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ORE HARDNESS PROPERTIES EVALUATION BASED ON INDUSTRIAL COMMINUTION CIRCUITS SURVEYS

The paper addresses determination of ore hardness and grindability parameters using the data obtained from the industrial comminutions circuits survey campaigns. The calculations use the earlier obtained relations between the high-energy impact fracture parameters A and b from JK DWT and SMC tests and the energy efficiency indices used in the Morrell method for the conventional grinding, coarse grinding and high pressure grinding roll milling. Using the simulation modeling of comminution circuits for two types of sulfide copper–nickel ore and one type of apatite–nepheline ore, it is shown that the relative error of the theoretical determination of the JK DWT and SMC testing data is never higher than 16.1%. The calculation method is recommended for application in design and optimization studies of process plants for various genesis minerals, including iron ore.

Keywords: *energy indices, ore strength properties, drop weight test, JK DWT, SMC test, comminution, crushing, grinding, Morrell*
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Introduction

The selection and sizing of the main technological equipment units for minerals comminution circuits is usually based on the required capacity, on the physical and mechanical properties of minerals, and on the required size distribution of the initial and final products of grinding [1–3]. The physical and mechanical properties of the ore can be described using different methods [4–6]. In Russia, the ore grinding calculations use the specific mill volumetric capacity by design size fraction (usually –0.074 mm) [7, 8]. The present study includes the wide-spread foreign approaches which characterize the hardness of raw materials using the energy indexes from the Bond Test [9, 10], JK Drop Weight Test (JKMRC) [11], SAGDesign (J. Starkey) [12–14] and SMC test (S. Morrell) [15, 16]. In 2016 the Global Mining Standards and Guidelines Group accepted the methods developed by F. Bond [17] and S. Morrell [18] for determining energy efficiency of ore comminution circuits as the industry standard. It is difficult to figure out the total number of tests accomplished using Bond's procedures as such tests have been carried out abroad necessarily in designing each pretreatment machine for estimating physical and mechanical properties of ore since the mid- 1900s. In 2020 more than 50 000 SMC tests have been accomplished, which is an evidence of the wider spreading of this method as compared with JK DWT and SAGDesign. In Russia these procedures have been applied since the late 1990s [19].

There is a list of standard laboratory tests to determine ore hardness properties:

- the crushing and rod/ball milling—Bond tests;
- the standard semi autogenous grinding (SAG mill with crusher for re-crushing critical size material)—JK DWT, SAGDesign and SMC tests.

Such laboratory tests consume much labor and need special and expensive equipment. Despite the labor intensity, these tests yet remain irreplaceable in modeling, design and upgrade of concentration factories for ferrous metal ore [20, 21], nonferrous metals [22–27], noble metals [28, 29] and nonmetallic minerals [30, 31].

The energy indices evaluated by means of the above-listed tests are the main characteristics of physical and mechanical properties of ore in software programs designed for the pretreatment process modeling, such as JKSimMet (JKMRC), USIM PAC (CASPEO) and Rocky DEM (ESSS Rocky DEM). Today JKSimMet (JKMRC) is the widest spread in the world as compared with the analogous software products. By 2021 JKSimMet (JKMRC) and USIM PAC (CASPEO) had sold 600 and 300 licenses, respectively. Simulation modeling software JKSimMet characterizes the physical and mechanical properties of ore using the parameters A, b and t_a obtained from the drop weight testing by JK DWT and SMC [32–34]. The numerical modeling of pretreatment circuits in software Rocky DEM (ESSS Rocky DEM) uses the impact model *Ab-T10* proposed by Vogel and Peukert [35], modified by Shi and Kojovic [36] and expanded by Tavares et al [37]. In this model, the test material particles breakage behavior is characterized by the parameters A and b.

In this respect, this study aims to analyze feasibility of determining physical and mechanical properties of minerals directly from the data of sampling from pretreatment circuits, without labor-intensive drop weight testing by JK DWT and SMC.

Materials and methods

The test objects were selected to be sulfide copper–nickel ore and apatite–nepheline ore. The ore samples were subjected to JK DWT, SMC and Bond Tests. The test data were input into models of pretreatment circuits in software JKSimMet (JKMRC). The modeling results were used in checking the calculated physical and mechanical properties and verifying their agreement with the JK DWT and SMC testing data.

