Research on the Revision of the Half- Theory Formula to Determine Mill Steel Ball Size ①

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Abstract In the past, the determination of mill ball size was mainly conducted by experts' experience and generally involved great deviation because not all factors were properly considered. Professor Duan Xixiang has developed a half- theory formula from principle of fragmentation mechanics. In practice, it has been proven that the formula can be satisfactorily applied to intermediate and fine grinding stages. However, it still results in obvious deviation to the large side although it is better than any other methods. In view of this, starting from rock's mechanical properties, we take pains to study the revision of the formula. After carried out a series of lab test and industrial experiments, we develop a scientific and reliable system of accurately determining mill ball size for coarse grinding as well as intermediate and fine grinding processes.

Key words coarse grinding; ball size; half- theory formula; revision

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Based on principle of fragmentation mechanics, an important half- theory formula of calculation mill ball size has been developed by Duan Xixiang in reference[1]. It is:

$$D_b = k \cdot \frac{0.5224}{\Psi^2 - \Psi^6} \cdot \sqrt[3]{\frac{\sigma_c}{10 \cdot \rho_e \cdot D_o}} \cdot d \qquad (\text{cm})$$

It has successfully been used to determine the exact mill steel- ball size in several ore dressing plants. It overcomes the problem of ball oversize regarding intermediate and fine grinding mill in these plants, thus achieves great technical effects and economical benefits through its practical applications. However, the ball size yielded by the formula is still oversize for coarse grinding mill, although it is closer to the exact value than by other formulae. So the mill ball oversize problem in coarse grinding is yet to be solved. This paper deals with the method of making amendment of the formula so as to enable it applicable not only to intermediate and fine grinding but also to coarse grinding.

1 Problems Deriving from Practical Application of the Half- Theory Formula

Grinding is divided into three ranges according to product's granularity or size in reference[2]. They are coarse grinding, 3.3~0.83 mm; intermediate 0.61~0.21 mm; fine 0.15 mm or less. We have already verified the validity of the formula in its application to intermediate and fine grinding by practical experiments and production. These experiments possess extensive representativeness for the grinding material includes copper ore, nickel ore, tin ore and so on; hardness of ores varies from medium strong, $f = 8-16$, to strong $f = 16-23$; grinding- mills for experiments include large, medium and small ones; rotation rate ranges from 66% to 82% and the production periods last from 3 to 5 years. Table 1 lists some application cases.

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Table 1 Cases of application of the half- theory formula to calculating the accurate ball- size for intermediate and fine grinding*.

Plants and grinding stage	Mill head Size / mm	Ore hardness (f)	Mill profile D×L/m	Rotation rate Ψ/%	Original ball size / mm	Calculated ball size / mm	Optimal ball size by experiments / mm
Qibeishan plant, Yunnan (YN) Tin Corp. stage 3 (fine)	0.8	8~ 12	1.65×3.0	82.21	Φ70, Φ60	20.5	20.0
Plant of Mouding copper mine, YN, stage 2 (fine)	0.35	16~ 23	2.7×3.6	80.85	Φ80, Φ60	14.8	14.0
Plant of Dayao copper mine, YN, stage2 (intermediate)	2.50	16~ 20	3.2×3.1	73.53	Φ80, Φ60	45.5	46.6
Plant of Dayao copper mine, YN, stage 3 (fine)	0.31	16~ 20	3.2×3.1	73.53	Φ60, Φ50	13.0	14.0
Plant of Luoci ferrous mine, YN, stage 2 (fine)	0.80	7~ 15	2.1×3.0	79.00	Φ80, Φ60	20.0	20.0
Chehe plant, Dachang mine, Guangxi, mill for middle ore (fine)	0.90	12~ 14	1.5×3.0	80.92	Φ80, Φ60	27.3	28.0
Chehe plant, Dachang mine, Guangxi, mill for sulfide ore (intermediate)	0.3	12~ 14	2.1×3.0	80.00	Φ80, Φ60	10.8	10.0
Chehe plant Dachang mine, Guangxi, mill for rough concentrate (intermediate)	3.00	12~ 14	2.1×3.0	66.67	Φ75, rod	50.0	50.0
Jinchuan. Corp. Gansu, ball grinding, stage I (intermediate)	1.60	12~ 14	2.7×3.6	82.00	Φ60, Φ40	30.6	30.0
Jinchuan Corp. Gansu, ball grinding, stage Ⅱ (fine)	0.30	12~ 14	2.7×3.6	82.00	Φ60, Φ40	13.5	14.0
Jinchuan Corp. Gansu, ball grinding, stage Ⅲ (fine)	0.27	12~ 14	2.1×3.0	82.00	Φ60, Φ40	11.4	11.5

* The mill ball size determined by theoretical calculation and verified by laboratory tests may be adjusted a little bigger according to concrete production conditions and supply availability. The plant of Jinchuan Corp. conducted only laboratory experiments. All the other plants have put the new ball size grinding system into production one after another since Feb. 1988~ Feb. 1994.

