:

$$V_{gwe} = V_{os} \cdot K_V, \quad (61)$$

where V_{os} is the speed of movement of the surface transmitting vibrations; K_V is the coefficient of speed that decreases with distance from the surface transmitting vibrations.

Expressions (62), (63) allow us to determine the collision force from the collision duration τ:

$$F_{E1} = \frac{K_d m_g V_{gve} (1+K) \cdot K_l K_\alpha K_m}{10 \cdot \Delta t \cdot K_\tau}, \quad (62)$$

$$F_{E2} = \frac{K_d m_g V_{gve} (1+K) \cdot K_l K_\alpha K_m}{10 \cdot \Delta t \cdot K_\tau} \cdot \frac{m_d}{m_g + m_d} \quad (63)$$

where K_α is the coefficient of the angle of contact of the pellet with the treated surface; K_l is the coefficient of the distance to the surface transmitting the vibrations; τ is the duration of the collision; K_τ is the coefficient of the duration of the collision; m_g and m_d is the mass of the pellet and the part.

$$\tau = A\omega^K \left(\frac{1-\mu_1^2}{E^2} + \frac{1-\mu_2^2}{E^2} \right) K^{0,8} t, \quad (64)$$

where t – the cycle time (period) of the collision of a group of granules, $t = R^* \cdot n(t)$.

To determine the recovery factor, we use the equation:

$$R = \sqrt{1 + \frac{T}{\frac{V_{gwe}}{\Phi}\sqrt{\frac{D_g}{4\omega}\sqrt{\frac{\rho(1-2\mu)}{Et_p}}}}}, \qquad (65)$$

where Φ – the criterion for the convergent Fourier series; ρ – the density of the granule material; ω – the ability of the material of the workpiece to transfer temperature; t_p – the relative length of the surface roughness profile.

The result of deformation processes during processing with a free working medium is influenced by such parameters as the variable value of the angle of contact and the coefficient of velocity recovery, the difference in the initial roughness of the surfaces of the granule and the part and the coefficient of friction, material, dimensions and shapes. To increase the accuracy of the calculation, it is necessary to take into account friction during oblique collisions, and a change in the roughness and hardness of the surface layer affects the coefficient of velocity recovery during collision.

In particular, when a granule collides with the sample surface, the value of the velocity recovery coefficient upon collision R for different values of the collision angle is

characterized by dependence:

$$R = \sqrt{H_{up} / H}, \qquad (66)$$

where H is the distance of the pellet's fall; H_{up} is the height of the pellet's rebound.

Conclusions. The physical nature of the process of machining with a combined abrasive medium under the action of vibrations is considered. The process is characterized by a complex interaction of mechanical, wave, thermal and chemical phenomena, which form a new structure of the surface of the part.

Combined abrasive machining is an oscillatory-impact system with non-stationary dynamics. The influence of external and internal oscillations causes the appearance of self-oscillating and resonant effects, which can be used to increase the productivity of the machining process.

The given ratios allow us to determine the impact forces, collision energy, velocity recovery coefficients, and damping.

It has been established that the efficiency of the process largely depends on the composition and condition of the combined working medium – the parameters of abrasive granules and technological solutions.

The use of multiple vibration sources with different parameters allows for local regulation of the movement of the medium, ensuring the required processing quality even in hard-to-reach areas.

The proposed processing method combines vibrational, mechanical, chemical, electrical and thermal effects on the surface of the part being processed. The method allows to ensure high accuracy, surface cleanliness and material strengthening while reducing energy and time costs.

References

1. Malkin S., Guo C. Grinding Technology: Theory and Application of Machining with Abrasives. 2nd ed. New York: Industrial Press Inc., 2008. 372 p.
2. Handbook of Machining with Grinding Wheels. Boca Raton / Marinescu I.D. and others. CRC Press, Taylor & Francis Group, 2006. 750 p.
3. Fang X., Wu C., Liao N., Yuan C., Xie B., Tong J. The first attempt of applying ceramic balls in industrial tumbling mill: A case study. *Minerals Engineering.* 2022. Vol. 180.
4. Iwasaki T., Yamanouchi H. Ball-impact energy analysis of wet tumbling mill using a modified discrete element method considering the velocity dependence of friction coefficient. *Chemical Engineering Research and Design.* 2020. Vol. 163. P. 241–247.
5. Tshimanga N., Combrink G., Kalenga M. Surface morphology characterization of grade 304L stainless steel after abrasive blasting. *Materials Today: Proceedings.* 2021. Vol. 38, No. 2. P. 544–548.
6. Jerman V., Zeleňák M., Lebar F., Foldyna V., Foldyna J., Valentinčič J. Observation of cryogenically cooled ice particles inside the high-speed water jet. *Journal of Materials Processing Technology.* 2021. Vol. 289.
7. Miturska-Barańska I., Rudawska A., Doluk E. The influence of sandblasting process parameters of aerospace aluminium alloy sheets on adhesive joints strength. *Materials (Basel).* 2021. Vol. 14, No. 21.
8. Nikolaenko V.H. Vibrational technologies of finishing treatment of parts. Kharkiv: NTU “KhPI”, 2020.
9. Marinescu I.D., Rowe W.B., Dimitrov B., Inasaki I. Tribology of Abrasive Machining Processes. 2nd ed. Boca Raton: CRC Press, Taylor & Francis Group, 2013. 600 p.
10. Thomson W.T., Dahleh M.D. Theory of Vibration with Applications. 5th ed. Upper Saddle River: Prentice Hall, 1998. 524 p.
11. Den Hartog J.P. Mechanical Vibrations. New York: Dover Publications, 1985. 436 p.

