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ESTABLISHING THE EFFECT OF DECREASED POWER INTENSITY OF SELF-OSCILLATORY GRINDING IN A TUMBLING MILL WHEN THE CRUSHED MATERIAL CONTENT IN THE INTRA-CHAMBER FILL IS REDUCED

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The influence of the content of crushed material in the intra-chamber grinding fill on the efficiency of the self-oscillatory grinding process in the tumbling mill was assessed.

A dynamic effect of a significant decrease in self-oscillatory action of the two-fraction fill of the rotary chamber with an increase in the content of fine fraction was revealed by the method of visual analysis of motion patterns. A decrease in values of the following inertial fill parameters was established: maximum dilatancy υ_{max}, the relative amplitude of self-oscillations $\psi_{R\upsilon}$ and a maximum share of the active part $\kappa_{fam\,max}$ with an increase in the degree of filling the gaps between particles of the coarse fraction κ_{mbgr}. A decrease in the generalized complex degree of dynamic activation K_a was also established. The effect is due to the strengthening of the cohesive properties of the incoherent coarse fraction under the influence of the fine fraction. There was a decrease in by 29 % for υ_{max}, by 7 % for $\psi_{R\upsilon}$, 2.9 times for $\kappa_{fam\,max}$ and 4.2 times for K_a with an increase in κ_{mbgr} from 0 to 1 at the degree of filling the chamber with the fill $\kappa_{br}=0.45$.

Technological effect of a significant decrease in specific energy intensity and an increase in productivity of the innovative self-oscillatory grinding process in comparison with characteristics of the conventional steady-state process at a decrease in the content of crushed material in the fill was established.

A process of milling cement clinker with grinding bodies at relative size of 0.026 and $\kappa_{br}=0.45$ was considered. A decrease in specific energy intensity by 27 % at $\kappa_{mbgr}=1$, by 38 % at $\kappa_{mbgr}=0.5625$ and by 44 % at $\kappa_{mbgr}=0$ was found. An increase in relative productivity by 7 % at $\kappa_{mbgr}=1$, by 26 % at $\kappa_{mbgr}=0.5625$ and by 39 % at $\kappa_{mbgr}=0.125$ was established.

The established effects will make it possible to forecast rational parameters of the self-oscillatory grinding process in a tumbling mill at the variation of the content of the crushed material in the fill

Keywords: tumbling mill, content of crushed material in intra-chamber fill, self-oscillations, energy intensity of grinding

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1. Introduction

Tumbling mills continue to be the main equipment for multi-ton fine grinding of various materials in many industries.

The application of the self-oscillatory grinding process is a new technological line to a significant increase in the relatively low energy efficiency of such mills. The auto-excitation of self-oscillations makes it possible to set in motion and activate the passive part of the intra-mill fill and significantly increase the intensity of interaction between grinding bodies and the crushed material.

Significant variability of pulsation behavior in the rotary chamber significantly complicates the establishment of rational conditions for the effective implementation of such a process depending on the complex multiphase polygrain structure of the fill.

The problem of forecasting the influence of the content of the crushed material in the intra-chamber fill on dynamic action of grinding bodies and technological and energy efficiency of the self-oscillatory process of grinding in a tumbling mill seems to be quite relevant.

2. Literature review and problem statement

The behavior of the granular fill of the rotary chamber significantly affects the technological characteristics and energy intensity of the drum-type machines [1]. Modeling of such circulating motion is of interest in the study of rotary technological systems [2]. Applied significance of the problem of forecasting working processes of drum equipment attracts an increased researchers' attention to the description of possible unstable behavior of the granular medium to be processed. The considerable complexity of this problem forces the application of new theoretical and experimental methods.

The problem of modeling the steady motion of a granular fill in a rotating drum was solved by analytical methods. The position of the boundary between passive and active filling zones was determined in [3]. Characteristics of the motion of the shear load layer were established in [4]. The analytical-experimental method of modeling patterns of the steady-state behavior of fill flows in the rotary chamber cross-section was developed in [5]. However, the problems of determining unstable transient behavior of the self-oscillatory flow of intra-chamber fill were not solved. They were not considered because of their high complexity [3–5].

The efficiency of the grinding process in tumbling mills is determined mainly by the dynamic action of the grinding fill on particles of the ground material. The dynamic action of the grinding bodies is considerably increased by auto-excitation of the pulsating behavior of the intra-chamber fill. Under certain conditions, steady-state behavior of the motion of drive units of the tumbling mills can change for unstable. This instability is accompanied by fluctuations in the power consumption of the loaded drum drive [6].

An analytical method of forecasting qualitative factors of auto-excitation of self-oscillations in a machine unit with a filled drum as its working machine was developed in [7]. Quantitative assessment of dynamic parameters of fill impact and energy and technological parameters of the innovative self-oscillatory grinding process was made in [8] for one discrete value of the degree of filling of the chamber with an intra-mill fill. The influence of variation of the degree of chamber filling by a fill on the efficiency of the self-oscillatory grinding process is considered in [9].

Characteristics of grinding processes in tumbling mills significantly depend on the content of particles of the crushed material in the intra-chamber grinding fill. However, the influence of variation of material content on the motion behavior of grinding bodies as an additional factor was not studied in [7–9]. A series of attempts were made for theoretical and experimental analysis of the influence of the processed material content on dynamic, energy and technological parameters of established conventional dry and wet grinding processes.

An analytical model of forecasting the effect of crushed material on a specific rate of dry grinding in a tumbling mill was proposed in [10]. The model is based on the concept absorption of the kinetic energy of motion of the intra-chamber fill by material particles.

A numerical discrete elements method (DEM) with experimental verification was used in [11] to study the influence of material's content on the power of the drive of the semi-autogenous grinding (SAG) mill during dry fine grinding of ore. The volume of the crushed material particles varied from 0 to 150 % of the volume of cavities between grinding bodies. A high value of power at high and low material content as well as a decrease in power at an intermediate significant content were found. The DEM method was used in [12] to model the effect of material on dynamic action of the grinding fill during dry grinding in the SAG mill. Energy dissipation in the collision of fill particles was taken into account. A decrease in brittle fracture during impact and an increase in the effect of abrasion with a decrease in the content of crushed material were established. The influence of material's content on the impact effect of fill and power of the mill drive during dry grinding of iron ore in a tumbling mill was numerically studied in [13] with the help of DEM and experimentally. It was shown that with an increase in material content, the height of the fill-lifting in the rotary chamber increases, fill circulation is activated and the power of the mill drive grows. Besides, an increase in the crushed material content significantly reduces the impact action of the fill due to the damping of the interaction of the grinding bodies.

