The Influence of Media Size and Density on Stirred Mill Energy Efficiency Based on a Stress Analysis Approach

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Abstract

Stirred media mills are widely used for fine or ultrafine grinding processes in the mining industry. Selecting media with physical properties best suited for a given grinding duty could improve the grinding energy performance as well as the quality of ground product. This study intends to investigate the impact of media density and bead size on stirred mill energy performance. The study was conducted on the feed sample of an IsaMill from a Canadian copper-gold mine where it is used in a regrind application. A total of 9 signature plot tests were performed with the 4-litre IsaMill (M4) charged with ceramic medias of different size and density combinations. The influence of media size and density on grinding efficiency were investigated via energy-size signature plot analysis, stress intensity analysis and size specific energy (SSE) analysis. Results showed that the media with 3.75 SG performs better than the media with 4.45 SG when mixed media size is used, and increasing the portion of large media benefits the breakage of coarse particles and hence reduces the specific energy required to achieve a relatively coarse grind size. It is also observed that the effect of media size on grinding energy efficiency differs as the media density increases.

Keywords: Ultra-fine grinding, IsaMill, grinding efficiency, media size, media density, stress intensity, size specific energy

1. Introduction

The average metal ore quality has declined over the decades, and many ores are becoming increasingly fine-grained. Therefore, improving the process of fine grinding has become more important for mining operations. Stirred media mills have been widely used by the mining industry for fine or ultrafine grinding to enhance liberation. The energy consumption of stirred mills is typically 30–40% less than ball mills at the same product size in fine grinding processes (Gupta & Yan, 2016).

Ceramic grinding media is the preferred media type for stirred milling processes. There are a wide range of ceramic media products of varying composition and quality. The media can be manufactured from refined industrial chemicals such as alumina (Al_2O_3), zirconia (ZrO_2), silicon carbide (SiC), and silica (SiO_2) depending on the desired properties.

The utilization of suitable media with optimized mechanical properties and bead sizing could increase the energy efficiency of stirred milling as well as improve the grinding product quality (Kotzé, 2012). The research from Gao et al. (2001) showed that for stirred milling lighter medium (specific gravity 2.6) was more energy efficient than the heavier media (specific gravity 3.7) but produced less final product per unit of time. Gao & Forssberg (1993) found that the energy utilization of stirred milling first increases and then decreases with the increase of media density. This phenomenon may be caused by the difference in the actual rotating speeds of different kinds of beads.

The size of the media also had a large impact on stirred milling performance (Jankovic, 2003; Celep et al., 2011; Jayasundara et al., 2012). Reducing the media size increased the energy savings in the stirred milling process, however, it might also increase the product size as small media was not as effective as big media in breaking the larger particles. Research from Farber et al. (2011) demonstrated that the selection of a high-density media with optimum sizing can improve the efficiency of stirred milling by approximately 30%.

The main objective of this research is to understand the effect of media density and size on the energy efficiency of stirred milling.

2. Materials and methods

2.1. Test sample

The feed sample from an operating IsaMill at a copper-gold mine in Canada was used for stirred media grinding tests. The mine uses the IsaMill to regrind rougher flotation product to a target P_{80} of 25 µm for subsequent cleaning flotation.

In total, 700 L of IsaMill feed slurry with 45 w/w% solid was received from the mine. The sample was oven-dried at low temperature and then split into representative sub-samples for the grinding tests. The PSD analysis of the feed sample is shown in Figure 1. The sample has a F80 of 64 µm and F50 of 22 µm.

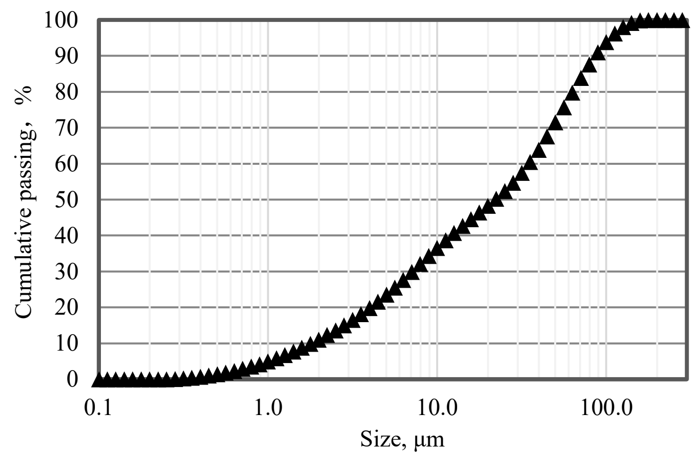

Figure 1: The particle size distribution of the test feed sample

2.2. Grinding media

Seasoned media from the IsaMill operation at the copper-gold mine was obtained. The discharged seasoned media were cleaned and crumbs below 2 mm were removed. The seasoned media has a density of 3.75 g/cm^3. The PSD of the prepared seasoned media is shown in Figure 2.