Earlier the authors [38] performed regression analysis of data bases on strength characteristics of different minerals and developed relations to determine the Morrell parameters from JK DWT testing:

$$DWi = 92.56SG(A \cdot b)^{-0.977}, \text{ kW·h/m}^3; \quad (1)$$

$$SCSE = 52.74(A \cdot b)^{-0.441}, \text{ kW·h/t}; \quad (2)$$

$$M_{ia} = 3\ 90(A \cdot b)^{-0.813}, \text{ kW·h/t}; \quad (3)$$

$$M_{ic} = 303.5(A \cdot b)^{-1}, \text{ kW·h/t}; \quad (4)$$

$$M_{ih} = 577(A \cdot b)^{-1}, \text{ kW·h/t}; \quad (5)$$

$$M_{ib} = 1.86BWi - 8.7, \text{ kW·h/t}, \quad (6)$$

where DWi is the drop weight index to characterize the impact and crushing strength of rocks, kW·h/m^3; SG is the volumetric density of material, t/m^3; A and b are the parameters characterizing high-energy impact fracture in drop weight test (JK DWT); $SCSE$ is the specific energy consumption in standard SAG mill circuit with pebble crushing, kW·h/t; M_{ia} is the Morrell index for coarse ore treatment in tumbling mills to the size $P_{80} > 750$ μm, kW·h/t; M_{ic} is the Morrell index for ore treatment in cone and jaw crushers, kW·h/t; M_{ih} is the Morrell index for ore treatment in HPGR circuits, kW·h/t; M_{ib} is the Morrell index for fine ore treatment in tumbling mills to the size $P_{80} < 750$ μm, kW·h/t; *BWi* is the Bond ball mill work index, kW·h/t.

The authors succeeded in finding a correlation $t_a = f(DWi)$, which was unpublished earlier:

$$t_a = 2.6132/DWi, \quad (7)$$

where t_a is the characteristic of ore strength in low-energy autogenous and semi-autogenous milling.

The Morrell procedure uses the equation below to find the energy intensity of pretreatment circuits:

$$W_o = S_o K_o M_{io} 4(P_{80}^{f(P_{80})} - F_{80}^{f(F_{80})}), \quad (8)$$

where W_o is the energy intensity of an *o*-th comminution circuit, kW·h/t; S_o is the specification coefficient for the coarse ore strength in the *o*-th comminution circuit; K_o is the specification coefficient for the operating conditions in the *o*-th pretreatment circuit; M_{io} is the Morrell index for the *o*-th pretreatment circuit, kW·h/t.

$$f(P_{80}) = -(0.295 + P_{80}/10^6); \quad (9)$$

$$f(F_{80}) = -(0.295 + F_{80}/10^6). \quad (10)$$

Hereinafter, the subscripts indicate belonging of a parameter to a certain comminution circuit, namely:

- the subscript *a* means ore work in tumbling mills to the size $P_{80} > 750$ μm;
- the subscript *b* means ore work in tumbling mills to the size $P_{80} < 750$ μm;
- the subscript *c* means ore work in cone and jaw crushers;
- the subscript *h* means ore work in HPGR mills.

Table 1 describes the coefficients in Eq. (8) for different circuits' types.

For the convenience, formula (8) can be rewritten:

$$W_o = S_o K_o M_{io} 4 f_0, \quad (11)$$

where f_o is the coarseness change function given by:

$$f_0 = P_{80}^{-(0.295+P_{80}/10^6)} - F_{80}^{-(0.295+F_{80}/10^6)}. \quad (12)$$

Hence it is possible to derive some other relations.

From Eq. (11):

$$M_{io} = W_o/(4 S_o K_o f_0). \quad (13)$$

From Eq. (3):

$$Ab = 1538/(M_{ia}^{1.23}). \quad (14)$$

From Eq. (4):

$$Ab = 303.5/M_{ic}. \quad (15)$$

From Eq. (5):

$$Ab = 577/M_{ih}. \quad (16)$$

Placement of (13) into (14), (15) and (16) enables expressing the parameter *Ab* as the function of the pretreatment circuit energy intensity and the material coarseness change. For instance, in coarse grinding toward the material size P_{80} not less than 750 μm, it follows from formulas (12) and (13) that:

$$Ab = 1538/(W_{ia}/(4 S_a K_a f_a))^{1.23},$$

or

$$Ab = 8462.3(S_a K_a f_a/W_a)^{1.23}. \quad (17)$$

In standard type grinding, it follows from formulas (12) and (14) that:

$$Ab = 1214 S_c K_c f_c/W_c. \quad (18)$$

Table 1. Coefficients in ore pretreatment energy intensity equation

Circuit	S_o	K_c
Conventional crushing	when $55(F_{80}P_{80})^{-0.2} > 1$ $S_c = 1$ when $55(F_{80}P_{80})^{-0.2} < 1$ $S_c = 55(F_{80}P_{80})^{-0.2}$	$K_c = 1.00$—closed cycle crushing with screening; $K_c = 1.19$—open cycle crushing
HPGR	when $55(F_{80}P_{80})^{-0.2} > 1$ $S_h = 1$ when $55(F_{80}P_{80})^{-0.2} < 1$ $S_h = 55(F_{80}P_{80})^{-0.2}$	$K_h = 1.00$—closed cycle HPGR milling with screening; $K_h = 1.19$—open cycle HPGR milling
Coarse grinding (to $P_{80} \geq 750$ μm)	$S_a = 1$	$K_a = 1.00$—AG/SAG milling with re-crushing of critical size material; $K_a = 0.95$—AG/SAG milling without re-crushing of critical size material
Fine grinding (from $F_{80} = 750$ μm to $P_{80} < 750$ μm)	$S_b = 1$	$K_b = 1.00$

Table 2. JK DWT and SMC test data on sulfide copper–nickel and apatite–nepheline ore

Sample	DWi, kW·h/m³	M_i, kW·h/t			A	b	Ab	t_a	SG, t/m³	SCSE, kW·h/t
		M_{ia}	M_{ih}	M_{ic}						
SCN-1	10.30	25.10	20.20	10.50	100.00	0.29	29.00	0.26	2.94	12.28
SCN-2	8.20	20.60	15.80	8.20	69.80	0.52	36.30	0.31	2.99	11.06
AN-1	4.30	12.60	8.50	4.40	70.10	1.03	73.00	0.32	2.90	7.99

Table 3. Parameter *Ab* for sample SCN-1

Parameter	SAG mill 10500×4600 (No. 1)	SAG mill 10500×4600 (No. 2)	Total
Drive power (total), kW	7294.0	7294.0	14588.0
Drive power (useful*), kW	6199.9	6199.9	12399.8
Capacity, t/h	570.8	570.8	1141.6
Yield, %	50.0	50.0	100.0
Feed particle size F_{80}, μm	150000.0	150000.0	150000.0
Product particle size P_{80}, μm	1639.0	1639.0	1639.0
$f(F_{80})$ from Eq. (9)	0.0050		
$f(P_{80})$ from Eq. (10)	0.1113		
f_{ia} from Eq. (12)	0.1063		
W_a, kW·h/t	10.86		
S_a from Table 1	1.00		
K_a from Table 1	1.00		
M_{ia} from Eq. (13), kW·h/t	25.54		
M_{ia} from Table 2, kW·h/t	25.10		
Difference M_{ia}, %	–1.80		
Ab from Eq. (16)	28.60		
Ab from Table 2	29.00		
Difference *Ab*, %	1.50		
W_a, kW·h/t	10.86		
W_a (predicted by the Morell method), kW·h/t	10.67		
Difference W_a, %	1.70		
*The useful power calculation uses the coefficient equal to 0.85			

Table 4. Parameter *Ab* for sample SCN-2

Parameter	SAG mill 9500×3800 (No. 1)	SAG mill 9500×3800 (No. 2)	Total
Drive power (total), kW	5204.1	5204.1	10408.2
Drive power (useful*), kW	4423.5	4423.5	8847.0
Capacity, t/h	381.0	38100.0	762.0
Yield, %	50.0	50.0	100.0
Feed particle size F_{80}, μm	151985.0	151985.0	151985.0
Product particle size P_{80}, μm	574.0	574.0	574.0
f (F_{80}) from Eq. (9)	0.0048		
f (P_{80}) from Eq. (10)	0.1529		
f_{ia} from Eq. (12)	0.1481		
W_a, kW·h/t	11.6100		
S_a from Table 1	1.0000		
K_a from Table 1	1.0000		
M_{ia} from Eq. (13), kW·h/t	19.6000		
M_{ia} from Table 2, kW·h/t	20.6000		
Difference M_{ia}, %	4.9000		
Ab from Eq. (16)	39.6000		
Ab from Table 2	36.3000		
Difference *A·b*, %	–9.1000		
W_a, kW·h/t	11.6100		
W_a (predicted by the Morell method), kW·h/t	12.2000		
Difference W_a, %	–5.1000		
*The useful power calculation uses the coefficient equal to 0.85			

