TOWARDS SUSTAINABILITY BY BRIDGING THE GAP IN COMMINUTION – FROM FINELY CRUSHED ORE TO STIRRED MEDIA MILLING

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ABSTRACT

Mining consumes approximately 7% of the world's energy from which almost half goes for comminution. Since the crushers are more energy efficient than mills, it is logic to push down-sizing in crushing stage(s) as far as possible. That has been Sandvik's strategy in supplying crushers, including ™ by which an exceptionally fine crushed product can be obtained.

The implementation of stirred media milling to grind the finely crushed gold ore by the ™ is presented and discussed herein. Experimental results showed there are potentials in saving energy and costs in comminution by bridging the gap between crushing and grinding in comminution practices.

KEYWORDS

Sustainability, Comminution, Energy Efficiency, Fine Crushing, Stirred Media Milling, Vibrocone™

INTRODUCTION

In spite of the current depression in global economy ever increasing global demand for natural resources indicates that the mining industry is expected to increase the production to cope with demands. The total mining production (excluding fuels) has exceeded 2400 Mt per annum with an annual investment of about 160 BUS$ (Ericsson, et al. 2015). As shown by Figure 1, recent investigations have revealed that although there has been a reduction in capital investment but it will be kept almost constant for the next 4 to 5 years. Considering the stronger position of the US$ in global exchange market, it seems that there will be no significant reduction in investment despite global market recession. In addition to the annual capital investment, more is spent to keep up the production (operational costs).

In mining and minerals industry, except profitability, there are some crucial factors that represent components in economic machinery of a mine and related activities. These are sustainability and minimizing environmental impact factor. Environmental concerns combined with the water and energy availability and related costs, as well as public license to operate, demand companies put more effort in targeting sustainability. The mining industry is highly energy-intensive (estimated to consume 6-7% of total world's energy), with varying the energy efficiency across the industry resulting in significant costs. Size reduction is the main energy consumer contributing to almost 50% of the total energy used in mining. That means efforts must be made to introduce energy efficient comminution flow-sheets and machineries for sustainable development. The recent projections by US Energy Information Administrative indicate an increasing of about 43% in world's energy consumption between 2008 and 2030 (Energy Outlook 2011). Accordingly, it is forecasted by 2020 the mining demands for energy exceed $1.75*10^{14}$ kWh.

To reduce the energy consumption in comminution, good classification to discharge the fines at different comminution stages is desired in order to reduce energy and avoid over-grinding of the final product. However, classification becomes increasingly difficult as the cut size is reduced, particularly if the material has low specific gravity or contained of significant fraction of fines and/or ultra-fines.

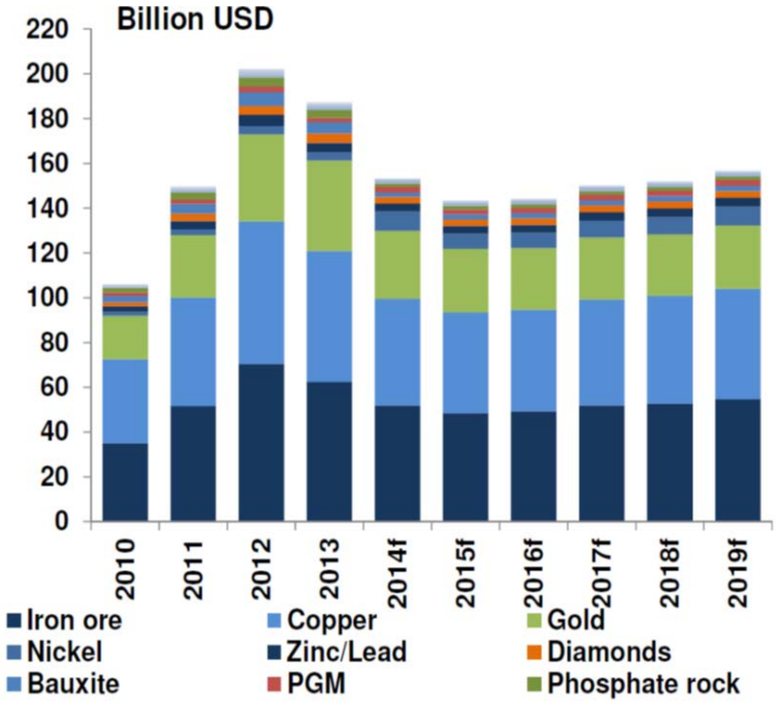

Figure 1 – Investment in mining industry by years, actual and forecasted (Ericsson, et al. 2015)

Considering the current trend towards production of fine and ultra-fine particles with higher surface areas as the head grade and grain size of value minerals are reducing and giant mines are brought into perspectives, the eco-efficiency and sustainably initiatives in comminution are not only closely linked to the energy and its related cost but to environmental and indirect operational costs.

Lowering the energy consumption and related costs as well as increasing throughput have been the main objectives in design and development of comminution circuits and related machineries. Inefficiency in comminution technology, in particular in grinding, has long been regarded as a major area for investigation and development, in particular when production of fines and ultra-fines are considered (typically from p< 45 µm). Conventional devices, mainly, tumbling ball mills, have been used to grind the ores, but the basic problem is that the power consumed is limited by the centrifugation occurring at speeds above the critical speed, and the grinding media could not be too small, for the impact energy. At low speed, large grinding media in a tumbling mill generate mainly impact and abrasive stresses, which is ineffective/inefficient in generating fines.

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Bridging Gap in Comminution

Technological innovation and development have played a vital role in improving and commercialization of the comminution operations in a way to reduce the related operational costs while improving the quality and quantity of the product. A comprehensive study at the University of Newcastle, Australia (Curry, et al., 2014) have revealed that, on average, overall relative mine and mill (i.e., milling and concentrating) are not significantly different in hard rock operations. The general and administration (G&A) costs occupy a small portion of the total. In general the distribution of the costs by % ranging from (43:43:14) to (45:45:10) for (Mine:Mill:G&A). These relative costs were found to remain almost constant in spite of diverging “Mine and Mill” costs in the beginning and end of the mine life. According to this study, the areas for potential saving are in comminution, especially milling, and pre-concentration at coarser fractions as well as flotation of coarse particles, although saving is ultimately limited by the particle size at which an effective separation can occur. Accordingly, the big challenge in comminution is bridge the gap between crushing and grinding for cost reduction.

