Experimental and Theoretical Study Focused on Transformation of the Processing Properties of Gold in the Operating Area of a Ball Tube Mill

I F Lebedev¹, D A Osipov¹, D M Gavriliev¹

¹Mining Institute of the North named after N.V. Chersky SB RAS, 43 Lenin Ave., Yakutsk, 677980, Russia

E-mail: ivleb@mail.ru

Abstract. The article is aimed at studying the process of free gold deformation extracted during grinding in various types of ball mills. Today, ball mills and similar machines are typically used for fine grinding of gold ores. Their working parts include armor plates of a shell, and balls used as grinding media loaded into the shell. Despite the fact that the ball mills dominate over the other fine grinding machines used to extract hard rock gold, they still have serious drawbacks. It is believed that only 2 to 20% of all consumed energy is spent directly on grinding, while the rest of it is used to overcome friction, heat formation, acoustic and mechanical vibrations, etc. In the meantime, mass deformation and degradation of free gold takes place in the mills. The particles degradation has a clearly adverse effect on their further beneficization, and their shapes change to various extents as a result of deformation. If the deformation is aimed at forming an isometric shape of particles, their recoverability increases, while the reverse process decreases it.

1. Introduction
The commercial component destruction, which occurs during grinding in ball tube mills, and the lack of possibility to control this process except for recovery using cheap gravity benefication methods complicates the beneficization technology involving cost intensive recovery processes (flotation, cyanidation, leaching, etc.). The data resulting from the study of a mechanism of gold particles deformation during extraction will be applied to improve the ball mill design and to develop new grinding machines and installations for enlarging hydraulic size of particles, which are intended for used at ore-dressing enterprises in the Republic of Sakha (Yakutia).

2. Relevance
Ball mills are extensively used to reach the highest possible level of commercial component extraction during ore disintegration. When ore is abraded in a ball mill, regrinding of gold occurs, which impairs its recovery using gravity methods. The extent of regrinding depends on the installation operating mode and ore type, and has a considerable importance when treating such mineral deposits as gold, platinum, tin ore, etc. In this vein, the elaborated recommendations apply only to the selection of mills with ‘gentle armor’ and the preservation of lining coatings [1-6], however, there is no data on studies indicating there was any success in preventing this adverse process. This is highly likely due to the
fact that the nature of change in the processing properties of gold during grinding has not yet been discovered.

3. Experimental procedure
As in the case of lead markers, gold particles, when ground in a mill, become localized in a certain area height-wise and continuously ‘slide’ along the inner surface of a rotating shell without breaking away from it. In the process of grinding, the bombardment with grinding balls and mill charge results in constant rolling of markers and their gradual thinning, i.e. producing particles of the smallest size. It is established that, the localization area changes depending on the particle thickness, i.e. the thinner the particle, the less is the particle elevation. Further on, when the lead markers are flattened to a thickness of less than 0.3 mm, the particles break away from the inner surface of the mill shell and fall into the process stream of the mill charge. Repeated flattening-out leads to a thinning of the plate to 0.15 mm. The plates are then dispersed and disintegrated into flakes 0.1-0.07 mm thick, mixed in the bulk of the mill charge and can be removed from the grinding. Aluminum markers with a density close to that of the mill charge (rock) (2.7 g/cm³), do not ‘slide’ along the inner surface of the shell, but rather spread throughout the entirety of the mill charge and are not rolled with grinding balls. Depending on the grinding time, the particles shape becomes near spheroidal.

Generally, once extracted, gold-containing material takes on the shape of a flat plate. Due to the area of contact, the plates move along with the balls following a circular path until they break away and drop.

At that, the size (thickness) and the speed of these plates change. Since the greater part of material is ground by impact, the dropping speed plays an important role in the research. When studying the dropping speed of particles in a liquid medium, hydraulic size is regarded as one of the important technological parameters. It determines the nature of the particles motion depending on the density, shape and size. The paper [7] shows that hydraulic size generally depends on the material thickness and is essentially independent of the shape and volume according to the formula:

\[
v = \sqrt{\frac{2(\rho - \rho_g)}{\rho_g}} gd
\]

During the shell rotation, the material may break away and drop at different angles.

During the first 2-3 hours of the ball mill operation, some lead flakes, which are less than 0.3 mm thick, swell along the edges (Figure 1).

Figure 1. A – a flake in the area, where swelling occurs along the edges and out of the rolling balls reach; B – a flake in the area of debris and balls moving in the opposite direction.

