Specific Energy - The Race to the Bottom

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As the mineral processing industry strives to achieve more efficient grinding capabilities, various tests can be undertaken to evaluate the range of alternative fine grinding technologies that may be appropriate for a project. As there is no acknowledged 'universal' methodology to evaluate stirred mills, each mill manufacturer proposes their own test methods for their proprietary products. In a technology trade-off, if a mill meets the minimum requirements to be deemed as suitable for a project, the option with the lowest specific energy is typically selected as more "energy efficient". However, this purported gain in "energy efficiency" based on the test results at face value, can often be a symptom of poor testwork design and risks the inability to translate to a full-scale installation. This paper will address the factors involved in the design of stirred mill testwork, how these can influence the overall specific energy, and why it is important to thoroughly evaluate the ability to scale up when conducting technology trade-offs.

1.0 Introduction

Communition circuits are the largest single consumers of final energy for hard rock mining operations, consuming one-quarter of the total final energy in mining (Allen, 2022). This has created several initiatives in the industry to improve efficient grinding capabilities, enabling stirred milling to become the accepted technology for optimising performance and reducing carbon footprint in grinding duties.

As the mineral processing industry strives to achieve more efficient grinding capabilities, various tests can be undertaken to evaluate the range of alternative fine grinding technologies that may be appropriate for a project. As there is no acknowledged 'universal' methodology to evaluate stirred mills, each mill manufacturer proposes their own test methods for their proprietary products.

Proprietary stirred milling tests (IsaMill™, VRM Mill, Jar Test) are effectively scaled-down Operating Work Index (OWI) comparisons. It is by conducting these OWI tests that engineering houses can determine the specific energy for the design constraints to size a mill. Typically, from the Vendor's perspective, the industry tends to accept these results as scalable with less scrutiny than would usually be afforded to a primary grinding circuit.

This paper will highlight how tests can be manipulated to produce the lowest specific energy, and the subsequent cause and effect of manipulating certain testwork on grind energy results, using the IsaMill™ as a case study.

2.0 Stirred Milling Tests

It has been established repeatedly that for fine grinding applications (sub 100 microns), the Bond Work index (BWi) should not be used (Doll, 2017 & Gurnett et al, 2022), because the exponent varies substantially under 100 microns for different ores. In in place of the BWi, there are an abundance number of vendor tests that can be carried out to establish the grind energy for a sample. Table 1 summarises the key differentiators between these tests;: method of power measurement, whether factors are involved in the scale-up, grinding chamber volume, sample size, sample collection method, and media selection.

Table 1: Summary of Differentiators between stirred milling tests (Thomson et al, 2024)

Mill	Vertimill	SMD	VRM	IsaMill™
Energy Measurement	Calculated from torque coupling and tachometer	Calculated from torque measurement through a load cell	Calculated via a torque strain gauge and tachometer	Power measured directly from drive energy consumption via a frequency inverter
Scale-up	Uses a scaleup factor which varies between 0.65 and 0.85. – depends on duty and feed size	Reported 1:1 scaleup Small sample causes specific energy bias	Reported 1:1 scaleup. Small sample causes specific energy under bias	Demonstrated 1:1 scaleup
Grinding chamber volume		1.4L	7.2L	4L

Sample size	1.5 kg	0.5kg	5-8kg (small sample) or 30-50kg (semi-continuous)	15kg minimum (semi-continuous)
Sample Collection Method	Sampled from top of mill – high likelihood of particle segregation	Sampled from top of mill – high likelihood of particle segregation	Product stream representatively cut	Product stream representatively cut
Media	19mm (single size) steel media	2-3mm (P80>20um) 1-2mm (P80<10um)	Media size optimised to F80 and P80	Media size optimised to F80 and P80

3.0 Scale-up in the Industry Today

Despite the importance of scalability in a milling test, a “close enough is good enough” attitude often prevails in industry, and if the energy difference can't be explained in ramp up it is often explained by ‘different mineralogy’. This is evident in cases of failures with tower mills to scale up 1:1 (Pease J, 2010) and continues today.

