Improving Energy Efficiency Across Mineral Processing and Smelting Operations – A New Approach

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ABSTRACT

With their commitment to sustainable development in an increasingly carbon-constrained world, many resources companies are focused on reducing the energy required to create their final products. In particular, the comminution and smelting of metal-bearing ores are both highly energy-intensive processes. If resource companies can optimise the energy efficiency across these two processing stages, they can directly reduce their overall energy consumption per unit mass of metal produced and thus reduce their greenhouse gas footprint.

Traditional grinding and flotation models seek to improve the efficiency of mineral processing, but they do not consider the energy used by downstream metal production, eg smelting and refining. Concentrators and smelters individually may be running efficiently, but are they optimising energy consumption of the overall system? A key step towards answering this question is to understand whether it takes less energy to remove an impurity in the concentrator or the smelter. Analysis of the complete concentrator – smelter process chain may show that there are times when the concentrator should use more energy to reduce the overall energy requirements across the mill and smelter.

The new methodology discussed here will integrate downstream processing energy with mineral processing energy, to find the overall most energy efficient circuit design and operating strategy. The proposed methodology includes:

- determining what grade and recovery positions can be achieved in the concentrator by using different combinations and amounts of grinding and regrinding,
- thermodynamic calculations of the energy used to process the different concentrate grades to metal, and
- integrating the concentrating and smelting models to find the lowest total energy for the system.

A case study which investigates the effect of increasing regrinding energy on the overall mineral processing – smelting energy consumption is presented. For the copper-nickel sulfide ore investigated the addition of regrinding results in 11 per cent less energy being used in the overall concentrator – smelter process chain per tonne of metal produced. Although regrinding is often seen as an energy-intensive process, in this case study the use of 1 kWh of energy for regrinding reduces the overall energy consumption by 12 kWh. The new mill to melt methodology will allow companies to model energy consumption from mill to smelter with a view to reducing the energy-intensity and greenhouse gas footprint of their processing and smelting operations.

INTRODUCTION

Global resource companies are currently operating under very challenging economic and regulatory conditions. In response to growing societal concern about the various impacts of the minerals industry, and the emergence of the concept of sustainable development as the key framework within which these impacts are analysed, most organisations in the sector are now reporting their performance in this area using a range of sustainability indicators. Among these, energy use and its impact on climate change are priorities, with many company sustainability reports including total energy use and associated greenhouse gas (GHG) emissions in both absolute and relative terms (ie normalised to a per unit product) among their key environmental sustainability indicators. Companies are setting targets to achieve improvements in these indicators, but at the same time there is a global trend to more complex and lower grade orebodies which are more energy-intensive to process. As a result, resource companies are having to become more innovative to improve the environmental sustainability and the efficiency of their operations. In particular, companies must address the specific energy consumption of their processes in order to reduce their emissions of greenhouse gases.

Mineral concentration and metal smelting are two energy-intensive stages in the production of metals. According to the Australian Government's National GHG Inventory (2009), the production of mineral and metal products generated 26 million tonnes CO2-e in 2005, equivalent to 4.5 per cent of Australia's total GHG emissions. Smelting is energy- and GHG-intensive, with emissions from smelting up to three to ten times greater than those from mineral concentration processes (Norgate, Jahanshahi and Rankin, 2007). These two processes offer real opportunities to reduce the energy intensity of metal production.

In practice, mineral concentrators and smelters typically operate as independent units with their own product specifications and energy targets. We believe that the overall energy consumption across the metal production chain can be reduced by:

- scrutinising the energy consumers in the concentrator and smelter,
- defining the concentrate that achieves the lowest overall energy consumption, and
- modifying the product specification of the concentrator accordingly.

In particular, this paper looks at the effect of changing the amount of grinding energy on the required smelting energy and therefore the overall energy consumed to produce metal.

This paper outlines a proof of concept investigation to determine whether the process and energy models of concentrators and smelters can be integrated to produce an effective energy and GHG footprint model for metal production. The investigation includes a case study on a copper-nickel sulfide ore to demonstrate how the methodology would be applied. Proving that the mill to melt concept is viable is the first step in the journey towards developing a methodology for minimising energy consumption and associated GHG emissions along the entire concentrator and smelter metal production chain.

THE MILL TO MELT METHODOLOGY

The objective of the mill to melt methodology is to provide a framework for minimising energy use and GHG production per tonne of metal produced in mineral processing and smelting. Metallurgists recognise that there is scope to tune the operation of a concentrator to change the product quality and also scope to tune the smelter operation to smelt a different grade of

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concentrate. However, there is no integrated tool currently available which allows companies to model the combined effect of these changes on overall energy consumption in the mill and smelter.

