

PAPER #

Bridging the Gap Between Crushing and Ball Milling

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ABSTRACT

One of the biggest challenges in the application of crushers in the mining industry is to bridge the gap between the final product of a tertiary crushing stage and the optimum feed to the ball mill. Ball mills typically prefer a P80 of about 6 mm; therefore it is important to achieve the highest degree of reduction ratio in the final stage of crushing. Particle sizes around 25-50 mm (one to two inches) cause a disproportionate number of the problems found in the effective utilization of comminution energy, and the use of fine crushing or coarse grinding to overcome this problem risks the introduction of significant inefficiencies into the typical comminution operation. The higher the reduction in the tertiary stage, the lower is the energy consumed by the ball mill. The challenge lies in the fact that it is difficult to reduce most metallic ores below the 10 mm mark by crushing with the currently existing equipment.

INTRODUCTION

Aesop's fable "The Tortoise and the Hare" concerns a hare that ridicules a slow-moving tortoise and is challenged by him to a race. The hare soon leaves the tortoise behind and, confident of winning, decides to take a nap midway through the course. When he awakes, however, he finds that his competitor, crawling slowly but steadily, has arrived before him.

In practical applications we see that in most cases we can conform to the words that Aesop uses to end his tale: "slow and steady wins the race".

What caused crushing manufacturers to opt for higher speed crushers in detriment to slower speed ones? What motivated them to modify the cone crusher chamber geometry from a long parallel zone with particle confinement to a wider nip angle on the upper part of the chamber?

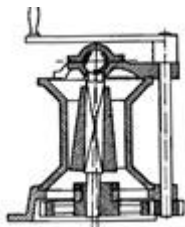
At first glance, it can be deduced that a need driven by the aggregate industry to produce a more cubical product meant to produce a cone crusher that used particle bed crushing rather than confined single-particle crushing. Moreover, it was clear that there was an advantage in creating a cone crusher that ensured seamless polyvalence between the aggregate and the mining industries, but after doing a more comprehensive analysis of the variability and dynamics of aggregate and mining processes, one can see that there exists a great difference between the behavior of most aggregates when compared to most ores processed in metallic mining.



As the focus shifted from crushers that were process oriented to polyvalent crushers, manufacturers started making concessions such as volumetric capacity in detriment to final reduction, production of cubical particles in detriment of efficient energy utilization, mechanical overload protection in detriment of higher crushing force. The concession may have left a gap between the final crushing process and the ball milling process.

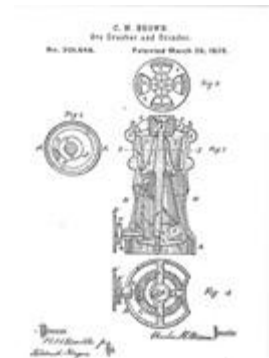
A LITTLE HISTORY

Until the 19th century nearly all rock was broken by hand. Eli Whitney Blake, developed the first successful jaw crusher patented in 1858. The gyratory conical crusher soon followed with an 1881 design by Philetus Gates, which included in its design all the essential features of the modern gyratory crusher.



James Rutter of St. Louis, Missouri, patented the first rotary crusher arrangement in 1869.

The first Smith & Post (precursor of Telsmith) product was a new crusher design, the Symons "Pillar Shaft" gyratory crusher. Approximately 50 units were put into service before the end of 1908.



Prior to World War I, crusher manufacturers were adapting secondary and tertiary gyratory crushers to yield a smaller product. Designs were adapted reducing the size of the crusher head. Crushing stresses were concentrated to a point that the top shell of the crusher could not withstand it.

In the 1920s, several manufacturers made progress by increasing eccentric speeds, and eventually the non-choking concave was designed to improve the crushing efficiency

Will Symons, a Chicago engineer, fled from Smith & Post and first offered Allis Chalmers the patent for a new design crusher for a high reduction crusher. Instead, Nordberg purchased the patents. In time the Symons crusher virtually killed the sales of Allis Chalmers Crushers. Symons crushers remained the crusher of choice for mining applications until the 1980s.

