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Mathematical Model of Motion of Balls in A Planetary Mill: Theory and Experiment

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ABSTRACT: Particle reduction in planetary mills is mainly due to impact and abrasion or shear. In our opinion, graphene nanostructures are formed most intensively when shear forces act on particles of graphite or graphite oxide. With regard to a planetary mill, shear effects on graphite particles are possible when the balls slide relative to each other, or when the balls slide relative to the inner surface of the drum. The most intense sliding of particles relative to each other occurs in the circulation mode of movement of the material in the cross section of a smooth rotating drum.

Keywords: Mathematical Model, nanoparticles, graphene nanostructures, planetary mill,

1. INTRODUCTION

Drum mills have been widely used in various industries since the 19th century for grinding solid materials. Grinding media and raw material are loaded into the horizontal drum. When the drum rotates, the particles falling between the moving grinding bodies or between the grinding body and the inner surface of the drum are crushed. Usually, in drum mills, grinding is carried out simultaneously by impact, crushing and abrasion. Which of the types of impact on the material prevails depends on the operating mode of the mill and, first of all, on the speed of rotation of the drum. At the end of the 19th century, the planetary mill was invented. It is based on the same principles as a drum mill, but in addition to rotation relative to its own longitudinal axis, the drum rotates relative to the axis of portable rotation (as a planet rotates around the Sun). Due to centrifugal accelerations arising due to portable rotation, the forces of the grinding bodies on the material particles increase tenfold, which significantly reduces the grinding time and specific energy consumption.

In recent years, planetary mills have been increasingly used for the production of nanoscale particles. When grinding aluminum oxide for 1 hour, the average size was 200nm, and after 4 hours – 100nm [Balkin]. When crushed for 1 hour with balls with a diameter of 1 mm and then, for 3 hours with balls with a diameter of 0.1 mm, the average particle size was 76nm.

Currently, two main methods are used to obtain nanoparticles: “bottom-up” (“bottom-up”) is a synthesis; “top-down” are grinding or abrasion processes. Mechanical devices in which energy is transferred to the final particulate material to reduce particle size are commonly referred to as "mills". Planetary mills are widely used for fine grinding in various industries. In recent years, ball mills have been used to obtain nanosized particles of various materials [1, 2], including graphene nanostructures [3,5]. In our opinion, graphene nanostructures are formed most intensively when shear forces act on particles of graphite or graphite oxide. We have developed a planetary mill in which the balls slide along the inner surface of the grinding drum [4,6]. In this mill, the balls are placed in the separator, and on one side there are several balls, for example three, and on the diametrically opposite side only one ball. The mode of movement of the balls depends on the ratio of the angular velocities of the grinding drums relative to the central axis (portable movement) and relative to their own axis of these drums (relative movement). The report presents the results of the

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analysis of the forces that act on the balls and the determination of the critical rotation speed of the grinding drum relative to its own axis, at which the balls stop sliding along the inner surface of the drum and begin to rotate with it.

2. Materials and methods

Figure 1 shows a Scheme of the action of forces on the balls that are in the grinding drum (the separator that connects the balls to each other is not shown). In general, the following forces act on each ball:

F_{CS} - centrifugal forces that arise as a result of the movement of the grinding drum relative to the central axis (together with the solar disk); F_{CJ} - centrifugal forces that arise as a result of the rotation of the grinding drum about its own axis; F_G - gravitational forces; F_c Coriolis forces; F_F - friction forces that arise as a result of the balls slipping relative to the inner surface of the grinding drum. If the balls do not slip relative to the inner surface of the drum, then $F_F = 0$, and if they slip and do not rotate relative to the grinding drum's own axis, $F_C = 0$ and $F_{CJ} = 0$. The force F_G can be neglected, since we are considering the case when F_{CS} is two orders of magnitude greater than the force of the weight.

Numerical values of forces will be considered on the example of the ball III, when it slips relative to the inner surface of the grinding drum. The scheme for calculating these forces is shown in Fig. 2.

