Comminution 14

*Larson M, **Morrison R, **Xie W, *Young M

Development of the Larson/Morrison IsaMill JKSimMet Model

*Glencore-XT
**JKMRC, SMI, the University of Queensland

Abstract

The IsaMill is a high intensity horizontal stirred mill utilizing small 2-6 mm ceramic grinding media for attrition grinding. Grinding duties range from feeds of up to 300 microns being ground to 40 microns and UFG grinds as fine as 5 microns. Being completely dissimilar to normal ball mill breakage it was desired to produce a model for this process in JKSimMet. The result of this study was the discovery that IsaMill breakage can be reliably predicted on a basis of energy versus the squared value of the percent passing given sizes. This relationship can be used to analyse circuit efficiency for varying feed sizes. By using this new relationship the product size distributions for new feed sizes and energies can be reliably predicted with simple math, something not previously possible with only a signature plot. This paper will provide details on the model development, validation and implementation.

Introduction

The IsaMill is a horizontal high speed attrition mill developed by Mt Isa Mines and Netzsch for the treatment of fine grained minerals at McArthur River Mine and Mt Isa where ultrafine grinds of sub 7 microns are necessary. (Johnson et al, 1998) As the development of the mill and ancillary items has progressed the mill has expanded its range of duties into relatively coarser concentrate and mainstream grinding duties with F_{80}'s of up to 300 microns. As acceptance of the mill has increased so too has the need to better understand the grinding action taking place. In 2006 Glencore-XT funded the JKMRC to develop a simulation model of the mill breakage. While the mill scaleup based on the proven signature plot is widely accepted, the signature plot has one major drawback in its comparison of P_{80} versus energy. The plot is only valid for the feed size and conditions tested. If a coarser feed size became part of the design criteria no adjustment was available as the signature plot line does not intersect zero energy at the feed size and cannot be reliably adjusted. A method is required to accurately predict the results of not only changing feed sizes but also different media size and rheological constraints.

IsaMill Grinding Variables

There are many variables within the IsaMill or any stirred mill; however, only a handful of these actually impact the grinding efficiency. Residence time and energy intensity may change but the actual energy input per unit of feed (kWh/t) to a given grind target is a quite robust number. Variation in factors such as disc shape, spacing, and size; mill speed, feed slurry density within a range, separator configuration, flowrate and media type as long as relatively round and an SG of 3.5-4 do not have much impact on the energy per tonne required for the same feed size distribution to achieve a target product size. This is well supported by experience as the original scaleup as performed by MIM went from lab units of 1.5 to 4 litre capacity to pilot and industrial scale units of 100 to 3000 litres per mill.

If the different mill configuration variables made a difference in grinding efficiency the team at MIM could be considered some of the luckiest engineers in the world in that each step scaled along the signature plot. Further, past work by Ming Wei Gao at CSIRO has shown the lab four litre IsaMill scaled from energy versus P_{80} to the full size 355 kW Century Zinc SMD's (Gao et al, 2007). This is despite the fact that the vertical SMD uses pegs to stir the media and slurry and the horizontal M4 and all IsaMills use discs at a higher speed. Similarly the lab scale IsaMills use round pegs with a large open area for a separator while full scale mills use square or rhomboidal fingers with far less relative open area. In all cases the mills are just stirring grinding media and slurry. With regards to mill speed the M4 has a tip speed of about 8.5 m/s, the M20 about 12-14 m/s and full scale mills about 20 m/s, yet they all scale from one another. The relative mill configurations also vary from size to size with regards to disc spacing and size compared to the shell volume. This suggests that the energy being absorbed by shearing the mixture of media and slurry may be the controlling factor. The sensitivity to changes in the shape of the feed size distribution also suggests that coarser fed particles may be contributing to grinding of the finer ones. Over complicating any of this serves no real purpose other than to distract from issues which actually do make a difference.

These can be summarized as media shape, media size, ore type, slurry viscosity (above an optimum point but not below that point) and feed size distribution.

Media shape is generally not considered as all but three IsaMill sites use modern ceramics which in most cases are generally round i.e. close to spherical. Full scale plant test work and pilot test work has shown that the round ceramic is generally 15-20% more efficient than competent sand or oblong shaped ceramics. Different ceramic manufacturers may claim energy efficiency advantages over competitors but the reality is that this media has become much more of a commodity where purchase price and wear rate (g/kWh) is a distinguishing factor, not grinding efficiency.

Media size has only been examined in limited detail but it is known that different size media will produce different energy versus grind slopes for each size fraction. Optimum media size will depend on the incoming ore feed size, desired product size, ore hardness and a myriad of other factors to lesser extents.

Slurry viscosity and its effect on stirred milling efficiency at fine sizes is poorly understood at this time. In general Glencore-XT will try to operate mills at about 20% solids by volume or 20-24 centipoise on the mill discharge. Above these values energy efficiency is lost. Below these values the efficiency will flatline before decreasing once the slurry is dilute enough that energy is spent contacting media against media with no ore particles present to be ground. Ideally in the future there will be a reliable model to predict viscosity based on the surface area present in a given volume calculated from the solid SG, slurry SG and laser sizer product size distribution.

Signature Plot and Scaleup

The ability to predict energy for varying feed size distributions is the main goal of the work described in this paper. The IsaMill signature plot with energy (kWh/t) versus P_{80} on a log-log plot is widely accepted as scaling to full scale IsaMills. This has been published over the past two decades showing accurate 1:1 scaleup from M4 and M20 test mills to the M1000, M3000 and M10000 IsaMill. Glencore-XT maintains relationships with a dozen independent laboratories around the world. The robustness and repeatability of the signature plot test was shown in IsaMill 1:1 Direct Scaleup from Ultrafine to Coarse Grinding presented at Comminution 12. However, it has one large limitation in that it does not cross zero energy at the feed size. Thus it can only be used for the feed size tested. If the same P_{80} is to be fed to the mill and the rest of the size distribution is different - for example far fewer fines or a sharper size distribution - then the signature plot will not be valid. A new method is necessary to provide the flexibility required to be useful for a JKSimMet model which must to able to handle reasonable variation in feed rate and feed size distribution in a reasonable manner. The proven robustness of the signature plot though means that any model will still use the signature plot. Given the fact that the entire size distribution, not just the P_{80}, can be determined from the signature plot test it can be assumed that any new model method based on the same information will be successful.