As a traditional way in ore processing, staged crushing (usually three stages) provides a feed for milling within size range of 10-20 mm. In milling, an action is taken to downsize the ore to micron sizes. Although milling is required to achieve liberation size for beneficiation, it would be meaningful to push the comminution towards crushing since the crushers are much more energy efficient than mills. For example, to grind an ore, having hardness of $W_i = 17$ kWh/t, to 210 µm, the overall energy cost in milling would be reduced by more than 10% if the milling feed at d_{80}=6.4 mm is provided instead of a feed at d_{80}=10 mm (Romero-Lage, 2012). That means by conducting coarse milling in crushing stage a considerable saving in total energy and cost can be gained. That has been the thoughts behind our strategy in research and development of rock processing at Sandvik Mining. Accordingly, the new powerful crushing devices such as Vibrocone^{TM} and the new range of cone crushers, CH860 and CH865 have been developed and offered.

In synergy with global attempts towards sustainability, Sandvik Mining has introduced the Vibrocone^{TM}, to change the traditional crushing concept. The new crusher has different features in comparison with the conventional cone crushers and has shown significant improvement in crushing characteristics of hard rocks. Its features and its performance do deal with different rocks/ores have been reported elsewhere (Manouchehri, 2012, 2013, and 2014). The machine enables providing suitable feed size for downstream milling and processing in a way to reduce water and energy consumptions. Finer/smaller and narrower size distributions of the crushed ore are provided to conserve energy and reduce the overall operational costs within the comminution circuits. Vibrocone^{TM} enables to crush and grind particles efficiently at a high reduction ratio than any available crushing device in an open circuit. Within the machine, particles are not only crushed between the liner surfaces in the crushing chamber; but, to a higher degree, crushed by each other in a high pressure inter-particle crushing action resulting in a transition towards grinding performance. Unlike conventional crushers, the Vibrocone^{TM} is an energy efficient inertia crusher in which comminuting part is driven by an unbalanced vibrating mass. The main shaft is supported by a spherical bearing and the crushing action originates from an unbalanced weight rotating around the main shaft. With the machine, the crushing performance is defined by rotational speed, the adjustable discharge opening, and the unbalanced weight setting (Manouchehri, 2012, 2013, and 2014).

In an attempt to explore the potential of fine crushing and its effects on milling and related energy consumption the fine crushing performance of Vibrocone^{TM} was compared with the performance of a conventional cone crusher, i.e., CH660, in a plant practice. The study was further developed to test the direct implementation of the Tower and/or stirred media mill to finely grind the crushed product from the Vibrocone^{TM}. It was aimed to explore the potential application of such combination and avoiding the conventional ball milling to save energy and reduce the related carbon-foot print towards sustainable mining.

ECO-EFFICENT COMMUNUTION (EXPERIMENTAL)

Among the applications of the Vibrocone^{TM} for crushing different ores, its performance to crush a hard gold ore was considered. Since end of 2012, a machine has been installed within the crushing plant to comminute a competence gold ore having a $W_{ic} \geq 20$ kWh/t. The crusher is installed in parallel to a Sandvik's CH660 crusher. The comminution circuit consists of the staged crushing followed by first stage rod and ball milling in parallel and the secondary ball milling to provide feed for gravity and flotation processes in downstream. The plant has a capacity of 1.1 Mt/annum (140-150 t/h) with a current expansion plan of 1.3 Mt which is then going to be further expanded to 1.7 Mt/annum within 3 to 5 years. The ore is a type of oxidized gold (quartzite type) with a head grade of 1 ppm Au.

After crushing the ore, the target for the first milling stage is to obtain a grind of 100% < 2mm. At secondary milling, the target is to gain a product of 100% < 1mm with a nominal d_{80}=550 µm. Within the crushing plant the secondary crusher provides a feed to the third crushing stage at d_{80}=35-40 mm and the tertiary crusher(s) provide a feed, having d_{80}=8-9 mm, for milling in a closed circuit.

On the basis of the plant's flowsheet, the total milling part of the plant, i.e., rod and ball mills followed by secondary ball mill, consume 12 kWh/t. That provides a milling product at d_{80}=550 µm. The analyses of the crushed product by Vibrocone^{TM} verified that, in an open circuit, the device is able to provide a product at a d_{80}=7-8 mm and d_{50}=3.5-4 mm or even smaller. Conventionally, the tertiary crushed product was screened at either 10 or 8 mm to obtain a target size of d_{80}=~8mm for milling. After installing the Vibrocone^{TM}, a 15% increase in mill throughput was observed in plant practice by directly feeding the mill with the crushed ore by Vibrocone^{TM}'s in an open circuit.

After first series of investigations and the proof of the good crushing concept, it was suggested to screen that product at 6 mm in order to have more favorable crushed product for milling. The particle size distributions of the feed, over screening and under screening of the crushed products by the two crushers are depicted in Figure 2.

From the figure, it can be confirmed that about 50% and 70% of the Vibrocone^{TM} product after screening (through screen) are finer than 1 and 2.5 mm respectively. The mass balancing of the circuit indicated the through screen product is between 80% and 85% of the total feed to the crusher. Taking into account that in current plant practice the first milling stage provides a ground ore at 100% < 2 mm, substantial reduction in milling energy can be expected, however; such a good crushing performance of the machine promises a potential of completely omit the first milling stage .

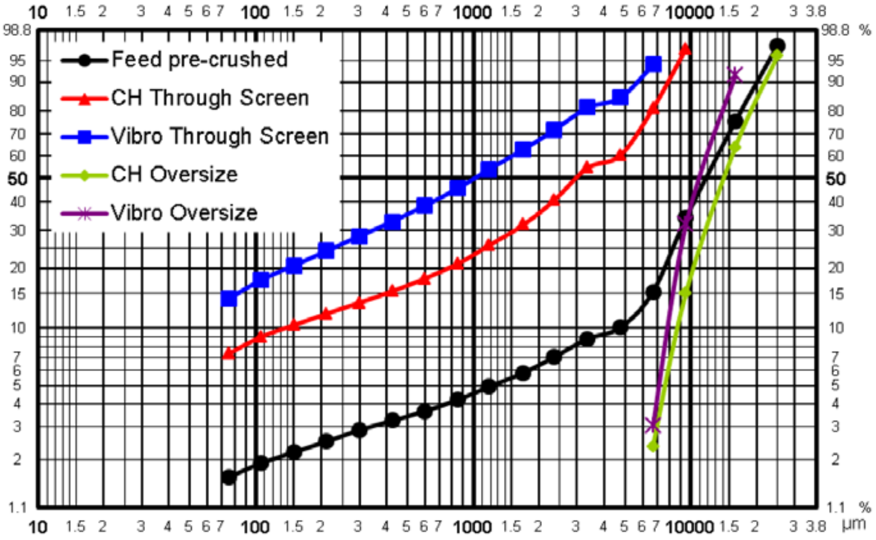


Figure 2 – Feed and crushed products for the gold ore (Vibrocone^{TM} versus CH660)

