Determining the loads acting onto a cylindrical classifier of a globe mill

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Abstract. Classifying devices have been developed that allow increasing the efficiency of operation of globe mills commonly used at industrial enterprises for milling various materials. Analytical equations have been obtained for the cylindrical classifier, allowing calculating the forces acting on the grate elements depending on design and process parameters of the mill. The forces acting onto the structure of a cylindrical classifier of an industrial globe mill were calculated, their changes have been analyzed. Stress in the design of the device were determined, its wear-dependent operability has been determined.

1. Introduction

Milling of materials is one of the main process operations in various branches of industry (construction material production, mining, chemical and others). Being an energy-intensive process, it largely defines the quality of the final product. For example, in cement production, milling covers over 50% of all electricity costs [1].

Cement plants commonly use globe mills (GM) for milling clinker and various raw materials. Their main disadvantage is increased specific energy costs. Depending on the properties of milled materials, the specific energy cost in such units may be from 20 to 60 kW-h/t. Low efficiency of the milling process in GM is due to the fact that the material in the mill chamber undergoes influence from the grinding bodies (GBs) for a prolonged period of time while moving from the loading end to the escapement end. In some mills, the length of the chamber reaches 15 meters and the material may stay inside for more than 10 minutes. The fine fraction of the material being milled impedes grinding of the coarse fraction of the material by large GBs, whose size in the first chamber reaches $100 \cdot 10^{-3}$ m. Timely removal of particles attaining a certain size and their transfer to the re-milling chamber with smaller-size GBs will allow increasing the energy efficiency of the process and increasing the productivity of the GMs. To that end, classifiers were developed that provide classification of the material inside the mill [2]. There is a large number of works dedicated to calculating various characteristics of interactions of grinding bodies with internal parts of globe mills and determining design and process parameters of globe mills [3-8]. However, complexity of application of their results demands development of additional mathematical descriptions.

2. General provisions

Taking into account the process and design parameters of the developed cylindrical intra-mill classifier (CIMC), let us formulate the requirements applicable to its design: Diameter of the grates is selected...
from strength calculation and shall account for abrasive wear during the operation.

Let us determine the forces acting upon the CIMC. During the GM operation, milling of material and their classification take place simultaneously inside the CIMC. The amount of material passing through the device primarily depends on the clear opening and the area of the classifying surface. Diameter or width of the element of the classifying surface (grate) is a parameter that influences its clear opening. To determine rational geometric parameters of CIMC grate, it is necessary to perform strength calculations based upon forces from the globe-and-material medium.

Let us divide the mill load into three circuits (Figure 1a, 1b, 1c), separated into a number of sectors, at that the number of sectors we will hold as being equal to the number of grates in the radial section.

\[ \alpha_{k+1/2} = \alpha_0 + \frac{d + a}{R_0} \left( k + \frac{1}{2} \right), \]  
\[ n = \left\lfloor \frac{2R_0 (\pi - 2\alpha_0)}{d + a} \right\rfloor, \]  
\[ F_i^k = L \frac{\gamma_{mV} \alpha_i^2}{3g} \left( \rho_0^3 - \rho_1^3 \right) AV_k, \]

Figure 1. The computational scheme for determining the geometric parameters of the sectors: (a) first circuit, (b) second circuit, (c) third circuit.

The angle \( \alpha \) between the vertical and the sector boundaries we will define as:

where \( R_0 \) is the CIMC grate radius; \( \alpha_0 \) is the separation angle of the GBs at the grate; \( d \) is the diameter of the grate; \( a \) is the width of inter-grate slot; \( k \) is the sector’s number \( (k = 1, 2, 3...n) \), \( n \) is the number of grates under the globe material medium.

where the brackets represent the integer part of the number.

Let us define action of the globe material medium for each sector in the form of a force applied to the interior surface of the grate. We will consider the point \( M \) as the rotary center. The expression for calculating the force acting upon the elements of the \( k \)-th sector of the CIMC is as follows:

where \( i \) is the number of the sector of the loading circuit \( (i = 1, 2, 3) \), \( L \) is the length of the sector, \( \gamma_{mV} \) – is the bulk density of the globe-and-material medium, \( \omega \) is the angular velocity of the device, \( g \) – is the free fall acceleration, \( \rho_0, \rho_1 \) are the lengths of the sector bisecting line segments.
\[ \rho_{0k} = R_0 \sqrt{1 + \frac{1}{\psi^2} - 2 \cos^2 \alpha_{k+1/2}}. \]  

The angle bounded by the sector \( V_k \) is equal to:

\[ V_k = \arcsin \left( \frac{\sin \alpha_k}{\sqrt{1 + \frac{1}{\psi^2} - 2 \cos^2 \alpha_k}} \right) \left( k = 1, 2, 3, ..., n - 1 \right). \]

The mill load in the radial section is divided between the three circuits. Thus, we have three different cases for finding the length of the internal bisecting line segments of the different sectors.

