Technological provision for vibration cleaning of products in preparing them for disposal

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Abstract. The article discusses one of the main stages of products’ preparation for disposal, providing for their cleaning from contamination; it is shown that the most promising methods of cleaning treatment are the mechanochemical cleaning methods based on the use of a different vibration spectrum of the processing substance. Depending on the nature of contamination, the material and shape of the processed parts, the conditions of vibration cleaning (mode, working environment, washing and dissolving liquids) can be varied. Based on the studies carried out, it has been established that the vibration cleaning of the surface depends directly on the work of the influence force on contamination which, in turn, depends on the dynamic activity of the particles of the working environment and the gravitational activity of the process fluid. An energy condition and calculated dependencies are proposed that can be used in the development of vibration cleaning technology for specified contaminants and product materials when solving a specific applied problem, as well as developing and optimizing the vibration cleaning process for products, describing and justifying the influence of mechanochemical phenomena on the intensification of the cleaning process in order to identify technical and economic effect from the use of vibration processing method.

1. Introduction
Disposal is a complex of technological, design and organizational measures aimed at restoring or giving a working resource to objects of material production, as well as using them for a new purpose with minimum energy and material costs, or for processing in order to obtain samples for subsequent use as material resources, in any branch of production or in the production of energy with minimum environmental harm. The most important technological stages that determine the life cycle of a product (LCP) at the disposal stage are the preparatory operations. Thanks to multi-stage cleaning and washing, alternating with product’s disassembly, as well as with fault detection and sorting, the efficiency of organizing and preparing the product or its components for further disposal is ensured.

2. Cleaning treatment as one of the main stages of products’ disposal
Mechanical engineering products for various applications have to work in different conditions, under different weather conditions. In this case, both external objects and internal surfaces of the product are contaminated.

Contamination is formed not only due to contact with soil, plants, fuel and lubricants, but also under variable temperature conditions, in the presence of friction between parts, when parts interact with each other and parts with the working environment and under the influence of other surface factors of combined parts. They reduce the resistance of protective and decorative coatings, increase the rate of corrosion processes, reduce the culture level of maintenance and repair of machines and, as a result,
serve as one of the reasons leading to a decrease in the reliability of machines and units and their life cycle. The mechanism of their formation is based on adhesion to the original surface. Figure 1 shows a classification description of various contamination types of mechanical engineering products [1]. These contaminants appear due to various physical and chemical processes, as well as various temperature modes of individual parts operation and are found partially or completely in products of agricultural machinery, automobiles, etc. during their life cycle.

Continuous improvement of cleaning and washing technologies remains one of the urgent tasks of recycling engineering products. The cleaning method depends on the type of contamination, the product being cleaned (the kind and composition of the material from which the part is made, its shape), the properties of the cleaning agents (their composition, physical state), the density of the pollution, etc. The cleaning substance can be solid, liquid, gaseous or mixed. Separate washing operations are combined with degreasing, i.e. with the removal of oils and fats from the surfaces of parts. Modern methods of cleaning the contaminated products provide for a complex mechanical, chemical and physicochemical interaction of cleaning solutions with contaminants and the surface to be cleaned.

**Figure 1.** Classification of the main contamination of mechanical engineering products

The most promising methods of cleaning treatment are mechanochemical cleaning methods based on the use of a different vibration spectrum of the processing substance such as vibration and ultrasonic treatment [2].

The process of removing contaminants during the vibration treatment is generally due to the presence of two of its main elements: the mechanical action in the form of particles micro-hit of the working
substance and washing off the contaminants with a circulating washing solution. Shaking the load entire mass, as well as the variable speed-up, caused by the vibration nature of the working chamber movement with a frequency of 5-50 Hz and an amplitude of up to 5 mm, cause the separation of relatively large masses (particles) of contaminants, with less force adhered to the cleaned surface. As a result of the parts collision with particles of the working substance, primary cracks are formed at the interface between the two materials, which, with repeated hits, lead to contaminants delamination and separation from the surface of the part. Performing the process of washing-off, the liquid, getting into the formed cracks and delamination, speeds up the cleaning process.

