UDC 621.9.048 **doi: 10.20998/2078-7405.2022.97.09**

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THE NATURE OF THE FORMATION OF SURFACE MICRO-ROUGHNESS IN VIBRATION FINISHING AND GRINDING PROCESSING

Abstract. *The main aspects related to the nature of the formation of surface micro-roughness during vibration finishing and grinding processing are given. It is indicated that the material removal from the surface of the part occurs as a result of the combined action of micro-cutting processes, chipping of metal particles during repeated deformation of the processed surface areas, their fatigue and destruction, the formation, destruction and removal of secondary structures, and adhesion phenomena. It is noted that the real surface after vibration treatment is a set of roughnesses of a certain size, shape and direction. It is defined that the micro-roughness of the surface of the part during vibration finishing and grinding is formed in the form of traces from numerous impacts of abrasive granules on the surface of the part. The largest value of the granule penetration into the processed surface is determined, that makes it possible to characterize the trace from plastic compression in the zone of collision between the granule and the part. The technique and study of the mechanism of formation of surface microroughness is considered. An expression is determined for the normal component of the impact force, which characterizes the main effect on the mechanism of micro-roughness formation. The value of penetration of the granule into the metal of the part is determined. The study showed that the surface micro-roughness during vibration treatment is formed by impacts of granules on the part at different meeting angles. The traces from action of straight and oblique impacts are established. The average height of micro-roughness is calculated. According to the hodographs, the normal velocities of abrasive granules and parts are determined. The average value of the angle of impact of the granules with the part at any point of the trajectory of their movement is also determined. It was revealed that the velocities of granules and parts change in magnitude and direction during one period of the reservoir oscillation, reaching their limiting values, which are proportional to the reservoir movement velocities. The degree of proportionality is expressed by the similarity coefficient for the granule and the part. The average similarity coefficient was also determined by the points of the hodograph. The average values of the movement velocities of the granule and the part in the reservoir are obtained. The minimum and maximum value of the granule penetration into the surface of the part is established. The formulas for the limiting values of the granule penetration depth are given, taking into account the coefficient of ellipticity. The results of calculations for determining the height of micro-roughness of the processed part surface are presented. A formula is obtained for determining the surface micro-roughness during vibration finishing and grinding processing.*

Keywords: *vibration treatment; abrasive granule; processed part; collision between granule and processed part; collision angle; surface micro-roughness; velocity hodographs.*

1. Introduction

In vibration finishing and grinding process, as well as in other finishing methods, the processed surface in terms of geometric parameters is the intersection of the original surfaces with new processing traces, characteristic for this process [1, 2].

The nature of this intersection may be different under different processing conditions. That is, the nature of the micro-roughness of the parts surface layer during vibration treatment is the result of its deformation by granules of a free abrasive medium, as well as by the action of physicochemical processes taking place in the zone of collision of granules with the processed part [3].

In this case, the removal of material from the surface of the part occurs as a result of the combined action of such processes as micro-cutting with the part metal removal, chipping as a result of multiple deformation of the processed surface sections and their fatigue and destruction, the formation, destruction and removal of secondary structures, adhesion phenomena. The real surface after vibration treatment is a set of roughness of a certain size, shape and direction [4].

The study of traces of processing, their structure and dimensions provides information about physical phenomena in the collision zone of granules and processed parts, and also reveals the nature of the formation of micro-roughness of the newly formed surface.

2. The nature of the collision of granules with the surface of the processed part

It is known from practice that the micro-roughness of the surface of parts during finishing and grinding processing is formed in the form of traces from numerous wave impacts of abrasive granules on the processed surface of the part [5, 6].

During vibration processing, inelastic bodies collide, as a result of which the depth β of indentation of a granule into the part surface can be determined by the equality $\beta = \beta_1 + \beta_2$, where β_1, β_2 is the elastic and plastic parts of local crushing and indentation.

The elastic part β_1 of the local collapse after the rebound of the abrasive granules from the processed surface is restored to its original state. The trace left on the part is determined by the size of the local collapse.