Another example of failure to scale up was the Coarse Particle Flotation expansion for Train 1 and 2 at Newmont’s Cadia Mine in Australia. Multiple regrind tests were used (Nippon-Enrich Tower mill test, Levin Test and Modified Levin test corrected for Vertimill) and the average specific energy was determined, and subsequently a mill sizing larger than required based on this average specific energy was selected (Haines et al., 2024) due to uncertainty about the mill power demand and known sizing issues inherent with vertical screw-type mills (Figure 1). However, when the mill was installed, the actual OWI was 10% above the design (Haines et al., 2024).

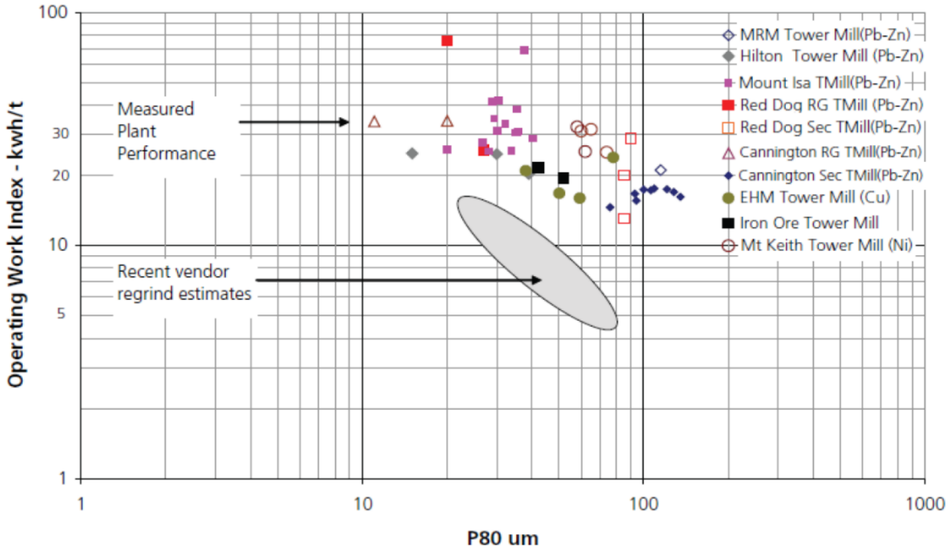

Figure 1: Tower Mill Operating Work Index Summary (Pease J, 2010)

This inaccuracy is not limited to screw-type mills; other examples are seen in Vertical Regrind Mills (VRM). A mill at Ero Copper was originally sized at 7.6-10.7 kWh/t (Pretorius et al., 2023), but the latest performance shows it requires 16.6 kWh/t (Cunha et al., 2004). Since then, a larger motor has been commissioned on the mill to ensure sufficient power (Cunha et al., 2024). Sunrise Dam commissioning data had indicated extreme variability, where specific energy variations to 10 microns are between 40-90 kW/t (Paz et al., 2021), with a potential variation of up to 35%.

