HOME

A Method of Calculating Autogenous/Semi-Autogenous Grinding Mill Specific Energies Using a Combination of Bond Work Indices and Julius Kruttschnitt Parameters, then Applying Efficiency Factors

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ABSTRACT

Since the days of mandatory high cost pilot plant testing in 6 ft × 2 ft SAG mills autogenous griding/semi-autogenous grinding (AG/SAG), mill specific energy is now calculated by various empirical formulae and pilot testing carried out in small laboratory mills. Barratt (1989) described a method using Bond Indices than adding a single factor of 1.25 to arrive at the AG/SAG specific energy. In 1991 the Canadians developed the SAGPower Index (SPI), test using 2 kg of material in a 300 mm diameter mill. This test has been further developed by Starkey, Hindstrom and Orser (2006). This test now includes a Bond Ball mill work index test.

The Macpherson test is still being offered by some testing facilities. This dry test requires at least 180 kg of material.

Morrell (2004) formulated an AG/SAG specific energy generator based on a drop weight index Value (DWi). This DWi value is related to the Ab parameter and the material specific gravity. Morrell reconfigured the Bond's Third Theory formula to cause extra power requirements to be inputed. This technique incorporates the material specific gravity (SG). The AG/SAG specific energy values produced using this method are susceptible to higher values of crushing and rod mill work indices.

This paper offered describes a more simple method to generate AG/SAG specific energies. This programme incorporates Bond work indices, the JKMRC parameter Ab measuring impact breakage and the parameter ta measuring the abrasion rate, then employs a series of efficiency values nominated for each transition size (AG/SAG T80). These efficiency values have been compiled over the years from actual operating plants and documented reports.

INTRODUCTION

Rotary mills have been found to be inefficient when grinding large hard material. Single stage balls mills, when processing hard to grind, large sized material incur an oversize inefficiency problem over and above the Bond oversize feed factor (EF4). Rod mills suffer from this inefficiency phenomenon and AG/SAG mills mimic the same shortcoming.

It follows that in order to obtain the specific energy (SE) to achieve a certain transfer size, based on the 80 per cent passing value, an inefficiency factor must be applied to the SE of single stage ball mills, rod mills or AG/SAG mills when calculating power according to the Bond Third Theory method.

Rod mill and AG/SAG mill products are similar and tend to be not as steep as a 0.5 slope when plotted on log-log paper. This is because the particle size distribution (PSD), these mills produce have a coarse fraction but also a fine fraction which is not credited for in an 80 per cent passing assessment. A slope less than 0.5 depicts finer material and a slope greater than 0.5 depicts coarser material where a slope of 0.5 equals a rise of one on the 'y' scale and two on the 'x' scale.

If the AG/SAG product size is assessed at the 80 per cent passing point as plotted on a log-log graph, then AG/SAG mills require more energy compared to the SE calculated using Bond rod mill work index (RMWI), and Bond ball mill work index (BMWI). However, the author has developed a relationship between the Bond third theory SE values and the AG/SAG SE values to enable the additional power required for AG/SAG milling to be determined.

AG/SAG inefficiency varies according to the transfer size (T80), whereby the finer sizes have less inefficiency than the coarser sizes. This means a closed circuit single stage AG/SAG mill can operate at a reasonable efficiency if the final product is in the 75 µm range. Burgess (1991) stated that the AG/SAG inefficiency factors to be applied to Macpherson test results were 1.10/1.25 for closed circuit grinding and 1.40 for

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an open circuit operation. This paper suggests the factors vary from 1.17 to over 2.5, depending on the transfer size.

Morrison *et al* (2011) stated that the Ab value generated from the drop weight tester (DWT) is equal to only 40 per cent of the energy required by a SAG mill. Put another way, the SAG mill energy required according to this statement, is 2.5 times more than the Ab value to produce the same degree of particle breakage.

There is a specific gravity factor that affects AG/SAG power draw. The lighter material, in the 2.5 specific gravity (SG) range, will require more energy to grind to the same transfer size than an ore with a 3.5 SG. This fact is not evident in the JKSimMet Simulation software where only the Ab and ta parameters are inputted for the specific power calculation. The SG value is included, but only used for charge weight and volumetric flow calculations.

Morrell (2004), SE calculation is sensitive to SG values. One single Ab value can equal many different drop weight index (DWi) values depending on the SG of the ore.

In regard to the author's method the ranges of T80 sizes are discussed relating to the various modes of comminution. This range covers crushing, DWi, Ab, rod milling and ball milling where different work index values are applied to each range to arrive at the Bond SE value. After applying the AG/SAG factor to the Bond SE value corrections are made for the SG, Ab values and low aspect (LA) mill configuration if applicable.

The final DB Consulting (DBC) AG/SAG SE calculation is based on an AG/SAG circuit without a pebble crusher.

Comparisons are made between the SMC and the author's method of AG/SAG SE evaluations using examples. Two published graphs, relating to Ab and DWi values, are discussed highlighting the nature of their contents.

ROD MILLS

Rod mills are limited in size to 2000 kW because the longest commercial grinding rod available is 6 m long. For this reason rod mills are rarely selected in the present day environment of large AG/SAG mills and large ball mills. However, it is necessary to discuss their operation because a Rod mill product has a similar slope to AG/SAG mills. This product slope averages less than 0.5 when plotted on log/log paper and therefore contains an extra amount of fine material compared to a PSD, having a 0.5 slope. This fine material, when received by the following ball mill, gives a credit to the ball mill SE. When assessing the operating work indices using the plotted 80 per cent passing values the rod mill averages an inefficiency value in the region of 1.25 because the design 80 per cent passing value is not achieved. The ball mill usually assesses at an efficiency of 0.85 or better because the cyclone oversize P80 is achieved seemingly from an over coarse rod mill product. This then makes the efficiency of the total circuit close to or better than 100 per cent efficient.

