metals

Article

Variability of the Ball Mill Bond's Standard Test in a Ta Ore Due to the Lack of Standardization

Gloria González García [1], Alfredo L. Coello-Velázquez [2], Begoña Fernández Pérez [1] and Juan M. Menéndez-Aguado [1],*

[1] Escuela Politécnica de Mieres, Universidad de Oviedo, Gonzalo Gutiérrez Quirós, 33600 Mieres, Spain; gloria.glez.gcia@gmail.com (G.G.G.); fernandezbegona@uniovi.es (B.F.P.)
[2] CETAM, Universidad de Moa Dr. Antonio Núñez Jiménez, Moa 83300, Cuba; acoello@ismm.edu.cu
* Correspondence: maguado@uniovi.es; Tel.: +34-985-458-033

Abstract: There is no doubt about the practical interest of Fred Bond's methodology in the field of comminution, not only in tumbling mills design and operation but also in mineral raw materials grindability characterization. Increasing energy efficiency in comminution operations globally is considered a significant challenge involving several Sustainable Development Goals (SDGs). In particular, the Bond work index (w_i) is considered a critical parameter at an industrial scale, provided that power consumption in comminution operations accounts for up to 40% of operational costs. Despite this, the variability of w_i when performing the ball mill Bond's standard test is not always understood enough. This study shows the results of a variability analysis (a 3^3 factorial design) performed to elucidate the influence on w_i of several parameters obtained from the particle size distribution (PSD) in feed and product. Results showed a clear variability in the work and grindability indexes with some of the variables considered.

Keywords: comminution; grindability; work index; energy efficiency

Citation: García, G.G.; Coello-Velázquez, A.L.; Pérez, B.F.; Menéndez-Aguado, J.M. Variability of the Ball Mill Bond's Standard Test in a Ta Ore Due to the Lack of Standardization. *Metals* **2021**, *11*, 1606. https://doi.org/10.3390/met11101606

Academic Editors: Giovanni Principi and Antoni Roca

Received: 12 August 2021
Accepted: 5 October 2021
Published: 9 October 2021

1. Introduction

There is no doubt about the importance of Fred Bond's methodology [1–5] and its practical value in the field of comminution, not only in tumbling mills design and operation but also in the characterization of mineral raw materials grindability. The Third Law of Comminution, also known as the Bond's Law, is summarized in Equation (1) [5].

$$W = 10 \cdot w_i \cdot \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) \quad (1)$$

wherein:

W is the specific power consumption [kWh/t];
w_i is the Bond work index [kWh/t];
P_{80} is 80% passing size in the grinding product particle size distribution (PSD);
F_{80} is 80% passing size in the feed PSD.

Increasing energy efficiency in comminution operations globally is considered a significant challenge involving several SDGs, especially goals 7 (affordable and clean energy), 9 (industry innovation and infrastructure), 12 (responsible consumption and production) and 13 (climate action), since the increasing energy efficiency reduces waste and emissions production and increases energy availability. In particular, the Bond work index (w_i) is considered a critical parameter at an industrial scale, for power consumption in comminution operations accounts for up to 40% of operational costs [6–8]. Moreover, w_i should be one of the key parameters to consider in a potential process plant digitalization action, using adequate measurable parameters correlation. Despite this, the variability of w_i when performing the ball mill Bond's standard test is not always considered or understood at an industrial scale [9–13]. In the study presented by Mosher and Tague [9], they addressed the variability of Bond test results independent of sampling or procedural variation. They discussed test sensitivity and detailed test procedures to maximize the accuracy and precision of the test, concluding that the Bond tests within one laboratory showed repeatability of less than ±4% at two standard deviations. They also recommended not to report Bond work indices beyond 0.1 kWh/t, based on the precision of the test and suggested that determination of the reproducibility of w_i can be improved significantly by accurate determination of the fresh feed and product PSD. Rodríguez et al. [11] studied this extent, showing that the methodology used for F_{80} and P_{80} determination by interpolation significantly affects w_i calculation.