Allis Chalmers pioneered the use of hydraulics in their design of cone crushers. The hydraulics were used to raise and lower the main shaft to change the discharge setting hydraulically, including under load adjustment. This allowed much faster and precise adjustments to meet output specifications. It also allowed for hydraulic relief from the introduction of uncrushables such as pieces of steel. Today the Allis Chalmers design legacy still lives in the design of Sandvik cone crushers.

Nordberg and then Metso Minerals, opted to obsolete the Symons crusher design in the late 80s and introduced a high speed designs, first the Omnicone, and then the HP and the MP lines, aiming for the polyvalence of use for aggregates and mining.

Amongst a few other successful US manufacturers, Telsmith of Milwaukee, WI successfully produces a high speed efficient cone crusher, the SBS model, which is also a polyvalent design with very good success in the aggregate industry.

Trio Engineered products, of Irwindale, California, designs and produces two types of cone crushers, one high speed polyvalent crusher that relies on both interparticle crushing and also single particle confinement, and also the TC model cone crusher, which successfully preserves the Symons crusher type of design and updates it to the current needs of the mining industry by providing it with hydraulic adjustment and clearing plus automation options, thus preserving the legacy and filling the niche that other modern crushers have left in the mining industry.



COMPRESSION CRUSHING AS MEANS OF COMMINUTION

As the name implies, crushing by compression is done between two surfaces, with the work being done by one or both surfaces. Jaw crushers and cone crushers using the compression method are suitable for reducing extremely hard and abrasive rock.

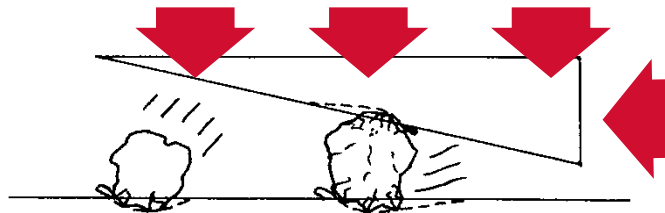


Figure 3: Compression

In the analysis of comminution processes as they relate to mineral processing, it is necessary to have a detailed understanding of what occurs in the comminution sub processes such as the transportation of the particles to the breakage zone, the orientation of the particles, the removal of the fragments that are smaller than the limit size, and the prevention of agglomeration. These sub processes have been researched for over 100 years, although in detriment of the most important variable to understand: the entropy of the breakage phenomena, caused by the heterogeneous nature of the raw material. These phenomena can only be understood by applying the principles of fracture physics to obtain information about the stress-strain behavior in particles loaded either by compression or by impact, and by interpreting the consequent results. The best way to interpret results should be by controlling crushing conditions by means of single particle crushing, packed bed crushing, measurement of energy needed for complete fracture, and fragment size distribution. Results will vary greatly and will depend on the following specimen variables: crack behavior, confinement, nature of specimen, size of specimen, and viscoelasticity of the specimen.

The main comminution conclusions are,

- Kinetic energy is to be most efficiently used in a process for size reduction,
- The time of impact should be as short as possible, and the intensity of impact as large as possible.
- The compression method is the most energy efficient process.

Schonert (1984, 1986) did a detailed study on compressive and impact comminution of single confined particles as well as non-confined particle beds of various materials. His conclusions were that compression yields higher energy utilization than impact, and that energy utilization in the

compression mode increases with decreasing particle size and decreases as the energy input becomes larger.

Kerber et al, (1985) proved that single particle compression is the most efficient, similar to Schonert's findings. Hanisch and Schubert (1986) in their studies, concluded that energy utilization can be increased up to 50% when the right distribution is fed to the crushing chamber.

Theoretically, for the compression occurring in a cone crusher, up to 4 layers of particles may be involved during the compressive loading phase of the crushing cycle, although, these particles need to meet certain conditions in order to be reduced as efficiently as single particle confined crushing.