An unpublished survey by Rowland (1976) regarding the Mt Isa No 4 concentrator in 1976 showed the 12.5 ft rod mills were operating at an average inefficiency of 1.25 and the 16.5 ft ball mills with an efficiency of 0.88.

A study carried out by the author in 2004 on the Worsley Alumina Rod/Ball Circuit Line No 1, showed efficiencies of 1.27 for the rod mill and 0.67 for the ball mill. The particle size distributions reported are shown in Figure 1. It follows that the No 1 rod mill/ball mill circuit was operating very efficiently when comparing the combined operating work indices for both mills with the rod mill and ball mill laboratory work indices.

Note, in Figure. 1, that the rod mill product slope is less than 0.5 due to an extra amount of fines present being finer than 650 μm. These fines proceed to the ball mill improving the ball mill efficiency.

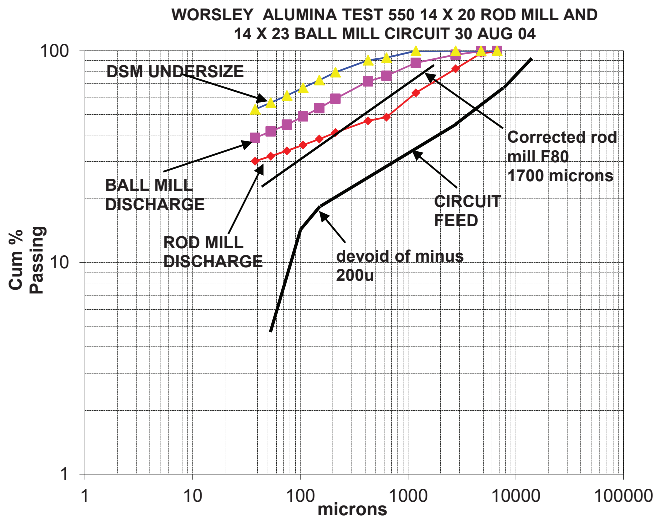

FIG 1 - Worsley circuit power size distribution.

Also, the plotted rod mill P80 value, as shown in Figure 1, is 2900 μm. If the rod mill fines are taken into account the rod mill product can be theoretically corrected to show a P80 of 1700 μm, the plotted 80 per cent passing size divided by 1.7.

It should be remembered, Rowland and Kjos (1978), stated that if a rod mill is operating alone, an inefficiency factor of 1.2 should be added provided the mill feed is screen undersize. If the rod mill feed is produced from an open circuit crusher the factor to be applied increases to 1.4.

SINGLE STAGE BALL MILLS

Single stage balls add to the argument that rotary mills are not efficient when processing large hard material. If a single stage ball receives material of 80 per cent passing 6 mm and larger, then the Bond oversize inefficiency factor EF4, will apply even if the material has rod and ball mill laboratory work indices as low as 10 kWh/t and a reduction ratio as high as 30.

Actual cases are, the initial nine 18 ft ID × 21 ft EGL overflow ball mills installed at Bougainville in 1969. An unpublished survey by Rowland (1975) and inefficiency values calculated by Steane and Hinkfuss (1978), both calculated inefficiency values of 1.18 to 1.25. Rowland (1975), theorised the problem was low retention time averaging 0.85 minutes and Steane and Hinkfuss (1978), claimed the 18 ft diameter mill size was less efficient than smaller mills. However, the author argues the hard coarse ore was the culprit. It was surprising that the ball mill work index was averaging only 11.6 kWh/t, which is not hard. A rod mill work index figure was not found but was thought to be in the 16 kWh/t to 18 kWh/t range.

The Xstrata Zinc 22 ft ID × 40 ft EGL overflow ball mill was installed at Mt Isa in 2009. This mill was put into single stage service due to the installation of the original circuit, including a 32 ft SAG mill, being put on hold. This mill has been operating inefficiently due to the hard coarse feed. The rod mill work index has not been defined as yet. The ball mill work index is confirmed at 16 kWh/t. The operating work index, though, is in the range of 21 kWh/t to 25 kWh/t showing high inefficiency.

This raises the point that, in some cases, the Bond EF4 oversize factor calculation is not sufficient to compensate for the milling inefficiencies that arise. This can result in the mill being undersized. To counter this problem it is recommended that the rod mill work index is used for the bond Fo, the optimum feed size calculation, and the highest work index, whether rod or ball, used for the EF4, the oversize feed inefficiency factor calculation. However, in any case the ball mill specific energy should not be more than ten per cent higher than the standard method of calculation.

AUTOGENOUS/SEMI-AUTOGENOUS EFFICIENCY FACTORS

We know how to calculate the power an AG/SAG mill will draw at the pinion based on the charge levels, mill speed and material weights using comparative methods, SMC's method or empirical formulae. This task has been solved. The problem is how to calculate the process SE in kWh/t at the pinion to do the work, applying only laboratory parameters.

Several practitioners use empirical methods to calculate AG/SAG mill SE. OMC, Lycopodium, Fluor, and Ausenco are some Australian companies using such methods. It is thought that none of these companies have published facts and figures relating to their various energy programs, although OMC does compare the AG/SAG SE results with a F_{SAG} factor. The F_{SAG} factor is the difference between the SE for a conventional crushing, rod/ ball circuit compared with the SE for a AG/SAG circuit. Julius Kruttschnitt Mineral Research Centre (JKMRC), JKSimMet simulation software does not explain how the Ab and ta parameters are transformed into AG/SAG SEs.

Morrell (2004), published the only program to date, that can be used to calculate AG/SAG specific power from laboratory parameters.

