

1. Introduction

Tumbling mills remain the main equipment for large-tonnage fine grinding of various materials in many industries.

A new technological direction for a significant increase in the relatively low energy efficiency of such mills is the use of self-oscillating grinding process. Auto-excitation of self-oscillations allows to set in motion and activate the passive part of the internal long filling. This mode of movement significantly increases the intensity of the interaction of the grinding bodies with the crushed material.

The complex multiphase polygranular structure causes a significant variability in the pulsating behavior of the feed in the rotating chamber. The above significantly complicates the establishment of rational conditions for the effective implementation of such a process.

Under certain conditions, the established modes of motion of the drive units of rather tumbling mills become unstable [1]. Such instability can be accompanied by fluctuations in the power of the fed drum rotation drive [2].

The applied value of the pulsating behavior of the intra-chamber feeding lies in the use of an innovative self-oscillating grinding process in a tumbling mill [3]. The energy efficiency of such a process increases with a decrease in the degree of filling the chamber [4] and the content of the crushed material in the feeding [5].

On the other hand, the technological efficiency of the implementation of the auto-rolling process depends significantly on the adopted value of the rotation speed corresponding to the achievement of the maximum swing of self-oscillations.

The behavior of the granular filling of the rotating drum has a pronounced unstable character [6]. In [7], it was found that such instability manifests itself in the appearance of an avalanche-like collapse of the free surface.

The increased applied relevance of the problem has recently caused a sharp increase in research activity in predicting the unstable behavior of the granular filling of a rotating drum. Of greatest interest is the behavior of the free filling surface, which undergoes significant complex deformations during self-constriction of pulsations [8–14].

However, the results obtained earlier relate only to periodic flows of monodisperse granular filling, mainly with a rather slow rotation of the drum and small swing of self-oscillations. On the other hand, the filling of a tumbling mill has a pronounced two-fraction structure, consisting of a coarse

ESTABLISHING THE ROTATION SPEED VARIATION RANGE LIMITS FOR AUTO-EXCITATION OF SELF-OSCILLATING GRINDING IN A TUMBLING MILL

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Abstract: The influence of the structure of a two-fraction polygranular feed of the chamber on the value of the drum rotation speed at auto-excitation of self-excited oscillations with a maximum swing is considered. Such a pulsating mode of movement of the charge is used in the self-oscillating process of grinding in a tumbling mill. The coarse fraction simulated the grinding bodies was steel bullets with a relative size $\psi_{db}=0.026$. The fine fraction, simulated the particles of the crushed material, was a cement clinker with a relative particle size $\psi_{dm}=0.00013$. Variable factors of experimental studies were: the degree of filling the chamber in the state of rest $\kappa_{br}=0.25; 0.29; 0.33$ and the degree of filling the gaps between the particles of the coarse fraction with particles of the fine fraction $\kappa_{mbgr}=0.0625; 0.375; 0.6875; 1$. The method of visual analysis of transient processes of self-oscillating modes of feed behavior in the cross section of the rotating drum chamber is applied. Measurements of the speed limits of the drum rotation were carried out with auto-excitation of self-oscillations of the filling. The magnitude of the self-oscillation swing was estimated by the increase in the difference between the maximum and minimum values of the filling dilatancy for one period of pulsations. An increase in the upper limit of the speed range $\psi_{\omega 2}$ with a decrease in κ_{br} and κ_{mbgr} was established. The growth rate of $\psi_{\omega 2}$ increases at low values of κ_{br} and κ_{mbgr} . Some increase in the lower limit of the $\psi_{\omega 1}$ range with a decrease in κ_{br} and κ_{mbgr} was revealed. An increase in the range of speeds of rotation was recorded at the maximum range of self-oscillations $\psi_{\omega 1}-\psi_{\omega 2}$ with a decrease in the connected interaction of the intra-mill filling. This coherent interaction is due to an increase in κ_{br} and κ_{mbgr} . The value of the $\psi_{\omega 1}-\psi_{\omega 2}$ range varies from 1.01–1.03 at $\kappa_{br}=0.33$ and $\kappa_{mbgr}=1$ to 1.22–1.66 at $\kappa_{br}=0.25$ and $\kappa_{mbgr}=0.0625$. The range gets its maximum value with fine and superfine grinding.