In the case of the research presented in [10], the results of this research, carried out on a porphyry copper ore, concluded that the Bond work index values differ with different Bond ball mills and with different grinding ball charge distributions, but variations were higher when comparing different Bond ball mills than when comparing different ball charges in the same mill. Maximum variations of 8.6% with different mills and 6.2% with different grinding ball charges were measured.

The authors could not find a precedent comprising a variability study on the Bond standard test itself; mineral processing engineers sometimes attribute the w_i variations to ore grindability changes, while the reason can yield in feed PSD variations. Recently, it has been evidenced that, for a given ore, the grindability function (variation of the Maxon index, gbp, with P_{100}) can present a regular shape while the w_i function with P_{100} can be pretty erratic [14]. Some lack of standardization in the so-called standard test can be the most probable cause of w_i variability. This work presents the result of a careful experimental design defined to elucidate the influence of several parameters obtained from the particle size distribution (PSD) in feed and product on w_i determination.

2. Materials and Methods

2.1. Materials

In order to carry out the series of tests, a 400 kg Ta-Nb-Sn ore sample from the tailings deposit of former mining activities in the Penouta mine (Orense, Spain) was received. A detailed characterization of this ore sample can be found in previous research works [15–17]. The sample was fully sieved in the following size intervals (µm): 3150/2500; 2500/2000; 2000/1600; 1600/1250; 1250/800; 800/500; 500/400; 400/200; 200/160; 160/100. With adequate blending, using the aforementioned size intervals, nine composite feed samples were prepared to fulfil the requirements posed by the multivariate design. In each case, the composite sample was homogenized and divided, checking by PSD analysis that aliquots verified the requirements in each case (Figures S1–S27 at the Supplementary Materials).

2.2. Methods

2.2.1. Bond Ball Mill Standard Test

The procedure to carry out the Bond grindability test [1,18] is described below. The test is performed in the so-called Bond's standard ball mill, a laboratory mill 12″ × 12″, running at 70 rpm (BICO, San Francisco, CA, USA) with rounded inner edges and without lifters. The grinding charge is comprised of a steel balls distribution; Table 1 shows the distribution proposed by Bond in 1961 [5] and that proposed in 1999 [19]; the latter was selected for this test.

Table 1. Evolution of the ball grinding charge distributions proposed by Bond.

Ball Charge Distribution 1961				**Ball Charge Distribution 1999**			
Ball Size		**Balls**		**Ball Size**		**Balls**	
inch	**cm**	**Number**	**Weight (g)**	**inch**	**cm**	**Number**	**Weight (g)**
1.45	3.683	43	8803	1.500	3.810	25	5690
1.17	2.972	67	7206	1.25	3.175	39	5137
1.00	2.540	10	672	1.000	2.540	60	4046
0.75	1.905	71	2011	0.875	2.223	68	3072
0.61	1.549	94	1433	0.750	1.905	93	2646
	Total	285	20,125		Total	285	20,592

The mill feed must be prepared by controlled crushing to 100% passing 6 Tyler mesh (3.35 mm). The first grinding cycle feed must be 700 cm^3, and this volume's weight is fixed as the mill charge in all subsequent cycles. Fresh feed PSD is obtained to calculate the 80% passing size (F_{80}) and undersize weight already present in the feed. The test procedure consists of performing several dry grinding cycles to simulate a continuous closed-circuit operation with a 250% circulating load. The circuit is closed by a sieve (P_{100}) selected according to the industrial grinding size target, always between 28 and 325 Tyler mesh (600–45 microns). The detailed grinding cycles procedure can be found in [5,18].

Once finished the grinding cycles, a minimum of five, the ball mill Bond's work index w_i [kWh/sht] can be calculated using Equation (2). In order to express it in metric tons, the corresponding conversion factor must be used.

$$w_i = \frac{44.5}{P_{100}^{0.23} \cdot gbp^{0.82} \cdot \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \quad (2)$$

where:

w_i is the ball mill Bond's work index [kWh/sht];

P_{100} is the mesh size used to close the grinding circuit [μm];

gbp is the grindability index [g/rev].