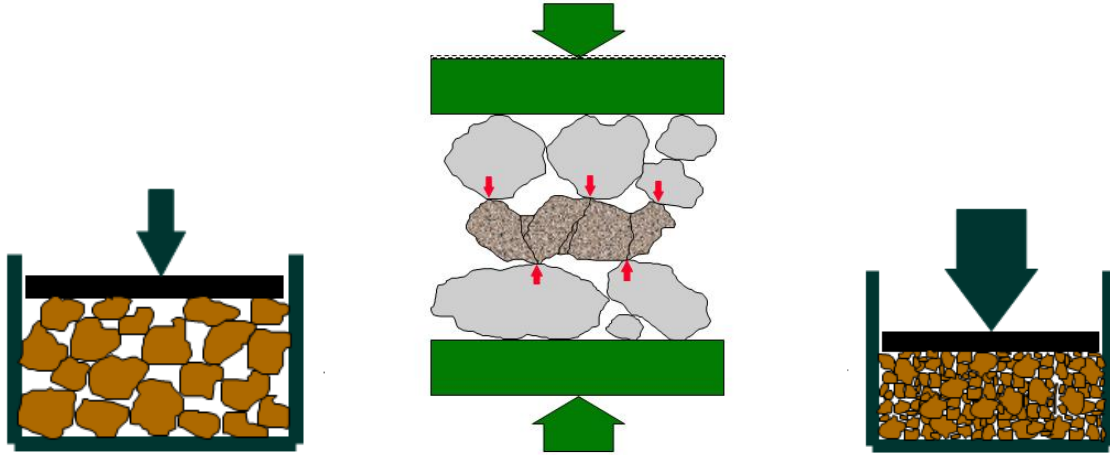
Lab tests conducted at Chalmers University in Goteborg clearly show that single particle breakage is most energy efficient and that multi-particle breakage has a packing limit and is associated with the probability of crushing success of the particle bed. The probability increases when the fraction length increases, and also increases when the material possesses the following characteristics:

- It has brittle behaviour
- It is free of clay
- It has low absorption
- It has low moisture

These characteristics are typical of aggregate processes, where in order for the rock to be an aggregate it must have an absorption of less than 2% and should have grain and cementation characteristics that will result in brittle behaviour. However, most metals mining ores will display characteristics completely opposite to the above,

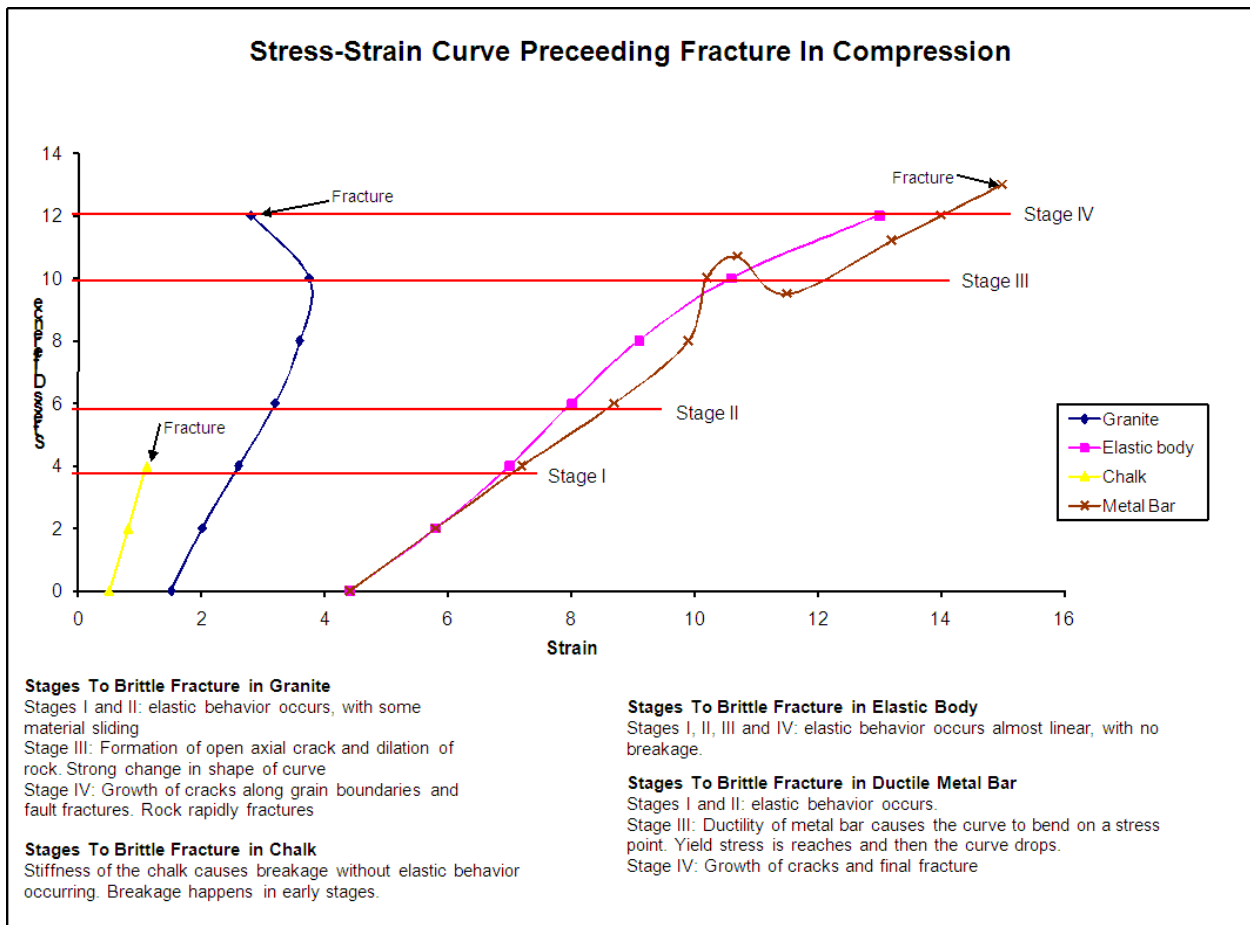
- Grain structure is heterogeneous, with irregular cementation which will create viscoelastic behaviour
- Silica and alumina clays are abundant and present in the mineralized ore
- Irregular grain structure and porosity results in high absorption levels