Grindability Tests

A series of comprehensive grindability tests was conducted to investigate the milling characteristics of the two different crushed products. The study was devoted to investigate the differences in grinding characteristics of different crushed products and explore the potentials for saving energy in obtaining a target grind size. Accordingly, the samples were ground to the following grind sizes:

a- Primary rod milling to a d_{80} = 600 µm and
b- Secondary ball milling to a d_{80} =150-200 µm

The grinding tests on feed to the tertiary crusher at 10 minutes rod milling followed by 15 minutes ball milling indicated it to be possible to obtain a product having a $d_{80} \approx$ 160-170 µm at total energy consumption of 14.1 kWh/t. The results from grinding tests are shown in Figure 3.

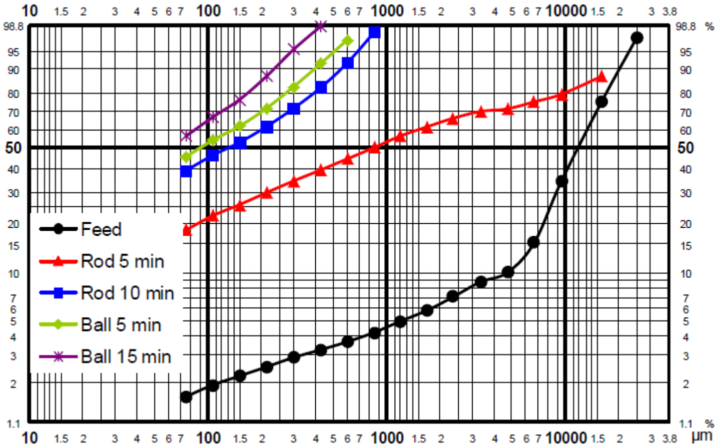


Figure 3 – The results from grinding the feed to the tertiary stage crushing

The grindability tests were conducted on over screen (oversize) products from the two crushers which revealed a significant differences in milling products after milling of the two oversize products (Figures 4 and 5). A glance at Figure 4 and 5 indicate that, in particular after first rod milling stage there is a significant difference in d_{80} products of the two samples. The d_{80} of the ground products are at 14.1 mm and 1.85 mm respectively for CH and Vibrocone^{TM} over screen products.

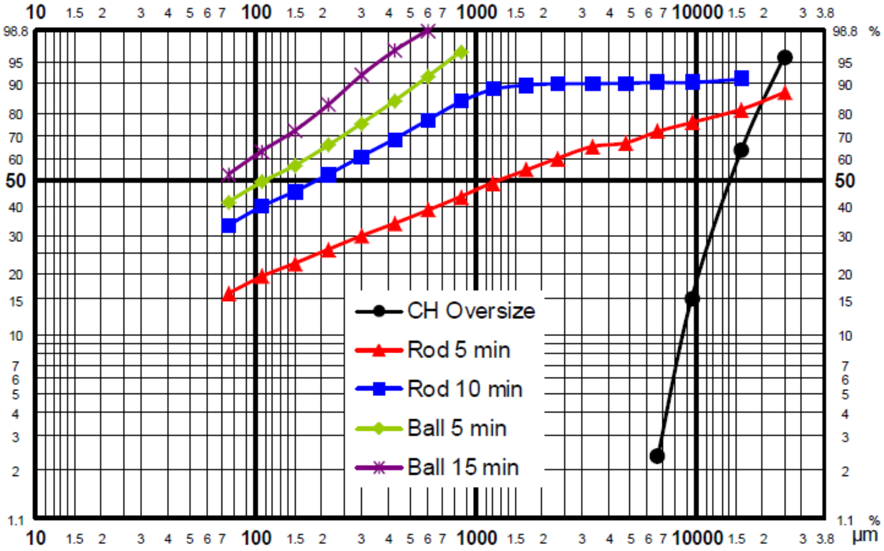


Figure 4 – Consecutive milling of the over screen product of the CH 660

Furthermore, at the final stage of successive rod and ball millings the d_{80} for the two ground products are about 200 µm and 150 µm respectively. Of course one reason for having such differences is the smaller size distribution for the Vibrocone^{TM} over screen product. Furthermore, as shown in Figure 4, due to the presence of a fairly large stone in the rod milling of CH over screen product, the particle size distribution after 10 minutes rod milling got a plateau. That was considered when the final evaluation of the energy consumption with size distribution was made. Considering the final products after succeeding rod and ball milling of the CH over screen with the final product size at d_{80}=190 µm, approximately, there is an extra 1.5 to 2 kWh/t energy is required to gain the d_{80} of 150 µm.

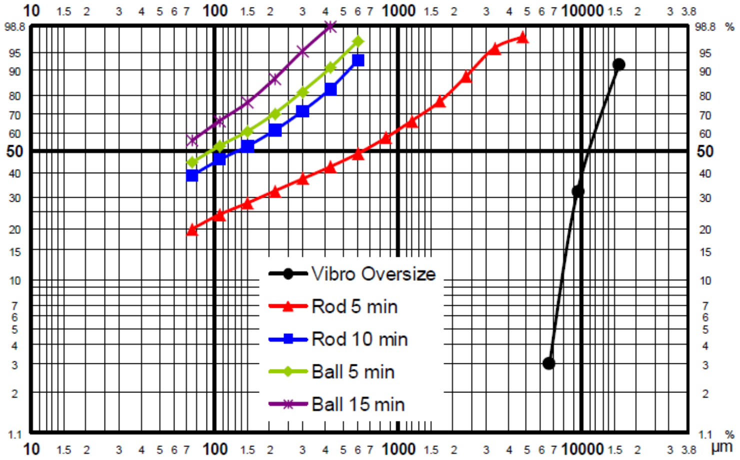
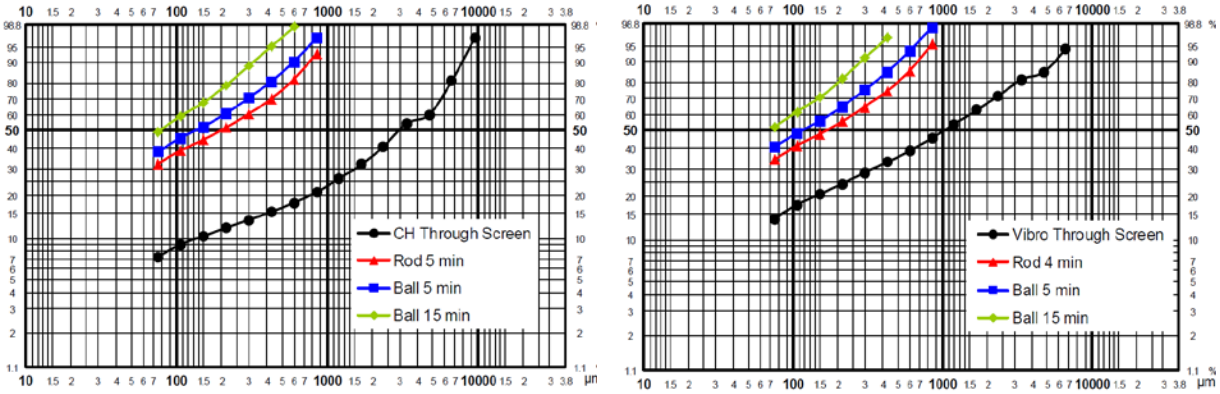


