Intensification of the grinding process in vibration mills

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Abstract. The paper deals with the problems of intensification of grinding in vibration mills with harmonic, biharmonic and polyharmonic vibrations. In particular, as one of the ways to solve this problem, it is suggested to use the adjustable amplitude-frequency characteristics of the movement of the vibrator with polyharmonic vibrations. The paper presents a new design of the vibration mill with polyharmonic vibrations, which has three vibratory drives mounted on the grinding chamber with the possibility of varying the frequency, direction of rotation, mass of unbalanced masses, as well as the geometric arrangement of the vibratory drives relating to the axes passing through the center of gravity of the vibration mill.

1. Introduction
The earliest industrial designs of vibration mills appeared in the late thirties of the last century. To date, they are widely used in various industries for fine and ultra-fine grinding of materials [1–3]. The main advantage of using vibration mills is the possibility of obtaining powders with a particle size of less than 5 µm with a specific surface area of up to 1000 m² / kg.

In addition, in comparison with other types of mills [4], in the production of fine powders with high volumetric capacity, vibration mills allow to obtain lower specific energy consumption. Using grinding media and lining of special materials allow to obtain a finished product without milling yield from the material of grinding media and lining [5].

Vibration mills with a cylindrical grinding chamber mounted on springs equipped with a single unbalance vibration drive are the most widely used.

When the vibration drive is turned on, the grinding chamber with the grinding bodies performs a harmonic oscillation in the plane along a trajectory close to the circular one. The trajectory of motion of grinding media at all points of the cross-sectional plane of the grinding chamber is homogeneous, since these trajectories have the same parameters. Grinding bodies in the cross section of the grinding chamber of the vibration mill move in the direction opposite to the rotation of the unbalanced drives. During this process, each grinding body additionally rotates around its own center of gravity, crushing material particles by impact, crushing and abrasion.

In the cross section of the grinding load, stagnant zones are formed in its central part and segregation of grinding media and particles of the crushed material occurs. Large grinding media and the smallest particles of the grinding material are moved to the upper part of the chamber, and small balls and large particles of the grinding material accumulate in the lower part of the grinding chamber. This significantly reduces the efficiency of the grinding process in the vibration mill.

The performance of the vibration mills, first of all, depends on the frequency and amplitude of the grinding chamber. At a constant amplitude with increasing frequency of oscillations, the productivity of
the mill is directly proportional to the increase of frequency). The increase in amplitude can partially reduce stagnant zones in the loading of grinding media and improve the efficiency of the grinding process. However, this significantly increases the dynamic load on the structural elements of the mills, which causes significant wear of the working bodies, reduces the operational reliability of the mills. The maximum acceleration achieved in vibration mills should not exceed 9 g [6].

One of the ways to improve the design of vibration mills is improving the efficiency of the grinding process (productivity and fineness of grinding) by creation of mills with biharmonic vibrations of the grinding chamber [6-8].

For example, in Germany, the mill was developed [6] with a cylindrical grinding chamber, from both end sides of which the unbalanced vibratory motors are fixed, that have the ability to control the speed and direction of rotation unbalanced masses. The axes of rotation of the unbalanced shafts coincide with the longitudinal axis of the grinding chamber, passing through the center of gravity of the entire oscillatory system. In this design of the vibration mill under the influence of two vibratory drives, the grinding chamber, together with the grinding bodies, performs biharmonic oscillation motion along complex trajectories, significantly different from the circular oscillations in ordinary vibration mills.

A mill with harmonic oscillations has a trajectory of the chamber and grinding media close to circular (figure 1.a). In a vibration mill with biharmonic oscillations, the trajectory of the chamber and the grinding bodies significantly depends on the frequency, direction of rotation and the mass of each of unbalanced mass.

If the frequency of rotation of one unbalanced mass is twice as large as that of the other, and its mass is half as much, and they rotate in opposite directions, then the trajectory of the oscillations of all the points of the grinding chamber will be similar to a triangle with equal concave sides and sharp corners (figure 1, b). If the vibratory drives rotate in one direction, the vibration trajectory will be close to circular (figure 1, c).

If under the same conditions, the mass of one unbalanced mass is 4 times larger than the mass of another, the type of the trajectory of all points of the grinding chambers will change – they will take the form of an equilateral triangle and smoothed vertexes (figure 1, d).