- Irregular grain structure and porosity results in high surface and inherent moisture.

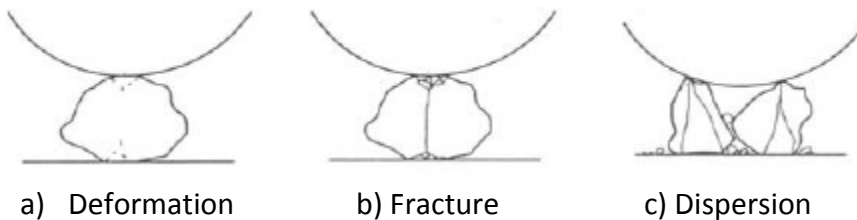


THE IMPORTANCE OF STRESS AND STRAIN IN ASSESSING THE EFFECTIVITY OF CRUSHING

When subjecting ores to reduction, one must take into account the characteristics listed before. These ore characteristics vary considerably even within the same mine. It is important to note that most ores exhibit a combination of brittle and viscoelastic behaviour. As detailed in the figure below, ores will show elastic behaviour at the earlier stages of stress, and even after the formation of the first axial crack, the rock may still have enough cohesion to withstand fracture. The cohesion presents a challenge in evaluating the behaviour of ores between the formation of the first axial crack and the final fault fracture.



As the crushing surface contacts the rock, the following stages occur:



The amount of deformation depends on the nature of the rock. Fracture will be dependent of the velocity and the propagation of the crack. Dispersion will cause reorientation of the particles.

Normalized rock strength depends on the rock specimen size. Weibull developed models to explain the increase in strength when the particle size decreases. The most ignored variable in crushing a confined particle versus crusher a particle bed is the capacity of the specimen to store elastic energy and the influence of plastic deformation. Since the capacity for storing elastic energy is a volume property, the energy consumption by a geometrically similar crack is proportional to the square of the diameter. Therefore, small specimens have less energy available for fracturing and consequently, require higher stress levels for crushing. In a fixed grip situation such compression crushing, a minimum length is needed before the crack will move completely through the

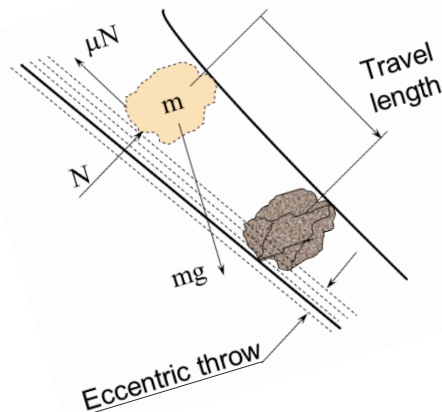
specimen. For a shorter specimen the crack cannot move across the specimen without new energy input from the outside. This means that the crack propagation is controlled by the energy input.