Rational values of the content of crushed material in the fill were experimentally established to optimize parameters of a series of conventional dry grinding processes. The rational value of content at the achievement of maximum efficiency of dry fine grinding of gypsum fineness was found in [14]. The influence of the material contained in the fill on the process of dry grinding of silica was studied in [15]. The crushed material volume was 5, 10, 15, and 20 % of the volume of cavities between the grinding bodies. A rational value of content was established at maximum productivity of dry grinding taking into account other process factors. The influence of material contained on the process of dry grinding of iron ore was studied in [16]. The material volume was 60, 80, and 100 % of the volume of cavities between the grinding bodies. It was found that rational material content at the achievement of optimal specific power intensity of the process is 80 %. The influence of material contained on the process of dry calcite grinding was studied in [17]. The ratio of material volume to the volume of cavities between grinding bodies was 10, 12.5, 15, 20, and 100 %. It was found that the rational value of material content at maximum process productivity is 12.5 %.

Regularities of influence of the crushed material content in the fill on parameters of conventional processes of wet grinding in tumbling mills were revealed using experimental methods.

The influence of material content on the behavior of fill and power of the mill drive during wet grinding was studied in [18] both visually and with the help of hardware. The volume of slurry with particles of crushed material varied from 0 to 300 % of the volume of cavities between the grinding bodies. A correlation has been established between power and material content. The influence of material content on the process of wet grinding of platinum ore was studied in [19]. The slurry volume was 0–300 % of the volume of cavities between the grinding bodies. It was found that the maximum value of the power of the mill drive is reached at a volume of 100 %. The influence of the content of slurry with material on power of the mill drive was studied in [20] during wet grinding of platinum ore. Power increase at a low content (0–100 %) and decrease at a high content (100–300 %) was found. Power reaches a maximum value at an intermediate value of slurry filling (100 %). The influence of the concentration of crushed material in the slurry in a range of 50–80 % on the efficiency of wet grinding of platinum ore was studied in [21]. A growth of relative productivity of grinding with a decrease in this concentration was established. The influence of material content on the behavior of the intra-mill fill motion was studied in [22] by visualization method. The ratio of slurry volume to the volume of cavities between grinding bodies was 0, 41, 84, 125, 166, 208, 250, and 292 %. The rational value of slurry content at the moment of reaching the maximum intensity of fill circulation and optimal conditions of realization of the process of wet grinding of copper ore (80–125 %) was revealed. The influence of material content on dynamic action of fill during wet grinding of copper ore was studied in [23]. The slurry filling varied within 0–250 %. It was shown that with an increase in slurry content, the impact action of the fill decreases because of damping the interaction of grinding bodies. The influence of material content on the power of the mill drive during wet grinding of copper ore was studied in [24]. Slurry concentration was 40, 50, 60, 70, and 80 %. The slurry filling was 0, 28, 56, 84, 112, 140, and 292 %. There was an increase in power at low content and a decrease at high contents. The maximum value of power was reached at slurry concentration of 60–70 %, slurry filling of 84 %, and an intermediate value of material content. The influence of material content on dynamic action of the fill during wet grinding of copper ore was studied in [25]. Slurry concentration was 0, 42, 84, 126, 168, and 210 %. Slurry filling was 40, 50, 60, and 70 %. It was shown that with an increase in material content, the fill impact decreases in magnitude and frequency because of damping the interaction of grinding bodies. It was established that the best grinding conditions are realized at slurry concentration of 50–60 % and its content of 100 %. The influence of material content on the energy of the fill motion and power of the mill drum drive during wet grinding of iron ore was studied in [26]. An increase in kinetic energy of the fill motion, the drive power at a low content, and a decrease at a high content were found. Maximum values of energy and power were achieved at an intermediate value of material content.

Thus, the obtained data of analytical and numerical modeling and experiments have shown a significant influence of the crushed material content in the intra-chamber fill on parameters of the grinding process in tumbling mills. This effect mainly consists in the reduction of dynamic fill action with an increase in material content because of the interaction damping and dissipation of kinetic energy of motion of the grinding bodies. Besides, when the material content increases, the power of the tumbling mill drive grows and relative grinding productivity decreases. However, such results apply only to the conventional grinding process with a simple steady-state behavior of the intra-mill fill.

At present, no models have been developed to determine the influence of the content of particles of the crushed material in the fill on dynamic and technological parameters of grinding during auto-excitation of a complex transient pulsation behavior of intra-chamber fill. This is explained by insurmountable difficulties of analytical and numerical modeling and high complexity of instrumental experimental study of the behavior of the polygranular fill of the rotating drum chamber during the auto-excitation of self-oscillations because of loss of the system stability. The absence of such models is especially negative in the case of implementation of the innovative self-oscillatory grinding process in the tumbling mills.

3. The aim and objectives of the study

The study objective is to establish the influence of the content of crushed material in the chamber fill on characteristics of the dynamic action of pulsation filling and parameters of conventional and self-oscillatory grinding processes in a tumbling mill. This will make it possible to predict the efficiency of the self-oscillatory grinding process when the content of the crushed material in the intra-chamber fill varies.

To achieve this objective, the following tasks were set:

– experimentally determine and compare values of inertial parameters and characteristics of the dynamic action of a coarse fraction of the two-fraction intra-chamber fill of the rotary drum in the self-oscillatory mode for various contents of the fine fraction in the chamber fill;

– based on the obtained experimental results, establish the qualitative nature of the influence of the fine fraction content on the degree of the dynamic action of the self-oscillatory two-fraction fill of the rotary chamber;

– experimentally determine and compare values of productivity and energy intensity of grinding in the conventional well-established and innovative self-oscillatory grinding processes in a tumbling mill for various contents of the crushed material in the intra-chamber grinding fill;

– based on the obtained experimental results, identify the qualitative nature of the influence of the content of crushed material in the fill on technological and energy efficiency of the self-oscillatory process of grinding in a tumbling mill.

