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Efficiency of Grinding and Mechanical Activation of Solids in Planetary Ball Mills

Yu.D. Kaminsky and **N.Z. Lyakhov**

Institute of Solid State Chemistry and Mechanochemistry SB RAS, 630128 Novosibirsk, Russia

We develop the algorithm of the procedure for determining the efficiency of operation of planetary mills which is based on the analysis of the movement of the entire load (balls and material) in drums, with the calculation of energy and frequency characteristics of the interaction between milling bodies and material under treatment. We describe the procedure of determination of the efficient power input consumed for driving the ball load of a planetary mill and thus for performing the work of grinding and mechanical activation of the material, and some practical examples of industrial applications of planetary-type mills.

Realization of chemical processes involving intense mechanical treatment of solid substances and heterogeneous mixtures in the centrifugal mills of planetary type has been in use for the recent decades to develop efficient technological processes. The mechanochemical approach turns out to be especially efficient in the cases when mechanical treatment can be combined with simultaneous chemical transformation of the substance. Preliminary mechanical treatment of products (mechanical activation) also allows one to intensify subsequent chemical stages of technological processes.

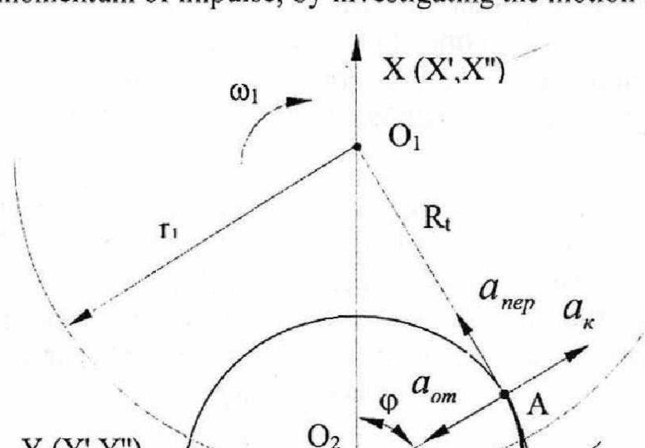
One of the most important problems of development and realization of technological schemes involving the processes of mechanochemistry and mechanical activation is estimation of the efficiency of the efficiency of the apparatus, which is conditioned by the choice of material treatment modes in the mills of the given type, or by comparison of the expected results achieved with the use of the devices of various types. The most widespread apparatus used to carry out mechanochemical processes are planetary mills.

Prediction of the efficiency of planetary mills at the stage of their designing is a necessary condition for the development of apparatus for mechanical activation or mechanochemical reactors. The known analysis methods based on description and calculation of the energy characteristics of movement of single balls in the crushing cylinders of planetary mills do not take into account the influence and interaction of the whole mass of the milling bodies and the material under treatment and do not allow one to determine and compare the performance efficiency of the devices.

The algorithm of the procedure developed for the determination of the efficiency of planetary mill operation is based on the analysis of the whole set of loaded matter (balls and the material) in the crushing cylinders, involving calculation of the energy and frequency characteristics of the interaction of milling bodies and the material under treatment [1].

According to the kinematic scheme of the planetary mill (Fig. 1), any body inside the cylinder is affected by the forces of the cylinder wall reaction (point A) or the charged material lying in contact with the cylinder wall (point B), the Coriolis body force, and gravity. The reaction force is the reason of the appearance of the acceleration of translation and the relative acceleration, while the Coriolis body force arising as a result of rotation of the system causes Coriolis acceleration. Calculations showed that the forces of gravity are unimportant for planetary mills, so they can be neglected.

The planetary mechanisms have three coordinate systems: the laboratory coordinates (XY), the planet carrier system (X'Y'), the coordinates (X"Y") of the satellite (cylinder). The moment of time when all the three coordinate systems coincide is shown in Fig. 1. The analysis of the kinematics (Fig. 1) shows that the main parameters of planetary mills determining the character of motion of the load in cylinders are the relations of angular velocities and radii of the central and planetary rotation of the cylinder. It is accepted to denote ω_2/ω_1=K, the kinematic characteristic (sign of rotation (ω_1 and ω_2) is plus for counter-clockwise and minus for clockwise rotation); r_1/r_2=m is the geometric characteristic. Depending on the relations between these characteristics of the planetary mills determining the angle of ball departure (φ_0) $\cos\varphi_0 = r_2/r_1\left(1+\varpi_1/\varpi_2\right)^2$ different modes of motion of the milling bodies can be realized: attrition, vortex-type, shock, supercritical). For each mill having definite construction and technical characteristics, its inherent mode of the movement of the ball load can be determined theoretically. The kinetic and energy characteristics of the mills can be estimated on the basis of the dynamic model of ball movement in the cylinders using the equations of conservation of impulse and momentum of impulse, by investigating the motion equation for the ball load in the integral form:



O_1,O_2 – axes of rotation of the planet carrier and the cylinder, respectively;
r_1, r_2 – radii of the planet carrier and the cylinder, respectively;
ω_1,ω_2 - angular velocities of the planet carrier and the cylinder, respectively;
curve ABO_2 – geometric line of ball departure;
A,B– the points of departure line on the surface and inside the cylinder, respectively;
φ - the angular coordinate of the points at the departure line ($\varphi=\varphi_0$ for point A);
a_{nep}, a_{om}, a_{κ} - acceleration in point A, acceleration of translation, relative, Coriolis acceleration, respectively;
R_t – radius from point A to the planet carrier axis;
O_2B – radius vector (r), the coordinate of points at the departure line ($r=r_2$ for point A);
τ, n – tangent and normal vectors of point B, respectively;
β - angle between the radius vector r and the perpendicular to the departure line.

Fig. 1: Kinematics of the Planetary Mill (Right-Hand Coordinates)

- the acceleration factor ($F = \varpi_1^2 r_1/g$).
- the number of active balls in the suspended state, with the total ball load being equal to N_0
  $N = \sigma_c h/\sigma_0 d^2 \sum_{i=1}^{S} v_i t_i$
- averaged velocity of the ball movement $v_{cp} = hd/N\sum_{i=1}^{S} z_i t_i v_i$;
- the kinetic energy of balls $E = \sum_{i=1}^{N} T_i$, where $T_i = mv_{cp}^2/2 + I(\varpi_1+\varpi_2)^2/2$;
- specific frequency of ball collisions $f_s = v_{cp}N/(a-d)G$;
- total area of the ball contact spots during the elastic collisions of balls with each other or with the cylinder wall (mirror balls) $S_\kappa = \pi d^2/4\,(5\pi\sqrt{2}\,\rho v_{cp}^2/E\,(1-\mu))^{0.4} f$;

- effective capacity power consumed for setting the ball load of the planetary mill in motion and correspondingly for the work of mechanical activation of the material

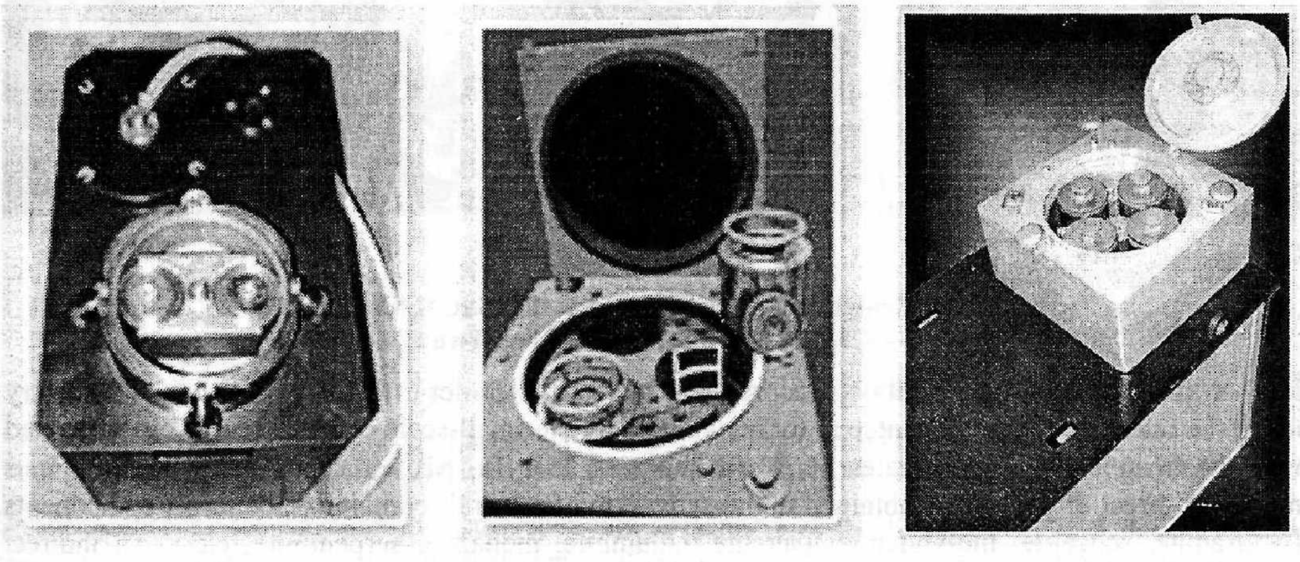
$$P = k\varpi_1 \sum_{i=1}^{n} g_i \left[\Delta \bar{r}_{Si} \times \bar{v}_{Si}\right]_Z \sigma_{II} h / d$$