12. Harris C.M., Piersol A.G. Harris' Shock and Vibration Handbook. 5th ed. New York: McGraw-Hill, 2002.
13. Blekhman I.I. Vibrational Mechanics: Nonlinear Dynamic Effects, General Approach, Applications. Singapore: World Scientific, 2000. 509 p.
14. Babichev A.P. Dynamics of vibrational processing systems with free abrasive media. Kharkiv: NTU "KhPI", 2019.
15. Hladkyi M.I. Mechanical waves and oscillatory processes in elastic media. Kyiv: Naukova Dumka, 2018.
16. Kaplunov S.V. Mechanics of materials and wave processes. Kharkiv: KhNU, 2019.
17. Radchenko V.A. Ultrasonic oscillations and wave processes in material processing. Dnipro: DNU, 2020.
18. Petrov I.H. Dynamics of elastic. Kyiv: KNU, 2015.
19. Popov O.M. Shock waves and their propagation in metal rods. Lviv: LNU, 2018.
20. Sidorenko A.I. Intensive material processing using mechanical vibrations. Kharkiv: Mashynobuduvannya, 2021.
21. Chernenko O.O. Wave processes in impact and non-stationary systems. Kyiv: Naukova Dumka, 2017.
22. Nikolaenko A.P. Increasing the productivity of vibrational processing by selecting the location of the vibration source relative to a U-shaped container: Dissertation… candidate of technical science: 05.03.01 Donetsk: Donetsk National Technical University, 2010. 243 p.
23. Bhushan B. Introduction to Tribology. 2nd ed. Hoboken: John Wiley & Sons, 2013. 711 p.
24. Kalpakjian S., Schmid S.R. Manufacturing Processes for Engineering Materials. 6th ed. Upper Saddle River: Pearson, 2014. 1018 p.
25. Evans A.G., Hutchinson J.W., Fleck N.A. Mechanics of Materials: Deformation and Contact Interactions in Particulate Systems. Cambridge: Cambridge University Press, 2001.
26. Rittel D., Chen W. High strain rate deformation and impact behavior of granular and composite materials. *Journal of the Mechanics and Physics of Solids.* 2005. Vol. 53, No. 12. P. 2711–2731.
27. Nguyen T., Papadopoulos C. Vibratory finishing and micro-cutting: Analysis of particle-surface interactions in abrasive media. *Wear.* 2010. Vol. 269, No. 11–12. P. 845–854.
29. Zhao Y., Guo X. Dynamic behavior of particulate media under vibration: Implications for surface treatment. *Powder Technology.* 2017. Vol. 319. P. 1–12.
30. Goldsmith W. Impact: The Theory and Physical Behaviour of Colliding Solids. London: Edward Arnold (Publishers) Ltd., 1960. 379 p.
31. Stronge W.J. Impact Mechanics. Cambridge: Cambridge University Press, 2000. 380 p.
32. Johnson K.L. Contact Mechanics. Cambridge: Cambridge University Press, 1985. 452 p.

Романченко О.В. Фінішна обробка деталей комбінованим робочим середовищем під дією коливань. Фізичні явища та динаміка контактної взаємодії..

В статті проаналізовані процеси фінішної обробки з використанням комбінованого абразивного середовища під дією коливань, що поєднує механічні, фізичні, хімічні та енергетичні явища. В роботі досліджується фізична природа коливальних процесів, закономірності взаємодії між абразивними частками та поверхнею деталі, а також визначаються умови, за яких досягається максимальна ефективність обробки. Представлено порівняльний аналіз традиційних методів фінішної обробки – шліфування, галтування, абразивно-струменева та вібраційна обробка. Визначено їх переваги, недоліки та межі застосування в сучасному машинобудуванні.

Запропоновано новий метод фінішної обробки – обробка комбінованим робочим середовищем, який поєднує абразивні, хімічні, термічні, електричні та механічні дії. Комбіноване робоче середовище складається з абразивних гранул, технологічних розчинів та інтенсифікаторів процесу, які під дією коливань здійснюють складний, детермінований циркуляційний рух, створюючи чисельні мікроудари на поверхні деталі. Це дозволяє проводити операції очищення, шліфування, полірування, зміцнення поверхневого шару, зняття залишкових напружень, покращення адгезії та підготовку поверхні до нанесення покриття. Як і традиційні методи, цей метод дозволяє одночасно обробляти велику кількість деталей, а його комплексний підхід дозволяє досягти необхідної якості поверхні за коротший час обробки.

Розкрито механізм контактної взаємодії між абразивним середовищем та поверхнею деталі. Встановлено, що процес супроводжується явищами удару, кавітації, адгезії, зношуванням, поширенням хвиль та розсіюванням енергії. Коливання поділяються на частотні діапазони, від інфразвукових до ультразвукових. Досліджено вплив вільних, вимушених, параметричних та автоколивань на процес, а також їх вплив на поведінку робочого середовища та деталей.

Показано, що процес обробки є складною коливально – ударною системою з розподіленими параметрами, в якій значну роль відіграють частота, амплітуда, властивості абразиву, геометрія деталі та режими роботи обладнання.

Досліджено динамічні властивості робочого середовища: циркуляційний рух, пружна ударна взаємодія частинок, формування хвиль тиску, контактні процеси та деформація поверхневих шарів. Надано інформацію щодо впливу технологічних розчинів на інтенсивність процесу. Представлено математичні залежності, що описують зміни параметрів контакту, енергії удару, швидкості часток, сили взаємодії.

Запропонований підхід розширює можливості фінішної обробки в машинобудуванні, зокрема для деталей зі складною геометрією та високими вимогами до якості поверхні, та створює основу для подальшого розвитку технологій обробки комбінованими робочим середовищами під дією коливань.

Ключові слова: *фінішна обробка, комбіноване робоче середовище, коливальні процеси, мікроудари, циркуляційний рух, технологічний процес.*

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