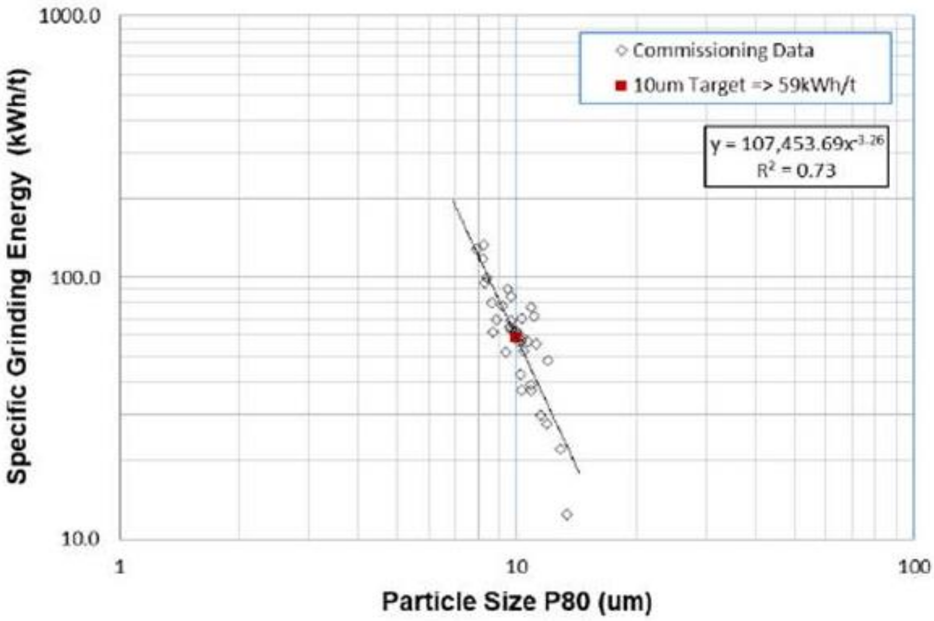

Figure 2:Sunrise Dam HIG3500/23000 Commissioning Data (Paz et al, 2021)

Recently, Altun et al. (2024) conducted a review on trying to validate the scale-up of the VRM/HIG Mill design. In this study, it was found that by reviewing signature plots, only 1 out 5 surveys demonstrated a 1:1 scale-up without a factor (Altun et al., 2024). The stress energy analysis approach indicated that the linear relationships of the two mills (pilot and full scale) are markedly different. However, the data can be fit onto the same line once the mill volume ratio to the power of 0.08 is considered as a scale-up constant. (Altun et al, 2024). It is the author's belief that once scale-up factors are considered, the claim of a 1:1 scale cannot be valid.

So fundamentally what drives this inaccuracy?

3.1 Sample Mass

One of the biggest concerns raised by clients with the Signature Plot tests is that accumulating 15 kg of material for a greenfield site is an expensive exercise, and many ask why smaller sample masses cannot be used. The 15 kg mass requirement for the IsaMill™ ensures there is sufficient material to allow the test to achieve steady state. Previous publications showed that for a stirred milling test to achieve a steady state, there must be sufficient samples to replace the mill voidage volume at least 3-4 times (Larson et al., 2011). This prevents the hold-up of coarse particles, which would result in an underestimation of energy in the range of 30-50%.

Figure 3 demonstrates this sample mass requirement quite clearly. A standard Signature Plot (dark blue) was conducted on an operating gold plant (3.5 SG feed). To validate the test conditions, the plant feed was surveyed (red dot). The graph shows that the plant feed falls on the Signature Plot line demonstrating the suitability of the Signature Plot relationship for predicting operating plant data – enabling direct scale-up from the Signature Plot test to full plant conditions (Gurnett et al, 2022).