Keywords: tumbling mill, rotation speed, maximum range of self-oscillations, two-fraction granular feed, fine fraction.

fraction of grinding bodies and a fine fraction of particles of the crushed material. The influence of the rotation speed of the range of self-oscillations of such a filling remains unknown.

2. Methods

As a research method, a visual analysis of the transient processes of auto-oscillation modes of behavior of a two-fraction intra-mill filling in the cross section of the chamber and measuring the rotation speed of the drum were used.

The degree of filling the chamber with filling in the state of rest κ_{br} and the degree of filling the gaps between particles of the coarse fraction with particles of the fine fraction κ_{mbgr} were chosen as the variables of the experimental studies.

$$\kappa_{br} = \frac{w_{br}}{\pi R^2 L},$$

$$\kappa_{mbgr} = \frac{w_{mfr}}{0.4 \kappa_{br} \pi R^2 L},$$

where w_{br} – the volume of a portion of the coarse fraction in the state of rest, w_{mfr} – the volume of a portion of the fine fraction, 0.4 – the volume fraction of the spaces between spherical particles of the coarse fraction in the state of rest, R – the radius of the drum chamber, L – the chamber length.

Discrete values of variable factors were: $\kappa_{br}=0.25; 0.29; 0.33$ and $\kappa_{mbgr}=0.0625$ (extra fine); 0.375 (fine); 0.6875 (medium); 1 (coarse).

According to the geometric characteristics of the elements of the coarse ψ_{db} and fine ψ_{dm} fraction of the filling, the relative sizes of the elements in the rotating chamber were taken

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

where d_b and d_m – the average absolute size of the grinding bodies and particles of the ground material.

The value of the angular speed of rotation of the drum ω when self-oscillations of the filling reached the maximum swing was estimated by the value of the relative speed of rotation

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

where g – the gravitational acceleration.

A laboratory tube mill with a transparent end wall was used to visualize the filling flow. The drive made it possible to smoothly change the angular speed of drum rotation.

The coarse fraction of the filling, simulated grinding bodies, consisted of steel balls with a relative size $\psi_{db}=0.026$. The fine fraction simulated the material to be crushed was made of cement clinker. The relative size of the particles of the material ψ_{dm} changed during grinding from 0.0059 to $0.13 \cdot 10^{-3}$.

The range of self-oscillations was estimated by the magnitude of the increase in the maximum and minimum values of the dilatancy for one period of filling pulsations.

The video recording rate was 24 frames per second.

3. Results

The limits of the range of rotation speed were visually determined for auto-excitation of self-oscillations with the maximum swing (Fig. 1) of the intra-chamber filling of a tumbling mill.

To analyze the results obtained, graphical dependences of the boundaries $\psi_{\omega 1}$ and $\psi_{\omega 2}$ of the range of the drum rotation speed were obtained when the maximum swing of the filling self-oscillations was reached from changes in κ_{br} and κ_{mbgr} .

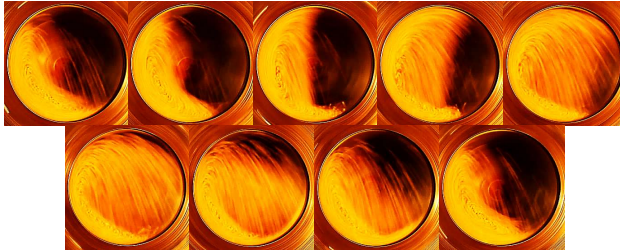


Fig. 1. Consecutive pictures of the filling movement for one period of self-oscillations at $\kappa_{br}=0.25$, $\kappa_{mbgr}=0.0625$, $\psi_{db}=0.026$ and $\psi_{dm}=0.00013$

Fig. 2 shows the graphs of the dependences of the change in the lower limit of the rotation speed range $\psi_{\omega 1}$ on κ_{br} and κ_{mbgr} .