Barrett (1989) described a method that can be used as a guide to calculate AG/SAG SEs but only one inefficiency factor is used. This paper details a mathematical relationship between the Bond third theory SE and the AG/SAG SE values.

The DBC method is based on the AG/SAG mill transfer size (T80), being the actual 80 per cent passing size as plotted on a log-log graph and not the corrected 80 per cent passing, when taking into account the fines in the T80 PSD as depicted in Figure 1.

This method can also be used even if an Ab or a DWi value is not readily available by employing just the RMWI and the BMWI. The crushing work index (CRWI), value is always helpful if available. The accuracy of this result will not be as reliable as having the full range of parameters available to be inputted into the calculation.

Sherman (2011) described an interesting relationship between rod mill and AG/SAG mill breakage rates. This theory was closely linked to the current author's method, whereby the RMWI is a key parameter.

The DBC method of generating AG/SAG SEs is by calculating the SE according to Bond's Third Theory equation (Bond, 1961), then adding a factor to increase the power to equal high aspect (HA) AG/SAG mill energy requirements. This calculation is based on a SG of 2.78 t/m^3 and an Ab value of 40.

In order to calculate a SE value by the DBC method, the Bond calculation is divided up into comminution ranges. These consist of crushing to 25 mm, the Ab drop weight value converted to a RMWI to 3 mm, rod milling from 3 mm to 1 mm then ball milling the remainder to the T80 value where 75 µm is considered to be the finest. Assessment is made of the ta value, if available, which is taken as an extension of the ball milling area.

Depending on the transfer size, the resulting Bond SE in kWh/t at the pinion is multiplied by the appropriate AG/SAG factor (refer to Figure 2). The resulting power is adjusted depending on the SG and Ab values of the material being assessed.

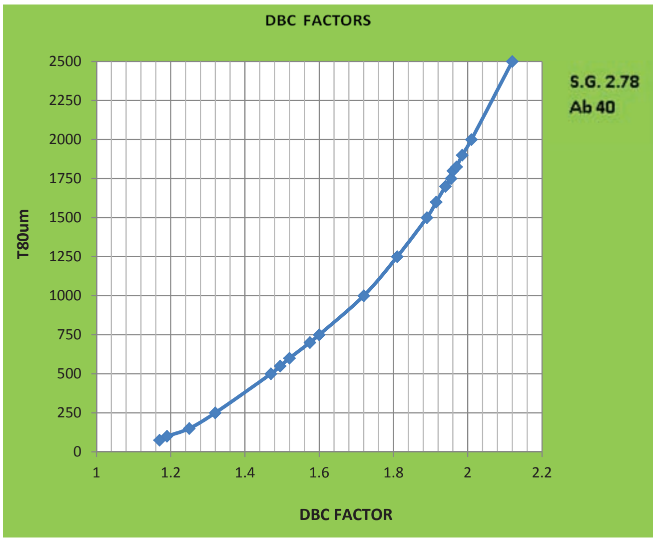

FIG 2 - Autogenous/semi-autogenous DB Consulting factors for material with a specific gravity of 2.78 and an Ab of 40.

A conversion of Ab and ta values to Rod mill and Ball mill work indices are achieved by using the formulae suggested by Julius Kruttschnitt Mineral Research Centre (JKMRC) in the publication Mineral Comminution Circuits: their Operation and Optimisation (Napier-Munn, 1999). However, the author has modified the Ab calculation to better reflect the relationship between the Ab and the RMWI range of comminution. This is because the Ab parameter is more related to rod mill grindability as the JK drop weight index (DWI), P80s range from approximately 15000 µm down to 3000 µm. The Ab parameter therefore, does not directly relate to BMWIs as the P80 range for ball milling is much less.

It follows that, to comply with the DBC method, the Ab value must be converted to a RMWI value (refer to Figure 3).

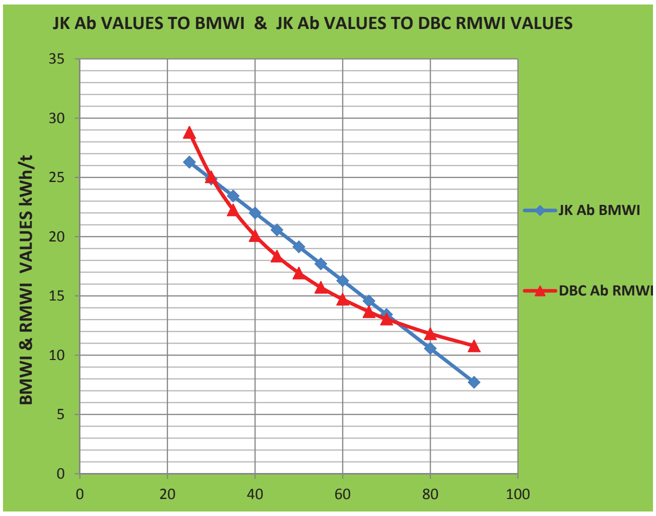

FIG 3 - Conversion of JK Ab to Bond ball mill work index values and JK Ab to DB Consulting Bond rod mill work index values.

Similarly, the ta value must be converted to a BMWI value (refer to Figure 4).