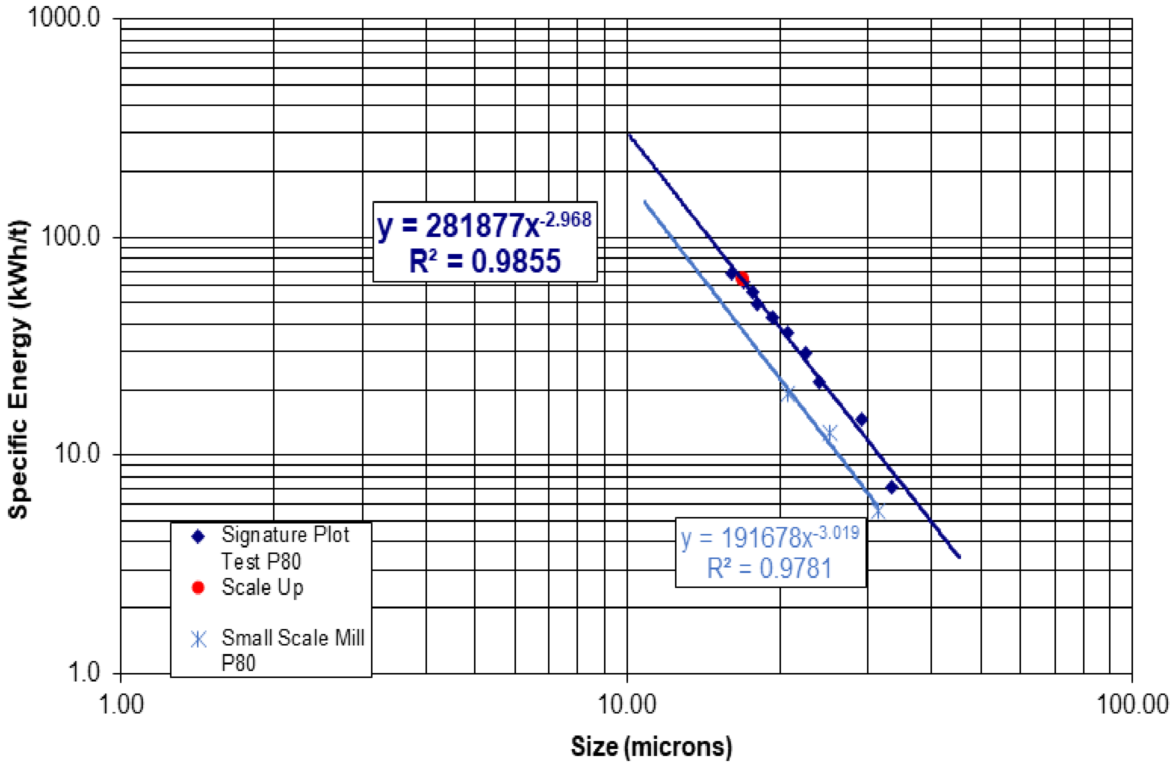

Figure 3 - Comparative scale-up Signature Plot with a small mass sample (Gurnett et al, 2022)

To demonstrate the impact of insufficient sample material and how this results in underreporting specific energy, a 5 kg sample was run through the IsaMill™ Signature Plot procedure. The results of this are shown in Figure 3 (light blue line). This reduced sample resulted in an underestimation of the grind energy of approximately 30-40% . This systematic bias was produced by a failure to reach steady state within the mill due to insufficient sample mass (Gurnett et al, 2022).

A mathematical demonstration of this is provided in Table 2 below. The data shows the effect of Specific Gravity (SG) and required sample sizes within a standard M4 (4L) IsaMill™. As shown, with the range of nominated SG of the material, between 13.4 to 22.4 kg is required to achieve steady-state conditions (Gurnett et al, 2022).

TABLE 2 - Explanation of sample requirements for the IsaMill™ to achieve steady state (Gurnett et al., 2022)

Media volume @100%, L	3.4		
Media volume @74%, L	2.5		
Void space between packed beads, %	24%		
Total available void space inside mill, L	1.5		
Volume of void space in between beads, L	0.6		
Void space in mill not occupied by media, L	0.9		
SG of solids in the sample	3.0	4.0	5.0
Volume of solids to reach steady state (3x), L	4.5	4.5	4.5
Minimum mass of sample required, kg	13.5	18.0	22.5

Based on the example above, a 5 kg sample (at a SG of 3.0) will provide sufficient material only for a single full pass, not reaching steady-state conditions. The inability to reach steady-state conditions will result in the coarse material inherently retained within the stirred mill thereby biasing the specific energy plot. Without reaching steady-state conditions, this will always result in underreporting of the energy required (Gurnett et al., 2022).

3.2 Energy Measurement

A point of contention between the different stirred media tests is the interpretation of power. In an IsaMill™ Signature Plot test, energy is recorded at the Variable Frequency Drive (VFD) with the No Load Power (energy required to move the shaft) subtracted to determine energy input. Glencore Technology measures power at the VFD as it allows for the 1:1 scale-up.

Other stirred milling tests measure power by interpreting torque. Glencore Technology recently conducted an exercise to evaluate whether this would influence the signature plot on the M4 IsaMill™. A supplier factory-calibrated torque meter was installed onto a new shaft for an M4. And the M4 shaft was then replaced and a side comparison was done to measure torque with the VFD. This signature plot was completed on an M4 by an accredited operator for steady-state conditions.

Figure 4: Torque Sensor installed on an M4 IsaMill™ Shaft

Net torque is obtained by taking the running torque and subtracting 'no-load torque' (again measured when operating the mill without media or slurry). Torque measurements were continuously monitored during the trial for stability. The power was then determined by the following equation:

Equation 1: Power Calculations by Torque

$$Power\ (kW) = \frac{T(Nm) * N(RPM)}{9549}$$

The torque meter's results suggested an average 13.5% energy reduction for a copper concentrate and 14.5% energy reduction for a silica powder when compared to the VFD. The results from the copper concentrate signature plot can be seen in Figure 6.