Table1 illustrates that the steel ball size computed by the half- theory formula is very exact. The error between theoretical size and experimental is only at the range of 1mm. In addition, most results have been confirmed through industrial production. The accuracy of the formula in determining mill steel ball size for intermediate and fine grinding is beyond the reach of any other currently available formulae. Therefore the formula should be regarded as effective in determining the accurate ball size for intermediate and fine grinding mills, and have received recognition in the world. However, its application to coarse grinding is not so ideal, though its result is more accurate than any ones by other formulae available home and abroad, as is showed by the author during the formula deduction process by comparing its result with others'. The coarse grinding mill is quite different from intermediate and fine ones in that it is much easy to make experiment in laboratory for smaller ore granularity size with the calculation results of the latter and easy to form unanimous conclusions, while the former makes even the lab verifying test very difficult because of the coarse ore grain, to say nothing of industrial experiments. As a result, it lacks a convincing basis to determine the diameter of the mill ball for the coarse grinding and there is multiplicity of views on this. Although some experts home and abroad point out that coarse grinding steel ball size is generally oversized, they do not yet put forward effective ways for accurate calculation and can not evaluate the deviation. The coarse mill ball sizes determined by either experiments or experiences in the country are full of empiricism and their accuracy is not certain although we can pick them up in the teaching books or monographs. For large mills 4~ 6 m in diameter, which are extensively used abroad, the steel balls inside will accumulate higher potential energy, so the ball size should be smaller. The higher potential energy compensates the smaller size. However, most mills used in the country are smaller, whose size are generally 3. 6m or less. Naturally, the potential energy of steel balls inside is less and the ball should be larger that those used abroad. No doubt, the mill steel ball size is much oversize from the foreign experts' point of view. But the experiences abroad are not necessarily fit for adjusting the ball size of the country because they stem from the operation of large- scale mills of other countries. On the one hand, because the coarse grinding ball size determination in the country is carried out under conditions of industrial production with arduous experiment work and variety of restrictions, it can not take all the factors related into consideration, so it is difficult to assert the accuracy of the experiment results. On the other hand, The empirical data about ball size coming from experiences are influenced by the experiences themselves, the conventions and particular production conditions, and can only be used for references because they lack more reliable foundation and authority, so they can not be considered accurate. Consequently it is not practical to cope with the problem of determining mill ball size accurately by the existing formulae or experiences available home and abroad. Although some mineral processing engineers have done practice of reducing mill ball size in some ore-dressing plants, their jobs are not deeply conducted. The phenomenon of ball oversize is still rampant and any suggestions of cutting down ball size confront with great difficulty to popularize and apply. Even the half-theory formula does not wholly get rid of the scope of experiment and empirical data and is still lack enough evidence and convincingness to settle the accurate calculation problem of ball size for coarse grinding.

Therefore, we can conclude that the half- theory formula is successful in its application to determine the exact ball size for intermediate and fine grinding, but with regard to coarse grinding, it will face problems such as if it is in itself correct, if the calculating and factor value selecting are properly carried out and more importantly, how to prove the accuracy of the calculating so as to assert the correctness of the formula itself and the calculation.

2 Research on the Revision of the Half- Theory Formula

2.1 Causes Analysis of Oversize Deriving from the Ball Size Calculation by the Formula for Coarse Grinding

The deduction of the formula is based on Davis- Левесон theory, which is universally acknowledged in mineral processing circles. So far there are no other new theories taking the place of its. It is also correct in both concept and logic. That is, it determine the striking force according to what is necessary for the ore blocks to disintegrate, then determine the ball size by the striking force. We can say that the formula itself is come from strict theoretical deduction without any defect. The structure of the formula and factors considered are appropriate.