VARYING LABORATORY PARAMETERS

Problems evaluating AG/SAG mill SEs occur when the converted Ab values are not close to the laboratory RMWI values. These cases arise when the Ab converted value is low and the RMWI value is high causing a higher AG/SAG SE

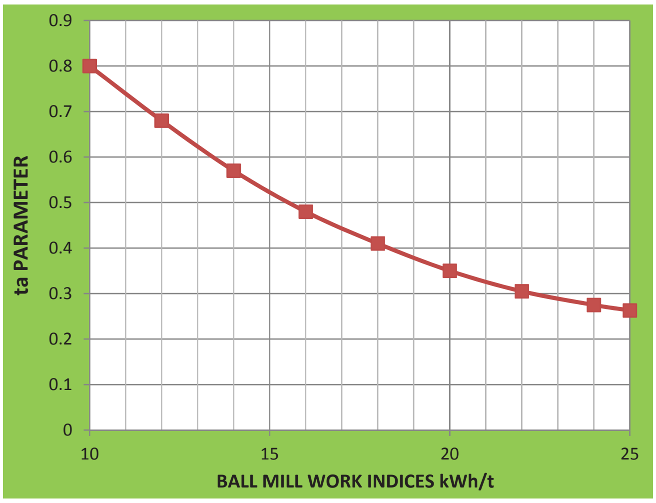

FIG 4 - Conversion of ta values to Bond ball mill work index values.

than when using only the converted Ab value. The opposite is true when the Ab converted value is higher than the RMWI value.

In these cases the Process Practitioner must make a judgement as to the best approach to achieve a reliable AG/SAG mill SE value.

Figure 2 shows the factors required to convert Bond SE to AG/SAG SE depending on the T80 value required. The factors are based on a SG of 2.78 and an Ab of 40.

Figure 3 shows a graph for converting Ab values to RMWI values. The JK graph has been modified by the author to better reflect a more realistic RMWI value.

Figure 4 shows the relationship for converting ta values to BMWI values.

Figure 5 depicts the Bond SE values plotted from 750 µm to 2500 µm T80 values calculated from the parameters shown on the graph. The efficiency factors from Figure 2 have been applied according to the DBC method to generate the AG/SAG SE values. Note how the two curves have similar slopes.

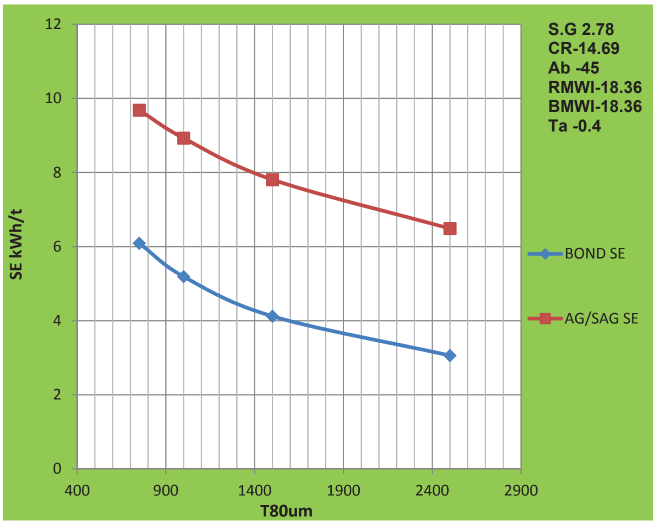

FIG 5 - Bond SE versus DB Consulting autogenous/semi-autogenous specific energy for T80s of 2500 µm to 750 µm based on the input parameters shown on the graph.

An example is shown in Figure 6 where AG/SAG SEs are calculated for T80s of 750 µm to 75 µm based on the parameters shown on the graph. Note how the two curves become near parallel when the T80 is equal to and greater than 250 µm.

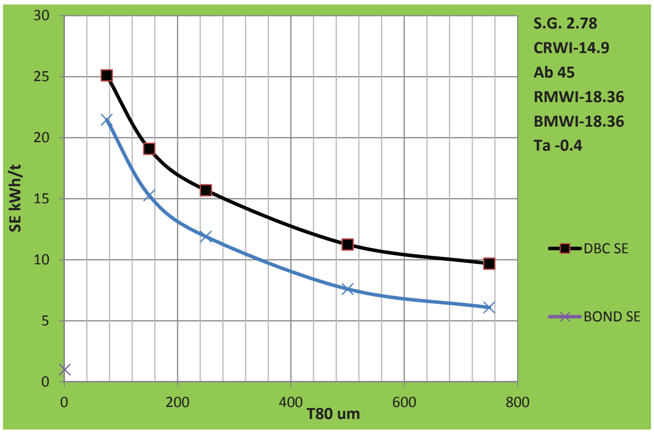

FIG 6 - Bond SE versus DB Consulting autogenous/semi-autogenous specific energy from T80s of 750 µm to 75 µm based on the input parameters shown on the graph.

Figure 7 shows Figure 6 with the addition of a graph calculated by the SMC method using the same parameters. In this case the DBC and SMC curves are almost identical.

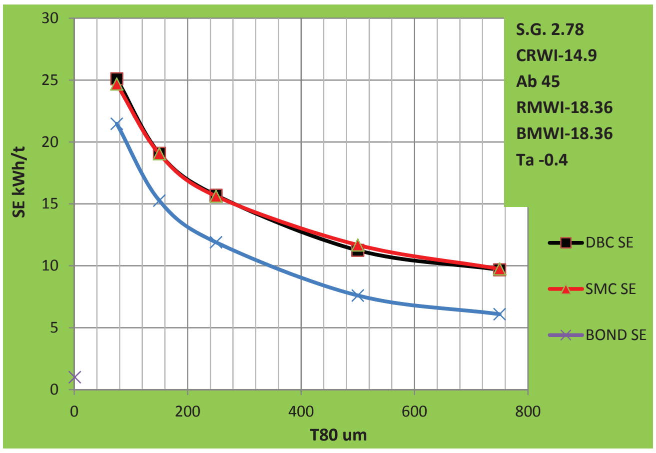

FIG 7 - Bond SE versus DB Consulting and SMC drop weight index autogenous/semi-autogenous specific energies from T80s of 75 µm to 750 µm based on the input parameters shown on the graph.