For the case in which the load remains constant, the energy content of the stress field increases as the crack extends, because the crack growth causes the stiffness of the specimen to decrease. A constant applied force increases the deformation and the stored energy content. The energy used to propagate the crack is given by the difference between the work done from the outside force and the energy increase in the field. From a theoretical viewpoint, thus, energy consumed by plastic deformation must be therefore considered as wasted energy.

From these data and theoretical considerations, the following conclusions can be drawn regarding the energy consumption in the breakage phenomena: For crack velocities very much lower than the maximum crack velocity, the specific fracture surface energy decreases with increasing crack velocity until a minimum is obtained. Further increases in crack velocity up to the maximum velocity cause an increase in the energy consumption.

Interparticle or particle bed crushing needs complete confinement of the particles, this time with the rock creating interparticle confinement. It is found that as confinement increases, the fracture process is more progressive and the failure mechanism changes from axial splitting to shear fracture. The interparticle breakage process in a particle bed under these confined conditions depends on the strength criterion which is a function of the confinement success, which depends on the ability of each particle to mutual interlocking, which is less likely when the particles show viscoelastic behavior. Viscoelasticity will act in detriment of the stress distribution and redistribution, since success depends on the heterogeneous distribution in the particle. Regardless of the particle shape or particle bed arrangement, the fragmentation starts from the particles which are loaded in uniaxial compression. Only the confinement from the neighboring particles, and depending on the location of the loading points, small fragments will be torn off at the loading points with a large piece preserved. Without true particle confinement, the cracks will not propagate across the particle bed and the bed specimen will do nothing but successively reorient itself with each eccentric revolution.

Moisture is detrimental to the net volumetric production of a crusher, because of the increase in friction and decrease of material flowability. However, it can be used to increase reduction by minimizing the sliding length of the ore and increasing the amount of time the material is compressed by the eccentric motion.