The boundary of the first sector corresponds to the angle \( V_1 \) in Figure 1, \( a \), thus, we keep calculating while the inequality \( V_k > V_1 \) holds. From the Figure 1, \( a \) the lengths of the interior bisecting lines of the first sector are:

\[ \rho_{1i}^I = R_0 \left( 1 + \cos \alpha_i \right) \left( 1 - \frac{1 - \cos^2 \alpha_{k+1/2}}{2 \cos \alpha_i \left( 1 + \frac{1}{\psi^2} - \frac{2 \cos \alpha_{k+1/2}}{\psi^2} \right)} \right). \]

The third case is possible when \( V_k < V_2 \). The expression for finding the interior bisecting lines of the sector of the 3rd circuit (Figure 1, \( b \)) is of the following form:

\[ \rho_{3i}^I = \frac{R_0}{\psi^2} \sqrt{\psi^2 + 1 - 2 \psi^2 \cos \alpha_{k+1/2} - \frac{\sqrt{3}}{2} \cos \alpha_{k+1/2} + \frac{1}{2} \sin \alpha_{k+1/2}}. \]

The forces acting in the first circuit onto the space between the two nearby-located grates are defined by the following expression:

\[ F_i^I = \frac{R_0^I \alpha^2 \gamma_{\text{cav}} L}{3g} \left( 1 + \frac{1}{\psi^2} - \frac{2 \cos \alpha_{k+1/2}}{\psi^2} \right) \left( 1 - \frac{3 \sin^2 \alpha_{k+1/2}}{2 \left( 1 + \frac{1}{\psi^2} - \frac{2 \cos \alpha_{k+1/2}}{\psi^2} \right)} \right) \Delta V_k. \]

Those acting in the second circuit are defined by the expression:

\[ F_i^{II} = \frac{R_0^{II} \alpha^2 \gamma_{\text{cav}} L}{3g} \left( 1 + \frac{1}{\psi^2} - \frac{2 \cos \alpha_{k+1/2}}{\psi^2} \right) \left( 1 + \cos \alpha_i - \frac{(1 + \cos \alpha_i) \left( 1 - \cos^2 \alpha_{k+1/2} \right)}{2 \cos \alpha_i \left( 1 + \frac{1}{\psi^2} - \frac{2 \cos \alpha_{k+1/2}}{\psi^2} \right)} \right) \Delta V_k. \]
Those acting in the third circuit are defined by the expression:

\[ F_{k}^{\text{III}} = \frac{R_{k}^{3} \omega^{2} \gamma_{\text{me}} L}{3g} \left( 1 + \frac{1}{\psi} - \frac{2}{\psi} \cos \alpha_{k+1/2} \right)^{3} - \frac{1}{\psi^{6}} \left( \sqrt{\psi^{2} + 1} - 2\psi \cos \alpha_{k+1/2} - \psi^{2} + \frac{\sqrt{3}}{2} \cos \frac{\alpha_{k+1/2}}{3} + \frac{1}{2} \sin \frac{\alpha_{k+1/2}}{3} \right) \]. \hspace{1cm} (11)

Following the determination of the values of the acting forces, it is necessary to decompose each of the sectoral forces \( F_{k}^{i} \) into the normal component \( F_{k}^{\text{in}} \), directed away from the rotary center of the sector, and the tangential component \( F_{k}^{\text{it}} \), directed along the tangent line to the sector.