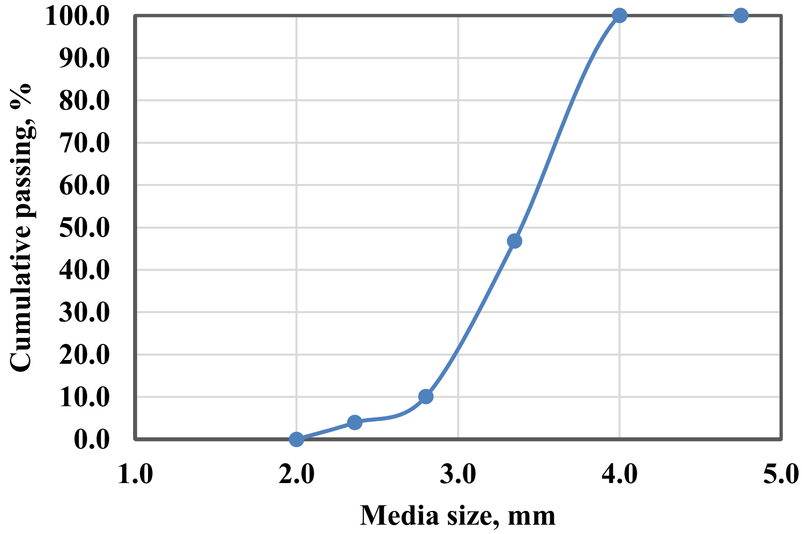

Figure 2: The PSD of the seasoned media

In addition, media of different sizes and densities from King's Beads were selected and tested, as summarized in Table 1. The sizes and densities conditions were determined considering the feed particle size and the target grind size P_{80} of 25 µm.

Table 1: Media densities and sizes determined for the tests

Test No.	Media Type	Density, g/cm^3	Size combination
1	Seasoned media	3.75	2~4mm
2	TA380	3.75	3mm=100%
3	TA380	3.75	2mm:3mm=30%:70%
4	TA380	3.75	3mm:4mm=50%:50%
5	TA380	3.75	3mm:4mm=30%:70%
6	TA450	4.45	3mm=100%
7	TA450	4.45	2mm:3mm=30%:70%
8	TA450	4.45	3mm:4mm=50%:50%
9	TA450	4.45	3mm:4mm=30%:70%

2.3. *Bench-scale IsaMill grinding test*

The stirred milling tests were conducted at UBC lab with a 4-litre Netzsch IsaMill (M4). The M4 was set up and calibrated with support from Glencore Technology to ensure that the test results are aligned with the standard practices. The particle size distributions (PSD) of the materials were analyzed using Malvern Laser Analyzer. The operating parameters for IsaMill testing are summarized in Table 2.

Table 1: Operating parameters for IsaMill testing

Testing condition	Value
Mill speed (rpm)	1500
Media filling level (v/v %)	65
Feed solid (w/w%)	45
Flow rate (L/min)	2

Signature plots were obtained by conducting pendulum tests with 8 grinding cycles. Samples of the feed and product from each cycle were collected for PSD measurement using Malvern Laser Analyzer. The IsaMill is installed with an electric power meter, and the electric power consumption for the no-load condition and for each grinding cycle was recorded to calculate the specific grinding energy.

2.4. *Stress analysis*

Stress analysis was used in this study to assess the effect of media density and size on energy efficiency. Based on the stress analysis approach, the process of ultra-fine grinding with stirred media mill can be treated as a series of stress events of varying stress intensity. The distribution of the stress number at varying stress intensity determines the product particle size distribution. It was suggested that an optimum stress intensity exists to achieve the lowest specific energy consumption for a given grinding process (Kwade,1999). Once the optimal stress intensity is identified, the mill operating condition such as mill speed, media density, and media size can be selected to target this optimal intensity and improve the grinding energy efficiency.

The stress intensity (Kwade 1996,1999) is determined by the mill operating parameters including media size, media density and mill speed and is proportional to the stress intensity of the grinding media, which can be defined using equation (1).

$$SI_{GM} = d_{GM}^3 . \rho_{GM} . v_t^2 \tag{1}$$

Where SI_{GM} is the stress intensity of grinding media; d is media size; ρ is media density; v_t is the tip speed of the discs.

One other significant indicator is the number of the stress events. In the grinding process the average number of stress events for each particle is determined by the media contact numbers, the probability that a particle is sufficiently stressed at a media contact, and by the number of product particles inside the mill (Kwade,1999). The probability that a particle comes in contact with media at a sufficient stress and the number of particles in a mill were considered for accurate calculation of the stress number (Kwade, 1999). The media-particle contacts inside the mill under different media density and size conditions are difficult to be accurately determined.

In this study, stress intensity for each level was calculated based on Equation (1) and the number of stress events was represented by the number of medias distributed within the mill active volume without considering the probability of particle-media contacts at sufficient stress for the sake of easy calculation and analysis. The stress event numbers may not fully reflect the actual grinding efficiency as a portion of the stress events may have minimal stress intensity and therefore would not contribute to the actual grinding.

It should be noted that the values from the stress analysis presented in this paper are considered qualitatively and should therefore be used only for relative comparison. More accurate estimations of such values could be obtained with computational modeling of the stress intensity distributions and the stress events number over intensities.

2.5. Assessment of grinding energy efficiency

In this study, the energy efficiency was assessed using the energy-size signature plot, which is a widely accepted and proven approach. The size specific energy (SSE) method (Ballantyne, et al, 2015) was also used where the target size of 25 µm (SSE25) was selected to calculate the energy (kWh) required to generate 1 tonne of new -25 µm product. For each test, the resulting signature plots and SSE values were compared to evaluate the influence of media size and density on the milling efficiency.

3. Results and discussion

3.1. Stress analysis

The stress intensity and stress numbers at different media density and size combinations were analyzed and the results are summarized in Table 3.

It was observed that for different media sizes and densities, stress intensity and the total number of stress events could vary significantly. Media size affected both stress intensity and the number of stress events. Generally, with a larger portion of large media (4 mm), stress intensity increased while the number of stress events would decrease. For high media density, the stress intensity was higher.