Table 5. Parameter *Ab* for sample AN-1

Parameter	CPS circuit
Useful drive power, kW	1685.7
Capacity, t/h	1650
Feed particle size F_{80}, μm	667478
Product particle size P_{80}, μm	14049
f (F_{80}) from Eq. (9)	0.0000
f (P_{80}) from Eq. (10)	0.0523
f_c from Eq. (12)	0.0523
W_c, kW·h/t	1.02
S_c from Table 1	1.00
K_c from Table 1	1.00
M_{ic} from Eq. (13), kW·h/t	4.89
M_{ic} from Table 2, kW·h/t	4.4
Difference M_{ic}, %	–11.1
Ab from Eq. (17)	62.1
Ab from SMC test	74.03
Difference *Ab*, %	16.1
W_c, kW·h/t	1.02
W_c (predicted by the Morell method), kW·h/t	0.92
Difference W_c, %	10.0

In HPGR grinding, it follows from formulas (12) and (15) that:

$$Ab = 2308 S_h K_h f_h / W_{ih}. \quad (19)$$

Thus, the actual practices with crushing and grinding (coarse grinding) machines can use: expressions (16)–(18) to find the parameter *Ab* of treated ore; expression (19) to find the energy intensity of pretreatment in crushers and grinders. Moreover, these formulas are applicable in design and modification of production processes.

Discussion

Verification of the developed formulas uses the data from industrial survey campaigns of different comminution circuits JK DWT and SMC testing results obtained for: two types of sulfide copper–nickel ore (SCN-1 and SCN-2) and one type of apatite–nepheline ore (AN-1). The simulation models showed high agreement of the theoretical estimates and the results of ore sampling from actual pretreatment circuits. **Table 2** compiles the JK DWT and SMC testing data on the three test ore types.

Table 3 gives the calculated parameter *Ab* from formula (16) for sample SCN-1 versus actual test results.

Table 4 presents the parameter *Ab* calculated from formula (16) for sample SCN-2 versus actual test results.

Table 5 compiles the calculated values of *Ab* from formula (17) for sample AN-1 versus actual test results.

It is possible to calculate the parameter *Ab* using developed formulas for grinding circuits of any layout.

The calculations from the proposed formulas show a good agreement and prove their applicability in finding parameters of JK DWT and SMC tests of ore pretreatment in:

- standard cycle SAG milling;
- three-stage grinding.

The offered method of calculation is usable in design and optimization of concentration plants for processing various genesis minerals.

Modeling of ball milling circuits can include test intensification by the Bond procedures, proposed by the present authors earlier [39].

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Conclusions

Solution of the inverse problem on the energy intensity of ore comminution machines allowed developing the formulas to determine the parameter Ab and the Morrell ore work indices using survey data of industrial circuits, in particular, cone and jaw crushing, HPGR milling, tumbling mill grinding (autogenous milling, semi autogenous milling, rod and coarse ball milling). Verification of the formulas shows that the integrated high-energy impact fracture parameter Ab, which is usually determined in the drop weight tests by JK DWT and SMC methods, can be calculated using the actual production data from circuits. As a case-study of two types of sulfide copper–nickel ore in SAG milling, the parameter *Ab* and the Morrell energy index are determined with a relative error of 1.5 and 9.1%, and M_{ia}—with a relative error of 1.8 and 4.9%, respectively. For apatite–nepheline ore in three-stage grinding, the parameter *Ab* and the Morrell energy index are calculated with a relative error of 16.1%, and M_{ic}—11.1%.

The parameter Ab is usable in simulation modeling of ore comminution machines in JKSimMet and Rocky DEM software, as well as in calculation of the Morrell indices without conducting expensive laboratory JK DWT and SMC tests.

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