Thus, the above mentioned factors help the removal of relatively large and less densely adhered parts of contaminants to the metal surface, providing, as it were, macro-cleaning. Macro-cleaning happen in the first processing period. This removes 60-75% of the entire mass to be cleaned. The rest of the contamination is removed mainly under the action of particles micro-hits of the working substance, which carry out, as it were, the process of micro-cleaning the surface, completing the removal of the most dense layers of contaminants accumulated on the surface.

In this case, the destruction and dispersion of contaminants take place as a result of the hits and scratching action of particles of the working substance. In this case, a significant role is played by the particles’ scratching effect of the working substance, which have the hardness of the cutting (scratching) elements (abrasive grains) greater than the material to be destroyed. The presence of an abrasive substance provides a more intensive removal of contaminants, which is a consequence of the relatively higher hardness of abrasive granules than hardness of the shot, stamping and other metal particles of the working substance.

When the appropriate chemicals are added, the TJ acquires the properties of dissolving the contaminants, and, thus, the vibration cleaning process of parts from contamination can be supplemented by a third element – the dissolution of contaminants. Therefore, during the vibration cleaning process, the surface is wiped (particles’ dynamic contact of the working substance with the surface to be cleaned) and the entire mass of the working substance and parts is mixed, the parts rinsing in a washing solution as a result of shaking, loosening of contaminants and weakening of their connection with the surface of the part due to the action of chemically active substances.

In the work [8] it is shown that the superposition of ultrasonic vibrations causes an increase in the intensity of vibration treatment and, as a consequence, to an increase in the efficiency of vibration cleaning.

Depending on the nature of contamination, material and shape of the processed parts, the conditions of vibration cleaning (mode, working environment, washing and dissolving liquids) can be varied.

3. Energy model of products vibration cleaning from contamination

Removal of contaminants is always, in one way or another, the work to separate contamination from the surface to be cleaned. In this case, the task is brought to overcoming the adhesion forces between the contacting bodies, which are determined by the interaction energy of the contamination particles both among themselves and on the division border between these bodies.

In general, the formula for calculating the forces \( F_z \), spent on the destruction of contaminants and their separation from the cleaned surface [3]

\[
F_z = W \cdot S,
\]

where \( W \) – is the adhesion of contamination, MPa;
\( S \) – contamination contact surface (contamination surface area), m².

Contamination formed on the surfaces of parts and products from the point of view of adhesive interaction can be of three types: liquids, old layers and particles. The adhesive interaction of contaminants with a surface is determined by methods of quantitatively assessing this interaction using adhesive strength. The adhesion of liquids, old layers and particles can be estimated by the force and work that must be applied to break the adhesive interaction, i.e. for tearing off. The strength of the adhesive bonds of various types of contaminants (liquids, old layers, particles) will be determined by
the properties of their intermolecular interaction [4]. Accordingly, adhesion will differ quantitatively for contaminants that are different in nature.

The adhesion of the contamination particles interaction with each other and with a solid surface can be estimated from the ratio.

\[ W = \frac{m g}{S} \]  

(2)

where \( m \) – is the mass of contamination particles, kg;
\( S \) – is the actual contact area, \( \text{m}^2 \);
\( g \) – gravity acceleration, \( \text{m/s}^2 \);

In turn, the adhesion of particles differs in air (gas) and liquid substance. If the height of the liquid layer in the gap between the contacting bodies exceeds the height of the meniscus formed when the contacting bodies are wetted, then adhesion is considered as liquid [4]. Removal of liquid contaminants from the surface cannot be carried out by the methods used in the case of adhesion of particles, i.e. by applying an external force exceeding the adhesive interaction [5]. The force deforms the fluid and changes the area of its contact with the surface.

Old layers adhesion is quantified using peel-off methods. The amount of adhesion of old layers cannot be precisely calculated [3]. The work required to pull them off can be determined experimentally, taking into account the individual properties of the materials.