However, it is still unclear which combination of stress intensity and the number of stress events would result in the best grinding performance. The following section investigated this question by comparing the energy-size reduction results for each test.

Table 3: The stress intensity and stress numbers of different media density and size combinations and the corresponding specific grinding energy

Media Density & Size	Stress Intensity, N·m	Total Number of Stress Events
Seasoned media	1189.4	923853
TA 380 3mm=100%	796	1257345
TA 380 2mm:3mm=30%:70%	628	1654402
TA 380 3mm:4mm=50%:50%	1341	1033157
TA 380 3mm:4mm=30%:70%	1559	826597
TA 450 3mm=100%	944	1295397
TA 450 2mm:3mm=30%:70%	745	1654402
TA 450 3mm:4mm=50%:50%	1591	911609
TA 450 3mm:4mm=30%:70%	1850	826597

3.2. Effect of media density on grinding efficiency

Figure 4 shows the effect of media density on signature plots generated using mono-sizes of grinding media. The effect of media density on the energy-size reduction signature plot is insignificant with the use of mono-size media at 3 mm. However, with the use of mixed media size (as shown in Figures 2, 3, 4), the effect of media density becomes much more significant showing lower media density has higher energy efficiency.

Based on the stress analysis, for the test with large media size (Figure 4), increasing media density from 3.75 to 4.45 significantly increase the stress intensity. The stress intensity at 4.45 media density may already exceed the intensity required to break the coarse particles in the feed and hence the grinding efficiency of the test with 3.75 SG media is higher. For the test with a small media size, the effect of media density become more significant for finer grind sizes (Figure 3 vs. Figure 5). With a small media size, the increased stress intensity resulting from media density increase is not high enough to significantly improve the coarse particle breakage. By contrast, for the comminution of fine particles, the test with lower density performs better due to the increase in the number of stress events at lower stress intensity.

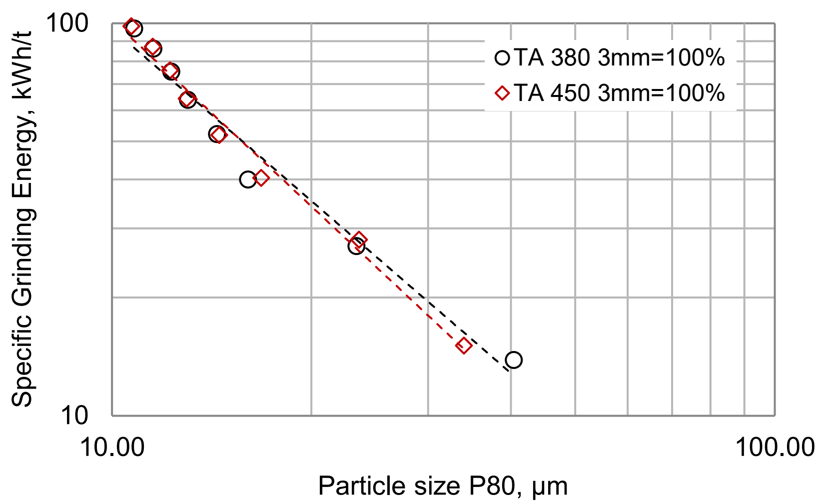

Figure 3: Effect of media density on signature plot with mono-size media

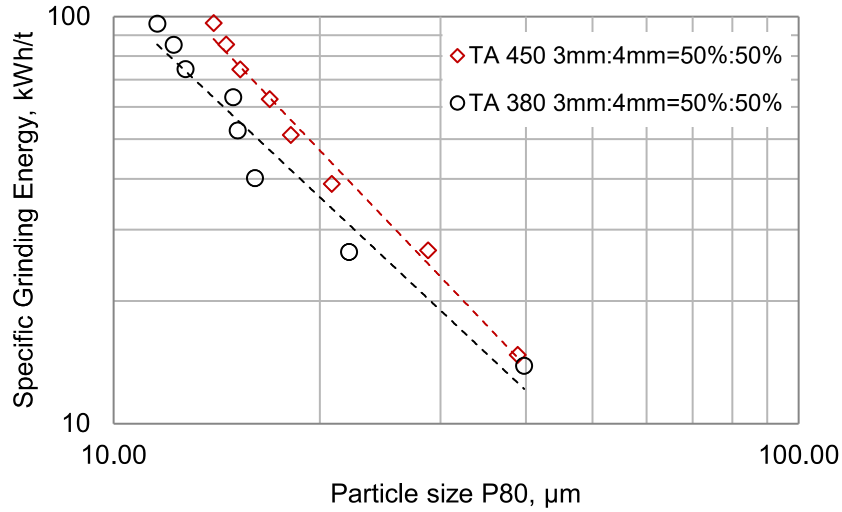

Figure 4: Effect of media density on signature plot with mixed media sizes, 3mm:4mm=50%:50%