As it is evident from Figure 1, a the normal \( F_{k}^{\text{in}} \) and the tangential \( F_{k}^{\text{it}} \) components are, respectively:

\[ F_{k}^{\text{in}} = F_{k}^{i} \cos \beta \], \hspace{1cm} (12)
\[ F_{k}^{\text{it}} = F_{k}^{i} \sin \beta \]. \hspace{1cm} (13)

From the Figure 1, a, the angle \( \beta \):

\[ \beta = \pi - \alpha_{k+1/2} - v_{k+1/2} = \pi - v_{k} - \frac{\Delta v_{k}}{2}. \hspace{1cm} (14) \]

### 3. Results

Let us use the obtained equations to compute the forces acting onto the device grates and plot the characterizing graphical dependencies. Figures 2–4 show the force diagrams in the polar coordinates as functions of parameters \( a, \varphi, \psi \) for a globe mill CIMC with the dimensions of \( D \times L = 3.2 \times 15 \text{ m} \).

**Figure 2.** Acting forces per 1 meter of CIMC length as a function of \( \varphi \) with \( \psi = 0.76; a = 4\cdot10^{-3} \text{ m}; 1 - \varphi = 0.238; 2 - \varphi = 0.28; 3 - \varphi = 0.322; \) (a) normal forces; (b) tangential forces.

Analysis of the diagrams in Figure 2 shows that with increased fractional volume of the CIMC chamber with GBs \( \varphi \) from 0.238 to 0.322, the acting forces increase in the first and the third circuit. A significant increase in forces in the first circuit is due to increased amount of the globe-and-material medium, leading to a shift of the boundary between the first and the second circuit. It also explains the insignificant reduction of forces in the second circuit. The boundary between the 2nd and the 3rd circuit...
is practically unchanged with the increase of $\varphi$, thus the increase in forces in the sectors of the 3rd circuit is due to an increased number of GBs in the inter-grate space. Maximum values of forces across all the sectors are increasing from 3600 N to 4030 N for the normal component, that is, by 11.9 %; tangential and total forces are decreased by 38.5 and 13.9 %, respectively: from 2985 N to 1835 N and from 4680 N to 4030 N. It may be concluded that with increased GB fractional volume $\varphi$, there is a growth in the normal component of the acting forces, accompanied with the relevant decrease in the tangential component of the force.

![Figure 3. Acting forces per 1 meter of CIMC length as a function of $a$ with $\varphi = 0.28; \psi = 0.76$: 1 – $a = 2.6 \cdot 10^{-3}$ m; 2 – $a = 4 \cdot 10^{-3}$ m; 3 – $a = 5.5 \cdot 10^{-3}$ m: (a) normal forces; (b) tangential forces.](image)

When the size $a$ of the opening in the classifying surface was increased from 2.6 to 5.5\cdot10^{-3} m, the forces acting upon the grates increased as well (Figure 3). It is explained by a somewhat increased area of the segment due to a larger distance between the grates, resulting in a more of globe-and-material medium inside the segment.

So, the maximum values of the normal components of the acting forces increase, respectively, by circuits: I – from 2500 N to 2740 N (by 9.6 %), II – from 3872 N to 3987 N (by 3 %) and III – from 2390 N to 2450 N (by 2.5 %). The tangential components of the forces increase as well: I – from 2600 N to 2740 N (by 5.4 %), II – from 1720 N to 1783 N (by 3.7 %) and III – from 352 N to 366 N (by 4 %). The total growth in forces for the first circuit is from 3610 N to 3880 N (by 7.5 %), for the second circuit it is from 3930 N to 4060 N (by 3.3 %) and from 2530 N to 2550 N (by 0.8 %). The maximum values of the acting forces as a function of inter-grate width $a$ increases insignificantly for all the sectors. The growth does not exceed 2.2 %, thus, with some reserve, we may hold that the acting forces are unchanged when $a$ is increased.

The highest changes in the values of the acting forces appear when changing the relative rotational frequency of the GM body $\psi$ (Figure 4). Increase in $\psi$ also causes a significant drift of boundaries between the circuits. It is due to the fact that when $\psi$ increases, the upward gradient of the globe material load increases, as well as the number of GBs in free fall. At that, the thickness of the GB layer at the CIMC surface decreases.
Figure 4. Acting forces per 1 meter of CIMC length as a function of $\psi$ with $\phi = 0.28$; $a = 4 \cdot 10^{-3}$ m: 1 – $\psi = 0.647$; 2 – $\psi = 0.76$; 3 – $\psi = 0.873$: (a) normal forces; (b) tangential forces.

