The Effects of Blasting on Crushing and Grinding Efficiency and Energy Consumption

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Abstract

Blasting has an important impact on mining and milling well beyond the necessary ability to dig and load the ore efficiently. There is an increasing body of blasting research indicating significant impacts in crushing and grinding. These include increased production through higher output and fewer delays for bridging and jamming by oversize. In addition, fragmentation better suited to the crushing and grinding system is indicated to lead to reduce energy consumption by these activities, an important result in today's environment. An important component of optimum fragmentation for this purpose appears to be micro-fracturing within individual fragments. This differs from fragmentation criteria for loading which focus mostly on fragment size. Therefore, one must analyze blasting broadly to obtain satisfactory results throughout the operation.

This paper examines the role blasting plays in optimum crushing and grinding with the emphasis on energy reduction. The role of different blasting energy input on fragmentation is studied, and related to needs at the plant. The effect of different feed sizes on energy consumption in crushing and grinding is studied. The role of micro-fracturing in this process is examined.

In the current environment, a policy of using energy where it is least costly, and conserving it where it is most expensive is essential. Both unit cost and efficiency of the various processes must be considered. Based on the results of this study, methods for a rational allocation of energy are discussed.

The need for more research in microfracturing and of how far downstream blasting improvements affect the results of subsequent unit operations is pointed out.

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Introduction

In recent years there has been increasing attention paid to the effect of blasting on subsequent operations. In the past, the primary focus was the ability of the excavation equipment to productively dig the blasted rock, and the amount of oversize chunks produced. Now, more consideration is given to the effect of blasting on operations beyond loading, such as crushing and grinding.

There are two important aspects of blasting on fragmentation; one is seen and one is unseen. The first is the size distribution of blasted fragments. This is often assessed qualitatively, by inspection, as good or poor. It can also be measured quantitatively by image analysis techniques. While these methods are not perfect, in terms of measuring fines, they provide much better results than previous techniques, are repeatable, and not intrusive to production processes.

The size of fragments is the “seen” part of blasting results. It is very important in crushing as it effects production and downtime. Overly coarse fragmentation will reduce primary crusher throughput. Coarse material will lead to more downtime for clearing crusher bridging and plugging.

Poor fragmentation will increase the load to secondary and tertiary crushing stages, if used, because there will be less undersize that can be split off to bypass these stages. This will affect productivity and energy consumption. It is highly probable that the blasted size distribution introduced to the primary crusher will affect the feed size distributions throughout the crushing stages.

The second effect of blasting, which is “unseen”, is the crack generation that occurs within fragments. There is substantial evidence that such cracking occurs. The work by Nielsen and Kristiansen (Fragblast5, 1996) is an excellent example.

Fractures generated in the fragments may be macrofractures or microfractures. Microfractures develop around mineral grains, and are seen through a microscope. Microfractures have the greatest chance of surviving the various stages of crushing and being present in grinding feed. The effect of internal fractures is to “soften” the fragments, making them easier to break. This has benefits to productivity, energy expenditure, and wear of consumable items.

Therefore, in the process of optimizing blasting it is very important, but not enough, to know that the fragmentation distribution is adequate. Consideration must also be given to how blasting will precondition individual fragments by internal fracturing. While the first factor is now measurable directly, the second must be assessed through study of production, energy consumption and supply cost.

Two factors standout as being of essential importance in determining crushing and grinding effectiveness. One is productivity. There are certainly examples of processing plants where poor crushing and grinding production have controlled overall plant production.

The second is energy consumption. Large, hard rock mines expend enormous amounts of energy, with associated costs. A substantial portion of this energy is expended in crushing and grinding. Most particularly, energy consumption in grinding is large. The reason is that the change from feed size to product size, achieved in grinding, is typically much greater than in crushing.

There is significant evidence that blasting does affect crushing and grinding results, and that large savings in cost can accrue (Eloranta, 1995; Paley and Kojovic, 2001). It is reasonable to postulate that the size distribution of blasted fragments, and the internal softening of individual fragments by blasting can affect crushing and grinding effectiveness, even though these processes are two to three unit processes downstream from drilling and blasting.

The role of microfractures is very important, especially at the grinding stage. It is generally considered that fragments become harder at each stage of sizing, because the feed is smaller and there are fewer geologic and blast induced fractures present in the fragments. Since grinding feed is typically less than 3/4 inch, it will only be the smallest macrofractures, and the microfractures that survive to reduce the resistance to grinding.