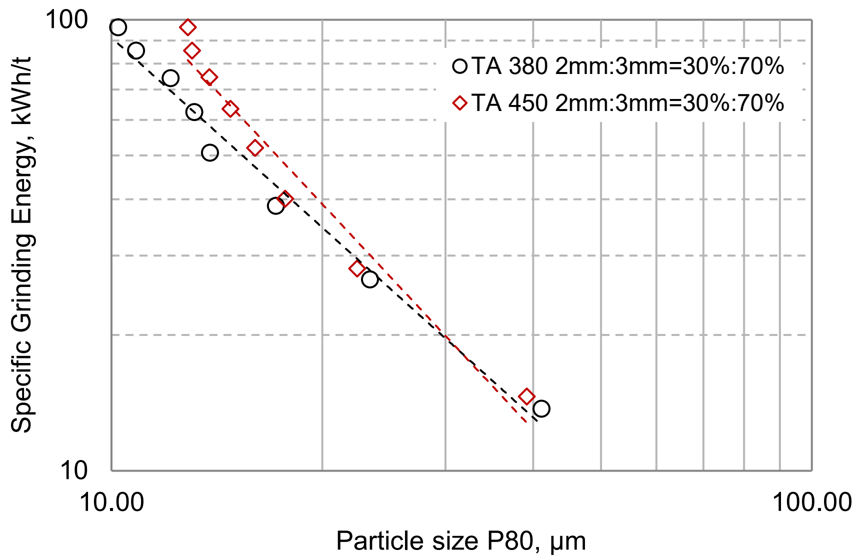

Figure 5: Effect of media density on signature plot with mixed media sizes, 2mm:3mm=30%:70%

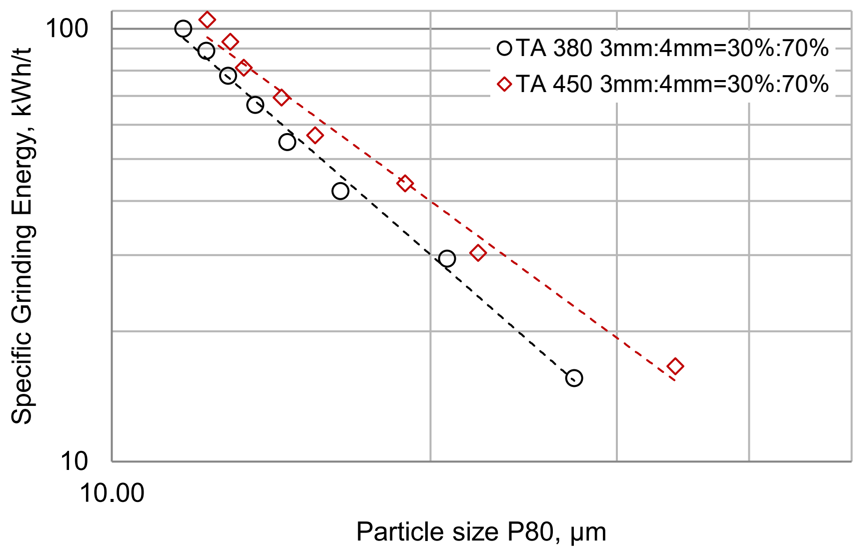

Figure 6: Effect of media density on signature plot with mixed media sizes, 3mm:4mm=30%:70%

3.3. Effect of media size on grinding efficiency

Four media size combinations using 2 mm to 4 mm beads were tested using King's TA380 and TA450, respectively. The signature plot results are shown in Figure 7 and Figure 8. For the test with TA380 (3.75 SG), small media size (2mm:3mm=30%:70%) shows better grinding efficiency at the fine grind size, while the large size media (3mm:4mm=30%:70%) grinds the coarse particles more efficiently. This is consistent with industrial experience of using larger beads for larger feed sizes and smaller beads for smaller feed sizes.

For the test with TA450, the mono-size 3 mm media shows better grinding efficiency than the mixed media sizes, which is not consistent with the trend observed for the test with TA380 media. The overall trend of how the media sizes affect the grinding efficiency for higher SG media is different from what is observed for TA380 media. It's suspected that, for different sizes of this higher SG media, the percentage of the additional energy input being consumed by only stirring the media (without mineral particles) will differ. Thus, the remaining energy for grinding varies for different bead sizes, and this affects the effectiveness of the grinding. More studies are required to validate this hypothesis.

Roufail's study (2011) showed that stirred mill broke the particles via both abrasion and fracture and the ratio of the above two breakage mechanisms varied with mill operating parameters. A small media size with higher media SG could achieve a similar stress intensity as the large media size with low media SG and result in similar fracture breakage results. Therefore, the effect of media size on grinding efficiency is complicated and it should be investigated with an overall consideration of media density as well as the mill operating parameters.