By increasing the frequency of rotation of unbalanced masses to 1:3 and the change of the ratio of the masses equal to 3:1, the trajectory of all points of the grinding chamber takes the form of a square with concave sides and sharp corners (figure 1, e). With rotating of unbalanced masses in one direction, the trajectory takes the form shown with a line (figure 1, f).

Thus, the creation of biharmonic vibration conditions allows to obtain different shapes and vibration trajectories of the grinding chamber and grinding media, which are significantly different from the circular ones with the harmonic motion of the vibratory drive.

Despite the possibility of changing the trajectory of the grinding chamber, the trajectory of grinding media in the cross-section of the chamber along its entire length is homogeneous, which also leads to the formation of stagnant zones and segregation of grinding media and grinding material. A vibration mill with biharmonic vibrations of the body in which two vibratory drives are located on the diametrically opposite sides of the grinding chamber in the plane of transverse symmetry of the grinding chamber [7] attracts certain interest.

This solution, along with the generation of the centrifugal exciting force by unbalanced masses, provides the occurrence of the exciting moment, the value of which is proportional to the exciting centrifugal force and the distance from the axis of rotation of the unbalanced mass to the center of mass of the oscillatory system. In this case, the trajectories of different points of the grinding chamber differ both in shape and parameters [9].

Figure 2 shows the trajectories of the characteristic points located on the end wall of the grinding chamber.

Comparative analysis of the trajectory of the three types of vibration mills shows the advantages of mills with biharmonic vibrations of the grinding chamber and the ability to control a wide range of grinding modes by adjusting the frequency and amplitude of the corresponding harmonics, as well as the reverse of one of the vibratory drives.
In this design of the vibration mill, as can be seen from the graphs shown in figure 2, the highest intensity of movement of grinding media occurs in the areas adjacent to the inner walls, especially the side of the grinding chamber. In the central part of the load, as a result of the damping of grinding media, the force of their interaction is reduced, the efficiency of the grinding process in the center of the load is reduced.

**Figure 1.** The trajectories of the grinding chamber of the vibration mill with biharmonic vibrations.

**Figure 2.** Trajectories of characteristic points of the grinding chamber.
2. New mill design with polyharmonic vibrations

We have developed a fundamentally new design of the vibration mill with polyharmonic vibrations of the grinding chamber [6], the cross section of which is shown in figure 3.

A significant difference of this design of the mill is that it is equipped with three vibratory drives 6, 7, 8, one of which (8) is installed at the bottom of the grinding chamber 1, and its axis of rotation E is located on the vertical axis F of the grinding chamber 1, and two debalance vibratory drives 6, 7 are installed on the opposite sides of the grinding chamber 1. In this case, the axis A, D of rotation of each of the vibratory drives 5, 7 is perpendicular to the plane of the transverse symmetry of the grinding chamber 1 and shifted in opposite directions.

Intensification of the movement of the grinding bodies 2 is provided as follows: since the axes of rotation of the vibratory drivers 5 and 7 are offset from the horizontal axis B and the vertical axis F and, therefore, from the center of gravity C of the grinding chamber 1, they generate not only centrifugal force but also torques relative to axes B and F of the grinding chamber 1.

The magnitude of the centrifugal force generated by vibratory motors 6 and 7 depends on their mass and speed.

![Figure 3. Vibration mill design with polyharmonic vibrations](image)

The magnitude of the generated torques depends, in turn, on the magnitude of the centrifugal force and the distance a,b of the unbalanced masses displacement 6,7 on the horizontal B and vertical F axes of the grinding chamber.

In this connection, in the grinding environment, the heterogeneous field of speeds and movements is created, stagnant zones are destroyed in all volume of grinding loading, segregation of grinding bodies and a crushed material is excluded.

The lower vibratory drive 8 creates directed vertical vibrations, prevents the segregation of grinding media in the grinding chamber 1.
3. Conclusion
The complex effect of vibratory motors 6, 7, 8 creates a non-uniform field of velocities and complex energies in the grinding medium and provides conditions for selective grinding of material particles. Thus, one of the directions of improving the design and process of grinding materials in vibration mills is to create a mode of motion of grinding media which would prevent their transverse segregation, destroying stagnant zones in the Central part of the load, providing conditions for selective grinding process. One of the possible design solutions is the development of vibration mills with polyharmonic vibrations of the grinding chamber and vibration drives removed at some distance from the center of mass of the oscillating system.

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