4. The procedure of studying the influence of the content of the crushed material on inertial and dynamic characteristics of two-fraction self-oscillatory intra-mill fill

The tumbling mill chamber fill usually contains two fractions. The coarse fraction consists of grinding bodies and the fine fraction consists of particles of the crushed material. Metal and ceramic grinding bodies are used in ball and tube mills. Large pieces of crushed material are used as grinding bodies in self-grinding mills.

The relative size of the grinding body in the rotary chamber is the geometric characteristic of elements of the coarse fill fraction:

$$\psi_{db} = \frac{d_b}{2R},$$

where d_b is the average absolute size of the grinding body; R is the radius of the drum chamber.

The value of ψ_{db} for different types of tumbling mills varies mainly within 0.002–0.07. As the grind fineness increases, ψ_{db} usually decreases.

The fine fraction elements are characterized by the relative size of the crushed material particle in the rotary chamber:

$$\psi_{dm} = \frac{d_m}{2R},$$

where d_m is the average absolute size of the material particle.

The size of the ground material particle is much smaller than the size of the grinding bodies ($\psi_{dm} \ll \psi_{db}$), especially in the final stage of fine grinding.

Individual volumes of the fill and its fractions as granular media are usually estimated for the state of free rest. It is considered that filling of such volumes is carried out freely, without dynamic action. When the chamber is filled, particles of the fine fraction in their state of free rest are taking place mainly in the gaps between the grinding bodies. As a result, the fill volume is less than the sum of volumes of individual fractions:

$$W_{fr} < w_{br} + w_{mr}, \tag{1}$$

where W_{fr} is the fill volume in the state of free rest; w_{br} is the volume of the grinding bodies in the state of free rest; w_{mr} is the volume of particles of the crushed material in the state of free rest.

However, the volume of crushed material can vary significantly in a wide range depending on features of the process implementation, that is, properties of the material and the grind fineness:

$$w_{br} \geq w_{mr} > 0. \quad (2)$$

Taking into consideration (1) and (2), it is convenient to estimate the volume of the intra-chamber fill approximately by volume of the grinding bodies:

$$W_{fr} \approx w_{br}. \quad (3)$$

The expediency of this approach is confirmed by the fact that mass and hence the volume of the grinding bodies w_{br} are often strictly regulated by technical characteristics of the mill while the volume of crushed material w_{mr} is variable and determined by operating conditions.

Volumetric degree of the chamber filling in the state of free rest is a quantitative assessment of volumetric content of the fill in the drum chamber:

$$\kappa_{fr} = \frac{W_{fr}}{\pi R^2 L},$$

where L is the length of the drum chamber.

Content of the coarse fraction in the fill is determined by the volumetric degree of the chamber filling with the grinding bodies in the state of free rest:

$$\kappa_{br} = \frac{w_{br}}{\pi R^2 L}. \quad (4)$$

Considering (3), the content of the intra-chamber fill can be approximately estimated by the content of the grinding bodies:

$$\kappa_{fr} \approx \kappa_{br}. \quad (5)$$

Content of fine fraction of the fill is usually evaluated not by its content in the chamber but by the content in the intra-chamber.

Content of such a fraction in the chamber can be determined by the volumetric degree of the chamber filling with crushed material in the state of free rest:

$$\kappa_{mr} = \frac{w_{mr}}{\pi R^2 L}.$$

Instead, the content of the fine fraction in the fill is practically set by the volumetric degree of the chamber filling with crushed material in the state of free rest. Taking into account (5), its expression takes the form:

$$\kappa_{mr} = \frac{w_{mr}}{\pi R^2 L}.$$

At the same time, the content of the fine fraction in the fill can be conveniently estimated by the volumetric degree of filling the gaps between the coarse fraction elements. In the case of spherical grinding bodies of the same size d, the expression for the volumetric degree of filling of the gaps between the grinding bodies with particles of crushed material in the state of free rest takes the form:

$$\kappa_{mbgr} = \frac{w_{mr}}{0.4\kappa_{br}\pi R^2 L}, \quad (6)$$

where 0.4 is the approximate value of the volumetric fraction of gaps between spherical bodies of the same size in the state of free rest.

It is known that the content of the material in the fill affects the technological parameters of the conventional grinding process in a tumbling mill with a steady movement of the fill, in particular fineness of the grinding product. The volumetric degree of filling is approximately $\kappa_{mbgr} \approx 1$ ($\kappa_{mbr} \approx 0.4$) for coarse grinding, $\kappa_{mbgr} \approx 0.5$ ($\kappa_{mbr} \approx 0.2$) for medium grinding and $\kappa_{mbgr} < 0.25$ ($\kappa_{mbr} < 0.1$) for fine and ultrafine grinding.

This variability of technical characteristics of the grinding process is determined by the influence of the material content on dynamic parameters of interaction of the grinding bodies with particles of the crushed material.

Rotating velocity of the mill drum can be conveniently estimated by the relative rotating velocity:

$$\psi_\omega = \omega\sqrt{\frac{R}{g}},$$

where ω is the angular rotating velocity; g is the gravitational acceleration.

It is possible to quantify the dynamic grinding action in the self-oscillatory grinding process with the help of a generalized complex criterion taking into account values of inertial characteristics of the fill motion per one period of self-oscillations. Inertial parameters of self-oscillatory motion of the intra-chamber fill include dilatancy, the amplitude of self-oscillations, and a share of the active part of the fill.

Positive shear dilatancy of the fill characterizes increase in the volume of granular fill of the chamber due to the movement of particles in a direction normal to the direction of displacement:

$$\upsilon = \frac{W_{fm}}{W_{fr}},$$

where W_{fm} is the volume of fill in motion.