Now, let's check whether the 6 factors k, Ψ, σ_c, ρ_e, D_o and d, which build the function D_b are properly and accurately determined under coarse grinding condition. The granularity sized of mill head is determined by production process and is an independent variable, so it is indisputable. The effective special gravity ρ_e of steel ball in ore pulp is computed by $\rho_e = \rho - \rho_n$ according to its definition, where ρ stands for steel ball's special gravity and ρ_n ore pulp's, and generally, $\rho = 7.8\ g/cm^3$, $\rho_n = [R_d + P_t(1 - R_d)]$. All of them are certainties. D_o and ϕ are definite values introduced into the formula according to Davis- Левесон theory for certain mill, so they are also beyond any questions. k is the empirical factor deriving from experiments and its validity has been verified in the application of the formula to intermediate and fine grinding. Then the steel ball oversize problem can only be caused by σ_c the rock's compressive strength, which generally takes a much higher value than it should be. The reasons are that.

1) σ_c comes from testing standard rock specimens, which are generally processed from stronger rock blocks. Unstable and low strength rock blocks are not easy to be processed into standard specimens because they have to withstand sawing and burnishing. Thus so far as the sampling process of rock pieces is concerned, it caused the strength to deviate to higher value.

2) The flat horizontal surfaces on both compressive ends of standard specimens eliminate occurrence of stress concentration and form uniform stress distribution under pressure. Consequently, the standard specimens can bear much higher load. Since the shape of ore blocks in mills is irregular and the striking force of steel ball is exerted on them in form of point load, so stress concentration will inevitably take place within them. Therefore the natural or irregular ore blocks are much easy to crush. All these mean the σ_c of standard rock specimens is much higher than that of natural blocks. In theory, it is the latter that conforms with reality more and is more scientific.

Wang Hongxun and his colleagues of Beijing Mining and Metallurgical Research Head Institute have once tested the crushing force of natural irregular rock blocks. The result shows the value surely is not high[1)]. To be more convincible, we conduct tests to measure both the σ_c of standard rock blocks and that of natural ones, then make comparison of them so as to know to what extent the latter is lower than the former for the purpose of practical application.

We choice 4 kinds of ore as studying object. We test σ_c and energy density Ev of each kind of rock in form of both standard specimens and natural blocks. The compressing area of an irregular block takes that of a standard specimen's, which has the same volume as the irregular block. In the testing operation, we should take great care in observing the rock's destruction process and record the crushing load. It is important to distinguish local break from total crush. The test results are listed in table 2.

Table 2　σ_c comparison between standard rock blocks and natural rock blocks for 4 different ores

Ore type	Standard σ_c / kg·cm^{-2}	Standard E_v / kg·cm^{-3}	Natural σ_c / kg·cm^{-2}	Natural E_v / kg·cm^{-3}	Reduction of σ_c / %	Reduction of E_v / %
Vanadium bearing titanomagnetites	1392.90	149.10	358.28	60.15	74.28	59.66
Copper ore	1002.50	99.43	239.96	50.31	76.06	49.40
Aurum ore	500.40	54.39	246.64	40.99	50.71	24.64
Magnetite and hematite ore	1084.82	110.17	454.97	87.63	58.06	20.46

Table 2 illustrates that it is a universal law that the strength of natural blocks is much lower than that of standard ones. σ_c of the natural block's is about 50%～75% less than that of standard block's, and Ev of the former is also about 20%～60% less than that of the latter. Therefore, if we only know the hardness factor f of a rock, that is, σ_c of the standard rock block ($f = \sigma_c / 100$, where σ_c is the compression strength of standard block of the rock), and its strength in natural irregular form is not available, we can decrease σ_c by 50% and substitute it into the formula to calculate the required accurate diameter of steel balls considering the data of table 2 and the testing results of other people mentioned above. It goes without saying that the practical testing value of σ_c of irregular rock blocks is preferable to make the calculation more accurate.

The strength of natural rock blocks is also tested for several granular size groups. The test shows that the smaller the granularity size, the higher the strength as a result of less flaws in smaller blocks. The test also shows that the strength σ_c of natural blocks less than 10 mm in size already approaches to that of standard specimens' (5 cm × 5 cm × 10 cm or 4 cm × 4 cm × 8 cm). This explains why the calculated ball size by the formula with strength σ_c of intermediate and fine size ore granules is accurate while it is not for coarse grinding.

Thus, the revision of the formula is necessary only for the mill head with granularity size greater than 10mm. If condition permits, σ_c of natural rock blocks greater than 10mm in size should be measured directly. Otherwise, we can decrease σ_c's value of standard block's by 50%. For intermediate and fine grinding, we can make use of σ_c directly without any revision or amendment to compute the exact steel ball size.