It was empirically established that the specific structure of gold grains was formed as a result of microforging of the gold grains edges by sand grains pushed by the air flow [7-13]. Similar work was carried out in cooperation with research associates from Ammosov North-Eastern Federal University. Swelling at the edges of gold grain flakes is caused by frequent micro-bombardment by small debris.
It happens as a result of a considerable lag of the moving gold grains compared to the sand grains pushed by the air flow. Beside, this swelling of the open-worked structure remains due to the fact that large debris do not roll through them.

Consequently, the following conditions are created in the ball mill: the flattened markers are treated by small debris, while the grinding balls and larger debris do not roll through them.

This could be explained by the following. Due to their small size and high density, marker particles end up on the mill bottom. Each of them has certain forces acting on it: \( g \) – gravitational; \( F_{CF} \) – centrifugal; frictional – \( F_{FR} \). Therefore, on the one side, the acting gravitational force pulls the markers down and, on the other, the acting friction force, \( F_{FR} \), carries them away upwards with the moving mill bottom at a linear speed \( V_L \). These forces determine the balance of forces.

Sand grains surrounding a piece of gold constantly bombard it and change its shape. Gold has the highest forging properties, so a plastic deformation model could be used in modeling. During air separation, the sand grains near the considered piece of gold change the direction of movement due to the difference in speed, and there occur numerous collisions with empty rocks. At the same time, the piece under consideration also changes its movement direction and tumbles. Thus, an unregulated, random bombardment of the gold piece surface takes place. Therefore, it is fair to say that there happens a consistent isotropic bombardment with grains of sand. If a piece of gold has an irregular volumetric shape, i.e. all three linear dimensions are comparable, then, following the isotropic bombardment, the body is steadily shaped into a ball. The problem changes dramatically if a flat plate is studied. Consider a sufficiently large flat deformable plate exposed to the isotropic bombardment. The thickness of the plate is much less than its length and width (Figure 2). For simplicity, first, consider a plane problem. When exposed to the isotropic bombardment at the beginning, only those parts of the plate surface that have the least radius of curvature are deformed. Therefore, the deformation starts at the edges. Due to the isotropy of the sand grains stream, flat areas of the plate, i.e. infinite radius surfaces, remain undeformed. The particles flux hitting flat areas of the plate is not taken into account in calculating.

Figure 2. Bombardment of a Flat Particle with Sand Grains.

After some time, the edge of the plate will have a specific shape (Figure 3). The plate becomes shorter, but there appears a swelling at the edge, since the volume is retained.

Figure 3. Only non-flat areas of the particle surface are deformed during the isotropic bombardment.

Figure 4 shows only that particle flux, which deforms the body. As time passes, the swelling of the plate edge increases and shifts to the left, while the surface restricting the swelling increases. For a dynamic analysis of the swelling surface, it is necessary to solve a problem involving stress and strain tensors, i.e. the elasticity theory. As noted above, if an arbitrary shaped body confined in a certain region of space is exposed to the isotropic bombardment for a long enough period of time it becomes a ball. That is, the body that has the smallest boundary surface when the values of volume are set. Any plate with the proportionate width and length, following an exposure to the isotropic bombardment for a certain period of time, tends to take the shape of a torus, the inner part of which remains flat (Figure 4).
If a flat disc is considered, the disc edge will take the shape of a torus. It means, that the problem consists in determining the time value, during which the plate takes the shape of a torus of a certain size.

Consider the problem: a plate with an initial shape of a disc having a thickness equal to $2r_0$ and a radius $R_0$ is exposed to the isotropic bombardment with a uniform particle beam of the given mass $m_0$, average velocity $v_0$, and flux density $j_0$. First, the peripheral part of the disc is deformed, where there are surface areas with the least curvature. As a result, the disc edges swell and its linear size decreases respectively.

During deformation over time $dt$, the work is done on the body
\[
dA = \alpha dS
\]
where $dS$ is a change in the body surface during deformation, $\alpha$ is the proportionality factor, which can be determined through the experiment.

According to the energy conservation law, this work (if energy loss through heat dissipation is ignored) is equal to the total kinetic energy of the particles bombarding the deformable surface, i.e.
\[
dA = dE = dN \cdot \frac{m_0 v_0^2}{2}
\]
where $dN$ is a number of particles hitting the deformable surface over time $dt$.

A number of particles hitting the surface per unit of time is referred to as a flux $\Phi$; therefore, we introduce the concept of volumetric flux density $j_0$:
\[
\Phi = \frac{dN}{dt} = j_0 S
\]

If an isotropic and uniform flux is considered, then $j_0$ is a constant value.