The largest value of the penetration of the granule into the part surface is determined as,

$$\beta_{2\max} = \frac{a}{\pi D \sigma_s} P_N ,$$

where a is a constant coefficient, $a = 0.35$; D – imprint diameter; σ_s – yield strength of the material under simple tension; P_N is the normal component of the impact force in an oblique collision.

Elastic-plastic deformations of the abrasive granule in the zone of contact with the part are not taken into account due to the significant hardness of the material from which the part is made [7, 8].

Under the action of the normal component of the impact force P_N , the processed surface of the part under the granule flows and is squeezed out around its periphery, forming a trace from plastic compression.

3. Technique and study of the mechanism of formation of micro irregularity of the processed part surface

In oblique impact, the normal component of the interaction causes the penetration of the granule into the surface of the part, the tangential component causes the shear of the metal. The main action on the mechanism of formation of micro-roughness is exerted by the normal component of the impact force. It is determined by the expression:

$$P_N = \frac{2(1+k)mM\left(V_1 \sin\alpha_1 - V_2 \sin\alpha_2\right)}{\Delta T\left(m+M\right)}.$$

Hence, the value of the granule penetration into the metal is determined as:

$$\beta_2 = \frac{a(1+k)mM\left(V_1 \sin\alpha_1 - V_2 \sin\alpha_2\right)}{\pi D\sigma_s \Delta T\left(m+M\right)},$$

where k is the recovery factor; m – weight of the granule; M – mass of the part; V_1, V_2 – velocities of a granule and a part at the moment of their collision; ΔT – collision time; α_1, α_2 – angles between the direction of the velocity of the abrasive granule and the part and the normal to the line of centers of the colliding bodies; $D = \rho_x$ – grain size of the granule material; σ_s – the yield strength of the material of the part at simple tension.

Experimental studies show that the micro-roughness of the surface during vibration treatment is formed by impacts of granules at different meeting angles and has an irregular character [9]. You can determine the traces of the impact of direct and oblique impacts. There are n_1 traces from straight and n_2 traces from oblique impacts on the surface of the part with a length of l . The average height of micro-roughness, calculated on the basis of geometric constructions, is equal to:

$$H_{avg} = \frac{\left(\beta'_{2\min} + \beta'_{2\max}\right)n_1 + \left(\beta_{2\min} + \beta_{2\max}\right)n_2}{2\left(n_1 + n_2\right)},$$

where $\beta'_{2\min}$ and $\beta'_{2\max}$ – the smallest and largest depth of penetration of the granule during an oblique impact; n_1, n_2 – the number of straight and oblique impacts of the granule.

Obviously, the penetration depth is proportional to the normal component of the collision velocity, that is, $V_1 \sin\alpha_1 - V_2 \sin\alpha_2 = V_{avg}$, where V_{avg} is the average collision velocity.

The value $V_1 \sin\alpha_1$ represents the velocity of the granule directed along the line connecting the center of the colliding bodies. The value $V_2 \sin\alpha_2$ represents a similar value. These values are the velocity components V_1 and V_2 directed along the line of impact of the abrasive granule on the part.

The normal velocities of the abrasive granule and processed part can be determined from the hodographs of their velocities. By superimposing hodographs one on another, we determine the angles between their velocities at each point (Fig. 1). Then the angle between the velocities of the granule and the part at point *1* will be equal to α_1, at point 2 – α_2 , at point 3 – α_3, etc.

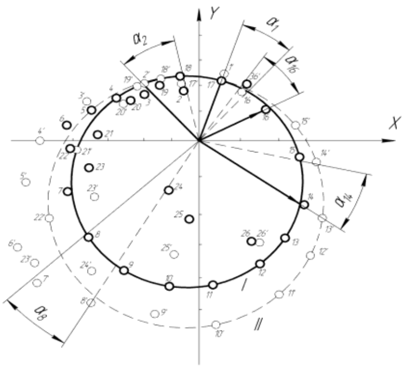

Figure 1 – Scheme for determining the angle of meeting of the granule and the part:
I – hodograph of the velocity of the part; II – hodograph of the velocity of the granule

The average value of the angle α_{avg} for the period of one oscillation is,

$$\alpha_{avg} = \frac{\alpha_1 + \alpha_2 + \alpha_3 + ... + \alpha_n}{n},$$

where n is the number of velocity measurement points along the hodograph.