VARIATIONS IN SPECIFIC ENERGIES DUE TO DIFFERENCES IN SPECIFIC GRAVITIES

Another problem arises with a variation in the SG of the material to be assessed.

The DBC method is based on a nominal SG of 2.78 t/m^3 with a bulk density of 1.67 t/m^3. If the material being assessed has a different SG value then a correction factor must be applied. The Bond SE power is calculated from the F80 down to a P80 of 750 mm and the factor taken from Figure 2 applied.

The correction formula is:

$$\text{SG factor} = \text{AG/SAG SE (at 750 mm)} \times (2.78/\text{SG})^{0.23} - \text{AG/SAG SE (at 750 mm)}$$

The reduction or addition of SE is then added to, or subtracted from, the final AG/SAG SE power. The increase or decrease can be as much as 7.8 per cent for SGs varying from 2.0 to 3.85.

Figure 8 shows the difference in specific energy varying from a SG of 2.78 to a SG of 2.0 and from a SG of 2.78 to a SG of 3.85. The higher the specific gravity the lower the specific energy required and vice versa.

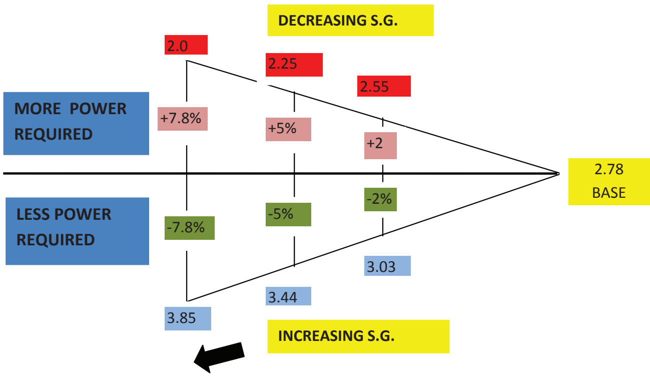

FIG 8 - Changes to autogenous/semi-autogenous specific energy due to specific gravity variation.

COMMENTS ON HOW EXISTING TEST METHODS ADJUST FOR VARIATIONS IN SPECIFIC GRAVITY

SMC method

The SMC method converts Ab values by dividing the SG by the Ab value then multiplying by 100. The SMC AG/SAG mill operating work index (SAGOWi), value is then selected based on the DWi value which has the units kWh/m^3. This is converted to kWh/t by dividing the SAGOWi by the SG of the material to achieve the Mia value which is the SMC AG/SAG mill work index. This process causes the Mia value to vary with the SG to the point where a low SG results in a higher Mia value and a higher SG results in a lower Mia value.

JKSimMet specific gravity adjustment

As far as the author is aware, the Ab value used in a JKSimMet simulation is not corrected for the SG effect to fine tune the AG/SAG specific energy.

JKSimMet does calculate the charge mass and mill power with varying densities but does not show an increase or decrease in SE for variations in SGs. This is because the Ab is calculated in t/kWh and not in kWh/m^3 as per the DWi method.

Starkey method

Starkey, Hindstrom and Orser (2006) state that less SE is required as the SG increases to achieve the same amount of comminution and more energy is required if the SG reduces. In other words the target P80 of 1700 µm takes less energy, as the SG increases in value and more energy as the SG decreases in value.

The Starkey formula is:

$$\text{SAG mill pinion power kWh/t(SE)} = \text{revs} \times (16\,000 + g)/(447.3\ g)$$

where:

g = weight of 7000 l of charge

If the standard 7000 l charge varies in weight (g), then the SE varies from a lower SE for a higher SG to a higher SE for a lower SG.

Pilot testing method

Pilot mill testing corrects for the SG as the mill charge is sensitive to weight difference, which reflects in a mill power draw increase or decrease.

Macpherson test method

The Macpherson test (Macpherson, 1989), corrects for the SG as the mill charge is sensitive to weight difference, which reflects in a mill power draw increase or decrease.

ADJUSTMENT REQUIRED DUE TO AB VARIATION

The DBC method is based on an Ab of 40. Should the ore being assessed be harder or softer than Ab of 40 then an adjustment is made according to Figure 9 for T80s less than 150 µm.

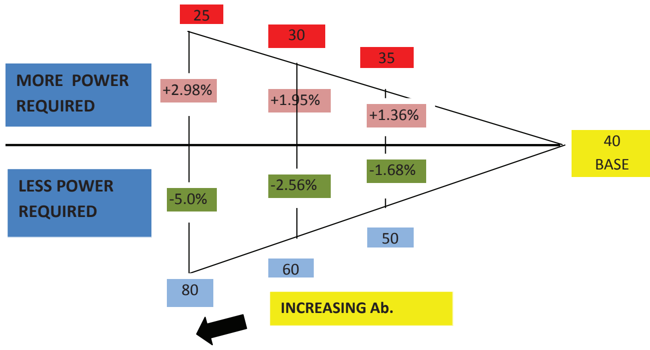

FIG 9 - Changes to autogenous/semi-autogenous specific energy due to an Ab variation.

ADJUSTMENT REQUIRED IF A LOW ASPECT MILL IS EMPLOYED

The DBC method of calculation is based on an HA mill configuration. If a LA mill configuration is used then inefficiency factors are required. Burgess (1989), stated that LA mills can be up to 16 per cent less efficient than an HA mill in some cases. The L/D ratio of HA mills range from 0.3 to 0.6. If the L/D of a LA mill is between 0.7 and 0.9, add a five per cent inefficiency factor. If the LA mill has a L/D ratio greater than 0.9, add a 7.5 per cent inefficiency factor.