From (1), (2), (3) we obtain an ordinary differential equation:
\[
\frac{adS}{dt} = j_0 S \frac{m_0 v_0^2}{2}
\]
or
\[
\frac{dS}{S} = \frac{j_0 m_0 v_0^2}{2\alpha} dt
\]
The solution of the equation (6) is given by:
\[
\ln|S| = \frac{j_0 m_0 v_0^2}{2\alpha} t + C
\]
Hence, the dynamic change of the surface in time is equal to:
\[
S = S_0 \exp \left( \frac{j_0 m_0 v_0^2}{2\alpha} t \right)
\]
The resulting formula holds for a case when the area of the deformable surface gradually increases, for example, for a plane problem. If a flat disc is considered, an increase of the lateral surface radius of curvature leads to a reduction of the disc linear size, which results in a reduction of the lateral surface.

Suppose the initial shape of the plate is a disc with a rounded edge (Figure 5), then $S_0$ is the area of the rounded part of the initial shape of the disc surface.

![Figure 5. The Initial Shape of the Disc.](image-url)
The disc thickness equals \(2r_0\), the disc edge in section has a shape of a semicircle with a radius \(r_0\). \(R_0\) is a distance from the axis of rotation to the center of the semicircle. Thus, the disc radius equals \(R_0 + r_0\).

The disc volume is determined through integration:

\[
V_0 = \pi \int_{r_0}^{R_0} R_0 + \sqrt{R_0^2 - x^2} \, dx = 2\pi \left[ \int_{r_0}^{R_0} R_0^2 \, dx + 2R_0 \int_{r_0}^{R_0} \sqrt{R_0^2 - x^2} \, dx + \int_{r_0}^{R_0} r_0^2 \, dx \right] - \int_{r_0}^{R_0} x^2 \, dx
\]

(9)

During the isotropic bombardment, only the disc edge is deformed. Besides, the section of the deformable surface becomes larger. The volume limited by this surface also increases. Therefore, the deformable part of the disc becomes larger, while the flat part of the disc is reduced. Considering that the volume of the deformable part (the disc edge) takes the smallest boundary surface under the isotropic action, the deformable area can be approximated by the shape of a dynamically changing torus. During this process, the torus surface increases, and its linear size decreases. The middle part of the disc remains flat.

The volume of the resulting figure is equal to the sum of the torus volumes \(V_t\) and the flat area in the middle \(V_p\):

\[
V_0 = V_t + V_p
\]

(10)

This volume is equal to the initial disc volume (9).

The torus volume is equal to:

\[
V_t = 2\pi R^2 r^2
\]

(11)

where \(r\) is the torus edge radius of curvature, \(R\) is a distance from the torus center to the edge center of curvature.

The volume of the middle flat part is calculated through integration:

\[
V_p = \pi \int_{r_0}^{R_0} R - \sqrt{R^2 - x^2} \, dx = \pi \left\{ \int_{r_0}^{R_0} R^2 \, dx - 2R \int_{r_0}^{R_0} \sqrt{R^2 - x^2} \, dx + \int_{r_0}^{R_0} r^2 \, dx - \int_{r_0}^{R_0} x^2 \, dx \right\}
\]

(12)

By making the resulting volume of the figure (10), (11), (12) equal to the initial disc volume (9), we obtain the quadratic equation in \(R(r)\):

\[
R^2 r_0 + R \left[ \pi r^2 - r^2 \left( \arcsin \left( \frac{r_0}{r} \right) + \frac{r_0}{r} \sqrt{1 - \left( \frac{r_0}{r} \right)^2} \right) \right] = r_0 \left[ R_0^2 + \frac{\pi}{2} R_0 r_0 + \frac{2}{3} r_0^3 \right] - r^2 r_0 + \frac{1}{3} r_0^3
\]

(13)

The solution to this quadratic equation is:

\[
R(r) = \frac{-b + \sqrt{b^2 - 4ac}}{2a}
\]

where \(a = r_0\),

\[
b = \pi r^2 - r^2 \left( \arcsin \left( \frac{r_0}{r} \right) + \frac{r_0}{r} \sqrt{1 - \left( \frac{r_0}{r} \right)^2} \right),
\]

\[
c = r^2 r_0 - \frac{1}{3} r_0^3 - r_0 \left[ R_0^2 + \frac{\pi}{2} R_0 r_0 + \frac{2}{3} r_0^3 \right].
\]