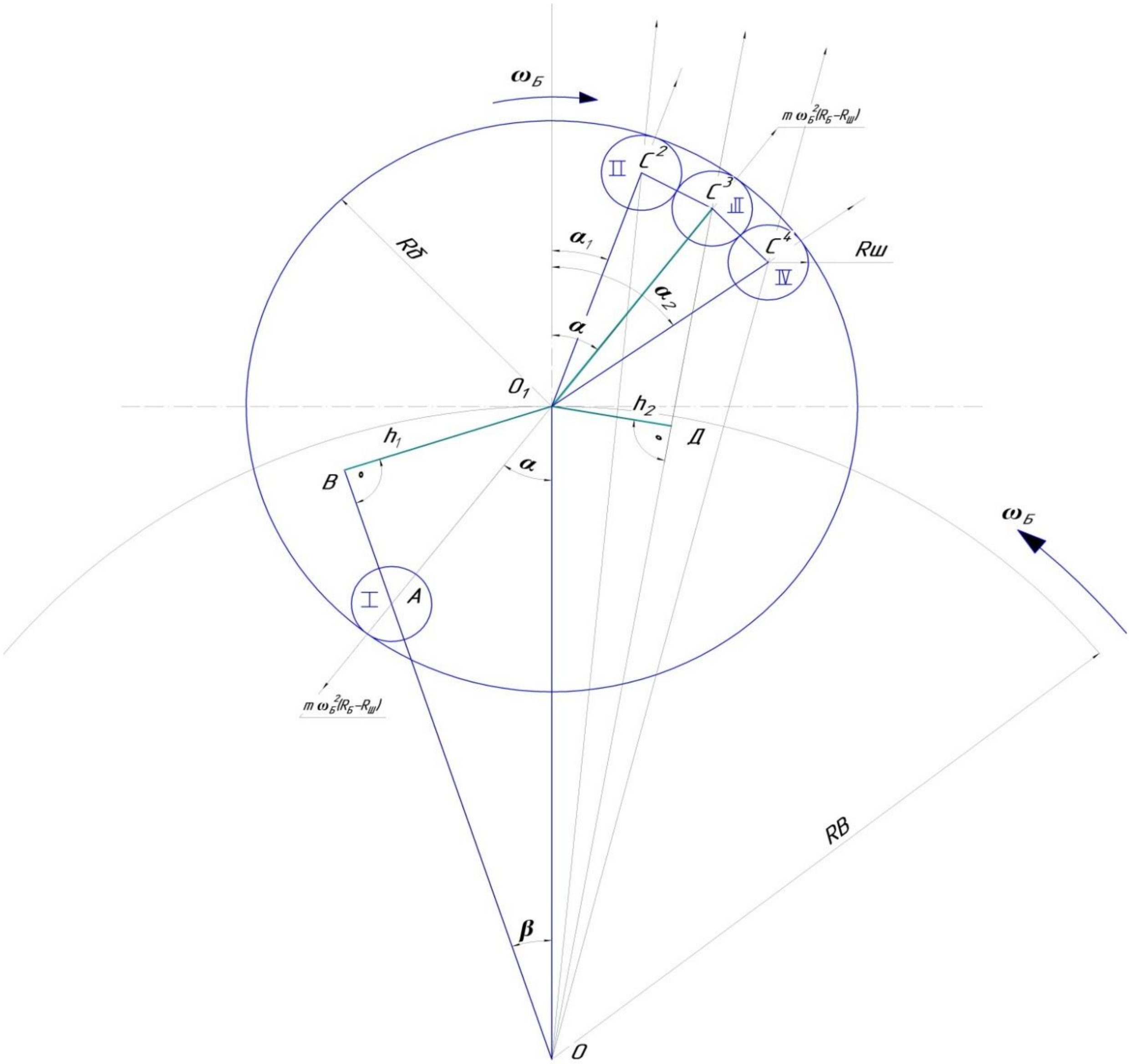

FIGURE 1. Scheme of the action of forces on the balls in the grinding drum of a planetary mill (separator not shown)