The degree to which this happens is presently unclear. There is evidence that Bond work index is significantly reduced by heavier blasting (Nielsen and Kristiansen, 1996). There is, however, recent research that suggests that while significant softening is seen at the crushing stage there is little change at the grinding level (Katsabanis et al, 2003, 2 papers). The work by Katsabanis is currently confined to granodiorite, so the role of rock type is not considered. As cited above there are also studies in operating plants that show important improvements to crushing and grinding production and cost associated with changes in blasting. For reasons made clear in this paper it will be important to clarify the survivability and role of microfractures in future study.

A third factor of effectiveness in crushing and grinding is mineral liberation. Greater liberation means improved downstream recovery. A currently unanswered question is whether blasting that creates more microfractures around or through mineral grains will improve liberation and recovery.

Energy Consumption in Crushing and Grinding

The energy input to size ore fragments is large. Overall reduction, performed in a series of stages may be from an eighty percent feed size passing of 40 cm (15.8 inches) to a final product size of 270 to 325 mesh (.053 to .045 mm). A lot of energy is expended to accomplish this, and it is not a particularly efficient, with much of the energy input being dissipated as heat. It has been estimated that grinding efficiency may be as low as one percent (Hukki, 1975; Willis, 1988).

The third theory of comminution developed by Bond (1952) is still used today, although there have been recent advances (King and Schneider, 1995). Using this theory, energy requirements to reduce fragments from an 80% feed size to an 80% product size can be calculated.

The Bond equation of comminution is stated as follows:

$$W = 10W_i\left(\frac{1}{P^{.5}} - \frac{1}{F^{.5}}\right)$$, where

W = work input, kwh/ton
W_i = work index for the specific rock type, kwh/ton
P = 80% passing size of the product
F = 80% passing size of the feed

One reason for using Bond's third theory is that work index W_i has been measured and reported for many rocks.

Using this relationship one can study the work input required for different feed sizes and work indices in the stages of comminution. In the current study W_i is held constant throughout the stages, although it may, in fact, vary. Provided consistency is maintained the trends in energy consumption and cost will be correct.

As a base case, we assume that taconite ore is being blasted with a heavy ANFO (HANFO) having absolute weight strength of 3.35 MJ/Kg (801 cal/gm). The 80% passing size of the blasted ore has been measured and found to be 40 cm (15.75 inches). The ore passes through primary and secondary crushing and grinding. The final product is 80% passing 270 mesh.

Bond has published a W_i for taconite of 14.87 (1961). This value is used in these base case calculations.

Table 1 shows the feed and product size, the calculated total energy input, and the energy cost for each unit operation. The explosive cost is based on the powder factor of 0.33 kg/tonne (0.65 lbs/ton) and an explosive cost of $0.264/kg ($0.12/lb). Electric energy cost is assumed to be $0.07 per kwh.

Table 1: Energy and cost calculations by unit operation

Operation	**Feed size**	**Product size**	**Work input**	**Energy cost**
	cm	cm	kwh/ton	$/ton
Explosives	∞	40	.24	.087
Primary crushing	40	10.2	.23	.016
Secondary crushing	10.2	1.91	.61	.043
Grinding	1.91	.0053	19.35	1.35
Totals			20.43	1.50

By far the greatest work input is in grinding. Size is reduced by a factor of 360. In primary crushing, it is reduced by a factor of four and in secondary crushing by about five times. Clearly, changes in blasting that reduce grinding requirements will have the biggest impact for energy savings.

The work input shown for blasting is calculated by the Bond equation. The actual energy input is .33 kg/ton, or .31 kwh/ton. Thus, the efficiency compared to Bond is 77 percent. This is likely due to the variable nature of rock and the transmission of the energy, and the possibility that W_i is greater than 14.87 in the unblasted state. The cost for the explosives however is that associated with the powder factor of .31 kwh/ton.

From an energy consumption viewpoint, it is clear that blasting that decreases the Bond work index will produce large savings if that reduction carries through to grinding.

Changing the Energy Consumption

The energy consumed can change in three ways. First, if the feed size to the primary crusher is decreased, less energy will be required to crush the ore to the same product size. Second, a decrease in W_i related to additional macrofracturing and microfracturing within individual fragments. Third, an increased percentage of undersize that bypasses stages of crushing thereby decreasing the percentage of total tons crushed.