PRODUCT SELECTION RATIONALIZATION FOR TERTIARY STAGES

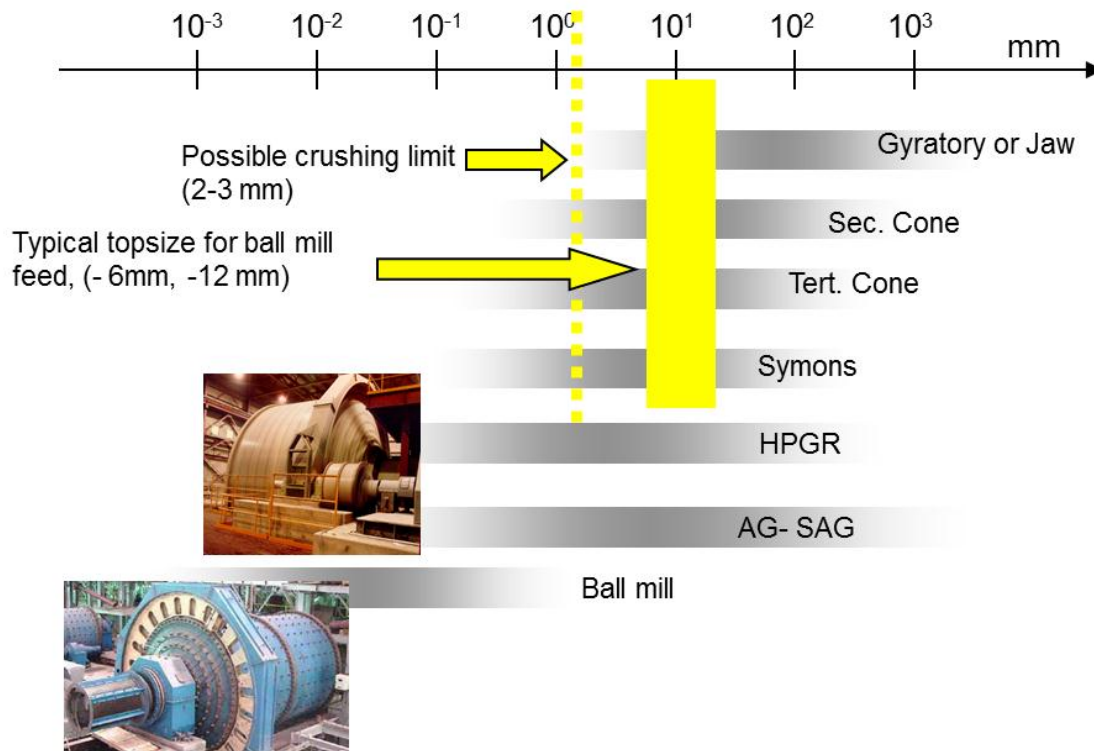
When the use of cone crushers is extended to fine crushing, the structural rigidity and controlled motion of these mechanisms can generate very high forces on individual particles (Flavel and Rimmer, 1988). These force levels can cause significant energy losses due to agglomeration or packing of particles in the crushing chamber and to actual elastic deformation of the crusher. This effect can be accentuated if bed particle confinement is unsuccessful. This wasted strain energy, which is observed to be cyclical, can also generate excessive fatigue stress levels, reducing the effective life of crusher components, as has been documented in many mining plants with many different types of cone crushers (Pascoe, et al., 1982; Thirwell, et al., 1982).

Comminution “typically” accounts for between 50-80% of all energy use at mine sites. "A significant 4% of the world's electricity is used for the size reduction of ores, rocks and cement" (Siddall, 2007). The goal of most crushing processes is to prepare feed to the ball mill. One of the biggest challenges in the application of crushers in the mining industry is to bridge the gap between the final product of a tertiary crushing stage and the feed to the ball mill. Ball mills typically prefer a P80 of about 6 mm, therefore it is important to achieve the highest degree of reduction ratio in the final stage of crushing. Particle sizes around 25-50 mm (one to two inches) cause a disproportionate number of the problems found in the effective utilization of comminution energy, and the use of fine crushing or coarse grinding to overcome this problem risks the introduction of significant inefficiencies into the typical comminution operation. The higher the reduction in the

tertiary stage, the lower the energy consumed by the ball mill. The challenge lies in the fact that it is difficult to reduce most metallic ores via tertiary crushing below the 12-15 mm mark.

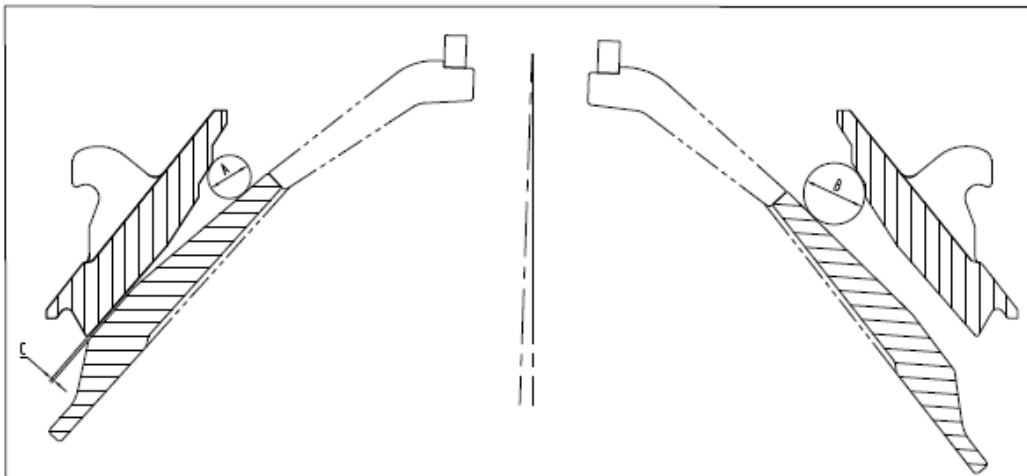
Bums and Erksine (1984) reported that when the feed size to a ball mill was reduced from 8.3mm to 6.4mm, the mill throughput increased by about 7% per mill. At BCL, where the tests were conducted, 12 mills were running. The annual savings incurred by this increase amounted to USD\$2 Million per year.