It has been recently proposed gbp be renamed as the Maxson index [14]. Walter Maxson led the first research in which gbp was named as the grindability index [1], and was also Fred Bond's mentor at the beginning of his successful career.

2.2.2. Multivariate Experimental Design

The standard test states tight conditions to some test parameters, while others can rest in broad validity ranges. For instance, F_{80} and P_{100} only limitations are being less than 3.35 mm and 600 microns, respectively. Moreover, the undersize content in the ore feed sample is considered by some authors as a variability source. Accordingly, with the same ore, minor differences under correct sampling procedures or even internal procedures in different laboratories could lead to different w_i values. Following the considerations above, the selected variables to perform a variability analysis on the Bond's ball mill standard test were the following:

- Feed particle size, F_{80}
- Closing circuit sieve (should coincide with maximum size in the closed-circuit product, P_{100}
- Undersize percentage in the feed for each P_{100}, % < P_{100}

It is important to notice that F_{80} and the undersize percentage in the feed (% < P_{100}) variations could occur easily due to changes in material preparation; changes in P_{100} should be justified due to changes in the ore liberation size, which is not a strange event in mine operations over time.

Table 2 shows the variables coding (D, C, F) and their values (level 1, 2 or 3) in each case. A total of 27 combinations of variables and levels defined the conditions of the 27 Bond standard tests. Enough ore feed was carefully prepared to fulfil D and F requirements (nine different feed samples prepared), and the Bond standard test was carried out at C value of P_{100} (three levels). It must be understood that, with the same ore and with no further specifications, each of the 27 possibilities fulfils the standard test requirements and the corresponding w_i should be considered with the same validity. The basis and practical use of the ANOVA (SPSS, IBM, Amonk NY, USA) test can be found in Navidi [20].

Table 2. Three levels multivariate experimental design.

Variables		Levels		
		1	**2**	**3**
F_{80} (µm)	D	2500	2000	1250
P_{100} (µm)	C	500	400	200
% < P_{100} (%)	F	0	10	20

3. Results and Discussion

Table 3 collects the results of Bond work index, w_i determination after performing the resulting 27 Bond standard tests; the Mosher and Tague repeatability estimation was considered adequate [9], lower than ±4% at two standard deviations, after checking it with preliminary tests. In Table 3 the *gbp* value obtained in each test is also included. Full details of the performed tests can be found in the spreadsheet file provided as Supplementary Materials.

Table 3. Experimental results of w_i and *gbp*.

	C1								
	D1-F1	**D1-F2**	**D1-F3**	**D2-F1**	**D2-F2**	**D2-F3**	**D3-F1**	**D3-F2**	**D3-F3**
w_i [kWh/t]	7.82	8.54	8.96	8.69	9.09	9.50	11.25	11.95	12.13
gbp [g/rev]	6.552	6.008	5.668	6.432	6.265	5.809	6.110	6.046	5.773
	C2								
	D1-F1	**D1-F2**	**D1-F3**	**D2-F1**	**D2-F2**	**D2-F3**	**D3-F1**	**D3-F2**	**D3-F3**
w_i [kWh/t]	8.07	8.39	8.45	8.49	8.84	8.80	10.16	10.79	10.69
gbp [g/rev]	5.427	5.220	4.995	5.504	5.383	5.332	5.506	5.377	5.241
	C3								
	D1-F1	**D1-F2**	**D1-F3**	**D2-F1**	**D2-F2**	**D2-F3**	**D3-F1**	**D3-F2**	**D3-F3**
w_i [kWh/t]	8.85	9.15	9.29	9.24	9.33	9.46	10.93	11.01	10.50
gbp [g/rev]	3.300	3.157	3.044	3.264	3.235	3.121	3.087	3.082	3.121