Test Mill Coarse Material Retention

Based on previous work it cannot be stressed enough that proper test conditions and data analysis are vital to the successful development and implementation of any IsaMill model. Without careful planning and observation results can deceive the user into thinking the mill performed better than reality. The combination of too small media and not enough sample volume can easily result in coarse material being retained in the lab mill. In these cases the too small media will only grind the fines and not have enough energy to break the coarsest material. The coarse material will be held in the mill by the centripetal forces as there is not enough material passing through the mill for those particles to fully build up where they would be discharged. This is usually recognized by either an unusually high power draw or a low density reading on the discharge.

Flaws in Other Models

It is well accepted that the Bond equation becomes much less reliable at product sizes finer than about 70 microns. As ore is ground finer, the key Bond assumption that the next increment of input energy will produce a similar increment of fine material (i.e. g/rev of the test mill) becomes invalid and the required energy for each increment of fines generated increases at finer product sizes. This means that the relationship between grind size and energy is not linear at fine sizes.

As shown in Figure 1, grinding from 50 to 33 μm requires significantly more power than the BWI suggests, with a much higher slope (-1.0345). Grinding finer still needs ever more energy. All three points on the graph come from the same test but the finer points look to be less energy efficient in terms of a Bond comparison.

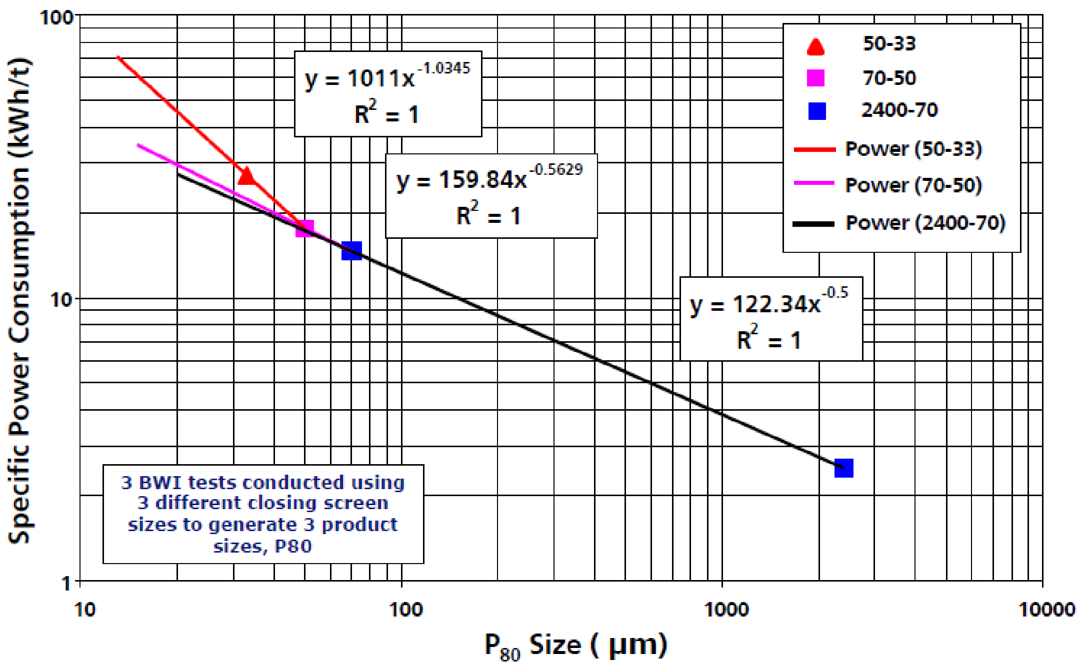

Figure 1. Flaws in using the Bond equation to compare fine grinding energy efficiency

Further, most Bond Work Index data is developed by testing run of mine ore. Most IsaMill feed will be a stream with quite different characteristics. The Bond test uses steel balls, while the IsaMill uses ceramic grinding media. In almost all cases the ceramic media will be harder than the ore it is grinding and of roughly similar stiffness. The steel balls used in a Bond test can vary widely in hardness compared with the ore being ground and will always be much more elastic. Stiffer media transfer energy more efficiently than elastic media.

The commonly used appearance function will also not be considered in this case as it assumes every particle breaks with the same progeny. The breakage rates are modelled but not changed for different energy, feed sizes or media size.

Other researchers (Mannheim, 2011) have attempted to utilize the existing signature plot line to predict results at different feed sizes. This is shown in Figure 2.