Taking into account (3), it can be assumed that:

$$\upsilon \approx \frac{W_{fm}}{w_{br}}.$$

Then, taking into account (4), the expression for dilatancy takes the form:

$$\upsilon = \frac{W_{fm}}{\kappa_{br}\pi R^2 L}.$$

To establish inertial parameters of the fill in the case of the self-oscillatory process, it is convenient to apply the method of visualization of motion patterns in a cross-section of the rotary chamber. Then the amount of fill in motion can be calculated from the following expression:

$$W_{fm} = S_{fm} L, \quad (7)$$

where S_{fm} is the area of a flat geometric figure of fill in the motion pattern in the cross-section of the chamber. Taking into account (7), the expression for determining dilatancy takes the form:

$$\upsilon = \frac{S_{fm}}{\kappa_{br}\pi R^2}. \tag{8}$$

Since self-oscillations of the rotary chamber fill have a complex inharmonic character, the oscillation swings equal to the difference between the largest and the smallest values during oscillation is used to estimate limit values of the oscillatory value of dilatancy. The expression for the absolute swing of self-oscillations for one period of fill pulsations has the form:

$$R_\upsilon = \upsilon_{\max} - \upsilon_{\min},$$

where $\upsilon_{\max}$ and $\upsilon_{\min}$ are the maximum and minimum values of dilatancy during one period of pulsations. Taking into account (8),

$$R_\upsilon = \upsilon_{\max} - \upsilon_{\min}, \quad \upsilon_{\max} = \frac{S_{fm\max}}{\kappa_{br}\pi R^2}, \quad \upsilon_{\min} = \frac{S_{fm\min}}{\kappa_{br}\pi R^2}, \tag{9}$$

where $S_{fm\max}$ and $S_{fm\min}$ are the maximum and minimum values of the area of the geometric figure of the fill in the motion pattern in the chamber cross-section during one period of pulsations. It is convenient to assess characteristics of the self-oscillatory process by the criterion parameter which is a relative swing of self-oscillations:

$$\psi_{R\upsilon} = \frac{R_\upsilon}{\upsilon_m},$$

where $\upsilon_m = \dfrac{\upsilon_{\max} + \upsilon_{\min}}{2}$

is the average value of dilatancy during one period of pulsations. The expression for determining the relative amplitude of self-oscillations takes the form:

$$\psi_{R\upsilon} = \frac{S_{fm\max} - S_{fm\min}}{2\left(S_{fm\max} + S_{fm\min}\right)}. \tag{10}$$

Activation of the fill movement during self-oscillations is estimated by the maximum mass fraction of the active part of the chamber fill:

$$\kappa_{fam\max} = 1 - \frac{S_{fpm\min}}{\kappa_{br}\pi R^2}, \tag{11}$$

where $S_{fpm\min}$ is the minimum value of the area of the geometric figure of the passive fixed part of the fill in the motion pattern in the chamber cross-section when reaching the maximum dilatancy value $\upsilon_{\max}$.

To quantify the intensity of the grinding action of the grinding bodies on the material particles during the self-oscillatory grinding process, the degree of dynamic fill activation can be applied:

$$K_a = \upsilon_{\max}\left(1 + \psi_{R\upsilon}\right)\kappa_{fam\max}. \tag{12}$$

This criterion is a generalized complex characteristic that takes into account inertial parameters of the self-oscillatory motion of the fill. The degree of dynamic activation K_a is the product of three factors. The first factor $\upsilon_{\max}$ determines the maximum value of dynamic action in one period of self-oscillations. The second factor $(1+\psi_{R\upsilon})$ characterizes the range of change of this action during the period of oscillations. The third multiplier $\kappa_{fam\max}$ determines the maximum mass fraction of the fill that performs this action.

5. Experimental determination of the influence of the content of fine fraction of the two-fraction self-oscillatory fill of the rotating drum chamber on dynamic action of the coarse fraction

The coarse fraction of the two-fraction intra-chamber fill was modeled by spherical particles of an incoherent granular material with an average relative size $\psi_{db}=0.0104$. The fine fraction consisted of particles of M500 Portlandcement with an average relative size $\psi_{dm}=(0.0236–0.236)\cdot 10^{-3}$ ($\psi_{dm}\approx 0.13\cdot 10^{-3}$).

The volumetric degree of the chamber filling with a coarse fraction in the state of free rest was $\kappa_{br}=0.45$. Discrete values of the volumetric degree of filling the gaps between spherical bodies with small particles in the state of free rest κ_{mbgr} were 0, 0.25, 0.5, and 1.

Patterns of the fill motion in the chamber cross-section at a maximum amplitude of self-oscillations were obtained by a video recording with a frequency of 24 frames per second. Consecutive motion patterns for one period of self-oscillations are shown in Fig. 1 for $\kappa_{mbgr}=0$, in Fig. 2 for $\kappa_{mbgr}=0.25$, in Fig. 3 for $\kappa_{mbgr}=0.5$ and in Fig. 4 for $\kappa_{mbgr}=1$.

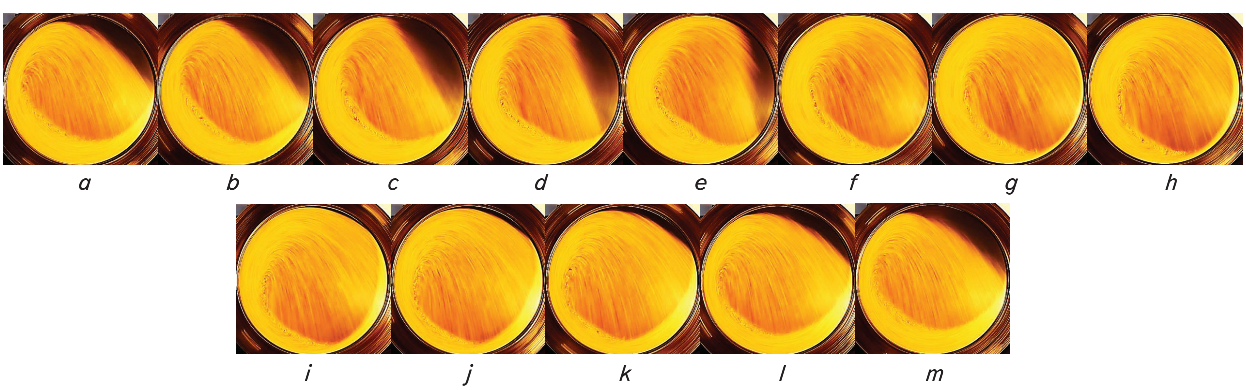

Fig. 1. Consecutive patterns of fill motion during time t for one period of self-oscillations T_{op} with a maximum swing at a relative coarse fraction particle size in the rotary drum chamber $\psi_{db}=0.0104$, degree of the chamber filling with particles of the coarse fill fraction in the state of free rest $\kappa_{br}=0.45$, the degree of filling gaps between particles of the coarse fraction by particles of the fine fill fraction in the state of free rest $\kappa_{mbgr}=0$ and relative velocity of rotation of the chamber $\psi_\omega \approx 1$: *a* – $t=0$; *b* – $t=4T_{op}/12$; *c* – $t=2T_{op}/12$; *d* – $t=3T_{op}/12$; *e* – $t=4T_{op}/12$; *f* – $t=5T_{op}/12$; *g* – $t=6T_{op}/12$; *h* – $t=7T_{op}/12$; *i* – $t=8T_{op}/12$; *j* – $t=9T_{op}/12$; *k* – $t=10T_{op}/12$; *l* – $t=11T_{op}/12$; *m* – $t=T_{op}$