If we consider the cleaning process as a process of destruction under the action of certain forces exceeding the adhesion forces, then, other things being equal, the work of the cleaning forces should be greater than the adhesion of the contamination.

\[ F_o \geq W \cdot S \]  

(3)

At the same time, it is necessary to do enough work to separate contamination from the body to be cleaned completely. This work can be effectively ensured under conditions of vibration treatment by the complex action of a granular working substance and an active process fluid. During vibration treatment, cleaning of the surfaces (erosion of contamination), dispersion of solid particles and emulsification are carried out mainly by two specific effects: shock-impulse force action of solid particles of the working substance and hydrodynamic cavitation caused by acoustic action of shock waves.

Let us consider the influence of these effects on the process of cleaning the parts surface from contamination.

The speed of collision of particles of the working substance with the processed surface of the parts is determined by the well-known formula [2]

\[ V_{w.e.p.} = 2\pi A f K_V \cdot \text{m/s} \]  

(4)

where \( A, f \) – are the amplitude (m) and frequency (Hz) of vibrations of the working chamber;
\( K_V \) – the coefficient of speed loss;
\( l \) – the distance from the wall of the working chamber to the point under consideration (particles of the working substance).

The functional dependence of the forces of the particles dynamic action of the working substance on the surface of the processing parts on the conditions of the process is described by empirical equations:

– when processing freely loaded parts

\[ F_{fr} = 6V_{w.e.p.} \left( \frac{1}{K} \cdot m_1 \cdot \delta_s \cdot R \cdot K_m \cdot K_D \cdot B \right)^{0.5} \cdot \frac{1}{K} \cdot m_1 \cdot \delta_s \cdot R \cdot K_m \cdot K_D \cdot \left(1 - \frac{3}{\delta_s} \cdot K_1 \right)^{0.5} \]  

(5)

– when processing fixed parts

\[ F_{fix} = 6V_{w.e.p.} \left[ \frac{1}{K} \cdot m_1 \cdot \delta_s \cdot R \cdot K_m \cdot K_D \cdot \left(1 - \frac{3}{\delta_s} \cdot K_1 \right) \right]^{0.5} \]  

(6)

where \( m_1 \) – the mass of a particle of the working substance, kg;
\( \delta_s \) – the fluidity limit of the working substance, Pa;
\( R \) – the radius of a particle of the working substance, m;
\( K_m \) – the coefficient of added mass;
$K_0$ – the coefficient that takes into account the deforming properties of the walls of the working chamber;

$K$ – the coefficient of repeated strikes;

$K_l$ – the recovery factor;

$B$ – the coefficient that takes into account the amount of hit energy going to rebound and to move the processing part.

Collision forces vary widely depending on the vibration mode and characteristics of the working substance, reaching 5 - 50 N and more.

Contact pressures $P_c$ (MPa) in the collision zone are determined from the equation

$$P_c = \frac{3 \cdot F}{2 \pi a \cdot b},$$

where $F$ – is the collision force, N; $a$ and $b$ – the dimensions of the semi-axes of the contact area formed on the surface by particles of the working substance.

During the vibration processing, the most characteristic is the collision of a spherical surface with a flatness, when $a = b$. In this case, the formula for determining the dimensions of the semi-axes of the imprint area is simplified and has the form

$$a = 0.0677 \cdot [2 \cdot F \cdot R]^{\frac{1}{3}}.$$

Vibration cleaning, as a rule, is carried out under conditions of continuous supply of the process fluid to the working chamber of the required composition according to the processing conditions [2]. The use of process fluid provides: removal of contamination products from the surface of the part. By adjusting the liquid level in the working chamber, the cleaning intensity is stabilized. Thus, the presence of liquid in the working chamber and on the surface of parts is the necessary condition under which the cavitation processes are activated, which cause gravitational erosion of contamination of the parts surface.

The finely dispersed contamination particles moving under the influence of acoustic currents along with the main particles of the working substance, getting into the shock waves zone arising from the collapse of cavitation bubbles, acquire high speeds and provide additional destruction of contamination due to the hitting the surface.