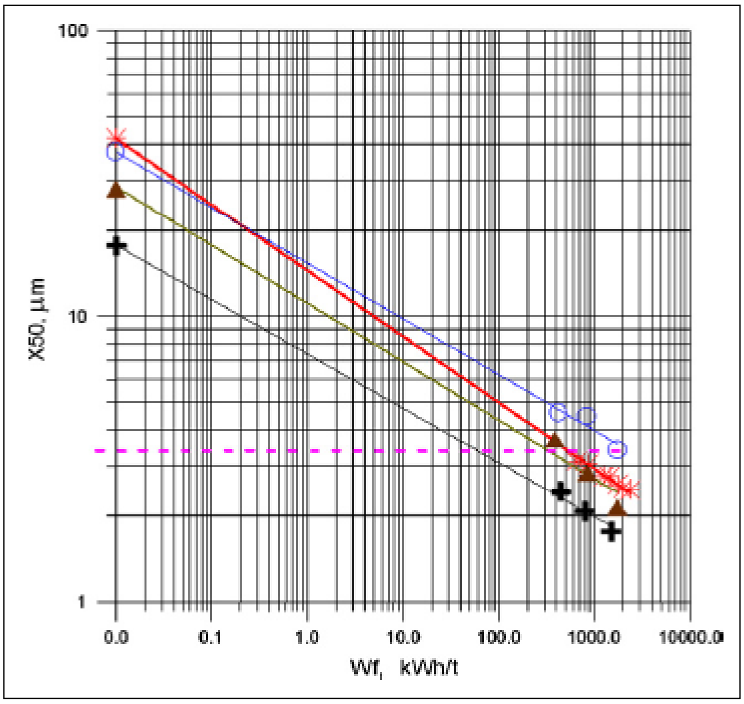

Figure 2. Relation between the grinding fineness and specific grinding work for several materials (Mannheim, 2011)

Forcing the signature plot lines through the origin in Figure 2 moves the lines from the original plots using only the mill products. While it may appear accurate at first glance, further inspection reveals that the energy predicted by the resulting line is in error by 200-300% compared to where the points actually sit. The use of the log-log plot with inclusions from 0 to 1 kWh/t and large symbols have effectively hidden this from casual observation. If samples had been taken below 100 kWh/t they would better demonstrate this inaccuracy. This approach cannot be considered sufficiently reliable for a model that will be used to size industrial machinery.

Reduction ratio type comparisons have also proven to be popular. In the example from Tati Nickel contained in Table 1, energy requirements were measured to differentiate between three types of stirred mills.

Table 1. Summary of mill performances (Nel et al, 2006)

		Mill A	Mill B	Mill C
Specific cumulative breakage rate at 10µm		0.015	0.02	0.055
Power at Reduction ratio of 4 with Ceramic	kWhr/t	*55	48	40
Power at Reduction ratio of 4 with Sand	kWhr/t	*110	97	55
Temperature increase	°C/(kWh/t)	N/A	0.71	0.49
Temperature for 60 kWh/t	°C	N/A	42.6	29.4

*At low density (30% solids).

Nel et al concluded "For the horizontal ultra fine mill with ceramic grinding media, 2.4 % of the particles bigger than 10 microns were reduced to less than 10 microns using 1 kWh/t specific energy input, thus 33.3 kWh/t specific energy was required to mill Phoenix concentrate to 80 % passing 10 microns."

The math used is basically that it took 1 kWh/t to reduce 2.4% of the feed to under 10 microns. Therefore it must take 33.3 kWh/t to reduce 80% of the feed to below 10 microns. 80%/2.4%=33.3. This approach while being convenient is not necessarily appropriate.

When examining grinding efficiency in this way the examples with the coarsest feed and or product will always appear to be the more efficient option. For reduction ratios to be a valid option in modelling of fine grinding, the relationship between grind size and energy would have to be linear. Unfortunately this is not the case and each step finer requires relatively more energy for smaller and smaller reductions in size.

Figure 3 is another example of a reduction ratio model used to justify a process decision, in this case comparing media type and size. However if the extreme point from the test work was used, the entire graph could be populated by columns of dots. For example, grinds of 60 microns to 30 microns and 40 microns to 20 microns both have reduction ratios of 2, but the finer example will require more energy.

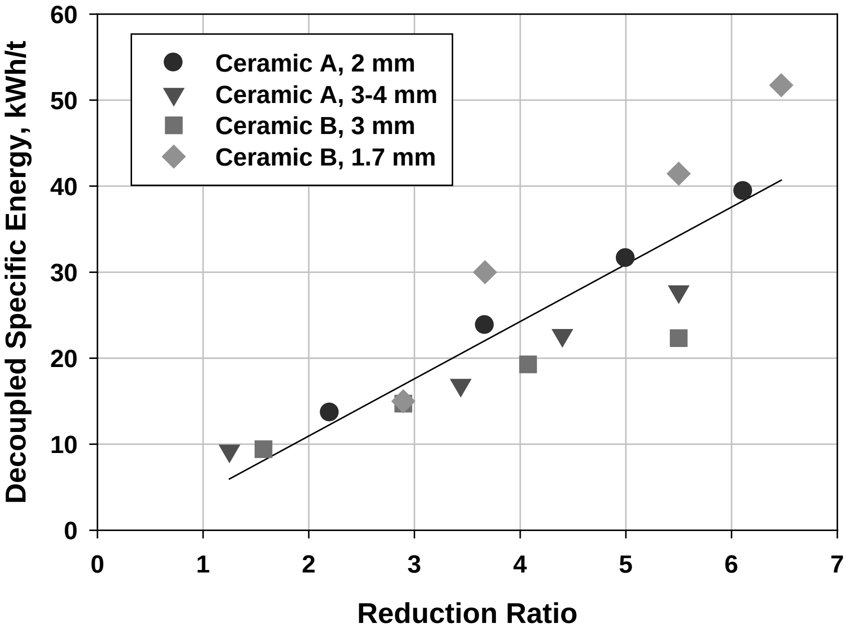

Figure 3. Comminution energy versus reduction ratio (Farber et al, 2010)

For these reasons reduction ratios are of limited use for comparison or prediction tools when dealing with fine grinding.

The Squared Function Dependence

Using the Finch McIvor method for particle production in ball mills as a guide, the first attempt at modelling the IsaMill on a size by size particle basis was made. While the relationship of energy versus percent passing of a certain size is linear for the ball mill, for the IsaMill the relationship was not linear. However it was observed from the curve produced that the relationship approximated a squared function.

Plotting these first attempts on energy versus percent passing 10 µm squared resulted in Figure 4. Not only does the squared function produce a straight line but that line passes through the feed size at zero energy.