Collision of granules with a part can occur at any point of their trajectory. At each point of the hodograph the angles between the velocity of the granule and the part is approximately equal to each other. Therefore, we can assume that the velocities at this moment are directed relative to each other at an angle of α_{avg}. In this case, two separate equally probable positions of the impact line $O_1 O_2$ (Fig. 2) are possible, when the latter coincides: with the velocity V_1 of the granule (line $O_1^{'} O_2^{'}$) and with the velocity V_2 of the part (line $O_1 O_2$).

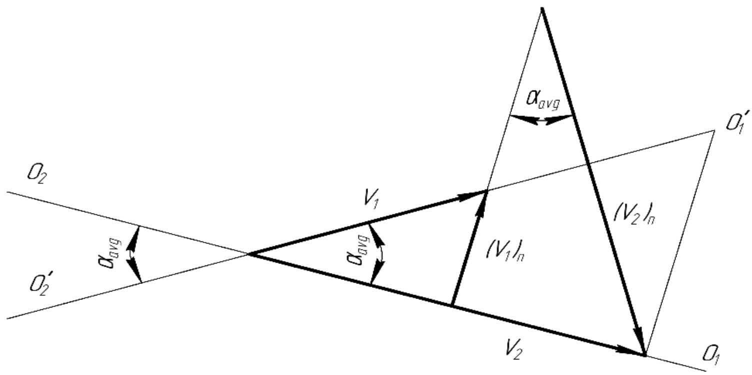

Figure 2 – Scheme for determining the collision velocity of the granule and the part: $(V_1)_n$, $(V_2)_n$ – normal components of the movement velocities of the granule and the part

Let us decompose the velocities V_1 and V_2 into normal (V_{1n} and V_{2n}) and tangential (V_{1t} and V_{2t}) components. As it was said, micro-roughness is formed due to the normal component. According to (see Fig. 2) the average velocity V_{avg} is determined as $V_{avg} = \frac{V_{1n} + V_{2n}}{2}$.

Since the collisions are carried out at an average angle of α_{avg}, then $\sin\alpha_1 = \sin\alpha_2$. Replacing the speed components V_{1n} and V_{2n} with their values, we get: $V_{avg} = (V_1 - V_2)\frac{\sin\alpha_{avg}}{2}$.

The velocities of granules and parts change in magnitude and direction during one oscillation of the reservoir, reaching their limiting values. They are approximately proportional to the velocities of the reservoir. The degree of this proportionality is expressed by the similarity coefficients for the granule F_1 and for the part F_2.

Then the average similarity coefficient for the full period of oscillation is determined as the probable value of the individual similarity coefficients according to the hodograph points:

$$F_1 = \frac{\sum_1^n \frac{V_{1i}}{V_{ri}}}{n},$$

where n is the number of points considered on the velocity hodograph; V_{1i} – granule velocity at the i-th point; V_{ri} – reservoir velocity at the i-th point.

Similarly, we determine the coefficient of similarity of velocities for the part:

$$F_2 = \frac{\sum_1^n \frac{V_{2i}}{V_{ri}}}{n}.$$

The probable velocity of the granule is determined from the expression: $V_1 = F_1 A\omega$, where F_1 is the similarity coefficient for a granule; A – oscillation amplitude; ω – oscillation frequency.

The probable velocity of the part will be equal to: $V_2 = F_2 A\omega$.The velocities of the granule and part vary from their location along the cross section of the reservoir. Since the force of interaction between the granule and the part is directly proportional to the velocity, the determination of the velocities over the cross section of the reservoir is proportional to the distribution of the pressure of the medium. Then the average probable value of the granule velocity in the reservoir will be equal to: $V_1 = \Delta_{avg}\,\xi_{avg}\,F_1 A\omega$, where Δ_{avg} is the average value of the power impulse damping coefficient; ξ_{avg} – coefficient of force action time.

The average value of the part velocity is equal to: $V_2 = \Delta_{avg} \xi_{avg} F_2 A\omega$.

