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Study of Forces during Ultrasonic Vibration Assisted Grinding

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Abstract

Radial and tangential grinding forces were presented as four components connected with workpiece material microcutting and plastic deformation, and friction of cutting and abrasive grains (AGs) with the workpiece.
The depth of abrasive grain penetration in the workpiece and the cutting width are determined with regard to ultrasonic vibrations (USV) amplitude and frequency. Summing up of the forces from single grains was conducted by using a multiple integral, provided that one of the integration limits is a function describing change of the depth of the AGs penetration in the workpiece material which depends on the USV parameters. Dependencies were obtained for calculation of all grinding force components at different vibration amplitudes and frequencies when various number of USV waves fits the contact arc of the grain and the workpiece.
Experimental values of grinding forces turned out to be 10 – 15 % lower than those when USV waves are not applied.

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*Keywords:*grinding; forces; workpiece; ultrasonic vibrations; kinematics; abrasive grain.

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1. Introduction

Process of grinding of tough material workpieces has high intensity of wearing and loading of grinding wheel (GW) working surface, as well as high heating rate. This factor makes difficult to have high quality surface at high productive process. Use of external energy forces, e. g. ultrasonic vibrations, is one of the ways to increase efficiency of the grinding process [1-4].

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A lot of Russian and foreign scientists have already detected the main mechanisms of the influence of ultrasonic vibrations on mechanical abrading processes. However, all these mechanisms were detected in field researches. The lack of analytical researches makes it hard to develop instructions on use of ultrasonic vibrations for increase of efficiency in the grinding process. Higher working efficiency of the disc during grinding with the use of USV is connected in many respects with lower force rate of this process. For this reason, analytical research of grinding forces with applying USV is a crucial task.

2. Analysis of scientific and technical information

Mathematical models for calculation of grinding forces with the use of an analytical method were developed by S. N. Korchak [5], L. N. Filimonov [6], V. I. Ostrovsky [7], V. V. Efimov [8], A. A. Dyakonov [9], J. Peklenik [10], A. Pahlitzsch [11] and a lot of other research workers.

S. N. Korchak [5] was among the first to determine physical interrelation of single AG cutting forces with main grinding process parameters and, particularly, shear and compression stresses which depend on workpiece material strength at real strain rates and temperatures in the grinding zone. When drawing functions for forces calculation, it was assumed that two processes occurred during microcutting with a single grain: chip formation (shear and compression) and friction, which determine two independent systems of forces acting on the grain.

L. N. Filimonov [6] derived equations for calculation of forces of cutting with a single AG with regard to an inertial component. It is relevant for high-speed grinding when an inertial component has significant value.

V. V. Efimov passed on from calculation of single AG cutting forces to grinding disc cutting forces taking into account not only grains conducting microcutting but also grains conducting plastic deformation. Influence on the radial component P_y of the hydrodynamic force was also taken into account. However, when drawing functions, the maximum depth of penetration of grains in the workpiece material was assumed constant along the full length of contact, which is inadequate for the real process of chip formation.

Surveys [12-15] derived with the use of an analytical method and experimentally confirmed functions for calculation of forces of grinding of workpieces made of plastic materials, taking into account change of depth of penetration of grains in the workpiece material along the length of their contact arc and size of piles along the edges of grinding scratches which is relevant for grinding of workpieces made of plastic materials.

V. N. Poduraev conducted analytical research of forces in case of applying USV during turning process [16].

None of known mathematical functions for forces calculation takes into account periodical change of depth of AG penetration in the workpiece material along the length of contact while applying USV on the workpiece and, thus, change of the grain operation mode.