The above-presented mathematical equations contain the symbols of parameters calculated in the computer model. The starting data are the characteristics of the planetary mills, ball load and material under treatment: the diameter of the planet carrier; the inner diameter of the cylinder; the height of the cylinder; the angular velocity of rotation of the planet carrier and the cylinder (taking into account the sign); ball diameter; the volume degree of filling the cylinder with the balls; the volume degree of filling the cylinder with the material; the bulk density of the material.

The proposed method realized by the computer program allows rapid and obvious determination of the optimal operation conditions of the planetary centrifugal mills, comparison of the efficiency of mechanical activation which can be provided by different devices, either existing ones or those under designing.

The analysis of the existing planetary mills showed that the velocities of milling balls are not very high for different operation modes: 10-12 m/s. Accordingly, total kinetic energy of the balls in each cylinder is not high: about 100-300 J. The main effect of mechanical activation is achieved due to the high frequency of ball collisions and high specific frequency of treatment of the material. For optimal operation modes of planetary mills, the frequency of ball collisions can reach more than 10 MHz, while total ball contact area per one second can be 4 $м^2$. The effective power for such a mill can reach 30-50% of the installed capacity of the electric drive. The results obtained make clear the reasons defining the possibility to use planetary mills as mechanochemical reactors.

Theoretical investigations and experimental development allowed creating a series of planetary devices for mechanical activation of various products and for realization of mechanochemical processes. Planetary mills of the periodic action for research purposes and for obtaining small portions of activated materials are shown in Fig. 2 [2]. In order to realize mechanical activation on an industrial scale, a planetary mill of the flow type MPC-3 is proposed (Fig. 3); the material is supplied into this mill in the form of a suspension with the solid to liquid ratio of 1:1 and the productivity of 500-1000 kg/h with respect to the solid [2,3] .



(A) (B) (C)

Fig. 2: Planetary Mills Designed at the ISSCM SB RAS A - AGO-2; B - AGO-3; C – APF

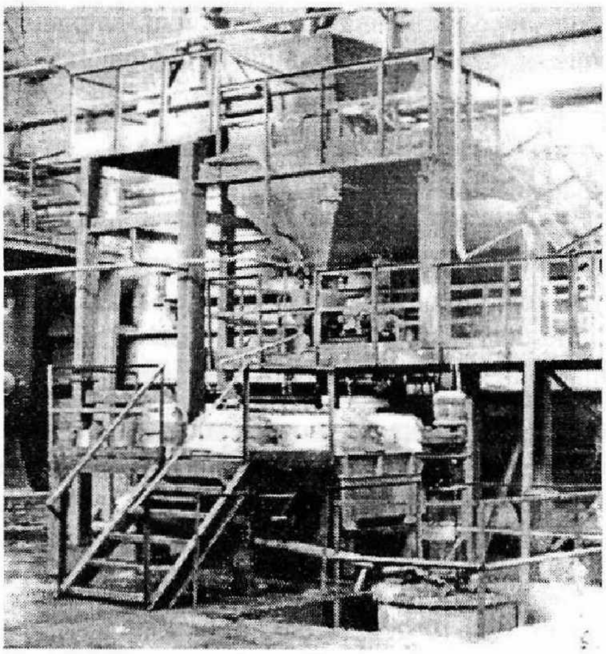
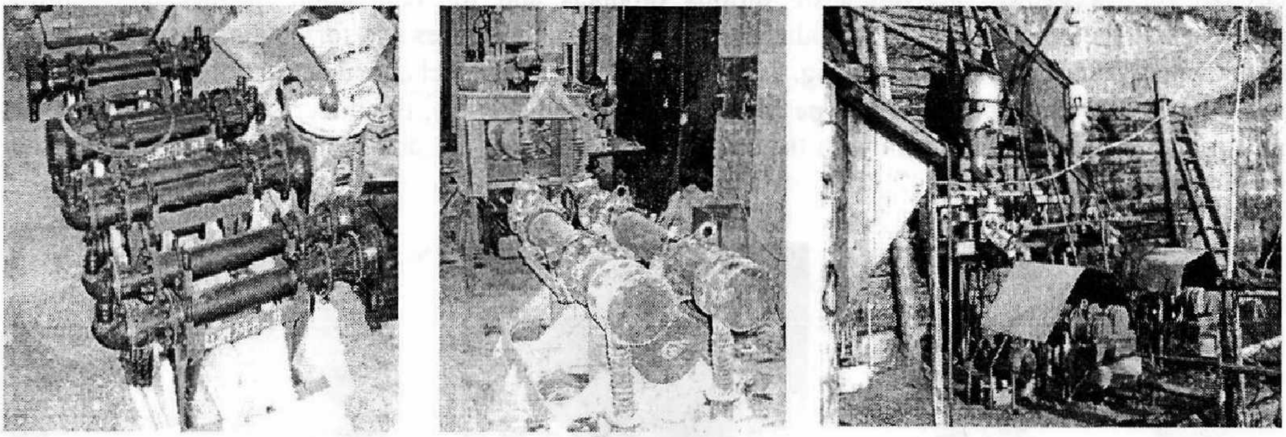