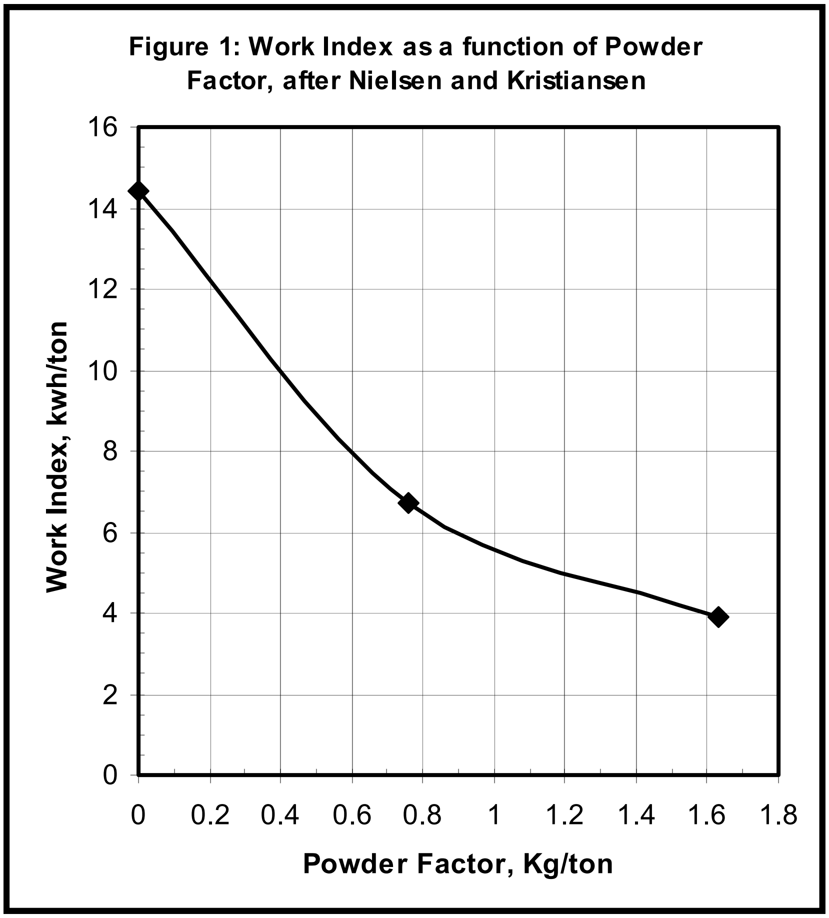
Consider the hypothetical case where the powder factor in the example above is increased to 0.45 kg/ton (0.90 lb/ton), and that an associated reduction in P_{80} size to 30 cm in the blasted ore occurs. The work input, assuming no change in work index, is .194 kwh/ton. For a mine crushing 50 million tons per year, a reduction of 1.8 million kilowatt-hours, or about $125,000 per year is realized.

The second possibility is a decrease in W_i. There is evidence that work index bears a relationship to powder factor. Nielsen and Kristiansen examined grinding results for core of three rock types when the core sample was not subjected to blast action, and when samples were subjected to blasting by one and by two pieces of detonating cord (1996). For taconite, a substantial reduction in work index was calculated. The reduction was greater for the two detonating cord case than for the one cord test.

We have used data about core dimensions and the detonating cord used, found in their paper, to calculate a powder factor. A taconite density of 3.93 ton/m^3 (6000 lbs/cyd) is assumed. This derived powder factor is to be considered as a first order approximation only. The results are displayed on the chart in figure 1.

This graph shows a marked decrease in W_i with increasing powder factor. It also illustrates that the incremental decrease in work index for higher powder factor is less, and eventually there would be no advantage to further increases in explosive energy applied. The trend suggests that the level of explosive energy at which there is no further improvement in W_i may be quite high.

For the proposed increase in powder factor to 0.45 kg/ton, this chart would suggest W_i of about 9.5. However, to be somewhat conservative, we have chosen a work index of 10.4 for this case. A W_i of 14.87 is still used for blasting the undisturbed ore.



Once again two stages of crushing, and a grinding circuit are considered. The ore is sized to 80% passing 270 mesh. Table 2 provides the results of this analysis. The same HANFO is used as the explosive, and the blasting cost is based on the powder factor, which is a higher work input than calculated by the Bond Equation.

Table 2: Energy and cost calculations by unit operation with a higher powder factor

Operation	Feed size	Product size	Work input	Energy cost
	cm	cm	kwh/ton	$/ton
Explosives	∞	30	.27	.119
Primary crushing	30	10.2	.135	.009
Secondary crushing	10.2	1.91	.428	.030
Grinding	1.91	.0053	13.55	.949
Totals			14.38	1.107

In the example, the required work input has decreased by 30%, and the total cost by 26%. The cost in crushing and grinding has been reduced by 30%. No consideration is given here to increased production, less wear, or increased undersize bypassing crusher stages.