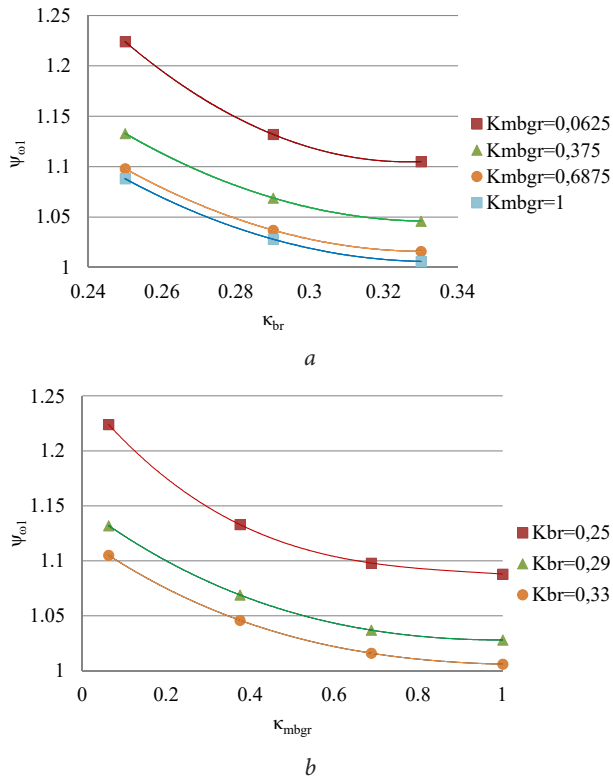


Fig. 2. Dependences of changes in the lower limit of the range $\psi_{\omega 1}$: a – on κ_{br} ; b – on κ_{mbgr}

Fig. 3 shows the graphs of the dependences of changes in the upper boundary of the velocity range $\psi_{\omega 2}$ on κ_{br} and κ_{mbgr} .

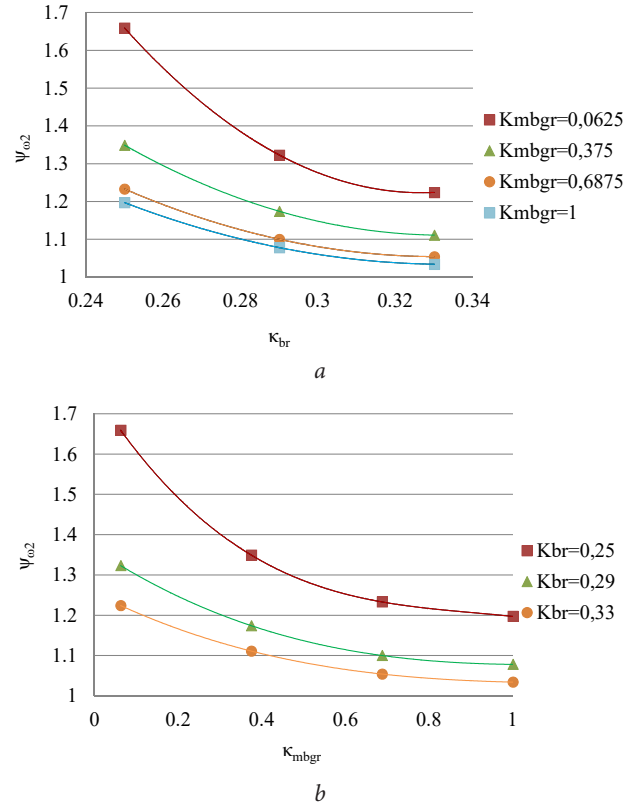


Fig. 3. Dependences of changes in the upper limit of the range $\psi_{\omega 2}$: a – on κ_{br} ; b – on κ_{mbgr}

Fig. 4 shows graphs of dependences of changes in the boundaries of the speed range $\psi_{\omega 1}-\psi_{\omega 2}$ on κ_{br} at $\kappa_{mbgr}=0.0625$; 0.375; 0.6875 and 1.