As documented by Pascoe, et al (1982) bringing down the mill feed size from 9 mm to 6 mm also amounted to a 7% increase in capacity.



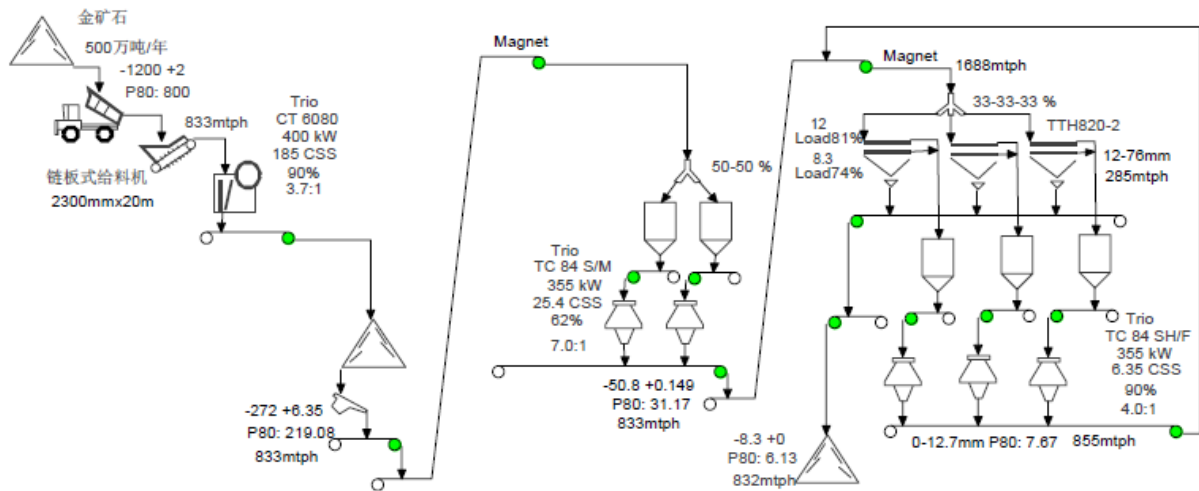
A sensible approach to plant design should take all variables into consideration. The following rationalization could be applied to plant design,

- For primary crushing, the use of either a jaw crusher or a gyratory crusher will be suited, since single particle confinement will exist.
- For secondary crushing, care should be exercised to provide a long fraction in the particle size distribution to the crusher to enable interparticle interlocking, however a single particle confinement approach could be a better solution when the ore displays viscoelastic behavior and a long particle size fraction cannot be achieved. This would mean to return to the use of a lower speed cone crusher with a much longer parallel zone which will create more single particle confinement.
- For tertiary crushing, the same rationale explained before should be applied, with much more emphasis on the need of using single particle confinement, since interparticle interlocking in the non-confinement zone of the crushing chamber will be very difficult to achieve.
- Quaternary crushing can be completely eliminated by means of using a tertiary cone crusher running at lower speeds and with a long parallel confinement zone, which in addition, can yield product particle size distributions with a P80 of 6 mm.



All Size In mm	ShF		最小 排矿口 Min	最大 排矿口 Max
闭式排矿口C	Closed Side Setting	C	6	25
闭式进料口尺寸A	Opening Closed Side	A	51	72
开式进料口尺寸B	Opening Open Side	B	105	125
最大进料尺寸	Max Feed Size		85	100

The crushing plant shown below produces 800 MTPH of ball mill ready feed with a P80 of 6.3mm. The “Symons style” tertiary crushers allow for a closed side setting of 6mm with material conditions that are less than desirable, with very high absorption and moisture and a considerable percentage of clay.