The actual work input by the explosives is 0.42 kwh/ton, whereas the Bond equation yields a requirement of 0.27 kwh/ton. The efficiency is 65%, and represents the variability of the field environment and nature of energy transfer to the rock.

Assume a mine crushes 40 million tons per year. In the base case, the mine will expend $60.0 million per year for energy as calculated in table 1. When the powder factor is increased, the requirement falls to $44.28 million. A savings of $15.72 million per year is realized, or $0.39 per ton. This is a substantial reduction in cost.

It is of interest to compare this to the savings reported by Paley and Kojovic, (2001) as a result of a drill-to-mill implementation at the Red Dog Mine. They reported savings exceeding $30 million per year, with the potential for additional improvement. Their case considered more than energy cost. What is important is that their results and the present analysis using assumed parameters are of the same order of magnitude. This suggests that, at least in some ores, improved internal fragmentation carries through the crushing and grinding circuits. However, considerably more study is needed to determine if this is true. The magnitude of the potential indicates that such study should be a priority.

Effect of Decreasing Work Index

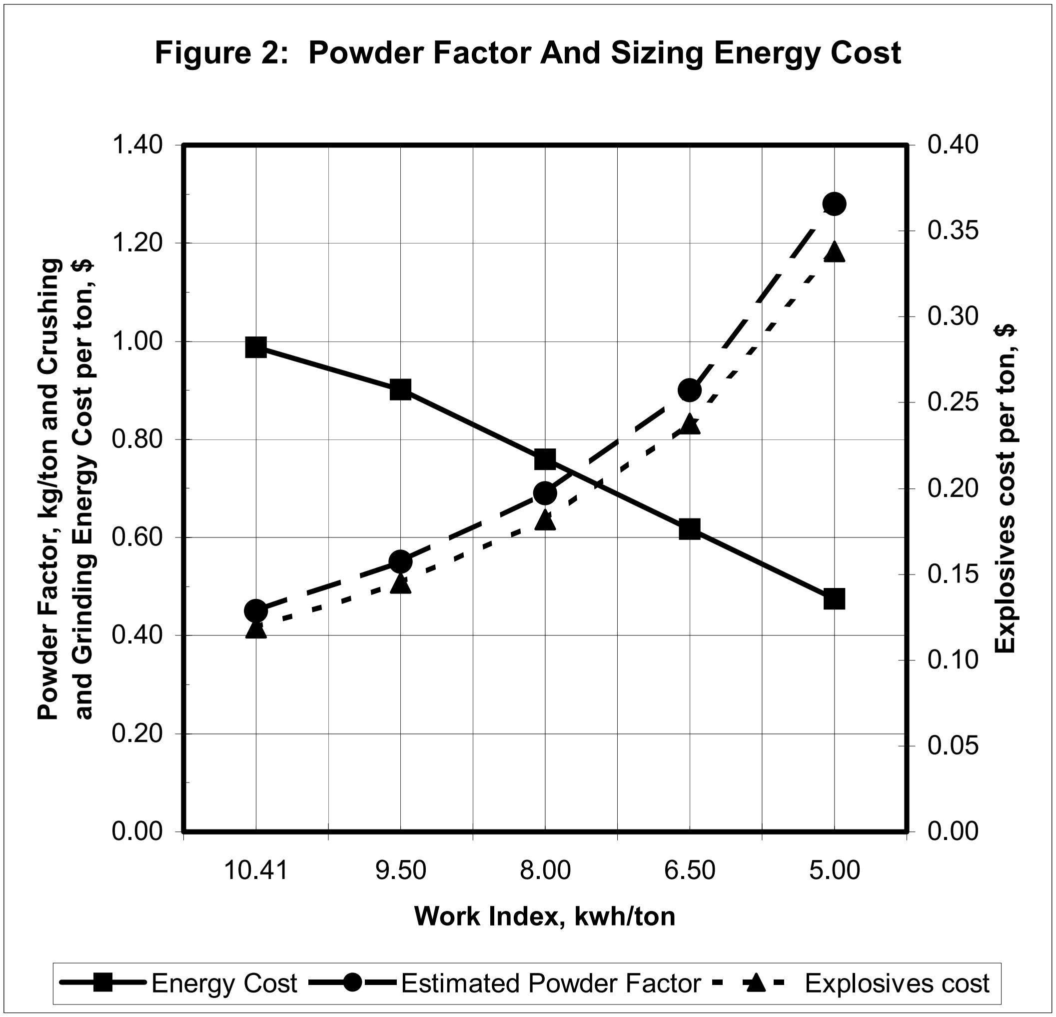
Clearly, reductions in work index have the potential to reduce costs for energy consumption. In figure 2 the powder factor and reduction in crushing and grinding energy cost are presented. Also plotted, on the second y-axis, is the increase in explosives costs associated with the decreasing work index.