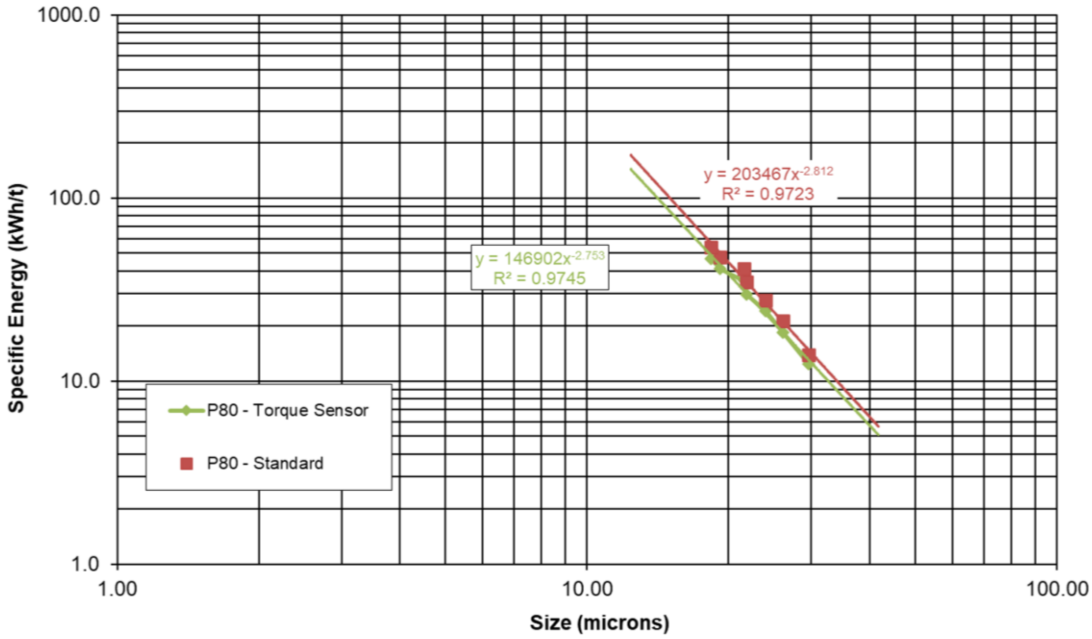

Figure 5: Signature Plot Comparison for a Torque Meter v VFD

This effectively outlines that reliance on torque measurement for power determination will result in an underestimation of grind energy. When reviewing the data, consistency between technologies when reviewing power is best practice.

3.3 Sample Method Collection

Sample bias is a significant issue in small-scale testwork. As with any mineral processing application, it is recommended to do a full cut of a stream to ensure sample integrity; not all tests follow this methodology due to design. During Vertimill and SMD tests, the mill is stopped and opened, and a sub-sample is taken from the top. The sample will naturally segregate, and the sample collected will result in a lower particle size for a fixed energy measurement.

Some segregation occurs naturally, even in an agitated, baffled tank. To ensure sample integrity in an IsaMill™ signature plot test, the entire stream is sampled when at least ¾ of the feed material has entered the mill to ensure steady-state conditions have been met. The entire sample is collected and put into a baffled container. It is then agitated for a minimum of 2 minutes, and then the sample is collected at the following location in the baffled beaker (Figure 6).