CONCLUSION

Three main postulates are made in this paper:

- The advent of a higher speed and more polyvalent crusher that introduced particle bed crushing with the purpose of increasing volumetric capacity and a more cubical product was not necessarily something geared to improve crushing efficiency in mining processes.
- Most tests conducted in the last 40 years regarding crushing efficiency fail to take into account that variables like fraction length, absorption, clay content and viscoelasticity are critical to achieve efficient crushing of a particle bed, are more critical when considering mining ores instead of aggregates.
- Single particle crushing remains the only crushing option that provides certainty when it comes to assessing the crushing efficiency despite of all variables.

As more research that targets the creation of better methods to improve crushing efficiency gets underway, it would be recommended for crushing manufacturers to better assess the efficiency of particle bed crushing and revisit the option of low speed, high particle confinement methods, since the results will align with the current mining needs of high reduction with the lowest energy consumption.

REFERENCES

- Siddall, B. and Putland, S., 2007 "Process Design and Implementation techniques for secondary crushing to increase milling capacity", SME Annual Meeting, Preprint 07-079
- Bond, F.C., 1960, "Crushing and Grinding Calculations," British Chemical Engineering, pp. 378–385, 543–548.
- Motz, J.C., 1978, "Crushing," Mineral Processing Plant Design, Chap. 11, SME-AIME, New York.
- Murrells, D.J., 1972, "Impact Crushers and Hammermills: State of the Arts," Institution of Mechanical Engineers, London, Mar.
- Evertsson, Carl Magnus., Chalmers Tekniska Högskola. "Cone crusher performance" / (2000) Thesis (Ph. D.)--Chalmers University of Technology, 2000. Publisher Goteborg, Sweden : Machine and Vehicle Design, Chalmers University of Technology.
- Taggart, A.F., ed., 1947, Handbook of Mineral Dressing, 2nd ed., Wiley, New York.
- Weiss, N.L., ed., 1985, SME Mineral Processing Handbook, Vol. 1, Sec. 3B, SME-AIME, New York.
- Colman, K.G., 1978, "Selection Guidelines for Size and Type of Vibrating Screens in Ore Crushing Plants," Mineral Processing Plant Design, A.L. Mular and R.B. Bhappu, eds., AIME, New York, pp. 341–361.
- Gluck, S.E., 1965, "Vibrating Screens," Chemical Engineering, Vol. 72, No. 4, pp. 151–168.
- Mathews, C.W., 1971, "Buyers Guide to Screens," Engineering and Mining Journal, Vol. 172, No. 12, pp. 53–65.
- Awaji, H. and Sato, S. "Diametral compressive testing method." J. Eng. Mat. Tech. 101,139,1979.
- Clark, I.H. "A role for geomechanics in minerals process engineering science." [in press]
- Cundall, P.A. "Numerical experiments on localization in frictional materials." Ingenieur-Archiv, 59, 148-159,1989.
- Flavel, M. D., and Rimmer, H. W., 1988, "Applied Crusher Research Related to Comminution Breakage Efficiencies," presented to the XVI International Mineral Processing Congress, held June 5-10, at Stockholm, Sweden, 25 pp.
- Flavel, M. D., Rimmer, H. W., Woody, R. N., Schmalzel, M. O., 1988, "The Relevance of Efficient Crushing in Comminution Systems ," presented at the SME-AIME Annual Meeting, Phoenix, AZ, Jan. 25-28, 28 pp.

Pascoe, G. J., Lees, M. J., and Langford, D. S., 1982, "Crushing Plant Development at Bougainville Copper Limited, Panguna, PNG," XIV International Mineral Processing Congress, October 17-23. Toronto, Canada.

Karra, V. K., 1989 "Extension of Conventional Fine Crushing for Progressive Substitution of Conventional Grinding." Challenges in Mineral Processing SME, 1989.

Schoenert, Klaus, 1972, "Role of Fracture Physics in Understanding Comminution Phenomena", Society of Mining engineers, AIME Transactions Vol 252.

Romero-Lage, Fernando and Dricken, Chuck, 2010, "The Importance of Efficient Mass Flow Balance in Crushing and Screening Plants". CIM Conference, Vancouver, Canada.