So, the maximum values of the normal components in the first circuit reduce from 3600 N to 1310 N, that is, by 63.6 %, in the 2nd and the 3rd, they increase from 3520 N to 4030 N – by 14.5 % and from 3430 N to 3950 N – by 15.2 %, respectively. Tangential components are reduced in all the circuits as follows: in I – from 2950 N to 1835 N – by 37.8 %, in II – from 1945 N to 1605 N – by 17.5 % and in III – from 1855 N to 1260 N – by 32.1 %. The total forces are reduced by 51.7 % in the first circuit (from 4680 N to 2260 N), while in the second and the third circuits they are increased by 4.7 and 5 %, respectively, that is, from 3850 N to 4030 N and from 3780 N to 3970 N. The maximum changes in the values of the component of forces per sector attain: for normal components from 3600 to 4030 N – a growth by 11.9 %, for tangential ones from 2985 to 1835 N – reduction by 38.5 %, the total forces are also reduced from 4680 to 4030 N, that is, by 13.9 %.

From the analysis of the above, the following conclusions may be made:

– normal components of the forces attain their maximum values $F = 4030$ N at $\phi = 0.238$, $a = 5.5 \cdot 10^{-3}$ m, $\psi = 0.873$;

– tangential components of the forces attain their maximum values $F = 2985$ N at $\phi = 0.322$, $a = 5.5 \cdot 10^{-3}$ m, $\psi = 0.647$;

– total forces attain their maximum values $F = 4680$ N at $\phi = 0.322$, $a = 5.5 \cdot 10^{-3}$ m, $\psi = 0.647$.

Strength calculations of CIMC were performed with the Win Machine software complex for a GM with $D \times L = 3.2 \times 15$ m. The material of the device was selected as 110G13L steel. The results of the calculations given in Figure 5 show that the maximum stresses never exceed 35 MPa in grates of 0.1 m diameter, with $a = 4 \cdot 10^{-3}$ m, $\phi = 0.28$, $\psi = 0.76$.

It allows constructing CIMC using the alloy steel traditionally used in intramill devices of globe mills, such as 110G13L (Russian grade), Vegaline 112. Construction of the devices provide for possible wear of its grate elements up to 50%.
4. Conclusion
Analytical expression have been obtained that allows computing the forces acting upon the grate elements of CIMC. The calculations take into account the rotational frequency of the device and its geometry. The forces acting upon the structure of CIMC were calculated for a globe mill with dimensions of $D \times L = 3.2 \times 15$ m. Changes in the acting force were analyzed depending on inter-grate width $a$, $(a = 2.6 \ldots 5.5 \times 10^{-3}$ m); relative rotational frequency of the BM $\psi$, $(\varphi = 0.238 \ldots 0.322)$; fractional volume $\varphi$ of the CIMC chamber with the grinding bodies $(\varphi = 0.238 \ldots 0.322)$. The Win Machine software solution has been used to determine the stresses arising in the construction of the device; a possibility of operation until 50% wear of grate elements has been established for grate elements made of 110Г13Л (Russian grade) steel.

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References
[1] Skorokhod M A 2009 Development of cement industry in Russian and CIS countries in 2008. Evaluation of the current situation and trends of post-crisis development. Cement and Its Applications 2 20-22
[2] Khanin S I, Starchenko D S, Mordovskaya O C, Kharin N P 2017 Applying CAD systems for calculations of strength parameters of globe mill classifiers. Bulletin of BSTU named after V.G. Shukhov 12 181-187
[3] Bogdanov V S, Hanin S I, Starchenko D N and Sagitov I A 2014 Distinctive features of the relations between grinding equipment and devices inside ball mill body. ARPN J. of Eng. and Appl. Sci. 9(11) 2344-50
[4] Bogdanov V S, Mordovskaya O S, Voronov V P, Khanin D S and Kirilov I V 2014 Specifying the parameters of flow aspiration in the tube mill. ARPN J. of Eng. and Appl. Sci. 9(11) 2371-75
[5] Pöschel T, Schwager T 2005 Computational granular dynamics. Models and algoritms. Springer – Verlang Berlin Heidelberg 322

[6] Reichardt R, Wiechert W 2003 Event driven simulation of a high energy ball mill. In Proceedings ASIM 2003 249

[7] Schwager T 2008 Coefficient of restitution for viscoelastic spheres: The effect of delayed recovery Physical review E V. 78(5) 1304-16

[8] Salewski G 2008 Grinding Technology for the Future. World Cement 11 139-143