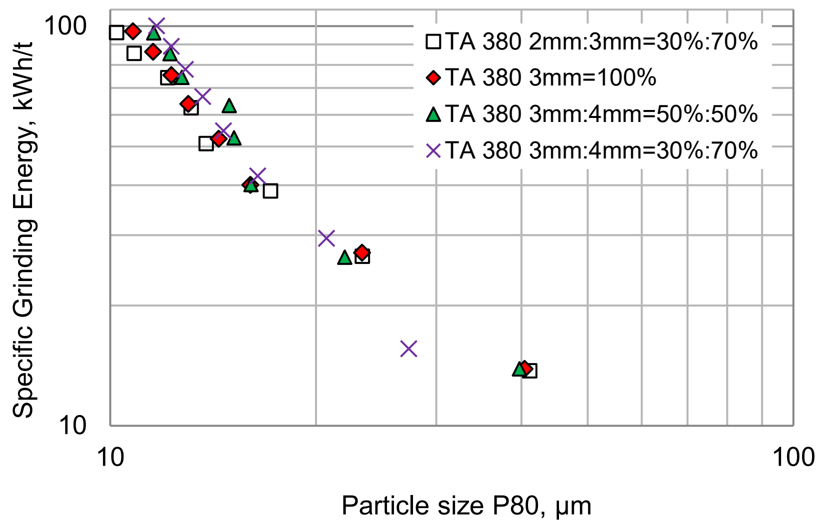

Figure 7: Effect of media size on signature plot – TA380 media

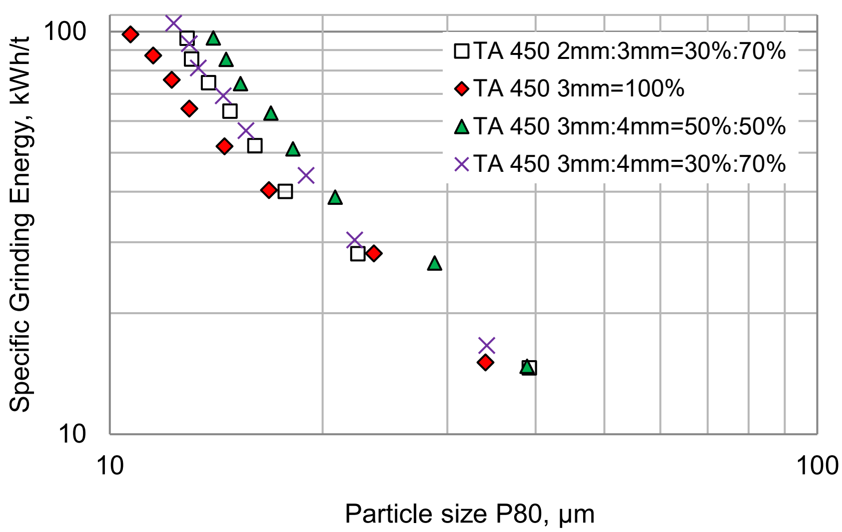

Figure 8: Effect of media size on signature plot – TA450 media

Figure 9 shows the energy-size reduction signature plot of the test with seasoned media and the test with TA380 media at mixed sizes (3mm:4mm=50%:50% & 3mm:4mm=30%:70%). Note that the actual size of the 3 mm and 4 mm media used in this study is 2.8-3.2 mm and 3.8-4.2 mm, respectively. It was found that the size distribution of the media has an important effect on the grinding energy efficiency. Figure 10 depicts the difference in size distribution of the media from the tests that were included in Figure 9. Increasing the portion of coarse media improves the grinding efficiency at a coarse grind size (>15 µm). The coarser the grind size, the bigger the grinding efficiency difference between the two grinding medias. At a fine grind size (<15 µm), the difference between the two tests becomes much smaller.

It is understood that the stress intensity and the number of stress events change with grinding media size. The mass of an individual grinding bead decreases as for smaller beads. Below a critical media size, the stress intensity will not be sufficient to break the particle at each stress event (Becker et al., 2001). For larger particles, a portion of large media is preferable so that at least some of the stress events are of sufficient stress intensity to break these particles generating smaller particles. The stress intensity of the smaller grinding media will be sufficient to break the smaller fragments further. These observations are supported by Becker et al. (2001) who found that, high stress intensity with a relatively small number of stress events could break the large particles effectively, while low stress intensity with a relatively greater number of stress events favors the comminution of small particles. Roufail (2003), showed that at high stress intensities, particle breakage was by massive fracture, while low stress intensities promoted breakage by attrition.

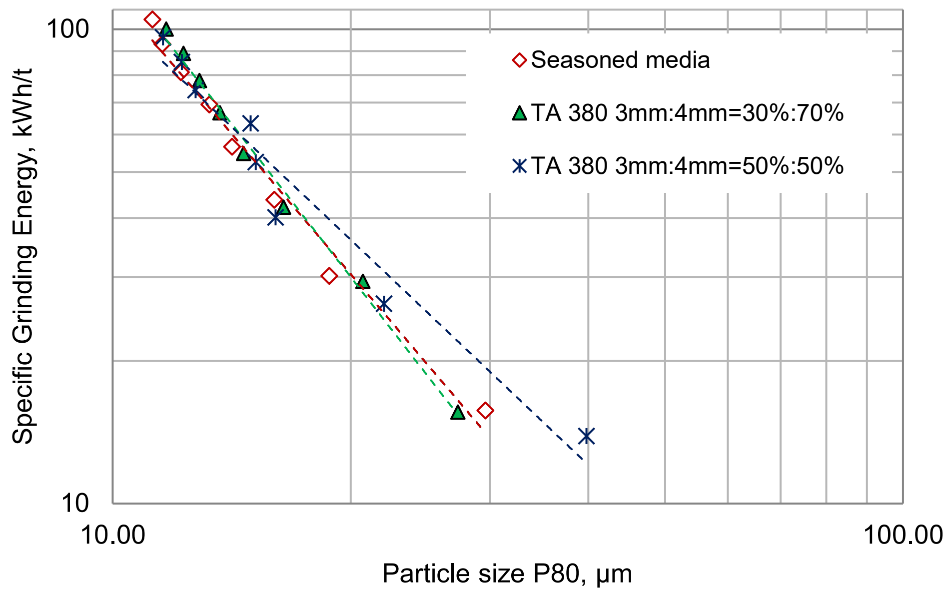

Figure 9: The change in signature plot with the change in the portion of large size media