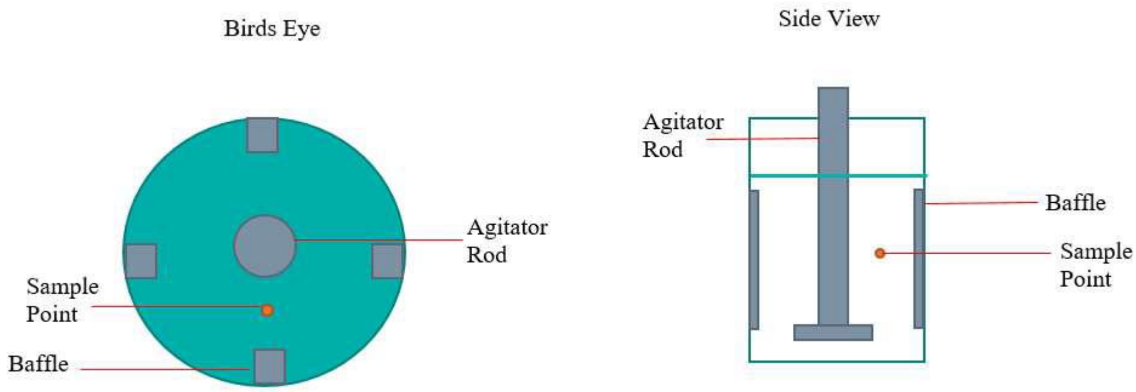

Figure 6: Malvern Subsampling Procedure (Glencore Technology, 2024)

Interestingly, one of the largest hurdles to passing IsaMill™ accreditation is the technique of operating a laser sizer. Therefore, it is always best to follow best practices from Original Equipment Manufacturers when operating the laser sizer.

<u>3.4 Volume of Media Mass</u>

The size of the mass of the media will significantly affect grinding efficiency. This is logical, as when the media mass size is increased, the number of stress collisions present will increase. This is demonstrated in Figure 7 below, as at increased filling up to 0.85, the specific energy curve shifts to the left, promoting the increase in efficiency.

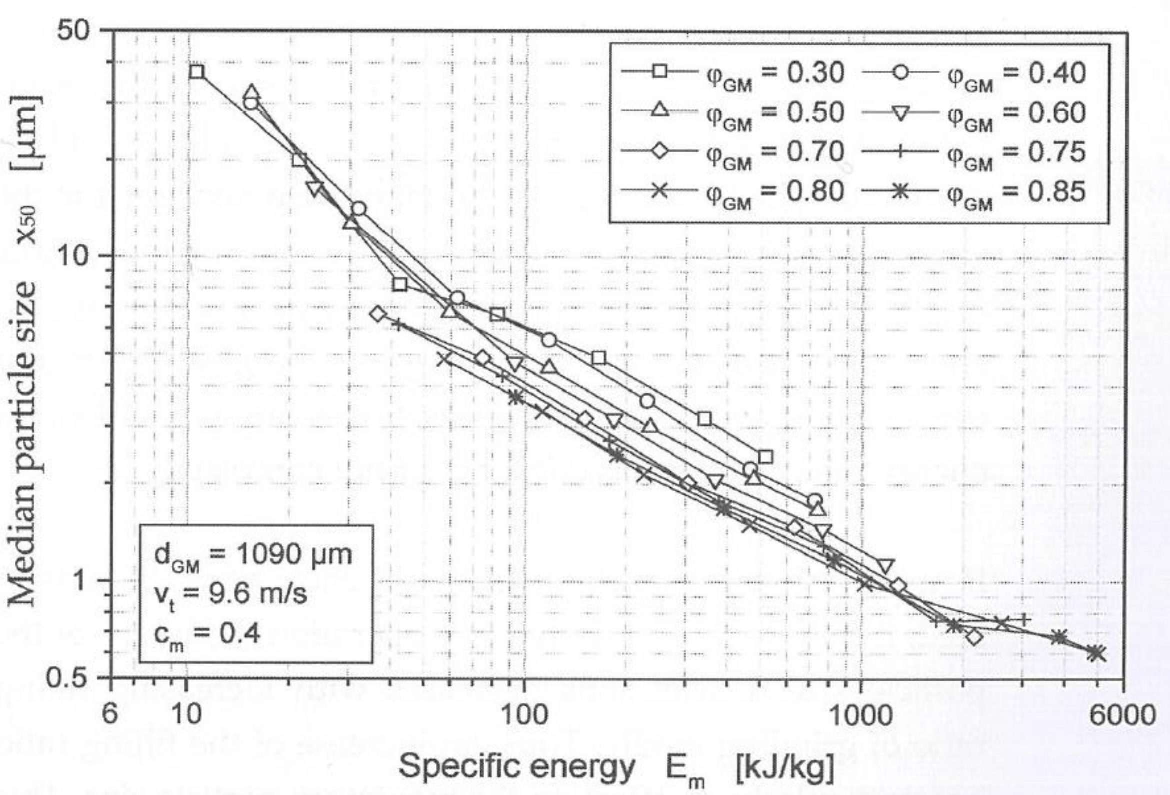

Figure 7- Effect of filling ratio of grinding media on the relation of product finess and specific energy(Kwade and Schwedes, 2007)

If you take the voidage and multiply it by the specific energy for a known particle size, these efficiencies seem to negate each other, and a linear relationship is generated. This identifies why testwork at 70%

media loading can scale up to a full-scale mill at 30% media loading. This trade-off is not typically looked at when technologies are evaluated for process efficiency. As tests with a higher media volume typically show better "energy efficiency".