2.2 Cases Analysis and check of the revision of the formula

The preceding section analyses the reasons of oversize in application of the formula to coarse grinding, and poses revision method of substituting directly measured σ_c for that of standard rock blocks. Here, we calculate the steel ball size by the formula with and without revision respectively for ore dressing plant A's medium mill (2.1 m × 3.0 m), which deals with magnetite and hematite and plant B's large- sized mill (3.6 m × 4.0 m), which deals with titanomagnetite containing vanadium. The operation conditions and calculation results are listed in Table 3.

Table3 illustrates that the ball size calculated by the formula with amendment is about 20% less than the practically used ball size. We can get the conclusion that the plants' ball is oversize by check it from the results of revised calculation. Which is correct or better need to make experiments to judge.

2.2.1 Laboratory Test

The test is carried out under the following operation conditions: Size of discontinuous ball mill- grinder: 400 mm × 450 mm ($D \times L$); Rotation rate: 67% (less than that of the plants, which is 78~ 79%); Filling degree of steel balls: 36.82% (less than the plants' 40% ~ 43%); composing ratio of steel ball: Each of the 3 ball size groups accounts for about 1/3, basically the same as what is in the plant's mill. In general, the laboratory condition is worse than those of the plants' and the feed ore material comes directly from the plants. Thus the test results would tend to be conservative and yet to the safe side.

The ore of plant A(same with B) is uniformly mixed and divided into 4 groups. Then we make the following experiments with the 4 groups.

(1) Comparative grinding experiment with same size steel balls of Φ120 mm versus Φ100.

(2) Comparative grinding experiment with mixed size steel balls of Φ120 mm, Φ100 mm and Φ80 mm versus Φ100 mm, Φ75 mm and Φ60 mm.

Since the ore from plant A is less strong, the milling time only last 25 minutes for reducing the ore to the size of the products of the plant, while for ore from plant B, it requires 45 minutes.

The ground products are screened and analyzed. Then we are able to make comparison of the grinding results for ores from plant A and B with the 4 size group steel balls.

Table 3 Related operation conditions and comparison ofsteel ball size with and without amendment

Plant	Hardness in designing (f)	Hardness measured (f)	Millhead size in designing d_{max}/mm	Mill head size measured d_{max}/ mm	Maximum ball size in production D_b/ mm	Ball szie without amendment D_b/ mm	Ball size with amendment D_b/ mm
A	7~ 15 Average 11	10.84	18.00	20.00	120	125	98.8
B	12~ 16 Average 14	13.92	25.00	23.25	125	124	97.7

The laboratory experiment results demonstrate that[1, 2]:

(1) The steel ball size Φ120 mm and Φ125 mm adopted by plant A and B respectively is oversize indeed.

The size of Φ100 mm according to the revised formula is already sufficient. By comparing the products yielded by Φ100 steel balls with those by Φ120 mm or Φ125 mm oversize balls, we can see that the former's maximum granule size, average granule size and content of + 0.3 mm oversize grains are cut down greatly, while - 200 mesh products and the mill utilization factor with regard to - 200 mesh products increase evidently. This shows that the substitution of Φ100 mm steel balls for Φ120 or Φ125 mm ones will not cause insufficient grinding problem. On the contrary, it will improve the grinding effect.

(2) As a result of exact choice of ball size, over pulverized products decrease obviously because of the proper crushing force. The content of the middle easy- to- extract particle increases and the granularity properties are improved. Accurately determined ball size will raise the selectivity of mineral disintegration, Thus increase the unit separation degree. These improvements are beneficial for the next mineral separating operation.

(3) The results from mixed size steel ball grinding are the same as those from same size ball grinding, which shows the same conclusion that the accurate size balls will effect much better results than oversize ones.

2.2.2 **Industrial Experiments And Production Application**

On the basic of the results of laboratory tests, we conduct industrial experiments and production application on a coarse grinding mill system in plant A and another in plant B to verify their validity.

The experiments were made during February ~ June, 1994 in plant A. For the experiments, big balls of Φ120 mm are removed from and small balls of Φ60 mm, added to the primary ball- fillings, thus each of the three ball- size groups Φ100 mm, Φ80 mm and Φ60 mm accounts for 1/3, approximately the same combination as the original mill ball fillings. The main purpose of the experiments in plant A is to increase products' fineness while keep the same yield of a mill in an hour. The results are listed in table 4.

Experiments at plant B are carried out in March ~ November, 1996. The Φ125 mm big balls were removed from the preliminary fillings and so was done to Φ60 mm balls because of their inferior quality. Thus, in reality, only Φ100 mm and Φ80 mm sized balls were put in with each accounting for 50%. The experiments at plant B are conducted on the purpose of increasing yield, improving products' quality and raising concentrate grade while remaining the products' fineness. The results are also listed in table 4.