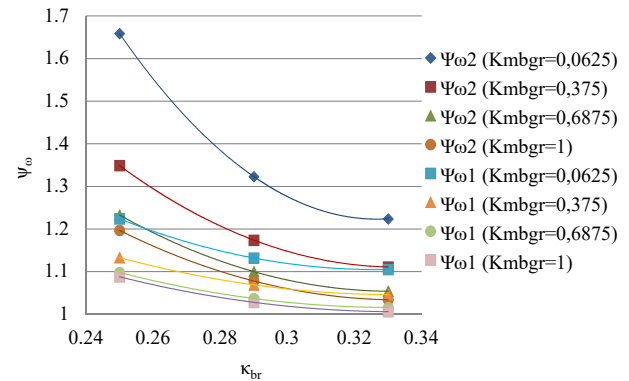


Fig. 4. Dependences of changes in the boundaries of the $\psi_{\omega 1}-\psi_{\omega 2}$ range on κ_{br}

Fig. 5 shows graphs of dependences of changes in the boundaries of the speed range $\psi_{\omega 1}-\psi_{\omega 2}$ on κ_{mbgr} at $\kappa_{br}=0.25$; 0.29 and 0.33.

The dependence of the numerical values of the boundaries characterizes the influence of the degree of filling of the chamber and the content of the crushed material on the speed range of the maximum swing of self-oscillations.

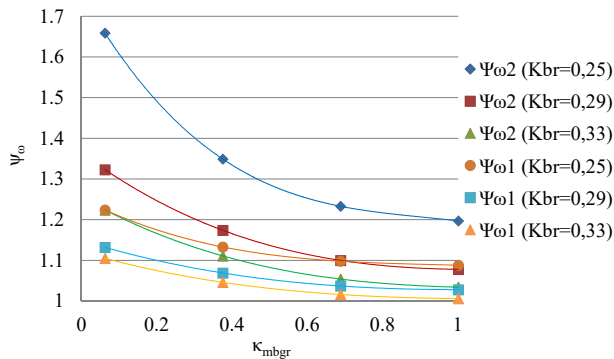


Fig. 5. Dependences of changes in the boundaries of the $\Psi_{\omega 1}-\Psi_{\omega 2}$ range on κ_{mbgr}

4. Discussion of results

The results obtained significantly refine the known data on the value of the boundaries of the speed range for the implementation of the self-oscillating grinding process in a tube mill.

The lower limit of the speed range $\Psi_{\omega 1}$ increases with a decrease in the degree of filling the chamber κ_{br} (Fig. 2, a) and the content of the crushed material κ_{mbgr} (Fig. 2, b). The growth rate increases at low values of κ_{br} and κ_{mbgr} .

The upper limit of the speed range $\Psi_{\omega 2}$ slightly increases with decreasing κ_{br} (Fig. 3, a) and κ_{mbgr} (Fig. 3, b).

The range of rotation speeds of the drum at the maximum range of self-oscillations $\Psi_{\omega 1}-\Psi_{\omega 2}$ (Fig. 1) increases with a decrease in the coherent interaction of the tube mill chamber filling. Such a connected interaction is due to an increase in κ_{br} and κ_{mbgr} (Fig. 4, 5).

The value of the speed range $\Psi_{\omega 1}-\Psi_{\omega 2}$ varies from 1.01–1.03 with $\kappa_{br}=0.33$ and $\kappa_{mbgr}=1$ to 1.22–1.66 with $\kappa_{br}=0.25$ and $\kappa_{mbgr}=0.0625$.

The advantage of the results obtained is that the effect of the degree of filling the chamber and the content of the crushed material on the self-oscillations is taken into account. The disadvantages include the consideration in the work of only two-fraction filling, which instead can be multi-fraction.

The range acquires its maximum value with fine and ultrafine grinding. Therefore, it seems that the greatest efficiency of the use of the self-oscillating grinding process in tumbling mills will be achieved at the last stage of grinding.

At the same time, further clarification requires the influence of the structure of the polygranular intra-mill filling on other frequency characteristics of self-oscillations, which self-excite.

5. Conclusions

The effect of dropping the boundaries and the value of the range of the drum rotation speed is registered, when the maximum range of self-oscillations is reached, with an increase in the coherent properties of the intra-mill filling.

An increase in the coherent properties of a two-fraction filling with an increase in the degree of filling the chamber and the content of fines is established.

The numerical values of the boundaries of the considered range of variation of the rotation speed of the tube mill are determined.

An increase in the activity of the self-oscillating grinding process with an increase in the fineness of grinding is revealed.

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