In works [6, 7, etc.] it was established that cavitation destruction is effective when the process proceeds at an increased static pressure compared to atmospheric pressure. During the vibration processing, the high hydrostatic pressure inside the mass of the charge performing a circulating movement in the working chamber is due to the high density of particles contact of the working substance, both with each other and with the processed parts. In addition, the hydrostatic pressure directly depends on the dynamic state of the vibration technological system, which is largely determined by the amplitude and frequency parameters.

On the contaminated surfaces there are always stress concentrators in the form of microcracks, uneven surfaces, etc. Under the intense microflows actions, liquid with cavitation bubbles (caverns) penetrates into pores, cracks, under the exfoliated contamination parts, where, when they collapse, a powerful local shock pressure with strong unevenness arises. In this case, the appearance of additional cracks and traces of erosion in the contamination layers causes the immediate destruction of contamination. In addition, the destructive effect of the cavity can appear during its expansion. In this case, the cavity, with a sharp expansion by its edges, can produce hits against the surrounding liquid, which can be transmitted to the destroyed material (contamination).

During the collapse, the cavitation bubble emits a shock wave, which near to the collapsing bubble can be strong enough to compress the nearest nuclei to an even smaller volume. After the shock wave passing, these nuclei are broken, and a collapse chain is created [7].

The acting load in the contact can be calculated analytically as an equivalent stress reflecting the energy of force action on microparticles located in the collapse zone of the cavitation bubble. According to studies [6], the specific pressure $P_{cav}$ (MPa) developed by the cavitation bubbles with radius $R_{max}$, can be calculated by the formula:

$$P_{cav} \simeq \frac{4}{3} \pi R_{max}^3 \cdot p_g,$$

where $p_g$ is the specific pressure of the gas.
where $R_{\text{max}}$ – is the maximum radius of the cavitation bubble at the moment of collapse; $p_g$ – the gas pressure in the bubble cavity.

Assuming that $p_g = p$, where $p$ – is the hydrostatic pressure in the surrounding fluid, we can write

$$P_{\text{cav}} \approx \frac{4}{3}\pi R_{\text{max}}^3 \cdot p.$$  \hspace{1cm} (10)

In [6] it is shown that the bubble size increases according to the law:

$$R = \sqrt[3]{2p \cdot t_m},$$  \hspace{1cm} (11)

where $\rho_l$ – is the density of the liquid; $t_m$ – the growth time of the cavitation cavity before collapse.

This dependence makes it possible to estimate the maximum radius of the cavitation bubble $R_{\text{max}}$.

The number of hits that destroy the contamination is only a small fraction of the number of collapsing bubbles. Depending on the initial parameters of the development of cavitation (flow rate, size of cavities, etc.), a sufficiently high pressure may or may not develop during the collapse on a contaminated surface. It may also turn out that the collapse center is located too far from the surface and the forming shock wave is not capable of causing destruction. The strongest hit on contamination is caused by the action of micro-streams formed when the bubbles collapse. The collapse of the bubble occurs in hundredths and thousandths of a second, so the liquid surrounding the bubble takes its place at a high speed, which leads to a local cumulative hit of the liquid. Cumulative streams destroy contamination on the surface of a solid due to the kinetic energy of the liquid. The liquid penetrating into the cavity of the cavity during its destruction produces a hit, which can be approximately estimated by the formula given in [6]:

$$P_{\text{cum}} = \sqrt{\rho_l \beta}, \text{ MPa},$$  \hspace{1cm} (12)

where $\nu$ – is the penetration speed of the stream into the cavity of the cavity; $\rho_l$ – the density of the liquid; $\beta$ – the fluid compression modulus.

According to the data from [7], the cumulative stream velocity is determined from the relation:

$$\nu = \sqrt{\frac{52p}{3\rho_l}},$$  \hspace{1cm} (13)

The liquid compression modulus is the relative change in the volume of the liquid per unit of pressure change:

$$\beta = \frac{\Delta V}{\Delta p \cdot V},$$  \hspace{1cm} (14)

where $\Delta V$ – is the volume of the affecting cavitation bubbles; $V$ – the volume of all cavitation bubbles.