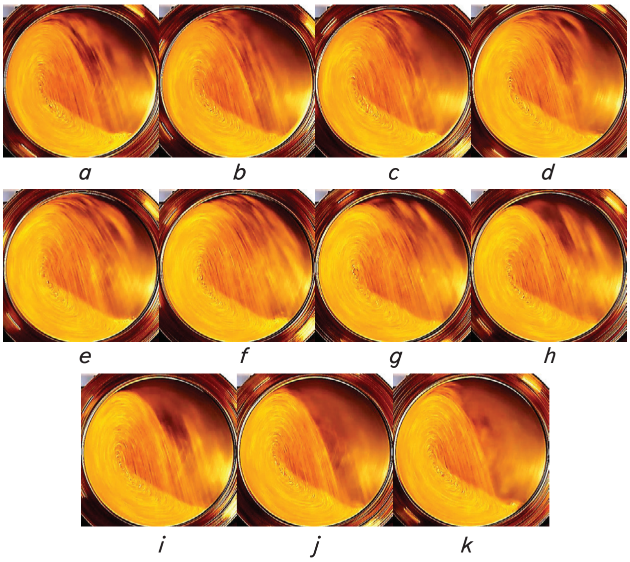

Fig. 2. Consecutive patterns of the fill motion during time t for one period of self-oscillations T_{op} with a maximum swing at ψ_{db}=0.0104, average relative size of the fine fraction particles in the chamber $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.45, κ_{mbgr}=0.25 and $\psi_\omega\approx 1$: $a - t=0$; $b - t=T_{op}/10$; $c - t=2T_{op}/10$; $d - t=3T_{op}/10$; $e - t=4T_{op}/10$; $f - t=5T_{op}/10$; $g - t=6T_{op}/10$; $h - t=7T_{op}/10$; $i - t=8T_{op}/10$; $j - t=9T_{op}/10$; $k - t=T_{op}$

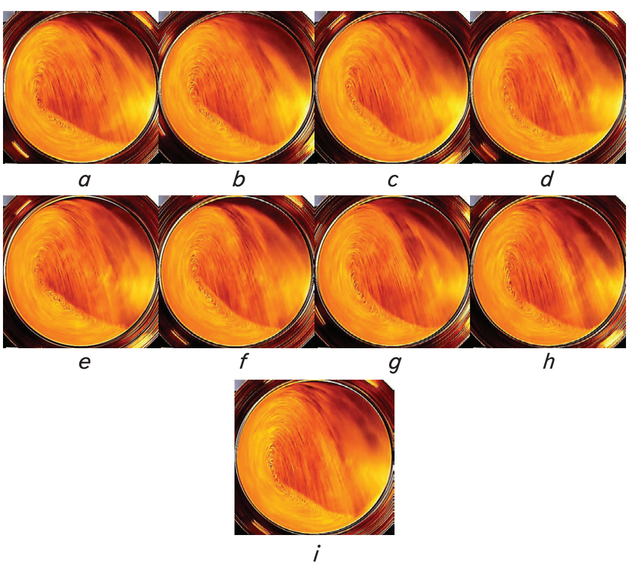

Fig. 3. Consecutive patterns of fill motion during time t for one period of self-oscillations T_{op} with a maximum swing at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.45, κ_{mbgr}=0.5 and $\psi_\omega\approx 1$: $a - t=0$; $b - t=T_{op}/8$; $c - t=2T_{op}/8$; $d - t=3T_{op}/8$; $e - t=4T_{op}/8$; $f - t=5T_{op}/8$; $g - t=6T_{op}/8$; $h - t=7T_{op}/8$; $i - t=T_{op}$

The values of inertial (9) to (11) and dynamic (12) parameters of self-oscillatory fill motion were calculated using the experimental method of visual analysis of motion patterns. The method implies the sequential performance of the following steps:

1) video recording of the self-oscillatory motion of the fill in a rotary chamber having a transparent face wall;

2) obtaining of motion patterns in the chamber cross-section corresponding to several periods of self-oscillations T_{op};

3) selection of planar geometrical figures in the patterns corresponding to the entire fill $S_{fm\max}$ and $S_{fm\min}$ and its passive part $S_{fpm\min}$;

4) measuring areas of these figures;

5) calculating values of $\upsilon_{\max}$, $\psi_{R\upsilon}$, $\kappa_{fam\max}$ and K_a from expressions (9) to (11). Graphs of the obtained results of experimental determination of the parameters change from the degree of filling of the gaps between the grinding bodies with particles of crushed material κ_{mbgr} for $\upsilon_{\max}$ (Fig. 5), $\psi_{R\upsilon}$ (Fig. 6), $\kappa_{fam\max}$ (Fig. 7) and K_a (Fig. 8).

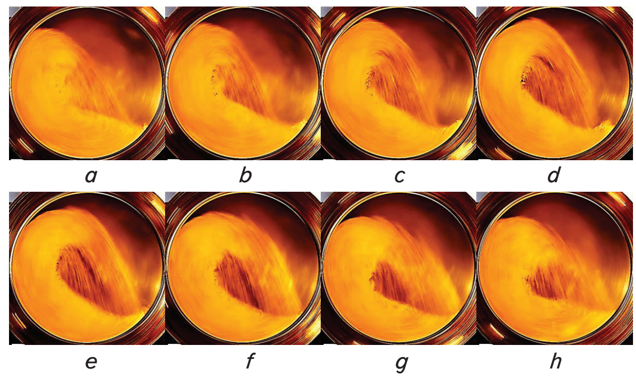

Fig. 4. Consecutive patterns of the fill motion during time t for one period of self-oscillations T_{op} with a maximum swing at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.45, κ_{mbgr}=1 and $\psi_\omega\approx 1$: $a - t=0$; $b - t=T_{op}/7$; $c - t=2T_{op}/7$; $d - t=3T_{op}/7$; $e - t=4T_{op}/7$; $f - t=5T_{op}/7$; $g - t=6T_{op}/7$; $h - t=T_{op}$