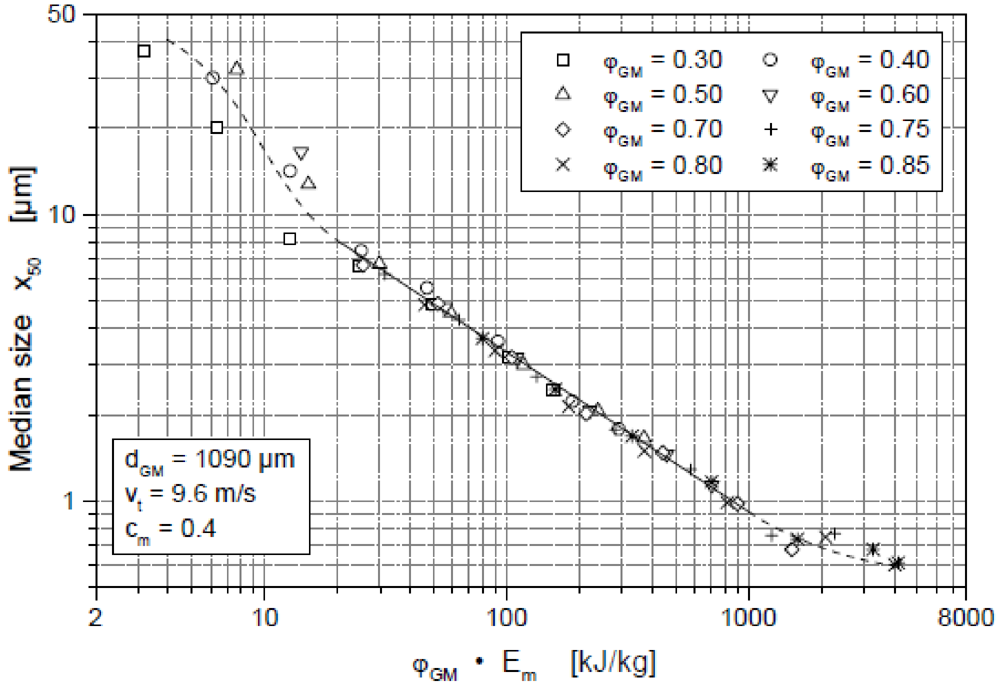

Figure 74: Relation between the product fineness and product of specific energy and filling ratio of grinding media (Kwade and Schwedes, 2007)

3.5 Particle Size Methodology

Due to the fundamental principles on which laser particle-size-analysis units (e.g. Malvern Mastersizers) work, they generally report a coarser result compared with a screen sizing method. This is because laser sizers utilise an "equivalent sphere" method (Gurnett et al, 2022). They measure the volume of non-spherical particles, calculate the diameter of an equivalent sphere, and use this as the particle diameter for the Particle Size Distribution (PSD) calculations (Malvern 2014). In Figure 12 below, an example of how shape influences the design is seen when a 100 µm long, 20 µm wide particle could potentially pass through a 21 µm aperture screen but would measure as a 39 µm particle in the Malvern laser sizer (Gurnett et al, 2022).