Fig. 3: Module of Mechanical Activation Based on Two Planetary Mills MPC-3

In addition, a series of centrifugal flow mills for dry milling was developed at the ISSCM SB RAS (Fig. 4). The kinematic scheme of the drive of milling cylinders of these devices can be described as a particular case of planetary motion when the planet carried and the cylinder rotate in opposite directions with identical frequency ($\omega_1 = -\omega_2$), while the radius of cylinder rotation is larger than the radius of the planet carrier rotation ($r_2 > r_1$). Along with the dry method of grinding and activation of the material, these mills can also be used to treat suspensions.



(A) **(B)** **(C)**

Fig. 4: Centrifugal Mills Designed at the ISSCM SB RAS
A – CM-7; B – CM-20; C – a Set-Up Based on Two CM-30G Mills

In spite of the variety of mineral objects proposed by researchers for effective processing in planetary mills, the schemes of practical interest for metallurgy are the small-scale process flowsheets connected with the treatment of concentrates of rare metals (W, Mo, Ta, Nb, etc.), rare earths and precious metals. A direct effect can be obtained in the activation of minerals containing the target components (wolframite, scheelite, molybdenite, tantalite, columbite, monazite, serpentinite, etc.). An indirect effect connected with intensification of concentrating process and treatment of the raw material is achieved by activation of the matrix minerals containing small amount of valuable components, for example gold-containing concentrates.

Activation of the target minerals can be illustrated by the results of research and industrial introduction of the technology of processing tungsten-containing concentrates of scheelite ($CaWO_4$>70%) and wolframite ($Fe(Mn)WO_4$>80%). For the autoclave soda leaching of scheelite concentrates activated in a planetary mill, the consumption of soda is decreased by a factor of 1,5, leaching time by a factor of 2; the final tungsten content of dump product decreases from 1,5-3,0% to 0,5% in comparison with the basic version of the technology. Tungsten extraction reaches >98%. For wolframite concentrates, preliminary mechanical activation ensures an increase in tungsten extraction from 90% to 98% with a 2-fold decrease in soda consumption and time of leaching [2].

A set-up for mechanical activation of tungsten-containing concentrates based on two MPC-3 planetary mills is shown in Fig. 3. During its development and transfer into industrial operation in Uzbekistan, 440 tons of scheelite concentrate were processed; its efficient treatment was impossible with the previously existing procedures [3].

High efficiency was also exhibited by the method of mechanical activation of tantalum-containing concentrates in MPTC3 mill during the experimental industrial tests (the republic of Kazakhstan). It was established that the treatment of activated concentrates according to the fluoride technology provides an increase in the extraction of tantalum into solution by 0,7-4,4% while the consumption of hydrofluoric acid decreases by 20%. The degree of tantalum recovery from the concentrates, including persistent (non-yielding) stewerite ones, reaches 99,5-99,8%. Agglomeration of high-silicon concentrates with soda is excluded.

A vivid example of the application of mechanical activation of both the target and matrix components is shown in Fig. 5. Analysis of X-ray diffraction patterns shows that after mechanical activation in a planetary mill we observe a noticeable change in the lines characterizing the minerals of tantalum and niobium (tantalite, columbite, pyrochlor, microlite). A decrease in intensity and broadening of spectral lines are evidences of increased defect content of the crystal structure of the minerals and therefore an evidence of the increased chemical activity.