The first glance at Table 3 evidences a variability in both w_i and *gbp* values; this variability should be explained due to the sole effect of variables combination in each test. It must be highlighted again that feed preparation was performed carefully, and feed variations among synthetic feeds and a naturally taken feed could be similar to those produced in the field sampling process. In all cases, test conditions fulfilled the Bond standard test requirements (which, in passing, are very open; the only limitation is that feed top size must be under 3.35 mm). Therefore, in summary, the different nine synthetic feeds could be the result of different sampling procedures performed on the same deposit without enough representativity, provided that a tailings pond could show differences in the spatial distribution of particle sizes. Results are also depicted in the Supplementary Materials Figures S28–S30 in the case of w_i, and Figures S31–S33 in the case of *gbp*.

A formal analysis of results was carried out employing the ANOVA test [20], both on w_i and *gbp*. Table 4 garners the ANOVA test results in the case of w_i.

Table 4. Analysis of variance (ANOVA) test results on w_i.

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	p-Value
Main effects					
C	1.9777	2	0.9888	44.99	0
D	30.2763	2	15.1381	688.76	0
F	1.1734	2	0.5867	26.69	0.0003
Interactions					
C&D	2.2241	4	0.5560	25.30	0.0001
C&F	0.5885	4	0.1471	6.69	0.0114
D&F	0.1495	4	0.0374	1.70	0.2422
Residual	0.1758	8	0.0220		
Total (corrected)	36.5654	26			

Table 4 breaks down the variability of w_i into contributions due to individual variables effects and the binary interactions among them. Considering the sum of squares values and p-values in the case of individual variables and binary interactions, variable D (F_{80}) is identified as the primary source of variability among the studied ones. The second source of variability stems from C and D interaction, that is, F_{80} and P_{100} combined effect, which surprisingly has more significant influence than C alone effect. From a w_i variability point of view, F (undersize feed content) was identified as the third variable in importance. In the case of D and F interaction, the p-value is not less than 0.05, so this combination does not have a statistically significant effect on w_i, at the 95.0% confidence level.

Similarly, another ANOVA test was carried out on Maxson grindability index values, and the results are provided in Table 5. In this case, variable C (P_{100}) is identified as the most relevant source of variability; despite D, F and C and F having a p-value more than 0.05 (in consequence, they have a statistically significant effect on *gbp*, at the 95.0% confidence level), the difference in the sum of squares values lets us affirm that C can be considered as almost the only source of variability in this case.

Table 5. ANOVA test results on gbp.

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	p-Value
Main effects					
C	41.3668	2	20.6834	3653.30	0
D	0.0724	2	0.0362	6.39	0.0220
F	0.5276	2	0.2638	46.59	0
Interactions					
C&D	0.0656	4	0.0164	2.90	0.0937
C&F	0.1921	4	0.0480	8.48	0.0056
D&F	0.0941	4	0.0235	4.15	0.0413
Residual	0.0453	8	0.0057		
Total (corrected)	42.3638	26			

Results suggest that, under the conditions considered in the multivariate design described, the Maxson grindability index, *gbp*, represents more robustly the intrinsic grindability properties of the ore, being its source of variation the Bond standard test condition, P_{100}. This result reinforces the concept, first proposed by Maxson et al. [1] and subsequently adopted and disseminated by Bond [3–5], that *gbp* was the best index in characterizing the ore comminution amenability. This fact also justifies the proposal of renaming *gbp* as the Maxson grindability index.

On the other side, Bond work index variability has a more profound influence from feed PSD conditions (mainly F_{80} value), even to a far greater extent than P_{100} values. As the standard test established relatively frugal recommendations about feed PSD conditions (maximum feed size, F_{100}, less than 3.35 mm), it can be qualified as a worrying source of w_i variation, and the following additional recommendations should be taken into account:

- To establish desirable Bond test conditions, always consider performing feed preparation according to the planned/expected industrial conditions (for instance, by product size estimation on the previous comminution stage—fine crushing or coarse grinding);

- When reporting w_i results, P_{100} and F_{80} values in the test should always be indicated, especially F_{80}, which seems more responsible for w_i variability than P_{100} itself.