COMPARISIONS OF SPECIFIC ENERGIES BETWEEN THE DBC AND THE SMC METHODS

Example 1 – soft ore

The input criteria:

- AG/SAG mill SE grinding from a F80 of 150 000 µm to product size T80 of 80 per cent passing 75 µm
- CRWI – 7 kWh/t
- Ab – 70 RMWI equivalent =13.08 kWh/t (refer to Figure 3)
- RMWI – 13.0 kWh/t
- BMWI – 13.0 kWh/t
- ta – 0.63 (used only as a guide in the calculation)
- BMWI equivalent = 13.0 kWh/t (refer to Figure 4)
- SG – 2.5.

DBC method

- Bond SE 14.62 × factor of 1.18 (from Figure 2) =17.25kWh/t
- DBC SE = 17.25 kWh/t AG/SAG mill SE at the pinion at 2.78 @ SG
- Corrections for SG - SE to 750 µm = $(6.92 \times (2.78/2.50)^{0.23}) - 6.92 = +0.171$ kWh/t
- AG/SAG S.E =17.25 + 0.171 = 17.42 kWh/t
- Ab correct for T80 below 150 µm is $(70/40)^{2.3} = 3.62$ per cent less power (refer to Figure 9)
- SE for the operation = 17.42/1.0362 = 16.81 kWh/t.

SMC method

- DWi = 3.571 kWh/m^3
- Mia = 13.02 kWh/t
- SE at 750 µm =7.09 kWh/t
- Mib =17.56 kWh/t (Mib is the AG/SAG fine material work index derived from a BMWI of 13.0 kWh/t)
- SE at 750 µm to 75 µm = 9.73 kWh/t
- SE for the operation=16.82 kWh/t.

Comment

Both the results are similar. As the converted Ab value of 70 equals 13.08 kWh/t it is very close to the RMWI and the BMWI values of 13.0 kWh/t. This means the converted Ab value is taken through the comminution range from 150 000 µm to 75 µm in both cases.

Example 2 – medium-hard ore

The input criteria:

- AG/SAG mill SE grinding from a F80 0f 150 000 µm to product size T80 of 80 per cent passing 107 µm
- CRWI - 13.54 kWh/t
- Ab - 50 = RMWI EQUIVALENT =16.93 (refer to Figure 3)
- RMWI - 16.93 kWh/t
- BMWI - 14.85 kWh/t
- Ta - 0.53 (used only as a guide in the calculation)
- BMWI equivalent = 14.85 kWh/t (refer to Figure 4)
- SG - 2.78.

DBC method

- Bond SE 14.44 × factor of 1.2 (refer to Figure 2) = 17.32 kWh/t
- SG correction N/A
- Ab – 50 correction factor is minus 1.68 per cent (refer to Figure 9)
- SE for the operation = 17.32/1.0168 = 17.034 kWh/t.

SMC method

- DWi = 5.56 kWh/m^3
- Mia = 16.49 kWh/t
- SE to 750 µm = 8.98 kWh/t
- Mib = 18.5 kWh/t (derived from a BMWI of 14.8 kWh/t)
- SE AT 750 µm to 75 µm = 8.19 kWh/t
- SE for the operation = 17.16 kWh/t.

Comment

The results are very close. The converted Ab value of 50 equals 16.93 kwh/t. This value is the same as the RMWI value. However, the BMWI value is less at 14.8 kwh/t. The DBC calculation takes the Ab value through the comminution range from 25 000 µm to the rod mill F80 value of 3000 µm. The remaining calculation is ball milling from a F80 of 1000 µm at 14.8 kwh/t to a P80 of 107 µm. The two results are similar because the only difference is that the SMC calculation took the coarse range Mia, to a T80 of 750 µm whereas the DBC method reverts to the BMWI at a F80 of 1000 µm.

Example 3 – hard ore

The input criteria:

- AG/SAG mill SE grinding from a F80 of 150 000 µm to product size T80 of 80 per cent passing 750 µm
- CRWI – 17.80 kWh/t
- Ab – 35 = RMWI equivalent = 22.26 (refer to Figure 3)
- RMWI – 18 kWh/t
- BMWI – 16 kWh/t
- ta – 0.48 (used as a guide only in the calculation)
- BMWI equivalent = 16 kWh/t (refer to Figure 4)
- SG – 3.5.

DBC method

- Bond SE 6.51 × factor of 1.6 (from Figure 2) =10.42 kWh/t
- DBC SE = 10.42 kWh/t AG/SAG mill energy at SG of 3.5
- Correction for SG SE to 750 µm = (10.42 × (2.78/3.5)$^{0.23}$) - 10.42 = - 0.537 kWh/t
- SE for the operation = 10.42 - 0.537 = 9.88 kWh/t
- Ab factor is plus is 1.36 per cent (refer to Figure 8)
- SE for the operation is 9.88 × 1.0136 = 10.01 kWh/t.

SMC method

- DWi = 10.00 kWh/m^3
- Mia = 20.62 kWh/t
- SE to 750 µm = 11.23 kWh/t.

Comment

The SMC AG/SAG SE is 12 per cent higher than the DBC AG/SAG SE. The CRWI at 17.8 kWh/t accounts for more than two per cent of this difference compared to using a CRWI of 22.26 kWh/t. The Ab converted equivalent RMWI is 22.26 kWh/t, whereas the RMWI is stated at 18 kWh/t. The BMWI is lower again at 16 kWh/t. The SMC method takes the Mia of 20.62 kWh/t down to a T80 of 750 µm, whereas the DBC method uses the Ab converted value to a P80 of 3000 µm. Then the DBC calculation used the RMWI of 18 kWh/t to a P80 of 1000 µm before employing the BMWI of 16 kWh/t to finish at a T80 of 750 µm. This is a good example of SE differences in the SMC and DBC values due to the equivalent Ab RMWI value differing from the RMWI and BMWI.