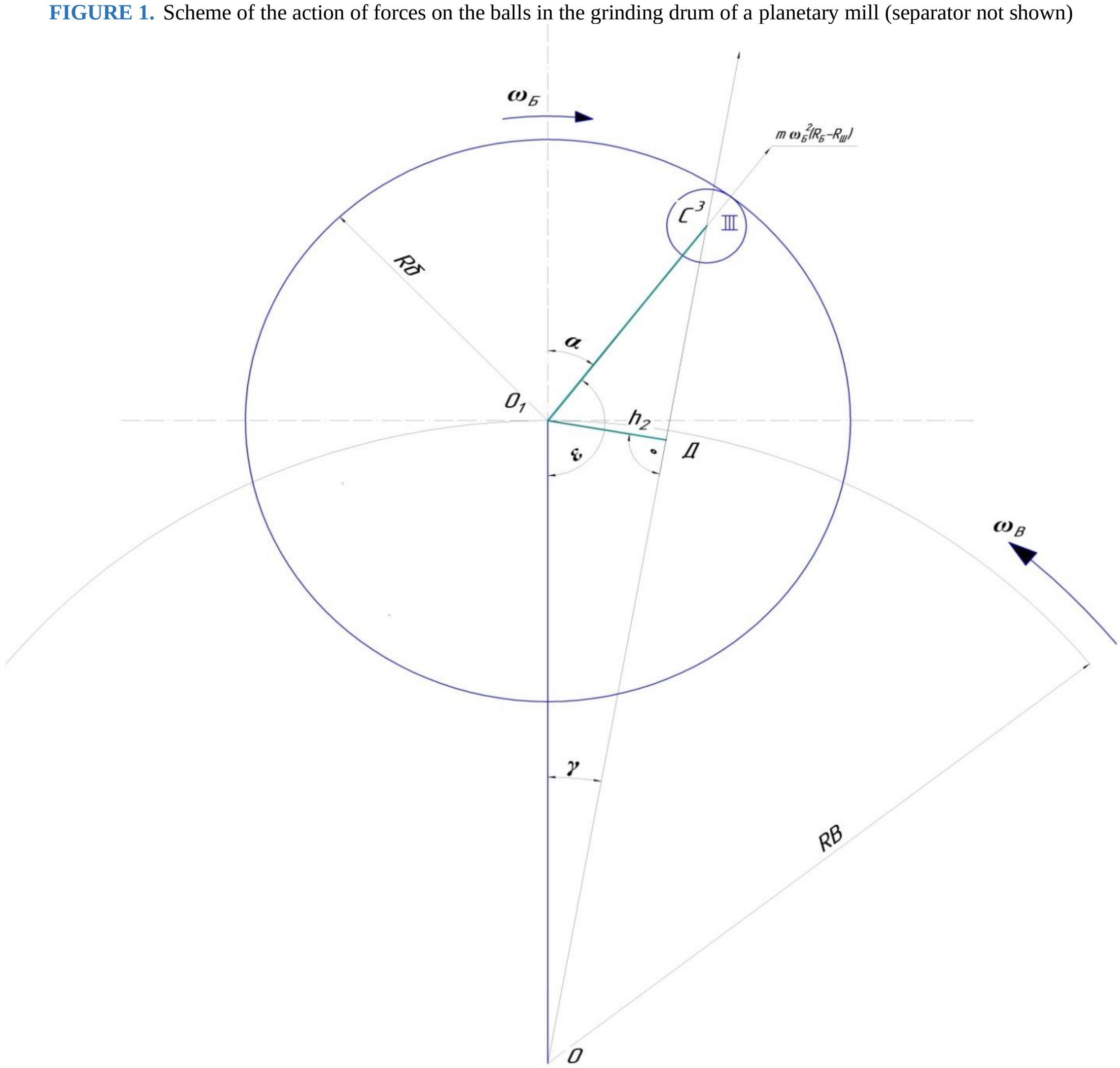

FIGURE 2. Scheme of the action of forces on ball III

If the ball slides along the inner surface of the grinding drum, but rotates about the central axis, then the centrifugal force $F^{III}{}_{CS}$ acts on it:

$$F_{CS}^{III} = m\omega_B^2 OC^{III}, \qquad (1)$$

где m - ball mass, ω_B - angular velocity of rotation about the central axis. Numerical value OC^{III} and angle γ we find from the triangle OO_1C^{III} using the law of cosines:

$$OC^{III} = \sqrt{(O_1O)^2 + \left(O_1C^{III}\right)^2} - 2(O_1O)\left(O_1C^{III}\right)\cdot \mathrm{Cos}\varepsilon, \qquad (2)$$

$$Cos\gamma = \frac{\left(OC^{III}\right)^2 + (OO_1)^2 - \left(O_1C^{III}\right)^2}{2\left(OC^{III}\right)\cdot (OO_1)}. \qquad (3)$$

From the triangle OO_1D we define $h_3 = O_1D$;

$$h_3 = Sin\gamma OO_1. \qquad (4)$$

Next, we determine the torque M^{III}, which creates the ball III relative to the point O1

$$M^{III} = m\omega_B^2 OC^{III} h_3 \tag{5}$$

In addition, there is a torque M_F^{III}, which arises from the action of the friction force F_F^{III}:

$$M_F^{III} = F_F^{III} R_J \tag{6}$$

$$F_F^{III} = f_F N^{III}, \tag{7}$$

where f_F - is the coefficient of sliding friction, N^{III} - is the normal force that arises from the action of F_{CS}^{III}:

$$N^{III} = F_{CS}^{III} \cos(180 - \varepsilon^{III} - \gamma^{III}). \tag{8}$$

Using formulas similar to (1-8), you can calculate the forces that act on balls I, II and IV.

Consider the limiting state of the system, i.e. when the moments acting clockwise are equal to the moments acting in the opposite direction:

$$M^{II} + M^{III} + M^{IV} + M_F^{I} = M^{I} + M_F^{II} + M_F^{III} + M_F^{IV}. \tag{9}$$

If we substitute (1-8) into expression (9), then we can solve the following problems:

- with known $\omega_Б$, ω_B, $R_Б$, R_B, f_F, $R_Ш$ can be found the angle α, that is, the position of the balls in which they will slide along the inner surface of the grinding drum;

- with known ω_B, R_B, $R_Б$, f_F, $R_Ш$, α can be found $\omega_Б$;

- with known $\omega_Б$, R_B, $R_Б$, f_F, $R_Ш$, α can be found ω_B;

- with known R_B, R_J, f_F, $R_Ш$, α can be found $\omega_B / \omega_Б$.

3. RESULTS AND DISCUSSION

It is also possible, with a smaller number of specified parameters, to find possible combinations of other parameters in which the balls will slide relative to the inner surface of the grinding drum.

Similarly, the problem of the motion of several balls that are not connected by a separator is solved, but in this case it is necessary not only to remove the ball I in Fig. 1, but also to add the forces that act between the balls.

Figure 3 shows the movement of the balls when $R_S = 75mm$, $R_J = 55mm$, $\omega_S = 31.4s^{-1}$, $\omega_J = 6s^{-1}$, $R_B = 6mm$, $f_f = 0.11$. In this case, the balls slide along the inner surface of the drum.

FIGURE 3. Movement of balls in the grinding drum of a planetary mill

4. Conclusion

Thus, dependence (9) has been obtained, which makes it possible to calculate the regime and geometrical parameters of a planetary mill, under which there is a stable sliding mode of grinding balls along the inner surface of the drum, which is necessary in the production of graphene.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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