The destruction of contaminants occurs under the influence of multiple short-term voltage impulses. The collapse of a single bubble is not enough to destroy the contamination, but the collapse of a series of bubbles in the same place is necessary. As a parameter, characterizing the effect of cavitation, a dimensionless value is taken – the cavitation index $k = \frac{\Delta V}{V}$, proposed in [6].

Since cavitation cavities can occupy (relative to the volume of the entire liquid) a volume from 0 to the entire volume, the cavitation index will lie within $0 \leq k \leq 1$. The number of cavitation bubbles per unit volume of liquid and the intensity of shock waves arising when they collapse determine the erosion activity of the washing substance. With an insufficient rate of formation of bubbles or in their complete absence, destruction does not occur. Assuming the ideal condition for the cleaning process ($k = 1$), in this case the maximum erosive activity of the washing liquid is represented.

Thus, the destruction effect of contamination from gravitational action in the process of vibration cleaning will be determined by the pressure from each collapsed bubble, both the action of the pressure of the shock wave from expansion and collapse, and from the action of the cumulative stream, multiplied by the number of collapsing bubbles in the local area of the contamination area, i.e.

$$P_g = (P_{\text{cav}} + P_{\text{cum}})K,$$  \hspace{1cm} (15)

where $K = 3\Delta V/4\pi R_{\text{max}}^3$. 

where $R_{\text{max}}$ – is the maximum radius of the cavitation bubble at the moment of collapse; $p_g$ – the gas pressure in the bubble cavity.
An increase in thermal conductivity and a decrease in gas content with an increase in the temperature of the surrounding liquid partly explain the presence of a maximum of cavitation erosion [8]. When a stationary flow of liquid moves in places of narrowing of the flow, where the speed increases, the pressure in the liquid goes down, the cavitation cavities appear in these places. The formation of different pressures zones in the flow occurs due to different curvilinear flows.

To assess the possibility of cavitation from work [7], the value of \( k \) is used – the number of cavitation, determined by the formula:

\[
k = \frac{p - p_r}{0.5 \rho \vartheta \vartheta^2}.
\]

where \( \vartheta \) – is the fluid flow rate.

It follows from (19) that the larger the value of \( k \), the lower the probability of cavitation.

Thus, from the results of the studies carried out, it can be concluded that the vibration cleaning of the surface directly depends on the work of the force influence on contamination, which in turn depends on the particles dynamic activity of the working substance and the gravitational activity of the process fluid. In general, the energy condition for vibration cleaning of the part surfaces from contamination can be represented as follows:

\[
P_p + P_{cav} + P_{cum} > W
\]

Using the energy condition, we will consider one of the main technological problems associated with the assessment of the duration of vibration cleaning of a contaminated surface.

4. The estimation of vibration cleaning duration of contaminated surface

In general, the equation for estimating the vibration treatment duration of a contaminated surface can be represented as:

\[
\tau_p = Z_{cr} \frac{Z}{Z} \frac{\partial t}{\partial t}.
\]

where \( Z_{cr} \) – is the critical value of the function that controls the contamination destruction; \( Z \) – the growth rate of this function, \( \partial Z / \partial t \).

As a function of \( P \), we will consider the removal of the contamination layer from the surface of the part. Then the equation of the vibration cleaning duration will take the form:

\[
\tau_c = \frac{Q_{cr}}{\gamma_0}
\]

where \( Q_{cr} \) – is the volume of the contaminated layer to be removed from the surface;

\( \gamma_0 \) – the rate of destruction of the contaminated layer in the process of vibration cleaning;