For each work index and associated powder factor the feed size to primary crushing is assumed to be 30 cm. In reality this might change, but in the absence of specific data to support changes to the feed size we have chosen to keep F_{80} to the crusher constant.

The chart relates to taconite. The powder factor trend is based on the values we derived from the study by Nielsen and Kristiansen (1996), but is increased from the trend line in figure 1 for a conservative estimate. These powder factors must be considered an estimate only. The relationships must be confirmed by field study in operating mines.

A reduction in W_i from 10.4 to 5.0 is accompanied by a decrease in crushing and grinding cost of $0.513 per ton. The associated increase in explosives cost for the HANFO at $0.264 per kilogram is $0.219 per ton. The net decrease in energy cost is $0.294 per ton. For a mine crushing 40 million tons of ore per year, the savings are $11.8 million per year. This is a very worthwhile reduction in cost.

One observes in figure 2 that the decrease in sizing energy cost flattens as the work index decreases and the increase in powder factor accelerates. However, the trend suggests that the limits have not been reached, if the relationships hold true in field practice. This would be consistent with findings by Eloranta (1995) and by Paley and Kojovic (2001).



Discussion

This paper is based on an examination of various research and implementation drill-to-mill projects that have been reported. It is intended to inform drilling and blasting personnel of the improvements that blasting can effect in the processing operations. The material presented should make clear that blasting engineers need to work closely with process engineers to achieve the best cost of operation.

The analyses presented are predicated on the assumption that internal fracturing that leads to softening of individual fragments, and a reduced work index, carry through to the grinding stage. By far the largest potential savings in energy input occur at this stage of sizing. There is evidence, as cited, to support this view. It is dependent on the production of microfractures within the fragments. There is, however, recent research that did not find reductions in work index carrying through to grinding, at least in granodiorite, unless very high blasting energy levels are employed.

The magnitude of potential savings make it imperative that these questions be resolved. Further research, and work in the operating environment will make an important contribution to the drill-to-mill understanding. Research should include various rock types and structural geologies, so the role of geology on internal fracturing and rock softening can be understood.

This paper does not examine quantitatively other beneficial results of improved blasting. However, these exist and they include:

1. Increased productivity in crushing and grinding.

2. More undersize that bypasses stages of crushing.

3. Reduced consumable wear in crushing, grinding, loading and hauling.

4. Increased shovel production and less energy expenditure in loading

5. Tertiary benefits such as the ability to use light weight truck boxes due to the less severe service encountered. This will also decrease energy consumption.

These factors will further improve the cost picture. Even if all the energy savings in crushing and grinding are not realized, significant cost savings are possible.

This study employs higher powder factor to achieve improved results downstream. We have observed numerous cases where this approach is beneficial. However, the fragmentation specialist must approach drill-to-mill optimization with an open mind. Depending on geology, and the crushing and grinding equipment employed, increasing powder factor may not always be the answer.

This analysis does not consider drilling cost. However, depending on how increased powder factor is achieved this cost may increase and reduce some of the projected savings. Blasting costs such as labor, equipment and accessories are not included as these are considered to be similar in all cases. The foregoing analyses indicate that drill-to-mill optimization opens up many aspects of blast design and implementation. These include explosive selection, powder factor, blasthole size, pattern dimensions and timing accuracy.

Conclusions

The following conclusions are made

1. The greatest energy savings available are in grinding due to the large change in particle size achieved.

2. Blasting related improvements in grinding will depend primarily on the degree of microfracturing achieve, as it is these cracks that will survive earlier stages of crushing.

3. Substantial improvement in cost can be achieved.

4. The use of greater energy input in the blasting unit operation will often be less costly than expending the energy downstream.

5. There remain unanswered questions about drill-to-mill optimization. The large cost savings projected, and in some cases seen in actual practice make research in this field an urgent priority for mining cost minimization.

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