Figure 5 – Consecutive milling of the over screen product of the Vibrocone^{TM}

Figure 6 depicts the results on consecutive milling tests on through screen products of the two crushers. It can be confirmed that two products at d_{80}= 500 µm and d_{80}= 570 µm are obtained respectively after 4 and 5 minutes rod milling of the Vibrocone^{TM} and CH660 through screen products. That means more to gain such a size fractions from the crushed products more than 20% energy is needed in rod milling (even a finer product is obtained by grinding the Vibrocone^{TM} through screen product at lower energy input). Consecutive ball milling of the rod mill products by additional 15 minutes revealed that although the d_{80} for the both products are almost identical at 200 and 225 µm respectively, there are obvious differences in top size and size distributions for the two through screen products, i.e., the top sizes are at 450 and 600 µm for Vibrocone^{TM} and CH660 crushed product respectively. Therefore a narrower size distribution is provided by grinding the Vibrocone^{TM} through screen product.



(a) (b)

Figure 6 – Consecutive milling of the through screen products CH 660 (a) and Vibrocone^{TM} (b)

Figure 7 depicts the results of the grinding tests with respect to the energy consumption to achieve specific d_{80} after grinding. By a glance at the figure, one can conclude that there is not any difference in grinding characteristics of different crushed products. Moreover, it must be noted that, although the grinding tests did not reveal any lasting effect of the type of crusher on the materials' key grinding properties such as conditional work index and grindability. Neither it was possible to conclude that there is lasting effect on size distribution of P < 75 µm or the specific surface area of individual size fraction. Therefore, all differences in grinding results seem to be assigned to the differences in starting particle size.

Both the over screen and under screen products of Vibrocone^{TM} have finer/smaller and narrower size distributions than equivalent products from conventional CH660 cone crusher (Pålsson 2013).

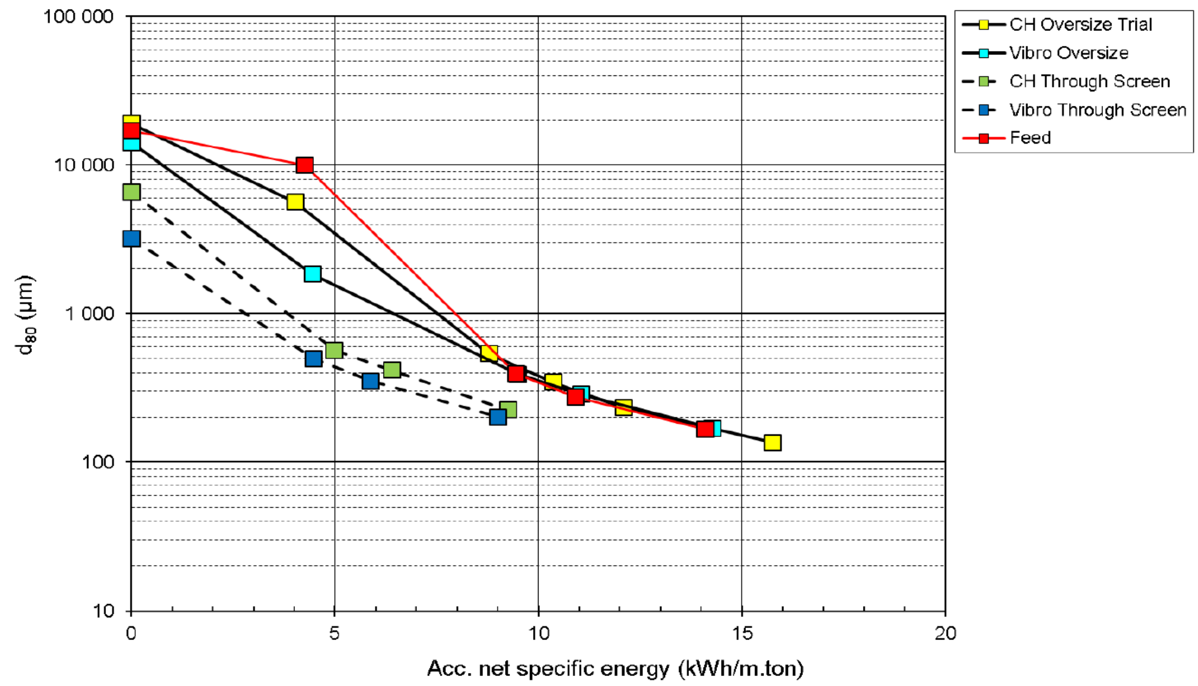


Figure 7 – The relationship between the particle size and the energy for the consecutive milling of different crushed products

Tower / Stirred Media Milling of Finely Crushed Ore (Vibrocone^{TM} Product to Tower/Stirred Mill)

Stirred media mills are currently available to deal with low grade ores with finely disseminated particle intergrowth that are being mined and challenging the industry. The advantages and developments in froth flotation in processing the sub 10 micron size range together the needs for production of fine and ultrafine particles with increased surface areas to enhance the reaction kinetics and recovery in various leaching processes have paved the way of introducing the stirred media mills for fine and ultrafine grinding in minerals industry. The emergence of stirred media mills has facilitated the production of fine and ultrafine particle economically. As the grain size for value minerals within the competent ores becomes finer and finer the need for fine and efficient grinding circuits becomes more evident. That requires step change in conventional concept of comminution circuits, in particular grinding parts, towards eco-efficiency.