Then the value V_{avg} of the normal component of the collision velocity of the granule and the part is equal to:

$$V_{avg} = \Delta_{avg} \xi_{avg} A\omega \frac{\sin \alpha_{avg}}{2} \left(F_1 + F_2\right).$$

The amplitude of the reservoir oscillations is not the same along the coordinate axes OX and OY. Therefore, depending on the setting of the vibrating machine, the minimum collision velocity $V_{avg\,min}$ corresponding to the elliptical-shaped trajectory of the reservoir $\left(K_A = \max\right)$ can be determined.

Hence, the value $\beta_{2\,min}$ of the penetration of the granule into the part will be:

$$\beta_{2\,min} = \frac{a \Delta_{avg} \xi_{avg} A\omega\left(1+k\right) m M \left(F_1 + F_2\right) \sin \alpha_{avg}}{2\pi \rho_x \sigma_s \Delta T \left(m+M\right)},$$

the value of the penetration of the granule into part $\beta_{2\,max}$ is equal to:

$$\beta_{2\,max} = \frac{a \Delta_{avg} \xi_{avg} A\omega K_A \left(1+k\right) m M \left(F_1 + F_2\right) \sin \alpha_{avg}}{2\pi \rho_x \sigma_s \Delta T \left(m+M\right)},$$

where k is the recovery factor; K_A – coefficient of ellipticity.

The highest normal velocities are possible at $\alpha_{avg} = 90^\circ$ and $\alpha_{avg} = 180^\circ$.

Then, for $\alpha_{avg} = 90^\circ$ we have $V_{avg\,max} = V_1 + V_2$. With $\alpha_{avg} = 180^\circ$ – $V_{avg\,min} = 0$. Average probable velocity V_{avg} will be equal to: $V_{avg} = \frac{V_1 + V_2}{2}$.

The limiting values of the depth of granule penetration, taking into account coefficient of ellipticity K_A, are determined by the formulas:

$$\beta'_{2\,max} = \frac{a \Delta_{avg} \xi_{avg} A\omega K_A \left(1+k\right) m M \left(F_1 + F_2\right)}{\pi \rho_x \sigma_s \Delta T \left(m+M\right)};$$

$$\beta'_{2\,min} = \frac{a \Delta_{avg} \xi_{avg} A\omega \left(1+k\right) m M \left(F_1 + F_2\right)}{\pi \rho_x \sigma_s \Delta T \left(m+M\right)}.$$

Carrying out transformations and substitutions, we get:

$$H_{avg} = \frac{a\,\Delta_{avg}\,\xi_{avg}\,A\omega(1+k)\,m\,M\,(F_1+F_2)}{\pi\rho_x\,\sigma_s\,\Delta T} \times \frac{\left[(1+2K_A)n_1 + (1+2K_A)n_2 \sin\alpha_{avg}\right]}{4(m+M)(n_1+n_2)}.$$

The values of the coefficients in the micro-roughness formula were found empirically on serial vibrating machines.

4. The results of calculations to determine the height of the micro-roughness of the processed part surface

Velocity hodographs were used to find the meeting angles of the abrasive granule with the processed part. The research results are summarized in table 1.

Table 1 – Values of the angles of the meeting of the granule with the part along the zones of the reservoir

Angle	The zones of the reservoir						
	1	2	3	4	5	6	7
α_{min}	20	35	17	22	29	23	28
α_{max}	28	37	39	30	29	31	29
α_{avg}	24	36	28	26	29	27	28

The determination of the micro-roughness of the processed part surface was carried out taking into account the values of the angles of the meeting of the granule with the processed part, passing through the zones of the reservoir. For these calculations, the hodographs of the movement velocities of the granule and the part were used. The values of the coefficients included in the roughness formula were also used (Table 2).