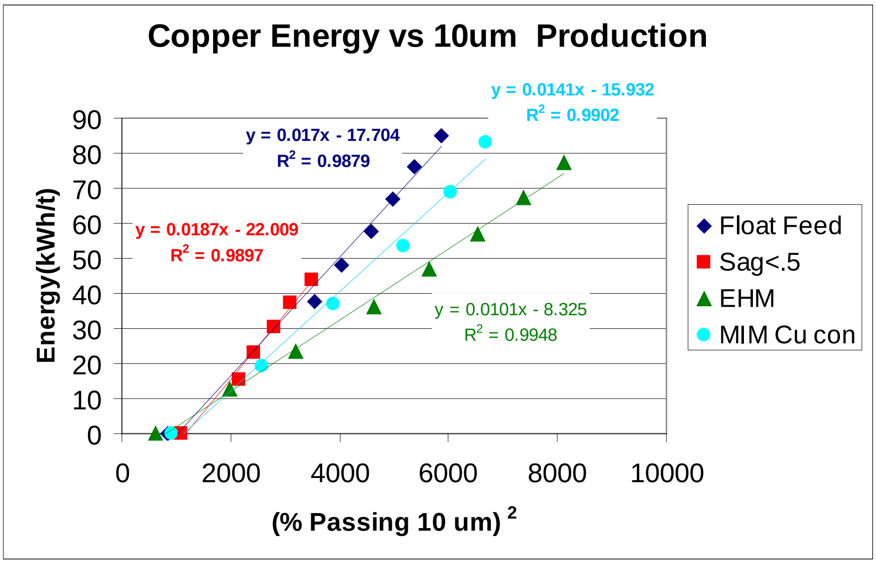

Figure 4. Fines production of various copper ores (Larson, 2013)

This shows promise that the mill is creating surface area through fines in a predictable reliable manner.

It was initially thought that by switching the axes, a simple easy to understand model could be used with the squared function as the basis. This is shown in Figure 5. A plot is developed using an original feed and energy values. Then for a new feed the new size is plotted and the line from the original feed is just moved up or down the y-axis while keeping the squared function lines parallel. The new energy to a given percent passing the size of interest can then be calculated.

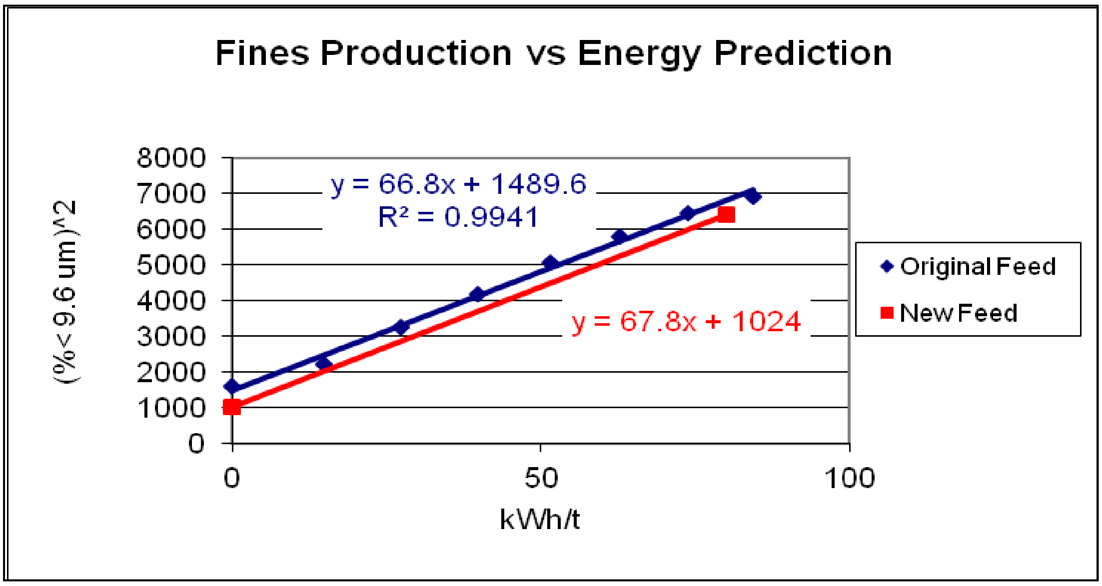

Figure 5. Graphical form of IsaMill squared function for fines production model (Larson, 2013)

Validation of Squared Dependence in MS Excel

To validate the basic idea of the squared function, the JKMRC ran a test program with multiple ores ground to varying size distributions in a rod mill. Different feed sizes were then ground in the M4 IsaMill using the same media size distribution to determine if one test could be used to predict the results of the other.

In the first case shown in Table 2, MIM run of mine copper ore was ground down to P_{80}'s of 72 and 47 microns. Bothe samples were processed through the M4 IsaMill using the same 2.5 mm top size graded ceramic media charge. The raw data for these two tests is shown below, with energy per pass, percent passing a given size and the percent passing that size squared.

Table 2. MIM Copper ROM sizing and energy per pass data (Larson, 2013)

	Energy	%<	%<^2										
		2.4 µm		5 µm		9.6 µm		13.5 µm		19 µm		27 µm	
P_{80}= 72µm	0	15.00	225.00	25.28	639.08	38.13	1453.90	45.00	2025.00	51.48	2650.19	58.11	3376.77
	9.3	18.33	335.99	31.46	989.73	48.41	2343.53	57.57	3314.30	66.38	4406.30	74.96	5619.00
	19.2	20.62	425.18	35.72	1275.92	55.58	3089.14	66.40	4408.96	76.49	5850.72	85.32	7279.50
	28.9	23.31	543.36	40.10	1608.01	62.33	3885.03	74.40	5535.36	84.58	7153.78	92.14	8489.78
	37.2	24.31	590.98	42.16	1777.47	65.77	4325.69	78.17	6110.55	88.05	7752.80	94.76	
				44.10	1944.81	69.31	4803.88	81.93	6712.52			96.91	
P_{80}= 47µm	0	16.23	263.41	28.11	790.17	43.49	1891.38	51.70	2672.89	59.58	3549.78	67.50	4556.25
	8.3	19.26	370.95	33.63	1130.98	52.71	2778.34	63.09	3980.35	72.81	5301.30	81.62	6661.82
	17.3	21.40	457.96	37.34	1394.28	58.51	3423.42	69.94	4891.60	80.24	6438.46	88.68	7864.14
	24.9	22.73	516.65	40.17	1613.63	63.30	4006.89	75.75	5738.06	86.17	7425.27	93.64	8768.45
	32.2	24.67	608.61	43.09	1856.75	67.48	4553.55	79.92	6387.21	89.43	7997.72	95.65	
	39.5	26.45	699.60	45.99	2115.08	71.83	5159.55	84.05	7064.40			97.37	