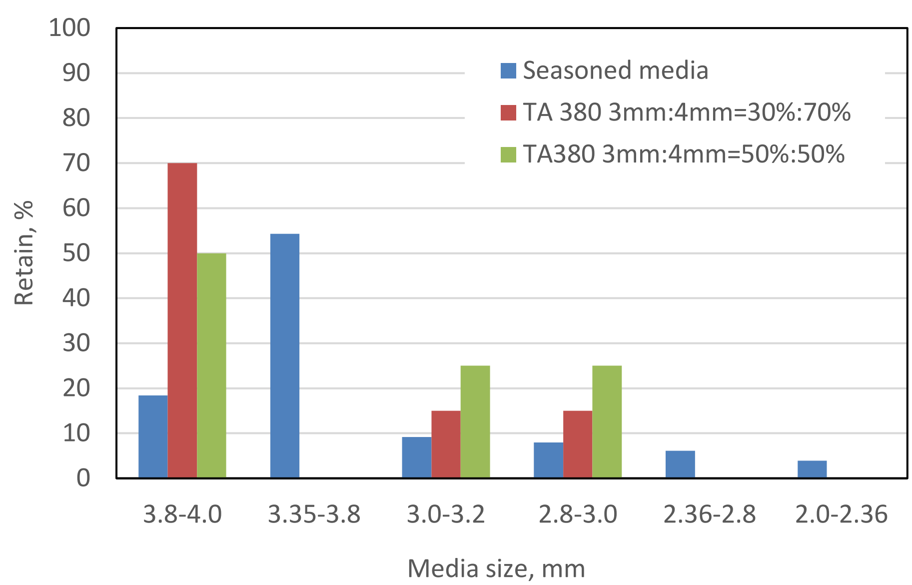

Figure 10: Comparison of media size distribution between the seasoned media and TA380 media size combination

Figure 11 shows the change in stress intensity with the change of media size and density. The stress intensity increases significantly with increasing media size (from 3 mm to 4 mm). The difference in stress intensity between the two media densities also becomes more significant as the media size increases. However, the test with the largest media size showed a slight improvement in the coarse particle grinding efficiency compared to the test with the seasoned media. The test with 50% of 4 mm media shows much lower energy efficiency at the coarse grind size range, possibly because the stress intensity is insufficient with a smaller number of coarse beads. For a given mill feed, the size and the portion of the large media should be selected to yield sufficient but not excessive stress intensities to effectively break the coarse particles.

As shown in Figure 12, the mill feed used for this study has a bimodal particle size distribution. Although the F80 of the feed is only 64 µm, there is significant material with particle sizes ranging from 90 to 160 µm. Therefore, a suitable portion of large media is required to break the coarse particles. The F50 is 22 µm, indicating there is a high percentage of fine particles that are smaller than the target P80 of 25 µm. Unnecessary comminution of fine material will consume energy and contribute to the slurry rheology which may negatively impact comminution. The influence of the minus 25 µm particles on grinding efficiency deserves additional investigation.