The concept of stirred milling was proposed by Szegvari in 1928, however, the industrial breakthrough of high-speed stirred media mills occurred in 1948 with the introduction of DUPont's "sand mill" (Kwade and Schwedes 1997). Nowadays, stirred mills comprise a group of mills, such as Tower mill, Sand mill, CoBall mill, Pearl/Perl mill, IsaMill, etc., which operate on some principle but having basic design and efficiency differences. In stirred media mills, the grinding is carried out between loose grinding media, usually made of glass, steel, or ceramic materials, however, the mill cam be used autogenously as well.

In fine and ultrafine grinding, the specific energy consumption of stirred media mill to gain specific size is considerably less than tumbling ball mills due to a very high number of stress events per unit time and volume as well as appropriate stress intensity in production of very fine particles. The need for higher grinding force, has lead the development of high speed mills at speed of 20 m/s or even higher.

Yue and Klein (2007) have categorized the stirred media mills according to how fast the stirrer rotates, i.e., low stirrer speed such as tower/verti mill which use larger media sizes and accept bigger feed size while high speed stirrer mills up to 23 m/s like IsaMill use the smaller media and feed sizes. In vertical stirring mills, the tip speeds are limited by pressure, i.e., at high speed a high pressure is generated at the bottom of the mill which may damage the drive shaft and produce uneven media wear. However, within the horizontal type, the pressure is distributed more evenly; therefore the mill can be performed at higher speeds. Stirrer speed strongly affect the power intensity which is define by the power draw per unit of mill; however it must be noted that the higher power intensity does not necessarily guarantee good grinding performance. A good grinding performance depends on how effectively the energy is used to cause size reduction. The power density is not equally distributed within the grinding chamber, but there are two high intensity zones, one near the outer tip of the stirrer and the other at grinding chamber wall, as the higher energy dissipated zones with about 90% (Kwade, 1999; Shi et al., 2009). Beside the stirrer speed which differentiates the stirred media mills, there are different types with differences in their chamber, the geometry of stirrer, and separating media and material device, etc. For example disc stirrer, pin-counter-pin, and annular gap geometry media mills are available as different types of mills.

The performance of the stirred media mills can be defined by stress intensity of the grinding media, SI_m (Kwade, 1995; Jankovic, 2001) as the following equation in which d_m, ρ_m, ρ, and ν_t are the media size , media density, slurry density and stirrer tip speed.

$$SI_m = d_m^3 (\rho_m - \rho) \nu_t^2$$

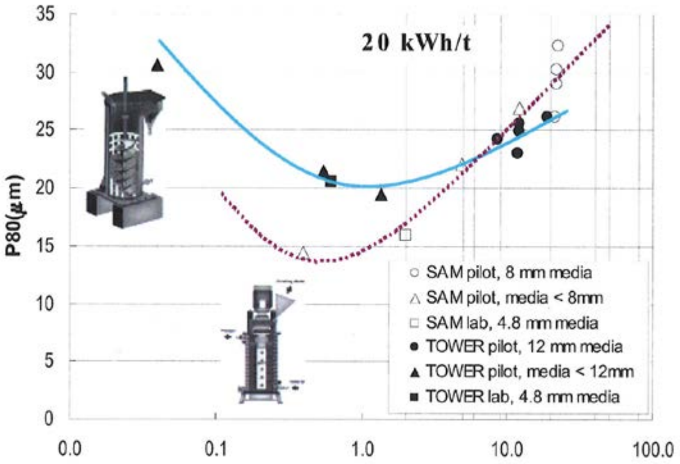


Figure 8 – Stirred milling product size in relation to stress intensity Nm*10^{-3} – (Jankovic, 2001)

By plotting product particle size against the stress intensity at specific energy input, the optimum stress intensity range can be defined where the finest product size can be achieved. In practices, the performance of stirred media mills can be optimized and scaled up by stress intensity at given energy input.

In recent years, the implementation of tower/stirred media mill has become “routine” as its exceptional operational performance to provide product sizes down to 20 µm and finer has been confirmed in plant practices. For finer products, mills using “natural” grinding media (silica sand, granulated slag etc.,) were found to be more energy and cost efficient, however, there are different types of media to be chosen on the basis of ore competency and application.

Implementing Tower / Stirred Media Mill to Finely Grind the Crushed Product

The fine crushing performance of the Vibrocone^{TM} was the motivation to explore further potential in eco-efficient comminution by feeding the through screen product directly to the Tower or stirred media mill. Tower Mill is vertical stirred type of grinding equipment developed in the early1950s by the Japanese which is most commonly used for regrinding concentrates with typical fine feed size. It consumes considerably less energy in fine and ultra-fine grinding or re-grinding in comparison to the tumbling ball mills because of the efficient use of grinding media to which a force of 30–33 times bigger than the gravitational force in tumbling mills can be applied. By having such efficient grinding a great potential of saving energy in fine grinding of hard ores can be sought. The saving in energy may be preeminent up to 40% in comparison to the energy consumed by tumbling mills.

It is known that specific energy for grinding in ball milling is sharply increased when targeting below 100 μm in grinding and the milling may become completely inefficient when a grind product finer than 30 μm is required.

For the fine grinding tests, two different feed sizes were prepared and fed to the stirred mill, using the Eirich laboratory/pilot tower mill. Accordingly, except the whole crushed product as the through screen coarse sample (a), the Vibrocone^{TM} through screen product was screened at 1.2 mm. The later comprises of 50 w% of the through screen (marked as through screen which is screened once more @ 1.2 mm, sample (b)). Table 1 shows the particle size distribution for the tested samples

Table 1 - Particle size distribution for the samples for fine grinding tower mill testing

Sample	d_{100}	d_{80}	d_{50}	d_{20}
Through screen Vibrocone^{TM} (100%) – coarse (a)	7 mm	3.5-4 mm	1.2 mm	0.25 mm
Through screen Vibrocone^{TM} screened @1.2 mm (b) (50% of total through screen sample)	1.2 mm	0.38 mm	0.125 mm	0.04 mm

Two grind target sizes, i.e., d_{80}=75 μm and d_{80}=45 μm, were considered and series of tests were conducted. Figure 9 depicts the Tower mill used and the related grinding system. For scaling up, the first series of the tests were conducted using the small tower mill. The screw speed of the mill was set at 85 revolutions min^{-1} with the media size of 20 mm. The second series of tests were conducted by using the bigger tower mill which was implemented at higher speed of 205 min^{-1} and the ball size of the 20 mm.