The main basis for this model is the assumption that the squared function lines for varying size fractions will be parallel for different feed size distributions and that the predictive process only has to move those lines up and down the y-axis depending on the amount of a given size present in the new feed to predict the new energy.
The results of doing this are shown in Figure 6 with individual lines for 27, 19, 13.5, 9.6, 5 and 2.4 microns plotted for both feeds tested.

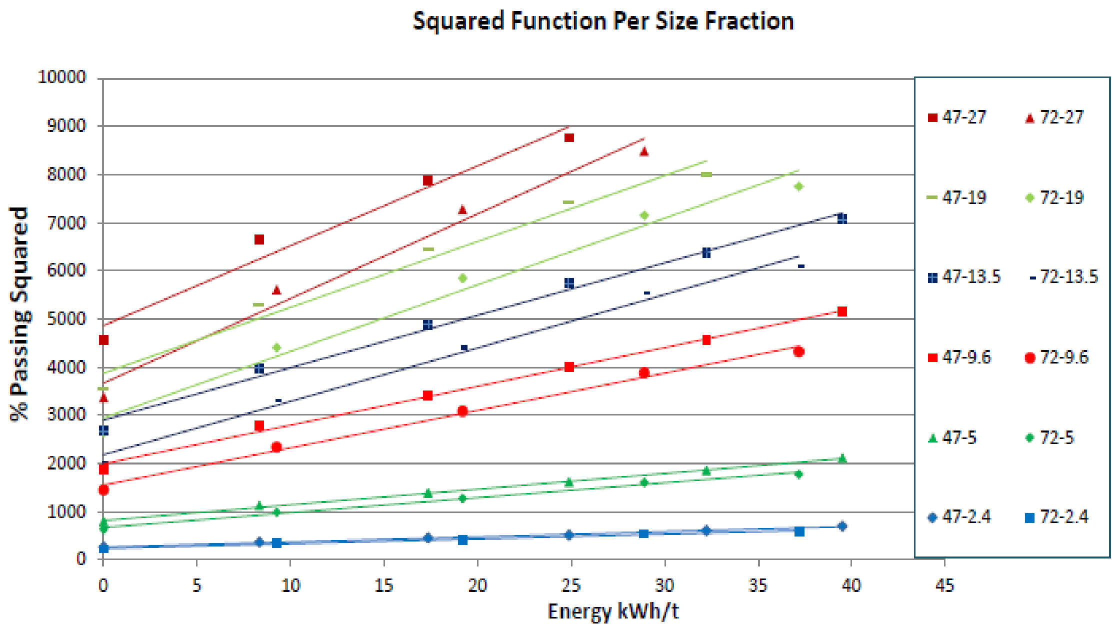

Figure 6. Complete comparison of different feed size squared function lines

It is assumed that as media size is changed to larger media, the lines for the coarsest size fraction will steepen and the finer size fraction will flatten. For smaller media, the coarsest fraction will flatten and the finer fraction will steepen as fine particles are preferentially broken compared to larger particles by the smaller media.

The actual slopes and error associated with Figure 6 are detailed in Table 3 below. The results of the 47 micron feed were plotted and used to predict the product size distribution shown in Figure 7. Given the +/- 5% error associated with the M4 signature plot test this can be considered a successful demonstration of the squared function model.

Table 3. MIM Copper ROM squared function predicted versus actual (Larson, 2013)

Size fraction (microns)	Slope 47 micron feed	Slope 72 micron feed	Error	New feed intercept	New feed predicted %passing	New Feed actual %passing
2.4	10.658	10.013	6.05%	225	24.93	24.31
5	32.6	30.85	5.37%	639.1	43.03	42.2
9.6	80.47	77.63	3.53%	1453.9	66.69	65.77
13.5	108.81	110.79	1.82%	2025	77.93	78.17
19	136.65	138.2	1.13%	2650.2	87.94	88.05
27	165.72	175.56	5.94%	3376.8	97.68	95.65