As the RMWI and the BMWI values are lower than the Ab equivalent kWh/t value the lower AG/SAG SE value of 10.01 kWh/t pinion shaft power is more accurate.

The difference with the SMC approach compared with the DBC method is that the SMC specific energy calculation only varies with the Ab and the SG for the coarse section of the calculation down to a T80 of 750 mm, whereas with the author's approach the SE can vary according to the values of the CRWI, the converted Ab, and RMWI.

COMMENTS REGARDING CURRENT LABORATORY TESTING METHODS

Drop weight test product sizes

Kojovik and Shi (2011), states the rotary JK drop weight test (JKDWT), crushes material in the size range of 50 to 16 mm. The resulting PSD for the percent passing one tenth of the original size (T10), are in a range of 20 per cent to 50 per cent and the 80 per cent passing values are in a range of 3 mm to 15 mm (refer to Figure 10).

In other words this test does not investigate the energy required to reduce material below the 3 mm product range. It would appear that this could be the reason the SMC method reverts to using BMWIs when calculating transfer sizes smaller than 750 µm. Also, the JKDWT does not cover the energy required to reduce the coarse range from an average primary crusher product of 80 per cent passing 150 mm down to 63/13.2 mm, the JKDWT feed sizes.

To develop an energy register for finer sized products a drop weight tester is required with the ability to crush small pieces in the 5 mm to 3 mm range.

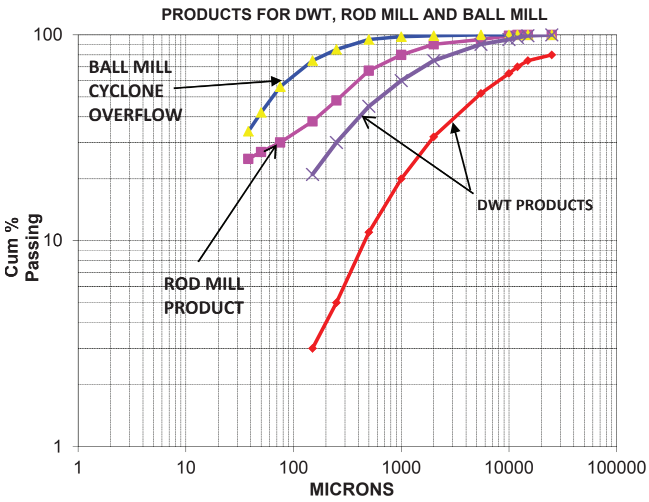

FIG 10 - JKDWT, DWT, rod mill and ball mill cyclone product slopes.

Starkey SAGPower test

The Starkey SAGPower procedure found that to cover the energy required for grind sizes less than a P80 of 1700 µm, some of the test mill product must be used to generate a BMWI value. This BMWI is then employed to calculate the SE required for the fine section of the grind. This SE is added to the SAGPower SE obtained from the SagPower test to arrive at the total power required. The Starkey SAGPower test does not calculate the energy required to reduce the coarse section from an average primary crusher product of 80 per cent passing 150 mm down to 80 per cent passing 19 mm, the Starkey SAGPower test feed size, only an assessment is made.

Standard drop weight index, energy versus autogenous/semi-autogenous energy

It is documented that tertiary crushing requires a 1.3 inefficiency factor to obtain the crushing power to equal the energy absorbed by the standard DWI for the same amount of comminution. It follows that the tertiary crusher is 77 per cent efficient compared to the DWI.

Details of a method to convert Ab values into AG/SAG specific energy values are few. Morrison *et al* (2011) states that AG/SAG mills need about 2.5 times as much energy compared to a DWI value to generate a similar PSD. In other words, an AG/SAG mill is only 40 per cent efficient compared with the DWI. The author assumes that the T80 size involved in this statement is in the range of 3 mm to 15 mm.

Working from the ball mill power back to the autogenous/semi-autogenous specific energies

The PSD from an AG/SAG mill does not follow a 0.5 slope. The average slope is less steep. This means more energy has been inputted into this material, making it easier to grind to a required finer product size when assessing the actual 80 per cent passing value against the corrected value. A ball mill that follows an AG/SAG mill can be reduced in size to allow for this phenomenon. However, it is far safer to leave the Ball mill at the original size calculated, using the uncorrected T80.

McKen, Raabe and Mosher (2001) suggested a method to compensate for the shallower slope of the PSD by correcting the AG/SAG T80 value. McKen, Raabe and Mosher (2001) also suggested that the average real T80 is 2.5 times smaller than the measured T80. Also, this method goes on to describe the phantom cyclone approach. Although this method compensates for the reduction of tonnes per hour to the ball mill by increasing the F80 of the scalped material, it does not suggest a method of increasing the material grindability value. This increase in hardness occurs due to the fact that the larger material has survived the AG/SAG process and, therefore, must be harder to grind than the original feed material.

One way to find the true AG/SAG T80 is to set the ball mill operating work index to an efficiency of 100 per cent. Knowing the ball mill circuit P80, the ball mill SE kWh/t value and the BMWI value, the ball mill F80 can be back calculated. This, then, is the corrected transfer size from the AG/SAG mill. The AG/SAG mill T80 should aim at this value times 1.70. This coarser transfer size will then produce the correct F80 to be fed to the ball mill.

FINE SEMI-AUTOGENOUS MILL FEED SIZES

When proposed SAG mill feed sizes are reduced as fine as 30 mm to 25 mm the AG/SAG mill mode of grinding changes from SAG mill to a single stage grate discharge ball mill operation.

This has been observed especially with LA SAG mills where the mill feed is so fine there is no large rock present to act as media. Mill operators then load up the mill with balls to make tonnage and grind converting the SAG mill to a grate discharge ball mill.