During the processing, the contaminated surface of the part is continuously exposed to the dynamic effect of abrasive granules and the gravitational activity of the process fluid. The uniformity of the processing of the contaminated surface will be ensured only when each single element of the surface conditionally allocated on the contaminated surface is subjected to destruction and, as a result, purification. Therefore, the intensity of contaminants removal from the surface during the vibration cleaning can be quite objectively estimated by simulating the process of processing a single element of the surface. If we take as a unit element the area of the square of the packing of abrasive granules of the processing substance on the surface with a side equal to the diameter of the circumscribed circle of radius \( R \), then the dependence for assessing the rate of removal of contaminants from the surface during the vibration effect of the flow of abrasive granules and the gravitational activity of the process fluid, by analogy with the dependence proposed in work [9] for metal removal, can be represented as follows:

\[
\gamma_0 = B_1 B_2 f q ; \text{ kg/s}
\]

where \( B_1 \) – is the geometric probability of the event that any point of the packing square in one cycle is subjected to the energy-force effect of the abrasive granules mass and cavitation bubbles;

\( B_2 \) – the probability of an event that the interaction of an abrasive particle and cavitation bubbles with the surface of the part will lead to the destruction of contamination;

\( f \) – vibration frequency of the working chamber, \( s^{-1} \);
\( q \) – the amount of contamination removal in a single act of interaction of an abrasive granule and the gravitational activity of a process fluid with a contaminated surface of a part, kg;

The presented dependence (20) was obtained from the condition of the similarity of the processes, both on the entire area of the contaminated part, and on the area limited by the square of the packing of abrasive granules.

Since during vibration cleaning the shock impulse action is the leading one for determining the parameters included in the calculation model (20), we will use the dependencies proposed in the robot [9], presenting them in the form:

\[
P_1 = \frac{\pi \cdot a^2}{\pi a^2 + 8Ra + 4R^2}; \quad P_2 = 0.67 ;
\]

\[
q = 15.5k_p k_g R^3 \left( k_m^0.5 P_{max} \sin \beta \sqrt{\frac{\zeta \rho_z}{M HV}} \right)^{5 \over 2} \left( \cot \beta - \mu \right) \rho_z ,
\]

where \( k_p \) - is the coefficient of the surface contamination;

\( k_g \) - the coefficient taking into account the effect of the grain size of the abrasive particle on the actual contact area;

\( k_m \) - is the coefficient taking into account the influence of neighbouring particles during processing;

\( \rho_z \) - the density of the contaminated layer;

\( P_{max} \) - the maximum energy-force effect of the abrasive granule and the gravitational activity of the process fluid on the contaminated surface;

\( \beta \) - the collision angle of abrasive particles;

\( \mu \) - the friction coefficient of abrasive grain on the contaminated layer;

\( Pp \) - the density of abrasive particles,

\( HV \) - the hardness of the contaminated layer,

\( \zeta \) - the compliance of the contaminated layer,

\( M \) - the reduced mass of abrasive particles affecting the contaminated surface.

Taking into account (17), the formula (22) for calculating the amount of contamination removal in a single act of an abrasive granule interaction and the gravitational activity of a process fluid with a contaminated surface of a part will have the following form:

\[
q = 15.5k_p k_g R^3 \left( k_m^0.5 \left( P_p + P_{cav} + P_{cum} \right) \sin \beta \sqrt{\frac{\zeta \rho_z}{M HV}} \right)^{5 \over 2} \left( \cot \beta - \mu \right) \rho_z
\]

The mass of the contaminated layer with the thickness \( \Delta L \) to be removed from the square of the package can be estimated from the dependence:

\[
Q = 4R^2 \Delta L \rho_z ;
\]

Using the dependencies (19, 20, 24), we obtain the formula for determining the vibration cleaning time to remove the contaminated layer from the surface:

\[
T = \frac{4R^2 \Delta L \rho_z}{B_1 B_2 f q}
\]

**Conclusion**

The proposed energy condition and calculated dependencies can be used in the development of vibration cleaning technology for given contaminants and product materials in solving a specific applied problem, as well as the development and optimization of the vibration cleaning process for products, description and justification of mechanochemical phenomena on the intensification of the cleaning process in order to identify the technical and economic effect from the use of vibration processing.
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