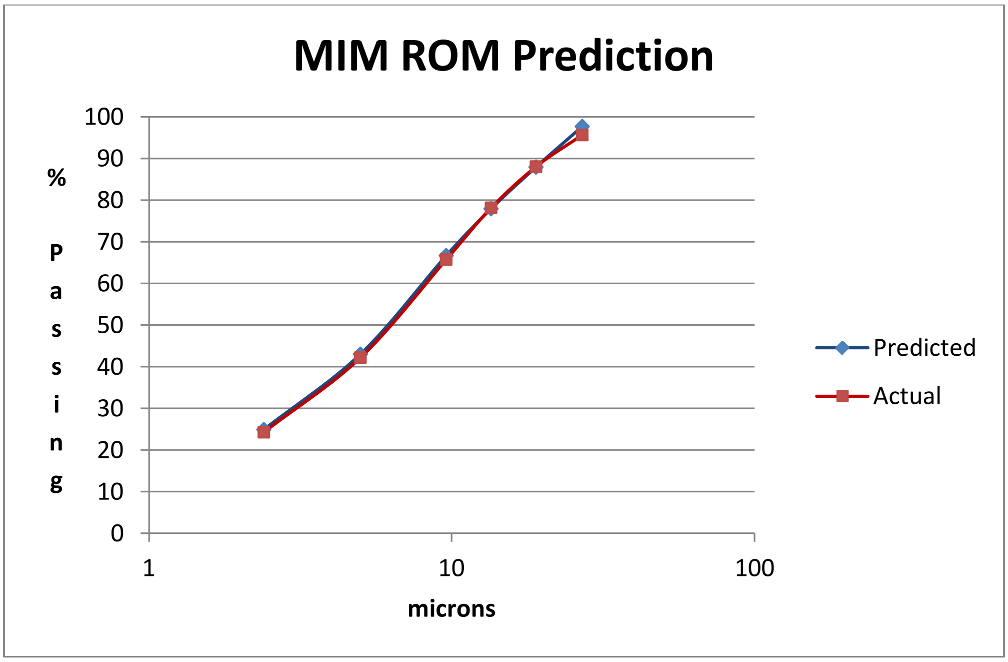

Figure 7. Predicted versus actual product size distribution MIM Copper ROM using the squared model (Larson, 2013)

A second validation example is detailed in Table 4. In this case, MIM lead/zinc run of mine ore was ground in a pilot rod mill to P_{80}'s of 131 and 68 microns. Both samples were then processed with the same 3.5 mm top size graded charge of media.

Table 4. MIM Lead Zinc ROM sizing and energy per pass data (Larson 2013)

	Energy	%<	%<^2										
P_{80}=		2.4 µm		5 µm		9.6 µm		13.5 µm		19 µm		27 µm	
131 µm	0	17.95	322.32	25.92	672.02	34.11	1163.72	38.02	1445.52	41.75	1742.78	45.71	2089.40
	7.9	27.14	736.58	40	1600.00	53.88	2903.05	60.64	3677.82	67.24	4521.89	74.36	5529.41
	15.0	31.14	969.70	46.61	2172.49	63.93	4087.68	72.9	5314.41	81.51	6643.88	89.385	7989.68
	22.0	34.22	1171.01	51.81	2684.28	72.42	5244.66	82.42	6793.06	90.44	8179.39	96.02	
	28.7	36.075	1301.41	55.365	3065.28	77.89	6066.85	87.63	7679.89	94.31		98.14	
	35.6	38.04		58.68		82.1		91.11		96.45		99.01	
P_{80}=	0	23.453	550.06	33.633	1131.20	44.29	1961.90	49.43	2443.65	54.31	2950.30	59.573	3548.98
68 µm	6.9	28.6	817.96	42.32	1790.98	57.56	3313.15	65.44	4283.05	73.37	5383.16	81.715	6677.34
	13.8	32.09	1029.45	48.265	2329.51	66.94	4481.63	76.63	5872.92	85.50	7311.11	92.82	8615.55
	20.0	34.61	1197.85	52.77	2784.67	74.36	5529.41	84.44	7130.11	92.05	8473.20	97.05	
	26.0	36.95	1365.30	56.44	3185.47	79.11	6259.18	88.72	7872.13	95.01		98.39	
	32.4	37.94		58.94		82.83		91.77		96.86		99.17	

In this test, the slopes matched up very well, with most error at the coarsest size fraction. This is shown in Table 5 and in Figure 8.

Table 5. Lead/Zinc ROM squared function prediction versus actual (Larson, 2013)

Size fraction (microns)	Slope 68 micron feed	Slope 131 micron feed	Error	New feed intercept	New feed predicted %passing	New feed actual %passing
2.4	30.88	33.63	8.18%	322.3	34.76	36.075
5	78.36	82.41	4.91%	672.02	54.05	55.37
9.6	166.08	170.33	2.50%	1163.72	77.01	77.89
13.5	210.87	218.63	3.55%	1445.52	86.59	87.64
19	276.89	294.01	5.82%	1742.78	98.31	94.31
27	367.1	393.84	6.79%	2089.4	112.35	98.14

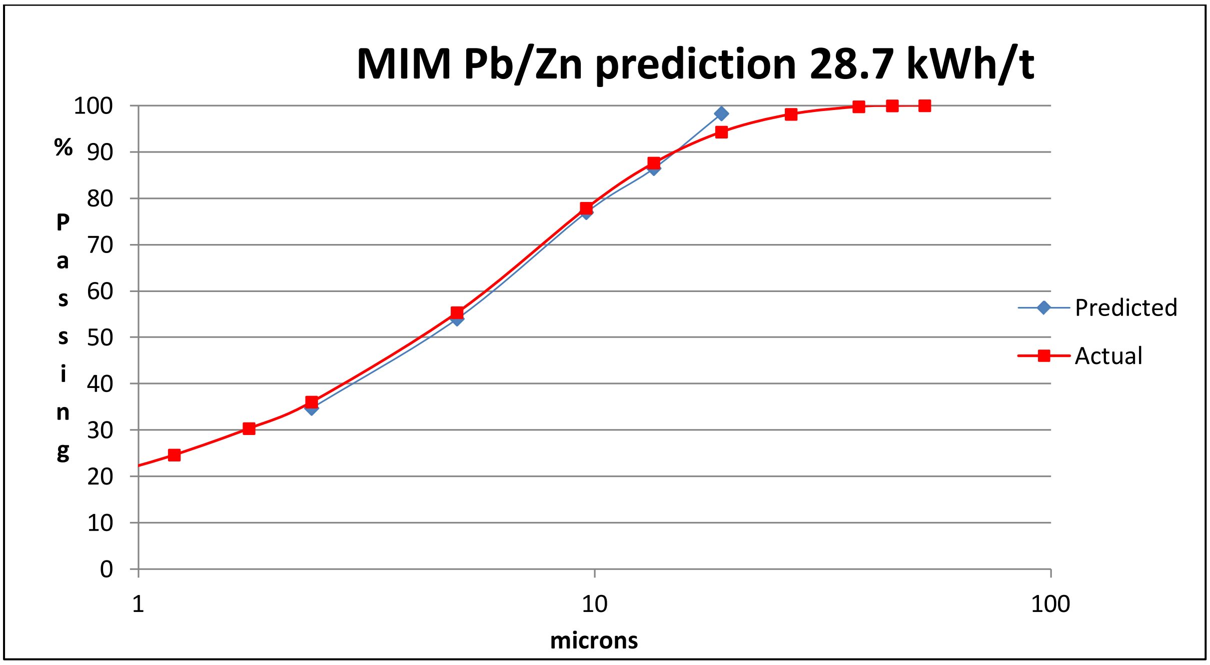

Figure 8. Predicted versus actual product size distribution MIM Lead/Zinc ROM (Larson, 2013)