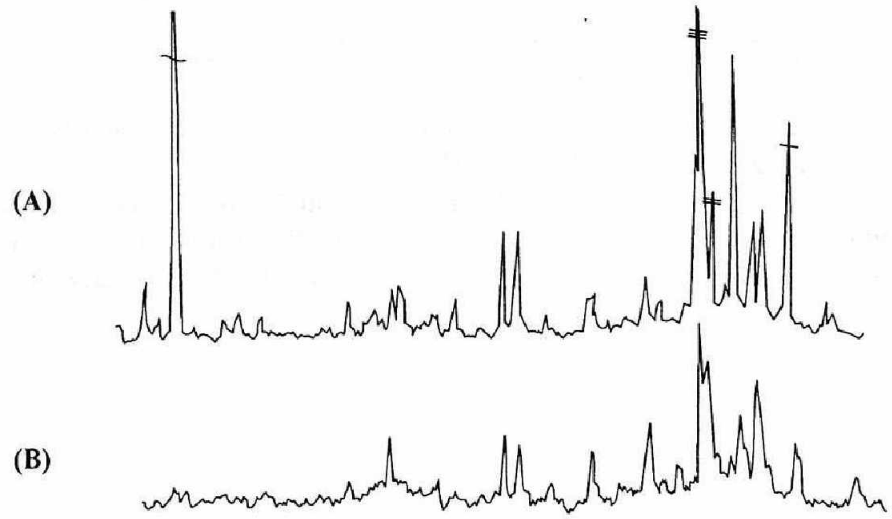


Fig. 5: The XPA Spectra of the Ta-Nb Concentrate: A-Attrited (Ground) B-Mechanically Activated

~ TOPAZ - 46% $Al_2(F,OH)_2sio_4$, - TANTALITE-COLUMBITE $(Fe,Mn)(Ta,Nb)_2O_6$
= PYROCHLOR $(Na,Ca)_2(Nb,Ti,Ta)_2O_6(OH,F,O)$, ≡ MICROLITE $(Na,Ca)_2(Nb,,Ta)_2O_6(OH,F,O)$

Disappearance of the spectral line corresponding to topaz ($2\theta=67^{O}$), the content of which in the concentrate was 46% mass, proves that topaz either passes into the X-ray amorphous state during mechanical activation (is ground, or becomes amorphous, or decomposes into oxides). In any case, such a behaviour of topaz causes good treatment of tantalum and niobium minerals during mechanical activation.

Subsequent technological investigation of the fluorine-free sulphuric acid technology of processing tantalum concentrate showed that with the preliminary mechanical activation the residual tantalum content of the dump products decreases by a factor of more than 3. The results obtained provide evidence that tantalum recovery exhibited by the mechanochemical technology is quite comparable with the results obtained by the fluorine-containing procedure. The effect of hydrofluoric acid on the treatment of the concentrate is thus compensated by mechanical activation.

The use of planetary and centrifugal mills for the treatment of concentrates containing precious metals provides a substantial increase in the recovery of gold and silver in subsequent technological processes. This was shown in a large number of laboratory studies and in the industrial test of the MPC-3 mill (the Chita District, Russia) in the cyanide leaching of activated gold-containing concentrates[3] .

The most effective application of process of mechanical activation for processing of the gold-arsenic ores containing the interspersed gold in arsenoperite [4].

A grinding set-up based on two centrifugal mills CM-30G is shown as an example in Fig. 4; it operates at the gold-concentrating works of the Khopto deposit (the republic of Tuva, Russia). Preliminary treatment of the ore in mills provided a 87 % extraction of fine gold in the concentrating cycle.

Activated Al_2O_3 used as a matrix for (Pt, Pd) catalysts, independent of the modification, is sufficiently well decomposed by NaOH solutions in autoclave, which helps solving the problem of processing the worked-out catalysts[2] .

The experience of the application of mechanical activation in planetary and centrifugal mills shows that efficient solution can be found for the problems connected with the treatment of persistent and non-traditional raw materials containing rare and precious metals, off-test products of operating plants. The possibility to decrease the consumption of reagents and to increase extraction of valuable components arises.

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[3] Kaminsky Yu. D., and Kopylov N. I., 1999, Tecnological Aspects Of Gold Recoveri From Ores And Concentrates, Novosibirsk: Pablishinc House of the Siberian Branch of the RAS.

[4] Kopylov N. I., and Kaminsky Yu. D., 2004, Arsenic, Novosibirsk: Siberian University Press.