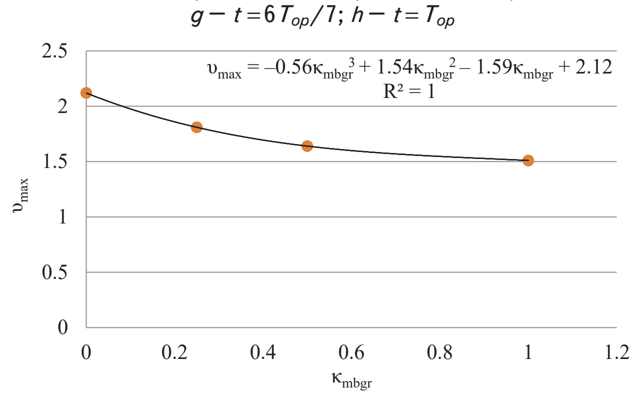

Fig. 5. Experimental dependence of change in the maximum value of fill dilatancy during one period of self-oscillations $\upsilon_{\max}$ on the degree of filling the gaps between particles of the coarse fraction by particles of the fine fraction κ_{mbgr} at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$ and κ_{br}=0.45

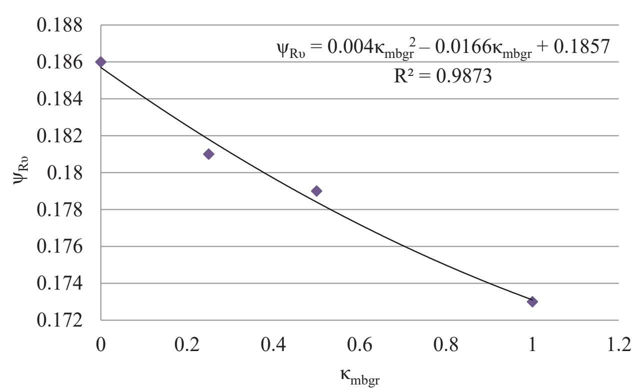

Fig. 6. Experimental dependence of change in the relative swing of self-oscillations of the fill $\psi_{R\upsilon}$ on κ_{mbgr} at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$ and κ_{br}=0.45

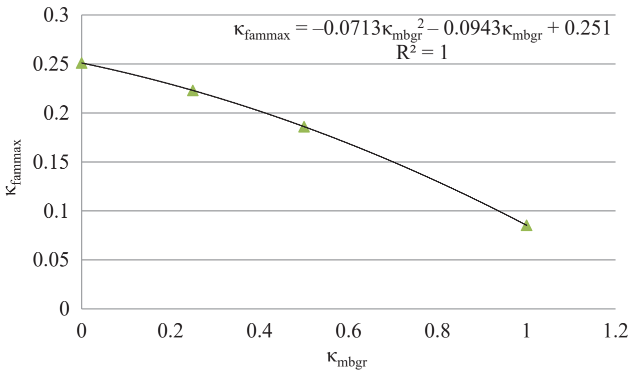

Fig. 7. Experimental dependence of the change in the mass fraction of the active part of the fill on κ_{mbgr} at $\psi_{db}=0.0104$, $\psi_{dm}\approx 0.13\cdot 10^{-3}$ and $\kappa_{br}=0.45$

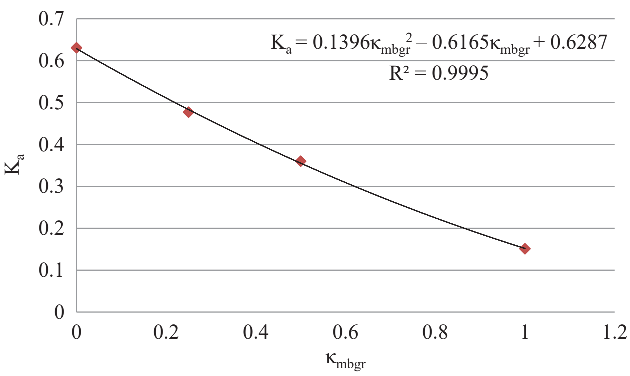

Fig. 8. Experimental dependence of the change in the degree of dynamic fill activation K_a on κ_{mbgr} at $\psi_{db}=0.0104$, $\psi_{dm}\approx 0.13\cdot 10^{-3}$ and $\kappa_{br}=0.45$

Experimental dependences of numerical values of maximum dilatancy, relative amplitude of self-oscillations, share of the active part of the fill and the degree of dynamic activation characterize the influence of the content of crushed material on dynamic action of the grinding bodies.

6. Experimental determination of the influence of the content of the crushed material in the intra-chamber fill on productivity and energy intensity of steady and self-oscillatory grinding processes

The influence of the content of crushed material in the intra-chamber fill on the efficiency of the self-oscillatory grinding process in the tumbling mill was evaluated for the case of grinding the cement clinker.

A coarse fraction of the two-fraction fill in the laboratory mill chamber consisted of steel ball grinding bodies of relative size $\psi_{db}=0.026$. The fine fraction consisted of particles of pre-crushed clinker with a relative size $\psi_{dm}<0.0059$.

The volumetric degree of filling of the chamber with grinding bodies in the state of free rest was $\kappa_{br}=0.45$. Discrete values of the volumetric degree of filling the gaps between grinding bodies with particles κ_{mbgr} in the state of free rest were 0.125, 0.5625 and 1. The degree of filling $\kappa_{mbgr}=0.125$ corresponded to fine and ultrafine grinding, $\kappa_{mbgr}=0.5625$ to medium grinding, $\kappa_{mbgr}=1$ to coarse grinding.

The productivity of grinding lasting 30 min was determined by sieving through a 0.08 mm sieve.

Technological efficiency of the self-oscillatory grinding process was evaluated by relative productivity:

$$\frac{C_o}{C_s}=\frac{1-m_{ro}/m_m}{1-m_{rs}/m_m}, \qquad (13)$$

where C_o – productivity of the self-oscillatory process ($\psi_\omega\approx 1$); C_s – productivity of the conventional steady process ($\psi_\omega=0.75$); m_{ro} – the mass of the crushed material residue on the sieve after sieving in the self-oscillatory process; m_{rs} – the mass of residue on the sieve in the conventional steady state; m_m – the total weight of a portion of crushed material before sieving.