The coarsest sizes tend to be more difficult to predict. As the sizes get closer to the P_{100} there is much less of the material to be created and the curve starts to flatten and give a worse prediction if the data is not cut off correctly. It is also generally a size fraction that is more likely to be held in the mill and is difficult both to sample and to measure correctly in the Malvern.

JKSimMet Model Implementation and Testing

Despite the apparent success of validating the model in MS Excel, it was still necessary to prove that JKSimMet programming could be implemented to duplicate these results without manual adjustments to the data.
The original signature plot data was provided to the JKMRC along with the feed size to a second test. Besides the new feed size distribution two energies were provided with the test from which the JKSimMet model was to predict the resulting product size distribution curves. The results comparing the model values to what was

actually ground in the M4 IsaMill are shown in Figures 9 and 10 for two MIM copper examples and one MIM lead/zinc sample.

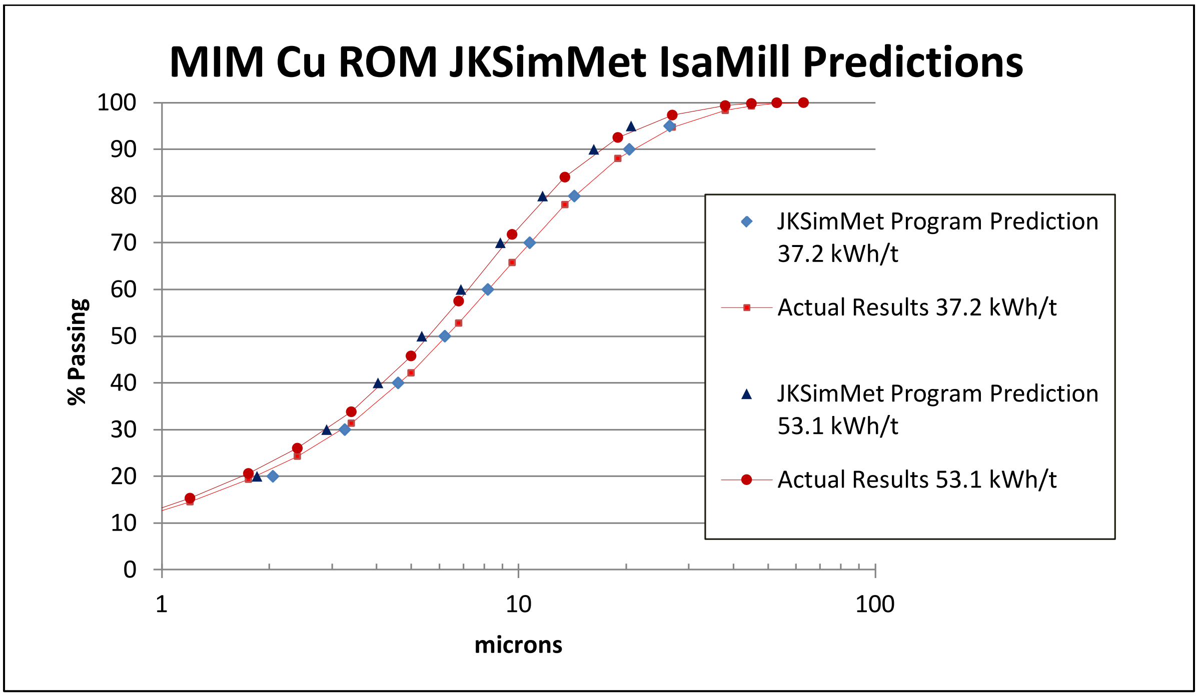

Figure 9. JKSimMet IsaMill model predictions versus actual for MIM Copper ROM

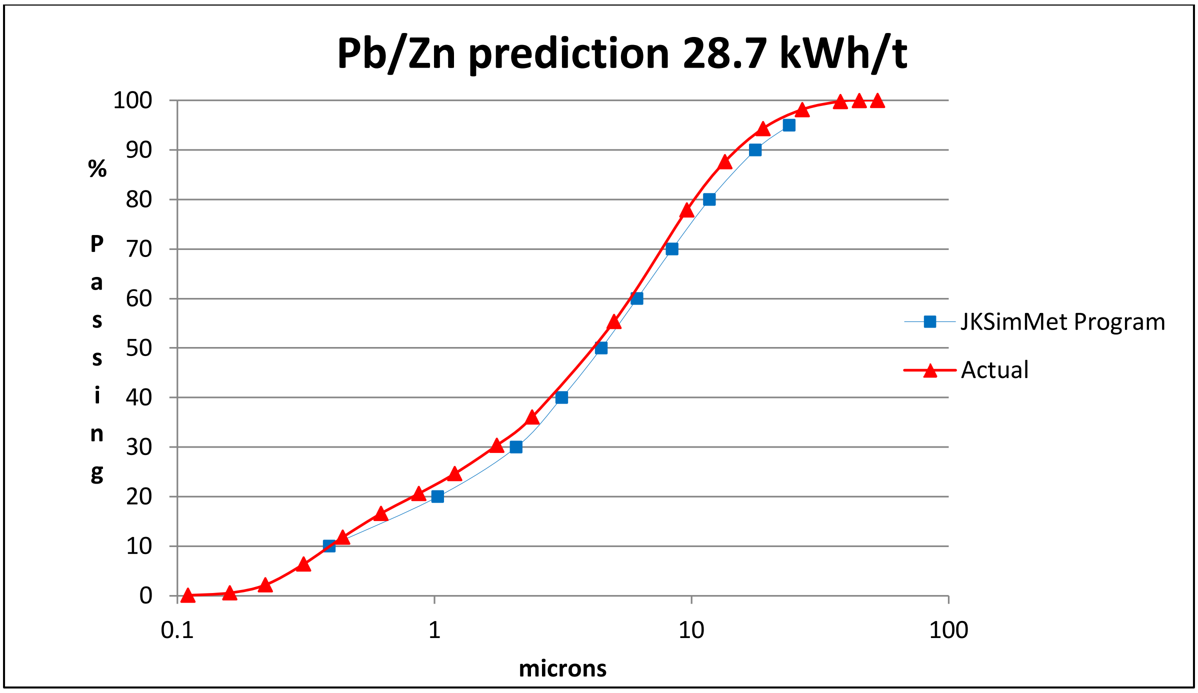

Figure 10. JKSimMet IsaMill model predictions versus actual for MIM Lead/Zinc ROM

These cases can be considered a success as they accurately match the results generated without the need for manually adjusting the settings. In this case all original data over a P_{95} is ignored automatically by the program.

Implementation into JKSimMet

A brief summary of the model implementation is included. The simplicity of the squared function allows for a relatively easy to understand model.
The IsaMill spreadsheet model was first converted into a MatLab program to allow ease of parallel testing. Once this testing was complete, the ability to predict the full product size distribution was added using spline functions.
The model was then converted into Fortran within the JKSimMet Model Developers kit.
At this point, the full calculation of the signature plot from measured data was also added to ensure a reproducible approach to interpolation and calculation.

The squared function is applied as follows:
The first step is to determine the linear relationship of energy versus the square of percentage passing 9.6um (or other size fraction that is valid for use) from the original feed. Any data from an individual pass that is coarser than the P_{95} for that pass is disregarded;
The second step is to calculate the point of new feed with zero energy input in the map of energy vs. the square of percentage passing 9.6um;
The third step is to plot a line parallel to the line in the first step from the point of new feed of the second step;
The final step is to find the value of the percentage passing 9.6um at the new input energy.
After the above method applied for a few size classes, the product size distribution can be interpolated.
The model was then tested against a range of reliable test work data.

Using the Model as an Evaluation Tool