3. Analytical research of grinding forces

Grinding forces P_y and P_z were presented as the sum of forces from cutting and plastic deformation AGs. Each one is connected with workpiece material dispersing and friction of AG with the workpiece [12-15, 17]:

$$P_y = P_{yr1} + P_{yr2} + P_{yd1} + P_{yd2}; P_z = P_{zr1} + P_{zr2} + P_{zd1} + P_{zd2}, \quad (1)$$

where P_{yr1} and P_{zr1}, P_{yr2} and P_{zr2} are radial (suffix *y*) and tangential (*z*) components of grinding force, accordingly connected to workpiece material microcutting (suffix 1) and friction of cutting AGs with the workpiece (suffix 2), N; P_{yd1} and P_{zd1}, P_{yd2} and P_{zd2} are components of grinding force, accordingly connected with plastic deformation of workpiece material and friction of plastic deformation AGs with the workpiece, N.

Every component was calculated by summing up relevant forces from grains which are in contact with the workpiece. The number of cutting and plastic deformation AGs depends on wheel characteristics and the depth of penetration of grains in the workpiece material. The depth of AG penetration in the workpiece is changed while changing position of the grain on the arc of its contact with the workpiece and depends on USV parameters (amplitude and frequency).

Cutting AGs are AGs located at the distance $0 \le y \le y(l)$ from the reference external surface of the grinding wheel, where $y(l)$ is a function describing dependence of the depth *y* of AG location on the length *l* of its contact with the workpiece. We can calculate the component P_{yr1} by using multiple integral during summing up of single grains microcutting forces.

$$P_{yr1} = \int_0^{l_k} \left[\int_0^{y(l)} P_{yr1i} \cdot n_{zk1} \cdot c_k \cdot dy \right] \cdot dl, \tag{2}$$

where l_k is the length of the arc of GW contact with the workpiece, m; P_{yr1i} is single grain microcutting force, N; n_{zk1} is the number of AGs on the wheel surface in its plane section which is parallel to the wheel axis, 1/m ($n_{zk1} = Z_0 \cdot H$, where Z_0 is the number of AGs on a unit of wheel area, 1/m^2; *H* is size of the processed workpiece surface in the direction with is parallel to the GW axis, m); c_k is coefficient which depends on GW characteristics [8].

$$y(l) = h_u + a_3(l) + A_y \cdot sin(\omega \frac{l}{V_k} + \varphi), \tag{3}$$

where h_u is total value of grains chipping while shaping and dimensional wear of the GW, m; $a_3(l)$ is function describing change of depth of AG penetration in the workpiece material along the contact length *l* during grinding without applying USV; A_y is amplitude of workpiece vibration which is perpendicular to the processed surface (in the direction of y axis), m; V_k is GW working speed, m/s; ω is vibration cyclic (circular) frequency, rad/s; φ is USV phase shift, rad.

Force of microcutting with a single grain

$$P_{yr1i} = \tau_s \cdot F_m \cdot k_y, \tag{4}$$

where τ_s is shear stress while microcutting the workpiece material with a grain, Pa [5, 12, 13]; F_m is area of the workpiece metal taken out with a single grain, m^2; k_y is coefficient [13].

As a result of calculations, the following function was obtained

$$\begin{aligned} P_{yr1} = {} & k_y \cdot \tau_s \cdot tg\gamma \cdot n_{zk1} \cdot c_k \cdot (2 \cdot h_u^2 \cdot a_{kp} \cdot l_k + (6 \cdot h_u \cdot a_{kp} + 7 \cdot h_u^2 + a_{kp}{}^2) A \cdot \frac{l_k^2}{2} + h_u \cdot a_{kp}{}^2 \cdot l_k + \\ & + (h_u + a_{kp}) \cdot h_u^2 \cdot l_k + \frac{h_u^3 \cdot l_k}{3} + K_{1UZ}), \end{aligned} \tag{5}$$

where K_{1UZ} is component taking into account change of microcutting kinematics in case of applying USV; a_{kp} is critical depth of microcutting (if this value is exceeded, the plastic deformation is changed to microcutting), m; γ is half angle at the AG top, deg.

$$A = \frac{V_{s\,np} \cdot sin\alpha_{max} \cdot l_m}{\pi \cdot D_k \cdot n_k \cdot l_k}, \tag{6}$$

where l_m is average distance between cutting AGs, m; $V_{s\,np}$ is traverse speed, m/min; D_k is diameter of the grinding wheel, m; n_k is wheel rotation speed, 1/min; α_{max} is angle corresponding to the length of the arc of AG contact with the workpiece, deg. [12, 13].