4. Conclusions

The following conclusions were derived from this research work and considering the tested ore:

- It was evidenced that the considered parameters induced variability in both Bond work index, w_i, and Maxson grindability index, *gbp*.
- The ANOVA test results suggested that, in the case of w_i, the primary source of variability is F_{80}, followed by the binary interaction F_{80} and undersize ($<P_{100}$) feed content.
- In the case of *gbp*, the ANOVA test showed that almost the only source of variability is P_{100}, with almost no influence of feed PSD.
- The following additional recommendations should be taken into account:
- To establish desirable Bond test conditions, always consider performing feed preparation according to the planned/expected industrial conditions
- When reporting w_i results, P_{100} and F_{80} values should always be indicated in the test.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/met11101606/s1, Figure S1: Feed PSD, test C1-D1-F1, Figure S2: Feed PSD, test C1-D1-F2, Figure S3: Feed PSD, test C1-D1-F3, Figure S4: Feed PSD, test C1-D2-F1, Figure S5: Feed PSD, test C1-D2-F2, Figure S6: Feed PSD, test C1-D2-F3, Figure S7: Feed PSD, test C1-D3-F1, Figure S8: Feed PSD, test C1-D3-F2, Figure S9: Feed PSD, test C1-D3-F3, Figure S10: Feed PSD, test C2-D1-F1, Figure S11: Feed PSD, test C2-D1-F2, Figure S12: Feed PSD, test C2-D1-F3, Figure S13: Feed PSD, test C2-D2-F1, Figure S14: Feed PSD, test C2-D2-F2, Figure S15: Feed PSD, test C2-D2-F3, Figure S16: Feed PSD, test C2-D3-F1, Figure S17: Feed PSD, test C2-D3-F2, Figure S18: Feed PSD, test C2-D3-F3, Figure S19: Feed PSD, test C3-D1-F1, Figure S20: Feed PSD, test C3-D1-F2, Figure S21: Feed PSD, test C3-D1-F3, Figure S22: Feed PSD, test C3-D2-F1, Figure S23: Feed PSD, test C3-D2-F2, Figure S24: Feed PSD, test C3-D2-F3, Figure S25: Feed PSD, test C3-D3-F1, Figure S26: Feed PSD, test C3-D3-F2, Figure S27: Feed PSD, test C3-D3-F3, Figure S28: Variability of w_i [kWh/t] (P_{100} = 500 µm), Figure S29: Variability of w_i [kWh/t] (P_{100} = 400 µm), Figure S30: Variability of w_i [kWh/t] (P_{100} = 200 µm), Figure S31: Variability of *gbp* [g/rev] (P_{100} = 500 µm), Figure S32: Variability of *gbp* [g/rev] (P_{100} = 400 µm), Figure S33: Variability of *gbp* [g/rev] (P_{100} = 200 µm).

Author Contributions: Conceptualization, J.M.M.-A.; methodology, G.G.G. and J.M.M.-A.; validation, G.G.G. and B.F.P.; formal analysis, G.G.G. and J.M.M.-A.; investigation, G.G.G.; resources, J.M.M.-A.; data curation, A.L.C.-V.; writing—original draft preparation, G.G.G. and J.M.M.-A.; writing—review and editing, B.F.P. and J.M.M.-A.; visualization, G.G.G. and J.M.M.-A.; supervision, A.L.C.-V. and J.M.M.-A.; funding acquisition, G.G.G. and J.M.M.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This work is part of the OPTIMORE project funded by the European Union Horizon 2020 Research and Innovation Programme under grant agreement No. 642201.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Maxson, W.L.; Cadena, F.; Bond, F.C. Grindability of various ores. *Trans. AIME* **1933**, *112*, 130–145.
2. Bond, F.C.; Maxson, W.L. Standard grindability tests and calculations. *Trans. AIME Min. Eng.* **1943**, *153*, 362–372.
3. Bond, F.C. Third theory of comminution. *Trans. AIME Min. Eng.* **1952**, *193*, 484–494.
4. Bond, F.C. Crushing and grinding Calculations, Part 1. *Br. Chem. Eng.* **1961**, *6*, 378–385.
5. Bond, F.C. Crushing and Grinding Calculations, Part 2. *Br. Chem. Eng.* **1961**, *6*, 543–548.
6. Rowland, C.A. Using the Bond work index to measure operating comminution efficiency. *Miner. Metall. Process.* **1998**, *15*, 32–36. [CrossRef]