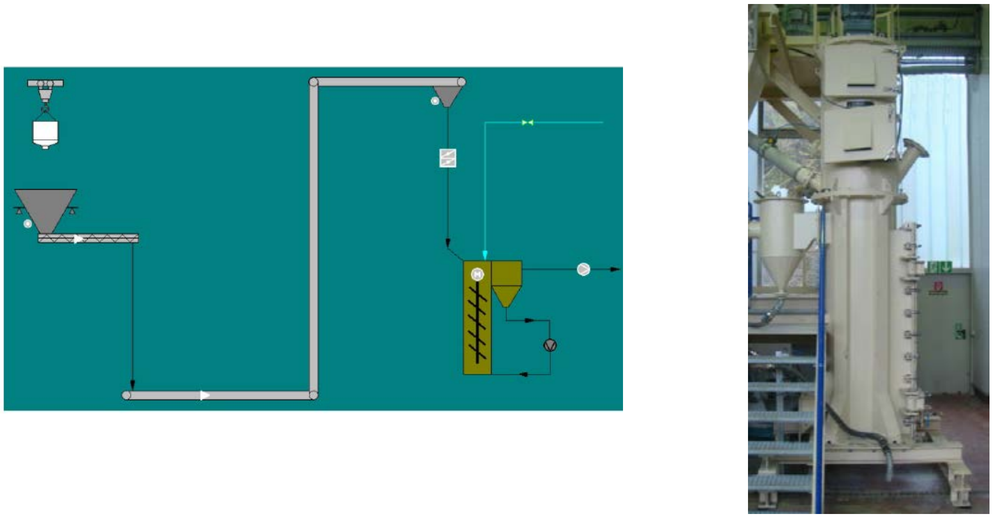


Figure 9 – The Tower mill and related grinding procedure

According to the milling procedure, the ground product leaves the mill over the part of the mill chamber through the overflow flange and enters firstly the coarse classifier. The very coarse fraction of the product is returned to the mill and the fines (fine fraction) leaves the mill via overflow to the product container. The samples were taken at the overflow to control the product size (measuring the particle size distribution of the product). Tests were conducted for 8 hours, i.e., overall duration of the test was non-stop for 8 hours. The samples were taken at regular intervals during the 8 hours grinding (i.e., at 0.5, 1, 2, 3, 4, 5, 6, 7, and 8h).

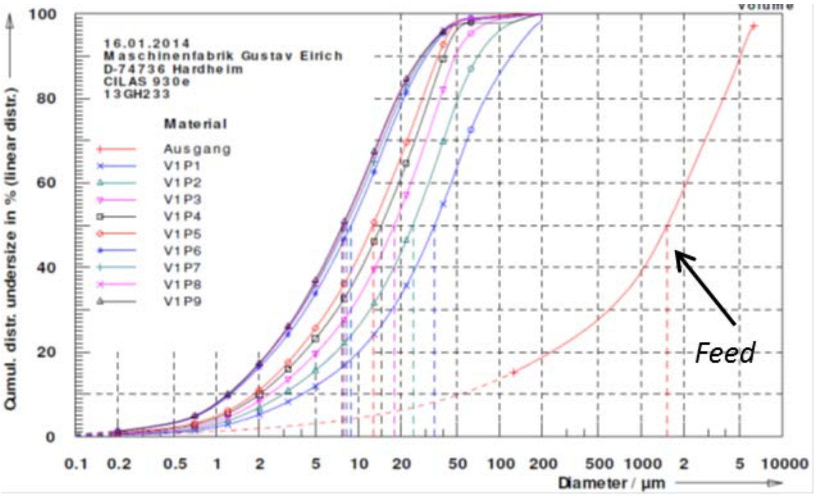


Figure 10 – Size distribution of tower mill grinding the through screen crushing product at 0,5, 1, 2, 3, 4, 5, 6, 7 and 8 hours

By measuring the grain size, i.e., determining the d_{80} values of the samples at different grinding time, and considering an extensive set of formulas, it was possible to determine the size of mill to achieve the required fineness and throughput rate. Based on the primary test the relation between the product's fineness and the mill size was established as the following (Eirich 2014):

$$\text{Particle Size } (d_{80}) = 6.0184 * (\text{mill throughput kg/h})^{0.53}$$

It must be noted that in order to determine whether the mill runs satisfactory when dealing with a coarse feed, the test must be conducted for a longer period. If the feed is too coarse then the mill shows an increase in power draw and the mill cannot handle such a coarse feed. Furthermore, the mass concentration of solids at the mill outlet would be lower in the beginning and increases by the time. However, no problematic condition was reported during grinding testing by the operators when coarse feed, i.e., Vibrocone^{TM} through screen at top size of about 7 mm, sample (a). For the tests, the target solid concentration was set at 60% at the throughput rate of 600 kg/h.

Scaling up the standard test

For grind the finer/smaller sized crushed product, i.e., sample (b) at d80=380 µm, the Eirich tower mill (ETM-1500) with 1.2 MW installed power was used. The results from the tests and related calculations indicated that at an energy consumption rate of 10 kWh/t, it is possible to have a 100 t/h product at d_{80}=75 µm. The energy consumption, however, the energy consumption will rise up to a value of 14.4 kWh/t if a target product size at d_{80}=45 µm is required. A rough calculation of the energy consumption for obtaining such fine products of 75µm and 45µm by ball milling indicated a need of bout 13 and 19 kWh/t respectively.

When considering the coarser feed, i.e., the Vibrocone^{TM} through screen sample (a), the tests results did not show any problem to grind such a coarse feed. That means the crushed product can be smoothly ground to micron sizes. The measured solid concentrations during milling period were very stable and the measured power draw showed unchanging for testing period. In this case, without using hydrocyclone, a product having a d_{80}=90 μm can be achieved at energy consumption of 19 kWh/t. The results indicate some advantages over the energy consumption and operational cost in grinding such a coarse feed by tower mill in comparison with conventional ball milling, however, more investigations is going on to proof the concept. Although, the reduction in energy consumption in this case would be a marginal in comparison with the ball milling, the results showed a promising prospect in implementation of tower/stirred media mill for such application. The differences in energy consumption between stirred milling and conventional ball milling for a such coarse feed is more pronounced if the final target size than d_{80}=90-100 μm is required.