The energy efficiency of the self-oscillatory grinding process was assessed by relative specific energy intensity:

$$\frac{E_o}{E_s}=\frac{P_{do}}{P_{ds}}\bigg/\frac{C_o}{C_s}, \qquad (14)$$

where P_{do} – the power of the drive rotating the filled drum during the self-oscillatory process ($\psi_\omega\approx 1$); P_{ds} – the power of the drive in the conventional steady process ($\psi_\omega=0.75$); P_{do}/P_{ds} – relative energy intensity of the self-oscillatory grinding process; $E_o=P_{do}/C_o$ – specific energy intensity of the self-oscillatory process; $E_s=P_{ds}/C_s$ – specific energy intensity of the conventional steady state process.

According to the obtained experimental data, technological parameters of grinding processes in the tumbling mill have the following values: $C_o=0.694$ and $C_s=0.499$ at $\kappa_{mbgr}=0.125$, $C_o=0.627$ and $C_s=0.498$ at $\kappa_{mbgr}=0.5625$, $C_o=0.464$ and $C_s=0.435$ at $\kappa_{mbgr}=1$.

The relative energy intensity of the self-oscillatory process becomes $P_{do}/P_{ds}=0.776$ [9].

Then, according to (13) and (14), relative productivity and specific energy intensity of the self-oscillatory grinding process have the following values: $C_o/C_s=1.39$ and $E_o/E_s=0.558$ at $\kappa_{mbgr}=0.125$, $C_o/C_s=1.26$ and $E_o/E_s=0.617$ at $\kappa_{mbgr}=0.5625$, $C_o/C_s=1.067$ and $E_o/E_s=0.728$ at $\kappa_{mbgr}=1$.

Graphs of the obtained results of experimental determination of the change of parameters depending on the degree of filling of the gaps between the grinding bodies κ_{mbgr} with particles of the crushed material are shown in Fig. 9 for C_o/C_s and in Fig. 10 for E_o/E_s.

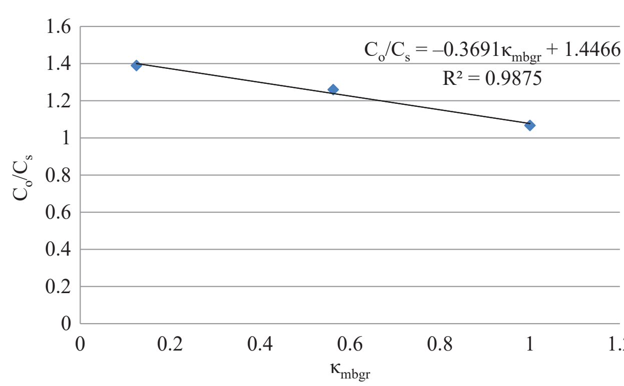

Fig. 9. Experimental dependence of the change in the relative productivity C_o/C_s of the self-oscillatory process of grinding cement clinker in a tumbling mill on the degree of filling gaps between the grinding bodies by particles of crushed material in the state of free rest κ_{mbgr} at $\psi_{db}=0.026$ and $\psi_{dm}<0.0059$

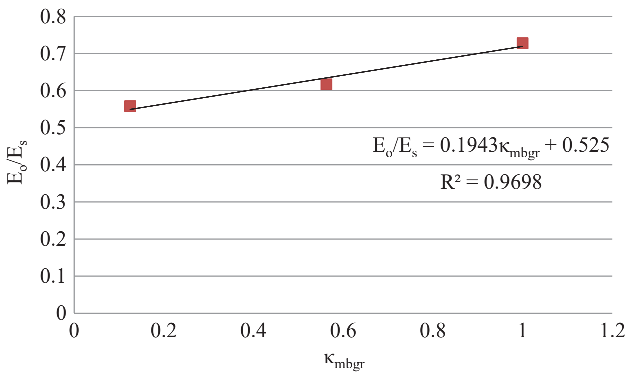

Fig. 10. Experimental dependence of the change in relative specific energy intensity E_o/E_s of the self-oscillatory process of clinker grinding in a tumbling mill on κ_{mbgr} at $\psi_{db}=0.026$ and $\psi_{dm}<0.0059$

Dependences of the numerical values of relative productivity and specific energy intensity characterize the influence of the content of the crushed material in the fill on the efficiency of the self-oscillatory grinding process in the tumbling mill.

7. Discussion of the results obtained in the study of the influence of the content of crushed material in the fill on parameters of the self-oscillatory grinding process

The obtained numerical results have allowed us to quantify the influence of the fine fraction content on inertial parameters and characteristics of the dynamic action of the two-fraction fill during the auto-excitation of self-oscillations. It turned out that with an increase in the fine fraction content, values of inertial parameters of the self-oscillatory motion of the fill decrease. Such parameters include maximum load dilatancy during one period of pulsations $\upsilon_{\max}$ (9), the relative amplitude of self-oscillations $\upsilon_{R\upsilon}$ (10), and the maximum mass fraction of the active part of the fill (11). Besides, with an increase in the content of such a fraction, the value of the generalized complex dynamic characteristic of the self-oscillatory motion, that is, the degree of dynamic activation of the fill K_a (12) decreases significantly. As the volumetric degree of filling of the gaps between spherical particles of the coarse fraction with particles of the fine fraction in the state of free rest κ_{mbgr} (6) increases from 0 to 1, values of a series of parameters decrease. In particular, $\upsilon_{\max}$ decreases by approximately 29 % (Fig. 5), $\psi_{R\upsilon}$ by 7 % (Fig. 6), $\kappa_{fam\max}$ 2.9 times (Fig. 7) and K_a 4.2 times (Fig. 8).

The abovementioned indicates a decrease in the self-oscillatory dynamic action of the fill caused by an increase in the share of the passive quasi-solid zone, a decrease in the share of the active pulsation zone in the cross-section of the chamber, a decrease in dilatancy and amplitude of self-oscillations with increasing κ_{mbgr}. This is determined by the manifestation of the established dynamic effect of strengthening cohesive properties of particles of an incoherent coarse fraction of the two-fraction fill under the influence of fine fraction particles.

The influence of the content of crushed material in the fill on the value of energy intensity and productivity of the self-oscillatory process of grinding in a tumbling mill was quantitatively evaluated in comparison with parameters of the conventional steady process. It was found that during self-oscillation, the relative specific energy intensity of grinding (14) decreased by about 27 % at $\kappa_{mbgr}=1$, by 38 % at $\kappa_{mbgr}=0.5625$ and by 44 % at $\kappa_{mbgr}=0.125$ (Fig. 9). Relative productivity of the process (13) increased by approximately 7 % at $\kappa_{mbgr}=1$, by 26 % at $\kappa_{mbgr}=0.5625$ and by 39 % at $\kappa_{mbgr}=0.125$ (Fig. 10).