7. Aguado, J.M.M.; Velázquez, A.L.C.; Tijonov, O.N.; Díaz, M.A.R. Implementation of energy sustainability concepts during the comminution process of the Punta Gorda nickel ore plant (Cuba). *Powder Technol.* **2006**, *170*, 153–157. [CrossRef]
8. Coello Velázquez, A.L.; Menéndez-Aguado, J.M.; Brown, R.L. Grindability of lateritic nickel ores in Cuba. *Powder Technol.* **2008**, *182*, 113–115. [CrossRef]
9. Mosher, J.B.; Tague, C.B. Conduct and precision of Bond grindability testing. *Miner. Eng.* **2001**, *14*, 1187–1197. [CrossRef]
10. Kaya, E.; Fletcher, P.C.; Thompson, P. Reproducibility of Bond grindability work index. *Miner. Metall. Process.* **2003**, *20*, 140–142. [CrossRef]
11. Rodríguez, B.Á.; García, G.G.; Coello-Velázquez, A.L.; Menéndez-Aguado, J.M. Product size distribution function influence on interpolation calculations in the Bond ball mill grindability test. *Int. J. Miner. Process.* **2016**, *157*, 16–20. [CrossRef]
12. Makhija, D.; Mukherjee, A.K. Effect of undersize misplacement on product size distribution of Bond's ball mill test. *Miner. Process. Extr. Metall.* **2016**, *125*, 117–124. [CrossRef]
13. Magdalinovic, N.; Trumic, M.; Trumic, G.; Magdalinovic, S.; Trumic, M. Determination of the Bond work index on samples of non-standard size. *Int. J. Miner. Process.* **2012**, *114–117*, 48–50. [CrossRef]
14. García, G.G.; Oliva, J.; Guasch, E.; Anticoi, H.; Coello-Velázquez, A.L.; Menéndez-Aguado, J.M. Variability study of bond work index and grindability index on various critical metal ores. *Metals* **2021**, *11*, 970. [CrossRef]
15. Alfonso, P.; Tomasa, O.; Garcia-Valles, M.; Tarragó, M.; Martínez, S.; Esteves, H. Potential of tungsten tailings as glass raw materials. *Mater. Lett.* **2018**, *228*, 456–458. [CrossRef]
16. Alfonso, P.; Hamid, S.A.; Anticoi, H.; Garcia-Valles, M.; Oliva, J.; Tomasa, O.; López-Moro, F.J.; Bascompta, M.; Llorens, T.; Castro, D.; et al. Liberation characteristics of Ta-Sn ores from Penouta, NW Spain. *Minerals* **2020**, *10*, 509. [CrossRef]
17. Nava, J.V.; Coello-Velázquez, A.L.; Menéndez-Aguado, J.M. Grinding kinetics study of tungsten ore. *Metals* **2021**, *11*, 71. [CrossRef]
18. GMG-Global Mining Guidelines Group. Determining the Bond Efficiency of Industrial Grinding Circuits. 2016. Available online: https://gmggroup.org/wp-content/uploads/2016/02/Guidelines_Bond-Efficiency-REV-2018.pdf (accessed on 29 September 2021).
19. BICO (Braun International Co.). *Standard Bond Ball Mill Operating Handbook*; BICO: San Francisco, CA, USA, 1999.
20. Navidi, W. *Statistics for Engineers and Scientists*, 5th ed.; McGraw-Hill Education: New York, NY, USA, 2019.