The following equations determine the other components of the grinding force P_y

$$P_{yr2} = \frac{\pi \cdot l_{2r}^2 \cdot k_y \cdot n_{zk1} \cdot c_k \cdot \tau_s}{12 \cdot \mu_s} \cdot (h_u \cdot l_k + \frac{A \cdot l_k^2}{2} + K_{2UZ}), \tag{7}$$

where l_{2r} is size of cutting AG blunting area, m; μ_s is internal friction coefficient of processed material; K_{2UZ} is dependence component taking into account change of microcutting kinematics while applying USV.

$$P_{yd1} = \frac{c \cdot \sigma_t \cdot n_{zk1} \cdot c_k \cdot tg\gamma}{2} \left(sin\gamma + \mu_0 \cdot cos\gamma\right) \cdot l_k \cdot a_{kp} \cdot (\frac{a_{kp}^2}{3} - h_{ud}^2), \tag{8}$$

wherec is c coefficient; σ_t is workpiece material yield stress, Pa; h_{ud} is wear of AGs which conduct plastic deformation of workpiece material, m; μ_0 is friction coefficient of the AG and the workpiece.

$$P_{yd2} = \frac{c \cdot \sigma_t \cdot k_y \cdot \pi \cdot l_{2d}^2 \cdot n_{zk1} \cdot c_k \cdot a_{kr} \cdot l_k}{12}, \tag{9}$$

where l_{2d} is size of blunting area of the plastic deformation AG, m.

Components P_{yd1} and P_{yd2} do not depend on ultrasonic vibration parameters.

The same way is applicable to derive dependences for calculation of the force component P_z.

The listed above functions for calculating forces are applicable for relatively low values of workpiece material particles vibration amplitude in the direction which is perpendicular to the surface being processed. If the values of amplitude are low (not more than the depth of AG penetration in the workpiece), the AG operation mode (microcutting or plastic deformation) stays unchanged in case of applying USV.

Workpiece vibrations make the dispersion process of workpiece material more efficient. Applying USV is attended by decrease of stress limit σ_b and yield stress σ_t of the workpiece material by 10 –15 % [1, 18].

In order to evaluate influence of kinematics of microcutting with USV on grinding force components, their calculation was conducted with the use of functions (1) without consideration of change (decrease) of ultimate resistance and yield stress of the workpiece material. Change of kinematics of microcutting with single grains by means of applying low amplitude USV does not cause change of grinding forces. The forces decrease due to decrease of stress limit and yield stress of the workpiece material under USV.

Grinding forces of plastic deformation grains P_{yd1}, P_{yd2}, P_{zd1}, P_{zd2} are insignificant compared with force components P_y and P_z. The sum of forces connected to workpiece material plastic deformation and friction of the grains and the workpiece is not more than 6 % of forces P_y and P_z.

In case of amplitudes close to the critical depth of microcutting, the AG operation mode changes while it moves along the arc of contact with the workpiece. On a part of the path, the AG can carry out microcutting with the depth of penetration in the workpiece which is larger than in the absence of vibrations; when the depth of penetration is lower that the critical one, the grain carries out plastic deformation (fig. 1).