This indicates a significant decrease in specific energy intensity and an increase in productivity of the self-oscillatory process due to the increased dynamic action of the fill with a decrease in κ_{mbgr} (Fig. 5–8).

The value and applicability of the obtained results are determined by the possibility of using the selected methods, by characteristics of the study objects and the boundaries of the considered subject of the experiment. In particular, we can note the following main limitations of the study. The results of dynamic studies were obtained at a content of small particles in the fill $\kappa_{mbgr}=0$, 0.25, 0.5 and 1 (Fig. 1–4), the relative size of large particles $\psi_{db}=0.0104$ and small particles $\psi_{dm}\approx 0.13\cdot 10^{-3}$. The results of technological studies were obtained at a content of crushed material in the fill $\kappa_{mbgr}=0.125$, 0.5625, and 1, the relative size of the grinding bodies $\psi_{db}=0.026$ and particles of material $\psi_{dm}<0.0059$. The volumetric degree of filling the drum chamber with particles of coarse fraction in the state of free rest (4) for all studies was $\kappa_{br}=0.45$.

Disadvantages of the applied approach to the assessment of the impact of self-oscillations on operation include a failure to take into account geometric criteria of similarity of the system under study with a multiphase medium of a variable structure.

In the future, it is advisable to determine the qualitative and quantitative impact of the degree of filling the chamber by a fill on dynamic and technological parameters of the process when the content of particles of the crushed material in the space between the grinding bodies. This will establish rational conditions for auto-excitation of fill pulsations during the implementation of the self-oscillatory grinding process in tumbling mills for various types of grinding.

8. Conclusions

1. Values of inertial parameters of the self-oscillatory motion of a two-fraction fill were calculated by the method of visual analysis of motion patterns in the cross-section of the rotating drum chamber. Relative particle sizes of the coarse and fine fractions were 0.0104 and $0.13\cdot 10^{-3}$ and the degree of chamber filling with particles of the coarse fraction in the state of free rest was 0.45. Besides, the degree of filling of the gaps between spherical particles of the coarse fraction by particles of the fine fraction in the state of free rest κ_{mbgr} was 0, 0.25, 0.5, and 1. Under these conditions, the parameters were: 1.51–2.12 for maximum filling dilatancy during one pulsation period, 0.173–0.186 for the relative amplitude of self-oscillations and 0.085–0.251 for the maximum mass fraction of the active part of the fill. The value of the accepted degree of dynamic activation of the fill varied in the range of 0.151–0.631.

2. It was established that with an increase in the content of fine fraction κ_{mbgr} the self-oscillatory dynamic effect of the fill decreases due to the increase in the share of the passive quasi-solid zone and the decrease in the share of active pulsation zone in the chamber cross-section, decrease in dilatancy and pulsation. This is because of the manifestation of the dynamic effect of a significant increase in cohesive properties of the incoherent coarse fraction of the fill under the influence of the fine fraction.

3. A decrease in relative specific energy intensity of the process of grinding the cement clinker for the innovative self-oscillatory process compared to the conventional steady

state was experimentally revealed. For the relative size of the ball grinding bodies 0.026 and the degree of filling the chamber with a fill of 0.45, such a decrease was approximately 27 % at $\kappa_{mbgr}=1$, 38 % at $\kappa_{mbgr}=0.5625$ and 44 % at $\kappa_{mbgr}=0.125$. Under such conditions, the relative productivity of the self-oscillatory process increased by approximately 7 % at $\kappa_{mbgr}=1$, by 26 % at $\kappa_{mbgr}=0.5625$ and by 39 % at $\kappa_{mbgr}=0.125$.

4. It was established that specific energy intensity decreases and productivity of the self-oscillatory grinding process in the tumbling mill increases with a decrease in the content of the crushed material in the intra-chamber fill κ_{mbgr}. This is due to the manifestation of the technological effect of a significant increase in the pulsating dynamic action of the grinding bodies on the crushed material particles with a decrease in κ_{mbgr}.

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DEVELOPMENT OF THE SINGLE-SETUP MILLING PROCESS MODEL OF THE SHAFT SUPPORT NECKS AND CAMS

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Three-dimensional geometrical modeling of the processes of allowance removal and shaping of support necks and cams of camshafts when milling with crossed axes of the tool and part is proposed. Single-setup milling of camshafts, which are widely used in automotive, tractor, shipbuilding and other industries, is carried out by a cutter with crossed axes of it and the part. The rotation angle of the cutter is selected from the condition of providing the required roughness of the treated surface and is regulated by the feed. At the same time, high processing productivity is provided by an increase in camshaft speed. A method of milling support necks and cams is developed, where the processing is carried out by a cutter, the height of which is less than the lengths of the processed surfaces. When processing the passage, the main allowance is removed by the end face of the quadrangular roughing carbide plate, and the finishing is carried out by the unloaded periphery of the cermet finishing plate. This allowance distribution increases the productivity and accuracy of processing, and the ability to rotate the roughing plate saves material and reduces the cost of processing. In the process of milling the curved surface of the camshaft cam, the depth of cut along the machined profile is always greater than the value of the removed allowance. This causes a decrease in the accuracy and productivity of processing. In order to eliminate this problem, it is proposed to stabilize the depth of cut and feed along the contour with uneven rotation of the part. The uniformity of the depth of cut and feed along the curved contour of the cam is achieved by simultaneous vertical and transverse movements of the cutter and uneven rotation of the camshaft. When milling the curved surface of the cam, the center of which does not coincide with the camshaft center, there is an uneven rotation of the latter and synchronous vertical and transverse movement of the cutter. When machining the cam section, the center of which coincides with the camshaft center, the cutter is given only rotation

Keywords: camshaft milling, crossed axes, camshaft cams, support necks

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1. Introduction

Modern automobile, tractor, shipbuilding and other machine-building industries are characterized by a wide range of products with curved working surfaces. Such surfaces include, in particular, camshafts, crankshaft necks, brake pads, etc.

The competitiveness of machine-building products is determined by the high surface accuracy of parts and productivity of their processing. In modern economic conditions [1],