While reduction ratios cannot be used to evaluate the efficiency of different fine grinding options, the squared function can be used to a certain extent. With just the IsaMill model, different variables including feed sizes can be tested for efficiency. In the case of only comparing IsaMills, the slope of the squared function line at a size or sizes of interest can be compared. The steeper the line the more energy efficient the grind is going to be. This is not proven to work when comparing different technologies. When comparing against a ball mill or tower mill or other high speed stirred mill, the comparison would only be valid if both received the same feed size. In those cases the squared function line could be developed for the IsaMill and just the product vs. energy point plotted for the other technology. If that point was to the right of the IsaMill squared function line, that option would be less energy efficient and if it were to fall to the left of the IsaMill line it would be more efficient. If the feed sizes were different, the analysis would be invalid as the shape of the line is yet to be established for other technologies.

Future Work

Future work to fully develop this model will focus on how a change in media size affects the individual particle size slopes along with how mineralogy and ore SG will impact on energy efficiency. It is thought that as media size increases the spread between slopes will increase. That is the finer particle lines will flatten and the coarser particle lines will steepen. These need to be able to be predicted to widen the size ranges that can be predicted where the change in feed size necessitates a change in media size.

Predicting the effects of mineralogy with regards to energy will be more difficult. There are some observations in XT test work database that a lower solid specific gravity in magnetite feed will result in a higher required energy to grind to a given target size. This may be due to the lower density material having more particles per tonne needing attrition breakage than a higher density magnetite feed along with the extra silica generally being harder. This explanation is more difficult when it comes to most copper and gold ores where the gangue material can vary more widely than just being silica. A pyrite gangue can increase the solid density but depending on the pyrite can either be very hard or quite brittle.

It is also accepted that the relationship between grinding achieved and incremental energy input becomes even more inefficient at still finer sizes. Hence, an increased exponent may be required for products very much finer than the “normal” IsaMill range.

Acknowledgements

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References

Farber B, Durant B, Bedesi N, 2010. Effect of Media Size and Mechanical Properties on Milling Efficiency and Media Consumption; Comminution 10; Cape Town, South Africa

Gao M, Reemeyer L, Obeng D, Holmes R; 2007. Efficiency of the Detritor Mills at Zinifex Century Mine; AUSIMM proceedings of 9th Mill Operators’ Conference

Johnson, N W, Gao, M, Young, M F and Cronin, B, 1998. Application of the IsaMill (a horizontal stirred mill) to the lead-zinc concentrator (Mount Isa Mines Ltd) and the Mining Cycle, in Proceedings AusIMM ’98 – The Mining Cycle, pp 291-298 (The Australasia Institute of Mining and Metallurgy: Melbourne)

Larson M; 2013. Experimental Study of IsaMill Performance Leading to a Preliminary Model, Master of Philosophy thesis, University of Queensland-JKMRC (unpublished)

Mannheim V, 2011. Empirical and scale-up modeling in stirred ball mills, Chemical Engineering Research and Design 89, (2011) 405-409

Nel G, Swarts A, Donegan S, Johnson G, 2006. Comparing the milling Efficiencies of Pilot Scale Horizontal and Vertical Ultrafine Grinding Mills for Tati Sulfide Concentrate; Proceedings of the Randol Innovative Metallurgy Forum 2005, Perth, Australia