The obtained formula (14) allows to find the dynamic change of the disc surface deformable part. During the isotropic bombardment, the torus linear size decreases, and the deformable section surface first increases to a certain maximum value, then decreases. This means that there is a peak value. Therefore, it may be said that thin plates take the shape of a torus fast enough, while thick plates tend to take the shape of a ball. After the maximum surface area of the torus is reached, there should be a slowdown in the process of deformation during the isotropic bombardment, since the torus area starts to decrease and its shape tends to take the smallest area, i.e. the body seeks to take the shape of a ball. Therefore, pieces of gold shaped as a torus having certain parameters depending on the initial thickness and size of the plate should often be found in the processed ore. Figure 6 shows a graph of the dynamic development of the disc surface deformation.
Figure 6. Qualitative Graph of the Dynamic Development of the Deformable Disc Surface.

The estimates suggest that with an initial disc thickness of 1 mm and a radius of 10.5 mm, the maximum deformable area is achieved when the torus thickness is 2.82 mm and the disc radius is 7.937 mm. Figure 7 shows the disc shape with these parameters.

Figure 7. The Disc Shape with the Maximum Surface of the Surrounding Torus

The time required to form a body shape with a maximum deformable surface area according to (8) is calculated as per the formula

\[ T_1 = \frac{2\alpha}{\log_{\alpha} S_0} \ln \left( \frac{S_{\text{max}}}{S_0} \right) \]  \hspace{1cm} (15)

where \( S_{\text{max}} \) is defined by the geometric model (9-14)

4. Conclusion

Through the example of analyzing the behavior of malleable markers, the process of transforming the shape of tough plastic (malleable) materials during ball grinding is found to require the retention of the initial particle size of commercial components (gold) after extraction from the ore mass, as well as timely removal from the grinding mill. Therefore, an appropriate design of the inner surface (lining) of the ball mill is required to reduce the rolling of gold particles.

References

[1] Gabibov I A, Hamidov F M, Chakraborti P P 2018 The results of improvements of SAG type mills used in the Azerbaijan International Mining Company Bulletin of the Ural State Mining University Issue 2 pp 102-106

[2] Erickson K, Gander M, Grebenshchikov A L, Fishev V Yu 2003 Development of mill lining systems Mining 1 p 24

[3] Abdellaoui M, Gaffet E 2005 The physics of mechanical alloying in a planetary ball mill: Mathematical treatment Journal of Process Control vol 15 pp 273-283

[4] Rodrigo M, Luis C, Tavares M 2013 Predicting the effect of operating and design variables on breakage rates using the mechanistic ball mill model Minerals Engineering vol 43–44 pp 91-101

[5] Schnatz R 2004 Optimization of continuous ball mills used for finish-grinding of cement by varying the L D ratio, ball charge filling ratio, ball size and residence time International Journal of Mineral Processing vol74 pp 55-63

[6] Yang J, Li S, Xi-Song C, Li Q 2010 Disturbance Rejection of Ball Mill Grinding Circuits Using
DOB and MPC Powder Technology vol 198 pp 219-228

[7] Osipov D A, Filippov V E 2011 Detailing the process of destruction of geomaterials in a laboratory ball mill Mountain Information and Analytical Bulletin 11 of 2011 p 223

[8] Osipov D A, Filippov V E 2017 Ball mill with a helical depression Mountain Information and Analytical Bulletin Special issue 24 pp 193-200

[9] Filippov V E, Nikiforova Z S 1998 The formation of gold placers under the influence of aeolian processes (Novosibirsk) Science, Siberian Enterprise of the Russian Academy of Sciences

[10] Osipov D A 2018 Determination of operational parameters of mills using malleable markers Materials of the international scientific-practical conference "Effective technologies for the production of non-ferrous, rare and precious metals" September 27-29, 2018 (Kazakhstan) Alma-ata. Electronic collection

[11] Osipov D A 2016 The evolution of the technological properties of gold particles during disclosure Science and Education 12

[12] Osipov D A 2012 An experimental study of the deformation of malleable particles in a centrifugal mill TsMVU-800 GIAB 10 pp 232-237

[13] Taburkin V I, Doronina M V, Udartseva O V, Solovev D B 2019 The Grounds of Subject Area of Technosphere Studies IOP Conference Series: Earth and Environmental Science 272 paper № 032022. [Online]. Available: https://doi.org/10.1088/1755-1315/272/3/032022

Acknowledgments
This work was supported by the RFBR grant 18-45-140036 p_a.