Even the total energy consumption may appear to be relatively high, during the large scale tests it was revealed that the gold ore can be easily ground. Considering that the grinding was accomplished without using a cyclone, a similar d_{80} product size with steeper size distribution and less energy consumption can be obtained using hydocyclone. Furthermore, the results can be improved by optimizing different parameters in milling, including the media size, stirrer speed, type of media, etc.

ECO-EFFICIENCY IN COMMINUTION & BENEFITS IN TOWER MILLING OF FINE CRUSHED ORE

Recently, the eco-efficiency concept has garnered considerable and widespread acceptance in mining industry. That is about doing more with less in achieving parallel ecological and economic gains without sacrificing one for the other. Eco-efficiency can be achieved by improving the material and energy efficiency of processes, reducing environmental and human health-related risks, and designing in accordance with ecological cycles, making products more easily recyclable, or extending their durability or functionality at relatively same cost.

In the minerals industry ball mills are the most common and versatile type of grinding device which can be used over a wide range of grinding applications, i.e., as primary, secondary, tertiary and re-grinding applications. However, since the 1970s implementation of AG and SAG mills, which replaced two stages of crushing and the primary grinding stage has been considered and succeeded within the comminution circuits. Although ball mills dominate the grinding market, their efficiency is dramatically decreases when dealing with fine and ultrafine milling. If the product size finer than 100 μm or in particular finer than 75 μm is required the implementation of stirred media mills are considered. Since the last few decades the implementation of stirred media mills within the comminution circuits has been sought due inefficiency in ball milling for fine grinding. The concept of fine stage crushing by implementing HPGR and fine crushing devices, such as Vibrocone^{TM}, to push the comminution towards crushing stage and removing the coarse grinding stage by directly feeding the tower and/or stirred media mills in plant practices has been considered a viable option as the technology continues todevelop. One strategy would be to develop the stirred media millling technology to accept coarser fractions at higher capacities towards eco-efficient comminution. However, to deal with high tonnage throughputs in practice, bigger size stirred mills are needed.

Technically, the efficiency in comminution refers mainly to the amount of energy consumed by the comminution circuit to comminute an ore from a certain feed size to a defined product size against a theoretical benchmark. However, from a business perspective, the efficiency may be measured according to the cost per unit of the ground product which comprises the capital cost as well as the operational cost (labour, maintenance, consumables, and power costs). Based on the ore's competency, required liberation size, plant location and selected circuit as well as its capacity, the relative importance of each of the above mentioned parameters will be different (Lane et al 2002). The ideal comminution circuit, therefore, must be energy efficient, easy to be operated and maintained, and consumes less media and liners. Considering emission reduction units factor, the energy efficiency in comminution becomes a significant factor particularly in the approval of the future projects. The effect of such a factor can therefore be minimized by designing eco-efficient comminution circuits. It is stated (Daniel and Lane, 2008) that by 10% improvement in energy efficiency in milling a reduction of 3% and 5% in opex can be expected for small and large plants respectively. However, a 10% reduction in manning levels, results in 5% and 1% reduction in opex for small and large concentrators respectively.

Fine crushing, using efficient devices like Vibrocone^{TM}, in combination with efficient grinding such as Stirred/Tower mills, can significantly contribute in minimizing the costs and energy consumption within a plant. By providing much smaller crushed products and narrower size distribution in crushing the milling performance can be significantly improves. Bearing in mind the direct effect of the milling energy on media and liner consumption for tumbling mills according to the following equations (Rowland Jr., 2002), the benefit of size reduction in crushing stage to bridge the gap between crushing and grinding become obvious. The media and liner consumptions is closely related to the competency for rock, i.e., hardness (Wi) and abrasiveness (Ai), for an abrasive and competent ore the saving will be very attractive if finer crushed product is fed to the mill. Considering the media costs for large plants comprise of 20% or more of operating costs, the need of fine crushing becomes more evident.

$$\text{Rod Milling-Steel Media (kg/kWh)} = 0.159\ (Ai - 0.020)0.2 \qquad (1)$$

$$\text{Rod Milling-Steel Liners (kg/kWh)} = 0.0159\ (Ai - 0.015)0.3 \qquad (2)$$

$$\text{Ball Milling-Steel Media (kg/kWh)} = 0.159\ (Ai - 0.015)0.34 \qquad (3)$$

$$\text{Ball Milling -- Steel Liners (kg/kWh)} = 0.0118\ (Ai - 0.015)0.3 \qquad (4)$$

It is estimated that for media production energy of about 6 MW/t is consumed which results in emitting 1600 kg/t of CO_2 as well (IPCC, 1996). The embedded energy in media consumption would be between 30-50% of the direct energy consumed by mill (Daniel and Lane, 2008). In our way towards sustainability both embedded and embodied energies must be taken into account and the comminution circuit must be designed in a way to integrate energy and economics while considering its environmental and social impacts. The efficiency in resource utilization can be further improved by implementing more powerful and well performing crushing devices in a way to change the comminuting characteristics of the ore, e.g., a reduction in ball milling work index by possibly inducing the micro-cracks within the particle grains due to higher forces implemented in crushing. That has been experienced and reported by different authors (e.g., van der Meer and Maphosa 2012, Manouchehri 2013 and 2014). Reduction in bond ball milling work index and inducing the micro-cracks would reduce the energy needed in milling and also improve efficiency in processing of the ore, in particular leaching characteristics and its kinetics can be improved by producing bigger/higher surface areas and facilitating the pathway of the leach solution within the grain sizes. That is why the industry needs to be challenged to be more innovative in manufacturing by considering eco-efficiency concept(s).