It is suggested that if contemplating using SAG mill process power calculations when confronted with fine feeds, consider using ball mill SE and ball mill power calculations to size the mill if the feed size is 30 mm or less.

COMMENTS ON PUBLISHED DROP WEIGHT INDEX VERSUS AB CURVES

Figure 11 shows SMC DWi values plotted against JK Ab values. This graph is a guide only and relates in general to the relationship between DWi and Ab values. As stated in this paper the DWi varies with the SG value for the same Ab value. Therefore, when comparing an Ab value with a DWi value the SG value must be known. In other words there are separate DWi/Ab curves for different SG values.

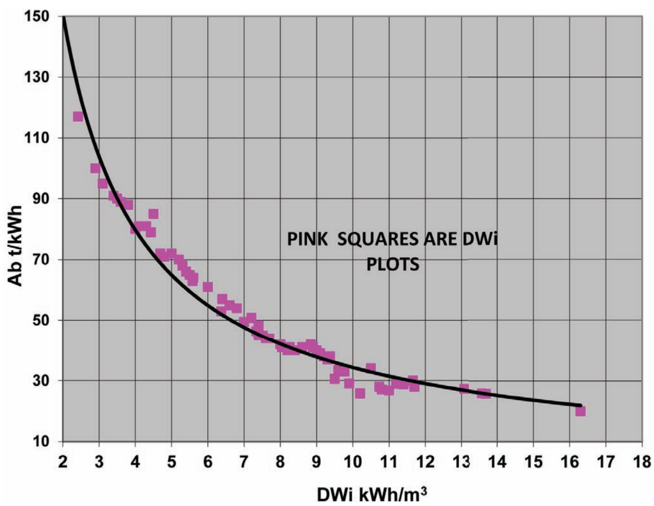

FIG 11 - DWi versus Ab trend curve.

COMMENTS ON PUBLISHED AB VERSUS AUTOGENOUS/SEMIAUTOGENOUS SPECIFIC ENERGY CURVES

Figure 12 shows the Ab parameter plotted against AG/SAG SE values. The format in which this graph is shown is a guide only. For a curve such as this to be meaningful the F80 and

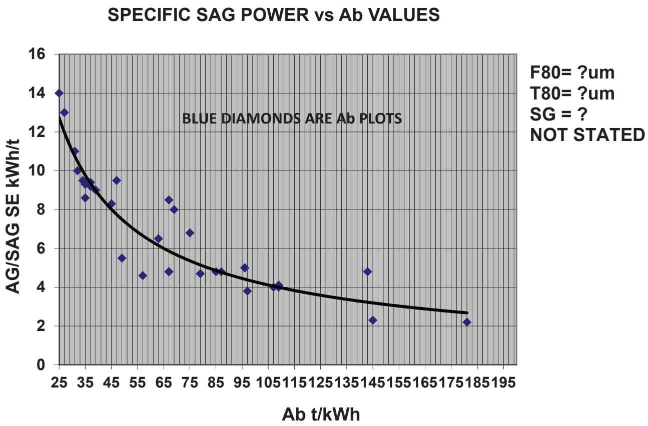

FIG 12 - Ab versus autogenous/semi-autogenous grinding, SE trend curve.

T80 and the SG must be stated for each plotted point. Any change to these inputs will reposition the plot location.

This means there are different AG/SAG specific energy values for one Ab value depending on the F80, T80 and SG values.

CONCLUSIONS

It has been stated on several occasions that scaling up from Bond third theory SEs to AG/SAG SEs was not possible.

This paper describes a mathematical relationship that the author has been found to exist between the Bond third theory SE calculation and AG/SAG mill SE requirement.

The method describes a quicker, cheaper, way to evaluate AG/SAG SE values compared to other methods such as the SMC method where the parameter Mia is proprietary and is only available through SMC sources.

The DBC method described in this paper has resulted in a robust set of calculations, without restrictions, that can be used by Process Practitioners with confidence, when assessing AG/SAG mill SE requirements.

The DBC method expands the current available methods of calculation using solely the DWi, Ab and ta parameters by providing a more comprehensive assessment of the power required by incorporating CRWI, RMWI and BMWI parameters.

This manuscript has explained how AG/SAG mill SEs can be obtained from laboratory work indices using the DBC method. Even if an Ab or a DWi parameter is not available, an AG/SAG mill SE can still be developed using only the RMWI and BMWI values and then applying a correction factor according to Figure 2.

As the Ab value only covers the coarse range of comminution, it follows that because AG/SAG products finer than 3000 µm are usually required, then the AG/SAG mill SE should be calculated incorporating the actual RMWI and BMWI values generated from the material to be assessed as well as the Ab or DWi parameters.

In order for an AG/SAG SE calculation to be made Ab and ta parameters must be converted to RMWI and BMWIs. A graph describing conversion of the Ab parameter to an apparent RMWI value is shown in Figure 3. A graph describing the conversion of a ta parameter to an apparent BMWI is shown in Figure 4.

Comparisons between the SMC method and the DBC method are described in the paper. These comparisons show a close correlation between the two methods. However, it transpired that if the laboratory RMWI has a higher value than the converted Ab parameter, the resulting SE will be higher. Conversely, if the laboratory RMWI is lower, the AG/SAG mill SE will be lower.

It was found that the AG/SAG SE calculation is sensitive to variations in SG and the Ab values. The DBC method requires corrections to be made to the AG/SAG SE if the ore S.G varies from 2.78 t/m^3 and the Ab value of 40.

A third correction is required if a low aspect mill is being considered.

Although the author has developed this method over a number of years, further refinement of the method will continue.

ACKNOWLEDGEMENTS

The author would like to thank Xstrata Zinc and Worsley Alumina for allowing certain process data relating to their grinding circuits, to be included in this paper.

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