Table 4　comparison of lab experiment results with industrial ones

Indexes	Lab (A)	Industry (A)	Difference of lab to industry	Lab (B)	Industry (B)	Differences of lab to industry
Yield / $t.(mill.h)^{-1}$	28.77	28.00	2.75% up	96.33	86.62	11.21% up
Maximum size of mill head / mm	24.86	23.75	4.76% up	26.14	25.70	1.71% up
Average size of mill head / mm	13.76	9.15	50.38% up	10.27	9.14	12.36% up
Percentage of - 200 mesh particles	5.55	14.38	61.40% down	4.19	4.80	12.71% down
Percentage of - 200 mesh overflow	59.96	53.84	11.37% up	48.10	47.52	1.01% up
Percentage of - 10 μm overflow	17.33	20.83	16.80% down	6.32	10.40	39.23% down
Mill utilization factor for - 200 mesh material	1.74	1.23	41.46% up	1.165	1.019	14.33% up
Consumption of steel ball / $kg.t^{-1}$	0.727	0.932	22.00% down	0.583	0.646	9.75% down
Consumption of Electricity / $kw.h.t^{-1}$	5.13	5.69	9.84% down	11.24	11.77	4.50% down
Noise / dB	89.0	91.0	2dB down	92.0	94.5	2.5 dB

Table 4 illustrates that:

(1) The replacement of Φ100 mm balls for Φ120 mm and Φ125 mm ones in industrial production is not only practicable, but also has better grinding effects than those from laboratory experiments. For the same yield at plant A, the fineness increases by 11.31%, the mill utilization factor for- 200 mesh ore granules increases by 41.46%. Besides, the maximum particle size in mill discharges and that in back fractions' decrease obviously. There is no problem of insufficient grinding. For the same fineness at plant B, the yield increases by 11.21%, the unit disintegrating degree rises obviously. Amount of overcrushing - 10 μm or smaller particles decreases by 39.23%. The product's quality is improved by a big margin and the concentrate grade increases substantially.

(2) The accurately determined ball size decreases the consumption of steel ball by 22% at plant A and 9.

75% at plant B.

(3) It reduces electricity consumption too.

(4) The noise is also suppressed to some extent, which is beneficial to improving the workshop environment and the workers' health.

After the industrial experiments at the two plants, the achievements were soon put into production, which proves that the experiment results are reliable.

3 Conclusions

The above exposition can be condensed into the conclusions below:

(1) Our formula is very accurate in calculating ball size for intermediate and fine grinding, which was verified in more than 10 mill plants. The formula supplies the solution to overcome mill ball oversize problem existing in many mill plants. The plants will increase efficiency, reduce energy and other productive material consumption and achieve brilliant technical effects and economical benefits thereby.

(2) There will be big deviation in application the half- theory to coarse grinding although it is less than that determined by any other formulae, so it is necessary to make amendment to balance the still unsatisfactory oversize result.

(3) The study on the characteristics of rock mechanics shows that σ_c of standard rock specimens is on the high side excessively. Consequently, the value of steel ball size calculated by the formula with the use of σ_c is oversize. Making amendment by means of removing the influence of the surplus value part of σ_c will yield exact value of steel ball size. This is realized by seeking σ_c of natural rock blocks' through tests or experiments, or making deduction on the strength value σ_c of standard specimen. The laboratory tests and industrial experiments carried out in the two mill plants prove that the calculated ball size from the revising is reliable and the approach is correct and scientific.

(4) The research solves the mill ball oversize problem. That is, it makes the ball size formula fit not only for intermediate and fine grinding, but also for coarse grinding, thus provide a scientific and reliable method to determine mill steel ball size.

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磨机钢球直径半理论公式的改进研究

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摘要 磨机钢球直径的选择历来主要是凭经验, 考虑的因素不全面, 故误差常常很大. 段希祥从破碎力学原理出发推导出理论性较强的球径计算半理论公式. 该公式在实际应用中表明, 对于中磨及细磨极为准确, 但对于粗磨, 误差还是偏大, 尽管仍比传统的方法准确. 为此我们从岩矿的力学性质开始研究该公式的修正, 通过试验室试验及工业试验, 得到了不仅能准确计算中磨、细磨, 而且能准确计算粗磨球径的方法.

关键词: 粗磨; 球径; 半理论公式; 修正