DISCUSSION & CONCLUSION

In its persistence towards sustainable development and being innovative in machinery manufacturing and offering solutions offer for sustainable development, Sandvik Mining has considered eco-efficiency by introducing new devices and smarter solutions to step change in conventional way of mining and crushing concepts while considering recent developments and innovations in the downstream processing step. Our comprehensive view considers the overall mining, comminuting, material handling and processing activities as a one scenario for sustainable development. Our attempts aim to improve the whole mining and processing activities/stages to gain more from our non-renewable natural resources through optimizing the current practices and developing new technologies/solutions. The general concept can be explained in Figure 10 (Manouchehri 2012):

good resource characterization (e.g., measurement while drilling)→ good mining planning → less dilution in extraction → selective mucking and less dilution (e.g., measurement while mucking and bulk sorting) → controlled crushing→ good feed for milling and processing (particle sorting) → controlled milling (less kWh/t of specified size) → controlled feed for processing → controlled flotation → higher recovery and efficiency in resource utilization at lower energy demand and cost

Figure 10 – Thought diagram (Manouchehri 2012)

By thinking smarter in plant design and implementation of the equipment and considering the new technologies and introducing powerful and productive and energy efficient devices the eco-efficiency in comminution can be achieved in a way to maximize recovery while reducing the related environmental impacts. The current study has revealed the potential application of the Vibrocone^{TM} to finely crush a competence gold ore to provide a favorable feed for consecutive milling process. The experimental studies in plant practices and laboratory grindability tests have revealed a considerable reduction in milling energy, potentially by 15%, and/or increase the plant throughput by the same number while using the current installed mill power. Furthermore analyses of the crushed product have shown promising prospect in dramatically change the process plant flowsheet and eliminate part of milling due to providing a finer crushed product (considering more than 60% of the crushed product by first stage of milling in plant practice is finer than 2 mm, to be possible to directly feed 50% of the Vibrocone^{TM} product to the gravity concentration circuit).

The experimental results indicated the energy consumption of 19 kWh/t to grind the crushed product to a fine milling size at d_{80}= 80-90 μm. Although, the reduction in energy consumption to gain such a product size may look tiny, it is still less than the required energy for ball milling. The experimental results and the ease of grinding coarser feed by the stirred mill have shown promising potential in improving the milling efficiency and reducing the energy consumption by adjusting different parameters in stirred media milling, including media size to increase the stress intensity, mill power and speed, etc. That must be considered and studied further to explore the potentials.

Further milling studies on the fine part of the crushed product, i.e., sample (b) that is 50% of the crushed product at top size of 1.2 mm, have revealed efficient milling with stirred media mill to gain a fine product sizes. The energy consumption to gain a milling product at d80=75 μm and d80=45 μm would be at 10 kWh/t and 14.4 kWh/t respectively which is less than the energy needed to grind that product by conventional milling. The gain is more significant when finer grind size is aimed. Nevertheless, the results can be further improved.

Besides the energy efficiency in comminution, the achieved results have opened a new concept in a way to be more effective in extraction of values from low grade and finely disseminated ores. The new concept would be to push the comminution circuit further towards the crushing by introducing efficient crushing and grinding a way to directly grind the fine crushed product by Tower and/or stirred media mills. In this case the coarse and fine grinding stages may be considered followed by the coarse and fine flotation/beneficiation practices within an eco-efficient flow-sheet such as the one depicted in Figure 10. Such dramatic change in plant practice allows gaining more from the natural resources. Implementing the coarse and fine flotation technology by splitting the ground feed allows gaining more through better controlling the flotation kinetics and avoiding grinding/over-grinding of barren particles to save energy.

Considering pushing comminution towards crushing stage and capability of the Vibrocone^{TM} to accept particles as coarse as 140-150 mm it would offer a potential to change the conventional concept of the energy intensive AG and SAG flow-sheets. That must be studied further and there are needs for emerging high capacity and reliable crushing and stirred milling machines in practices.

The study has indicated that improvement in mill performance, increase in mill capacity, as well as reductions in the energy and media consumption all are anticipated by improving crushing performance. Furthermore, increases in surface area production, reduction in ore competency, and possible inducing of micro-cracks in grain sizes are other potential outcomes which have been observed in some case studies but must be studied further. The latter ultimately results not only in further reduction in milling energy but improves the leachability and leaching kinetics of the ore, where required. However, further investigations are needed to accurately compare the total costs for implementing the stirred media mills against conventional ball mills for such applications. Furthermore, it is needed to define how far the stirred media mills can be pushed to directly accept the finely crushed ores (i.e., how coarse the feed can be in relation the ores' competency).

To pave our way towards sustainability, the mining and processing circuit must be designed in a way to respond well to the variations in ore and its characteristics (e.g., competency, abrasiveness, gangue mineralogy, liberation size, composition, etc.,) the mining condition, energy and water availability and related costs, as well as social and environmental factors. The smart implementation of the current technologies while considering the up-taking of tomorrow's technology is vital for smart and innovative mines of future.

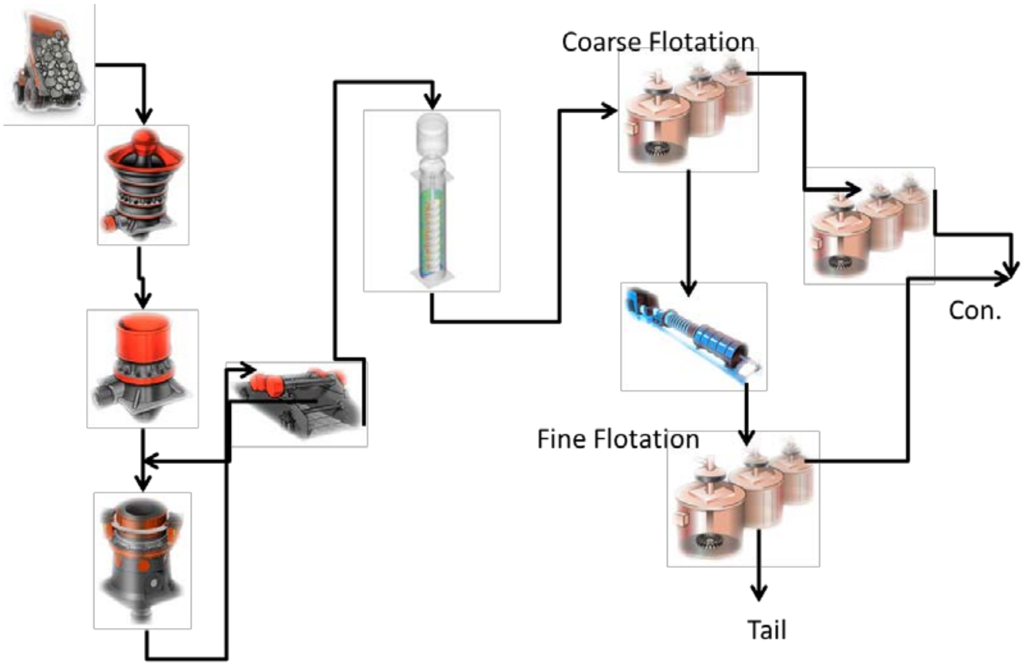


Figure 11 – Proposed flow-sheet for fine crushing, stirred media milling and flotation of coarse and fine particles

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