In case of vibration phase φ = 0°, the AG stops microcutting at $l = l_{nH1}$ (refer to fig. 1); for this reason the initial function for calculation of the radial force connected with microcutting is as follows at this phase:

$$P^0_{yr1} = \int_0^{l_{nH1}} I \cdot dl; \; I = \int_0^{y(l)} P_{yr1i} \cdot n_{zk1} \cdot c_k \cdot dy. \tag{10}$$

Several areas of microcutting may be located on the path of grain motion, e. g. at vibration phase φ = 90° (refer to fig. 1). The initial function for calculation of the force component P_{yr1} at this phase is as follows:

$$P^{90}_{yr1} = P^{90}_{yr11} + P^{90}_{yr12} = \int_0^{l_{nH2}} I \cdot dl + \int_{l_{nK2}}^{l_k} I \cdot dl. \tag{11}$$

As a result of calculations and transformations for computation of P^0_{yr1}, the following function is obtained

$$P^0_{yr1} = k_y \cdot \tau_s \cdot tg\gamma \cdot n_{zk1} \cdot c_k \cdot (K^0 + K^0_{UZ}), \tag{12}$$

where K^0 and K^0_{UZ} are dependence components which depend on microcutting kinematics while applying USV [19].

Functions for calculation of all grinding forces components P_y and P_z (refer to function (1)) at various vibration phases were obtained.

As occurrence of this or that vibration phase is equiprobable event, force components were determined at different phases, and actual value of forces was taken equal to arithmetic mean of these values.

The grinding forces were presented as follows:

$$P_y = \frac{1}{4} \cdot (P^0_y + P^{90}_y + P^{180}_y + P^{270}_y); \; P_z = \frac{1}{4} \cdot (P^0_z + P^{90}_z + P^{180}_z + P^{270}_z). \tag{13}$$

Force components determined at phases φ = 0, 90, 180 and 270 deg. respectively are written within brackets.

In order to calculate the forces, it is necessary to know coordinates on the arc of contact of the grain and the workpiece at which the grain operation mode changes under USV (l_{nH1}, l_{nH2}, l_{nK2} on fig. 1, etc.). These coordinates are determined by means of the numerical approach with the use of Mathcad package for various conditions and the grinding mode.

Calculation according to functions (13) stated that, due to change of process kinematics under USV, grinding forces should be expected to decrease by 10 %. Change of kinematics has the largest impact on the force component connected to friction between cutting grains and the workpiece (the force decreases to 40 %). decreases to the most extent at USV phases φ = 90 and 180° when the grain does not carry out microcutting on the most part of the contact arc.

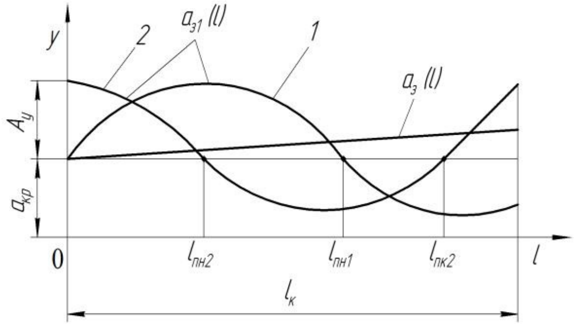

Fig. 1. Chart for calculation of the depth of cutting AG penetration in the workpiece: 1 – USV phase φ = 0°; 2 – φ = 90° (less than one USV wave fits the path of contact of the grain and the workpiece)

4. Field research of grinding forces

The field research of grinding forces was conducted during processing of workpieces made of steels 3KH3M3F (X32CrMoV3-3) and 12KH18N10T (X10CrNiTi18-10), which belong to the 1st and the 3rd groups of grinding properties respectively and have high plastic properties, with the wheel 25AF60K6V with diameter $D_k = 200$ мм. The size of the workpiece is H = 0.005 m. Grinding mode: $V_k = 35$ m / s, $V_{s\,np} = 10$ m / min, infeed motion was 0.01 mm/motions per act. Cutting coolant, 3 % calcined coda, was poured to the grinding zone as fast as 10 dm3/min.

Frequency of USV applied on the workpiece was f = 18.6 kHz. For applying vibrations on the workpiece, a special tool was used. In that case the workpiece was a part of the vibrating system [20, 21]. USV were applied in the direction which is parallel to the grinding disc axis (fig. 2). Grinding force components were calculated with the dynamometric tool UMD-100. Its signal went through the TDA amplifier to the ADC 16/16 – SIGMA/USB using the ZetLab Studio software.