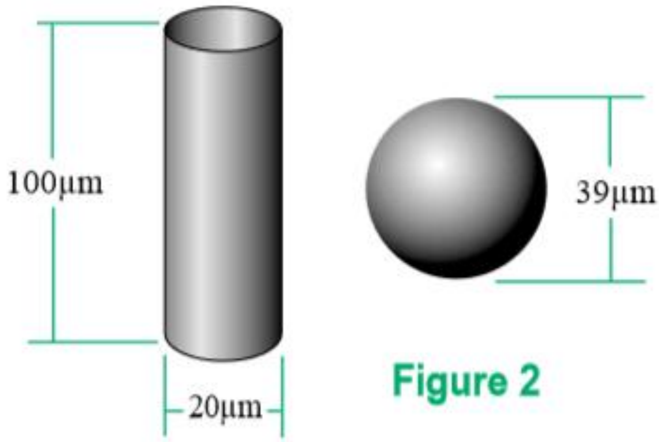

Figure 8 - Effect of particle shape on sizing (Malvern, 2014)

Therefore, if a sample has lots of non-spherical particles, e.g. micaceous silicates, the "coarseness" of the Malvern compared to screen sizing results will be exaggerated. A rough rule of thumb in laser sizing is that if the P98:P80 ratio exceeds 4, it is likely a particle shape issue. Surprisingly, if this is not picked up, it can be mistaken for coarse segregation, which can be an unfair reflection of the stirred milling technology. Evidence of the significance of the sizing technique can be seen in Figure 9 below, where a perceived 34% efficiency gain can be attributed to just how the particles are looked at.

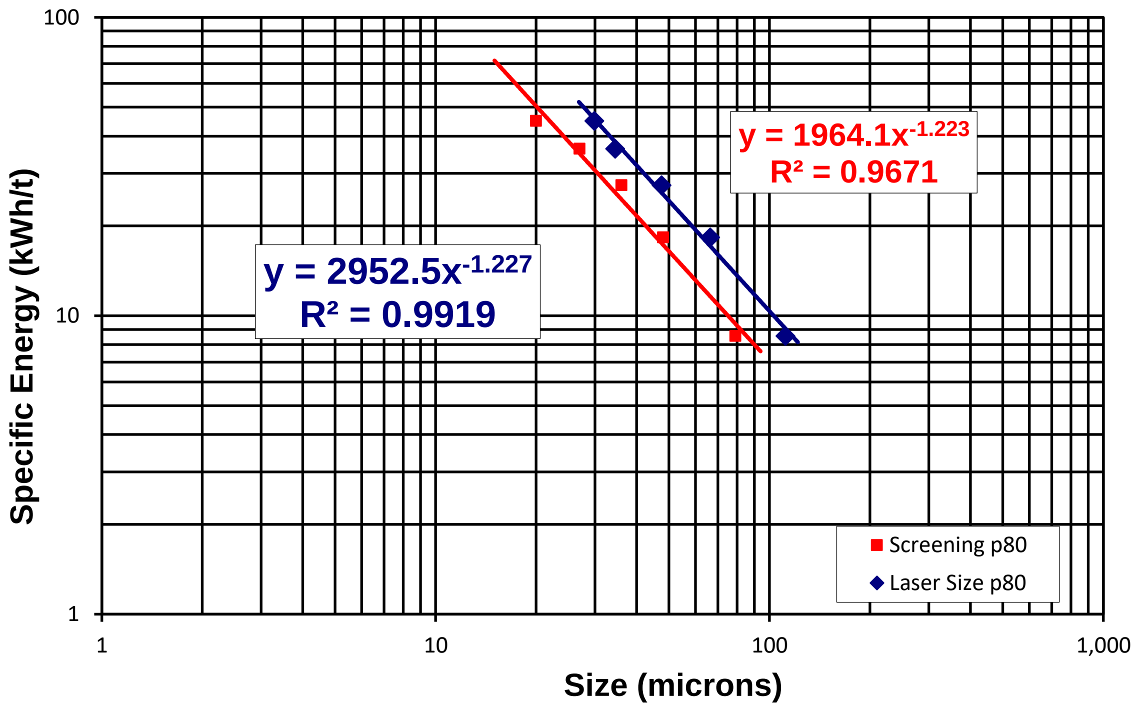

Figure 9: Tertiary Grinding – Signature Plot Laser Sizing vs Screens

4.0 Conclusion

This paper aims to provide a cause-and-effect structure to demonstrate "efficiency gains" in a stirred mill test. If a 1:1 scale-up is critical for project success, the authors hope that this paper acts as a benchmark to allow for the review of the specific energy results with greater context.

5.0 References

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