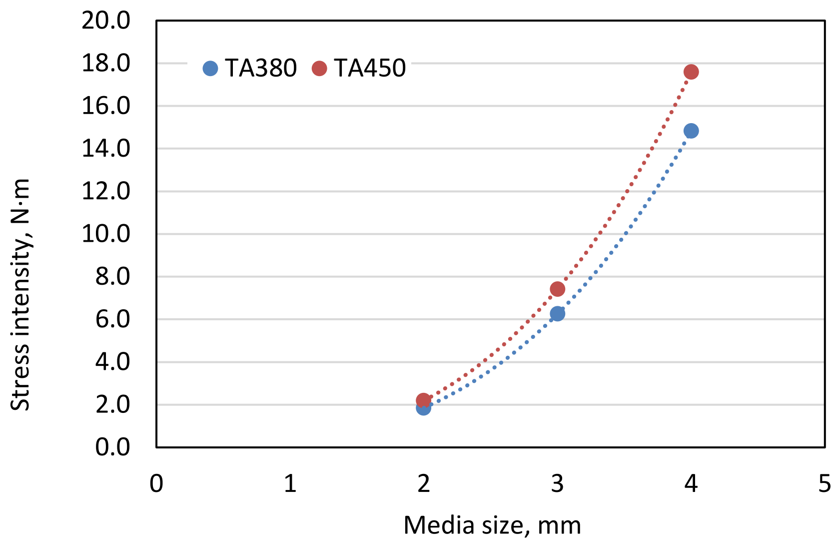

Figure 3: Change of stress intensity with changing media size and density

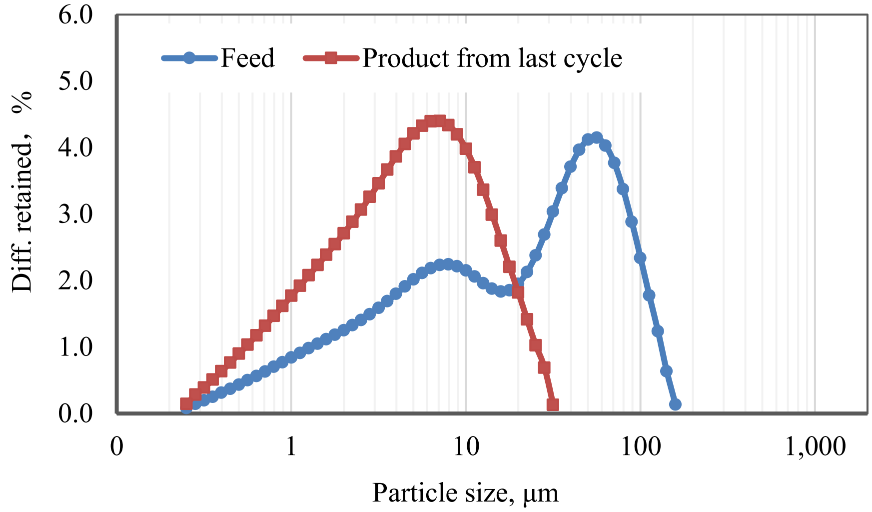

Figure 4: Particle size distribution of test feed and product - seasoned media

3.4. Change in grinding efficiency with target grind size

The test using TA380 media with 3mm and 4mm beads with a 30%:70% ratio had the highest energy efficiency at target grind sizes of 20, 25 and 30 µm. However, at a grind size of 15 µm, its advantage over other media conditions becomes insignificant. For grinding further to 10 µm, the test with lower media density and smaller media size, i.e. TA380 media with 2 mm and 3 mm beads with a 30%:70% ratio had the highest energy efficiency. This observation provides an opportunity for dynamic optimization of the media sizes according to the variation in target grind size.

The test with seasoned media is selected as the base case to compare with other media density and size combinations. The test with TA380 small media sizes (2-3 mm) had a very low stress intensity, which may not have been sufficient to break the coarse fractions effectively resulting a higher specific grinding energy at coarse target grind sizes (25 and 30 µm) compared to the base case test. The test with TA380 media using 3 mm and 4 mm beads at a 50%:50% ratio generated a slightly higher stress intensity than the base case season media and also had a greater number of stress events. It is likely that the number of stress event at this high stress intensity exceeds the number that is required to break the coarse size fraction in the feed, resulting in wasted energy and reducing the overall grinding efficiency.

The test with TA380 media using 3 mm and 4 mm beads at 30%:70% ratio achieved the best energy efficiency at the target grind sizes of 25 and 30μm. This test had significantly higher stress intensity than the base case but a smaller number of stress events. It is possible that the number of stress events at this high stress intensity is within the optimum range, just enough to break the coarse particles, resulting in higher energy efficiency. Comparing the results of tests that used the same media size but with higher media density (TA450), the numbers of stress events for the two tests are similar, however, the stress intensity is much higher. This intensity may exceed the intensity needed for coarse particle breakage resulting in wasted energy and a lower grinding energy efficiency.

The test with TA450 media using 3 mm and 4 mm beads at a 50%:50% ratio, achieves similar stress intensity as the test with TA380 media with 3 mm and 4 mm at a 30%:70% ratio, while the specific grinding energy for the former is much higher. This difference in energy efficiency is possibly caused by the number of stress events between the two tests. However, it should be noted that it is difficult to investigate the effect of media density on grinding efficiency using the stress intensity approach, especially not all media-particle interaction results in effective particle breakage. DEM simulation has been conducted in the past that showed the stress intensity distribution for mono-sized beads (Roufail). The work should be continued to understand the effect of different media sizes and density combinations on the distribution of stress intensity in the mil chamber.

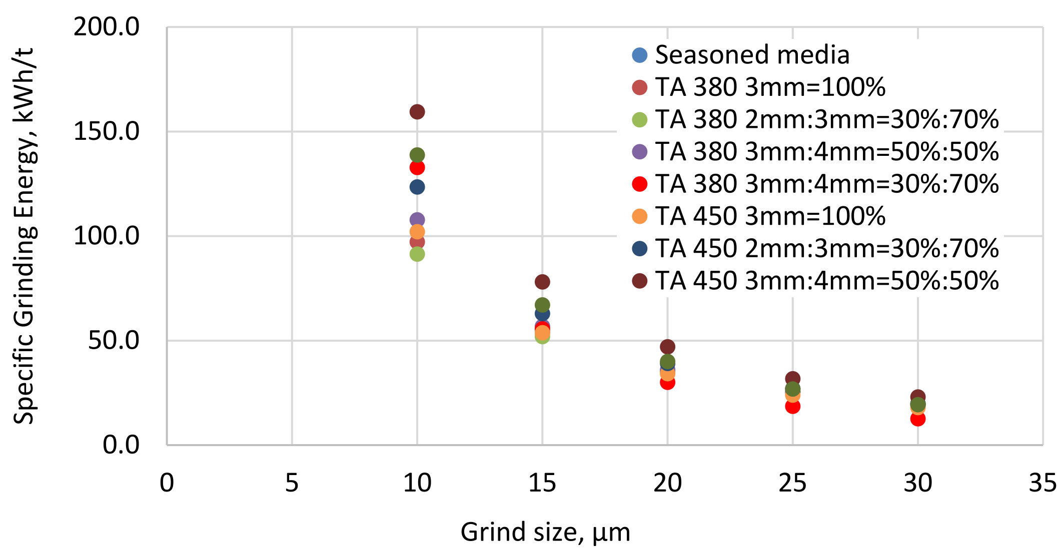

Figure 5: The change in specific grinding energy with target grind size

The specific energy required to generate new -25 µm product was also used to assess the energy efficiency of the tests with varying media conditions, and the results are shown in Figure 14. Figure 15 compares the SSE25 for the test at different media density and size combinations. The test with TA380 media with 3 mm and 4 mm beads at a 30%:70% ratio had the lowest SSE25, but the results were very close to those obtained with the seasoned media. Both sets of results are slightly better than for the test with TA380 media using 3 mm and 4 mm beads at a ratio 50%:50%. Note that the SSE25 values for these tests are high because the mill feed has bimodal PSD and already contains ~52% -25 µm materials.