Amplitude of vibrations in the direction corresponding to the disc axis was varied within the range $A_z = 0 \ldots 6$ μm. In this case the maximum amplitude of vibrations in the direction which is perpendicular to the workpiece processed surface calculated according to the function $A_y = A_z \cdot \mu$ (where μ = 0.3 is the Poisson ratio) was 1.8 μm.

The results of field researches and forces simulation given in the table show that the difference of calculated and experimental values of the force at the amplitude $A_y = 1.8$ μm is not more than 20 %. Experimental values of grinding forces turned out to be lower than those without applying USV by 12 –14 %. Discrepancy between calculated and experimental values of forces at USV amplitude $A_y \leq 1.5$ μm is not more than 14 %.

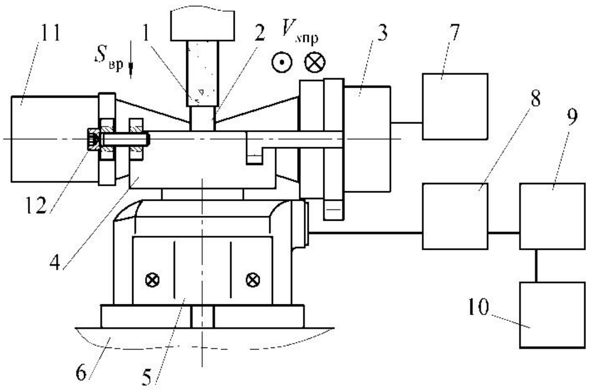

Fig. 2. Drawing of the unit for research of the grinding process with applying USV on the workpiece: 1 – grinding wheel; 2 – workpiece; 3 – ultrasonic transmitter; 4 – device for workpiece positioning; 5 – dynamometer UDM-100; 6 – machine table; 7 – ultrasonic generator (USG-641A); 8 – TDA amplifier; 9 – ADC 16/16 – SIGMA/USB; 10 – PC; 11 – reflector; 12 – screws

Table. Results of calculation and field research of grinding forces P_y and P_z : the workpiece material is steel 12KH18N10T; $A_y = 1.8$ μm

Grinding force component	Experimental value of force during grinding without applying USV, N	Grinding with applying USV	
		Experimental value, N	Calculated value, N
P_z	13.6	11.7	9.4
P_y	15.2	13.5	12.8

Variation of amplitude of USV applied on the workpiece in the direction of the grinding disc axis within the range from 1.5 to 6 μm during grinding of workpieces made of steels 3KH3M3F and 12KH18N10T showed that grinding force components decrease with the amplitude increasing.

The minimum value of forces was detected at the maximum used amplitude which is equal to 6 μm. During processing workpieces made of steel 3KH3M3F with this amplitude, grinding forces P_y and P_z were decreased by 10 % compared to processing without applying USV. While processing workpieces made of steel 12N18KH10T, grinding force components P_y and P_z were decreased by 15 and 11 % respectively.

In case of applying USV with amplitude A_z more than 6 μm, height-level parameters of roughness of the workpiece processed surface and the grinding disc wear increase significantly [17].

5. Conclusions

1. With the use of analytical approach, functions were obtained for calculation of radial and tangential components of grinding force in case of applying USV with various amplitudes, including one leading to change of abrasive grain operation mode.
2. nfluence of kinematics of microcutting with USV on grinding force components was determined. When using vibrations with amplitude leading to AG operation mode change, the force decreases to 10 % due to change of kinematics. The largest influence of kinematics is exerted on the force component connected to friction between cutting grains and the workpiece (the force decreases to 40 %).
3. Discrepancy between calculated and experimental values of forces is not more than 20 %.
4. The experimental approach stated that applying USV on the workpiece provides decrease of grinding forces by 10 – 15 %.

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