Table 2 – Values of coefficients for determining the height of micro-roughness of the processed parts surface

Quantities	Notation	Value
Constant factor	α	0.35
Power impulse damping coefficient	Δ_{avg}	0.55
Similarity coefficients:		
granules	F_1	0.47
parts	F_2	0.38
Coefficient of ellipticity	K_A	1.5
Straight impacts number	n_1	

Oblique impacts number	n_2	
Collision time	ΔT	$4 \cdot 10^{-5}$
Coefficient of force action time	ξ_{avg}	0.16
Recovery factor	k	0.9
Average meeting angle	α_{avg}	28º

The calculation determined the value of the average probable meeting angle, which turned out to be equal to $\alpha_{avg} = 28^{\circ}$. Based on them, the values of the similarity coefficients were: for a granule $F_1 = 0.47$, for a part $F_2 = 0.38$.

Taking into account the obtained data, the height micro-roughness formula will take the form:

$$H_{avg} = \frac{106\eta A\omega mM}{C\sigma_s \rho_x (m+M)},$$

where η is the abrasive ability of the granule grain; C – the number of simultaneously working grains of the granule; σ_s – tensile strength of the part material; ρ_x – diameter of the penetration of abrasive grain.

5. Conclusions

Thus, based on the analysis of the direct and oblique collision of the granule and the processed part, the values of the angles of contact with the processed part, as well as taking into account the velocities of their collisions and the proportionality of the speed of the reservoir, the micro-roughness of the part surface has been determined during vibration finishing and grinding processing To check the micro-roughness formula and establish the limits of its application, experiments were carried out that showed a good 80 ... 85 % convergence of experimental and calculated data.

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ХАРАКТЕР УТВОРЕННЯ МІКРОШОРСТКОСТІ ПОВЕРХНІ ПРИ ВІБРАЦІЙНІЙ ОЗДОБЛЮВАЛЬНО-ЗАЧИЩУВАЛЬНІЙ ОБРОБЦІ

Анотація. *Наведено основні аспекти щодо характеру утворення мікрошорсткості поверхні при вібраційній оздоблювально-зачищувальній обробці. Вказано, що видалення матеріалу з поверхні деталі відбувається в результаті спільної дії процесів мікрорізання, викришування частинок металу при багаторазовому деформуванні ділянок оброблюваної поверхні, їх втоми та руйнування, утворення, руйнування та видалення вторинних структур, адгезійних явищ. Зазначено, що реальна поверхня після віброобробки є сукупністю шорсткостей певної величини, форми та напряму. Встановлено, що мікрошорсткість поверхні деталі при вібраційній оздоблювально-зачищувальній обробці утворюється у вигляді слідів від численних ударів абразивних гранул по поверхні деталі. Визначено найбільшу величину проникнення гранули в оброблювану поверхню, що дає можливість характеризувати слід від пластичного стиску в зоні зіткнення гранули та деталі. Розглянуто методику та досліджено механізм утворення мікрошорсткості поверхні. Визначено вираз для нормальної складової сили удару, що характеризує основний вплив на механізм утворення мікрошорсткості. Встановлено величину проникнення гранули у метал деталі. Дослідженнями встановлено, що мікрошорсткість поверхні при віброобробці утворена ударами гранул о деталь під різними кутами зустрічі. Визначено сліди від впливу прямого та косого ударів. Обчислена середня висота мікрошорсткості. За годографами встановлено нормальні швидкості абразивних гранул та деталей. Також визначено середнє значення кута зіткнення гранул з деталлю у будь-якій точці траєкторії їхнього руху. Виявлено, що швидкості гранул і деталей змінюються за величиною та напрямком протягом одного періоду коливання резервуара, досягаючи своїх граничних значень, які пропорційні швидкостям руху резервуара. Ступінь пропорційності виражена коефіцієнтом подібності для гранули та деталі. Також за точками годографа визначено усереднений коефіцієнт подібності. Отримано середні значення швидкостей руху гранули та деталі в резервуарі. Встановлено мінімальну та максимальну величину проникнення гранули в поверхню деталі. Наведено формули граничних значень глибини проникнення гранули з урахуванням коефіцієнта еліпсності. Наведено результати розрахунків для визначення висоти мікронерівності поверхні та оброблюваної деталі. Отримано формулу для визначення мікрошорсткості поверхні при вібраційній оздоблювально-зачищувальній обробці.*

Ключові слова: *віброобробка; абразивна гранула; оброблювана деталь; співударяння гранули та деталі; кут співударяння; мікронерівність поверхні; годографи швидкостей.*