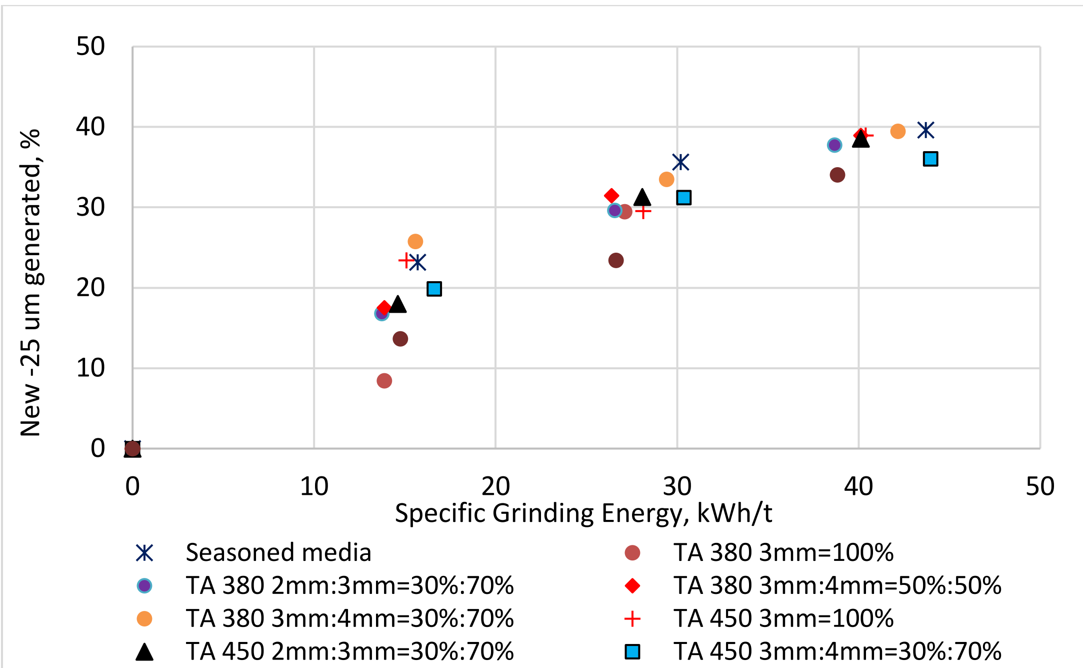

Figure 6: New -25 µm fines generation vs. Specific energy

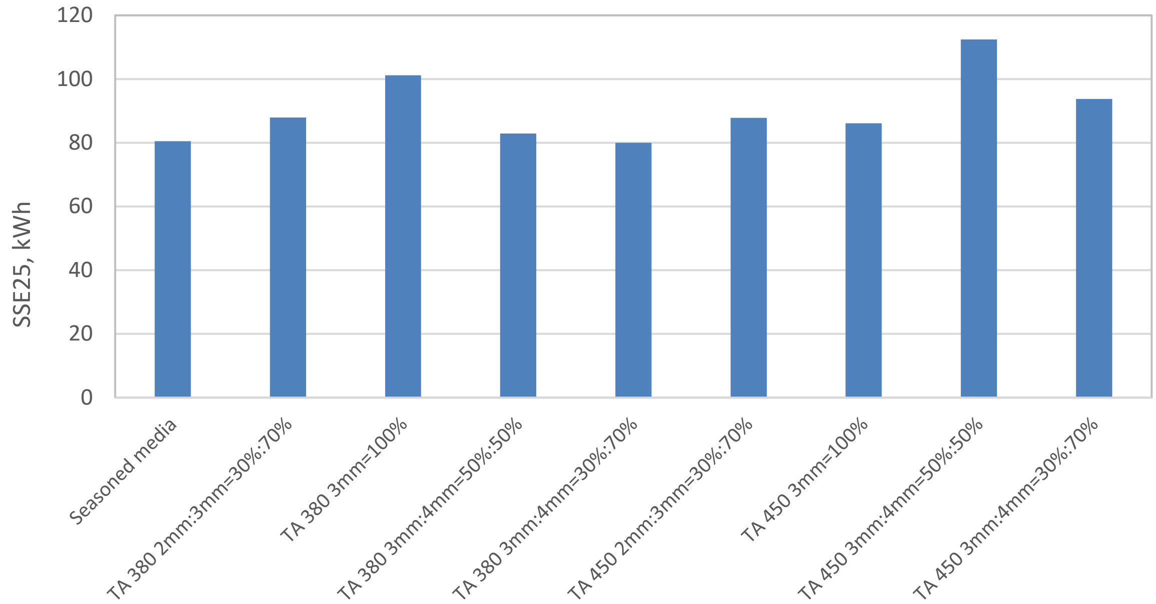

Figure 7: SSE25 comparison for different media density & size combinations

4. Conclusions

The test results indicated that:

- Since the regrind mill feed has bimodal particle size distribution with a significant amount of coarse particles, it is favorable to include a suitable portion of large media to enhance the breakage of coarse size fractions and hence improve the overall grinding energy efficiency.
- An interaction effect between media sizing and density on grinding energy efficiency was found, which could be explained using the stressing analysis approach. More work is required to validate these results.
- The selection of an optimal media density and size should also consider the variation of mill feed in terms of size distribution since the effect of media density and size on grinding efficiency may vary with the change of target grind size.
- There are also some limitations to this research including the limited number of tests and the simplified stress analysis. More IsaMill signature plot tests and analysis will be conducted to validate the findings from the research. In addition, the accuracy of stress

analysis will be improved by use of computational modelling in generating more accurate stress intensity and stress events information.

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