The mill to melt methodology aims to integrate mass and energy models of both mineral concentration and smelting stages to provide a tool for optimising overall energy consumption across these two energy-intensive processes. The methodology will identify the relationship between metal grade and recovery in the concentrate and the overall energy consumption across both the concentrator and smelter. This relationship can be expressed as a three-dimensional response surface and will allow the minimum energy operating point to be identified for a given operation. Note that the variation in ores, concentration and smelting processes between mining operations will mean that it is unlikely that a universal relationship which can model the response for all ores will be identified. In the mill to melt methodology the generic model will be fitted to the combination of ore, concentration and smelting processes at each site.

With the increasing focus on reducing GHG emissions from metal production a tool such as the mill to melt methodology is likely to find industrial application in both existing operations and new projects. It will be most beneficial in integrated operations where a single company owns both the concentrator and smelter.

Modelling mineral processing performance

Laboratory procedure

In the mill to melt methodology the process route used to concentrate an ore is implemented on laboratory scale equipment. This allows a variety of circuit configurations and operating strategies to be compared and is equally applicable to existing operations or greenfield sites. The laboratory procedure developed in the proof-of-concept work uses laboratory batch grinding mills and froth flotation cells in the same circuit arrangement as would be used in a full-scale industrial plant. Energy consumption during each of the grinding stages is monitored and recorded using an energy metre. A typical process flow sheet with two stages of comminution and separation is shown in Figure 1 and this is the process route used in the case study presented later in this paper.

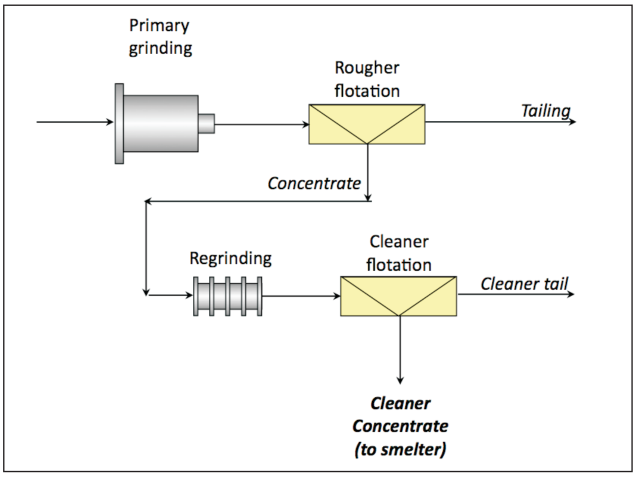

FIG 1 - A typical concentrator flow sheet with two stages of grinding and separation.

The laboratory tests generate physical samples of ore particles from the feed, concentrate and tail streams which are characterised using the JKMRC/FEI MLA automated mineralogy system. Information about the minerals which occur in a range of particle size fractions is used in the modelling procedure, together with data which describe how the ore particles behave in the separation processes.

Mill to melt modelling procedure

Since the link between the mineral concentration and smelting stages requires information about both the mineral and elemental composition of the process streams the modelling procedure tracks the flow of minerals in the circuit. It is a simple step to convert the mineral data into elemental composition data.

The aim of the modelling procedure is to minimise the amount of laboratory work required to identify the operating point at which the minimum energy and greenhouse gas footprint is achieved. This will make the mill to melt methodology a practical and affordable tool.

One approach reported recently (Wightman *et al*, 2008; Wightman and Evans, 2009) shows that, for many ores, assumptions can be made about how the minerals liberate during comminution. These assumptions allow the comminution and liberation response of the ore to be calibrated from one set of physical tests. These calibrated values can then be used to predict the liberation characteristics at a wide range of grinding energy inputs without further laboratory testing. This 'measure few, model many' approach saves considerable time and money in applying the methodology.

The flotation modelling also requires laboratory tests to measure the response of the ore. This calibration of flotation response is essential because the variability between ores as naturally occurring substances means that each ore requires a set of flotation conditions tuned to its particular natural characteristics. The ongoing flotation modelling work seeks to minimise the amount of physical testing required by tracking the flotation response of the particles into the various concentrate and tailing streams.

Modelling smelter energy requirements

The smelter modelling stage uses computer-based, thermodynamic models of the smelting process to predict the input energy requirements. Depending on the ore being modelled there may be one or two final concentrates whose smelting energy requirements need to be taken into account separately. In the case study presented in this paper two concentrates are produced in the concentrator and thus two parallel smelting operations are included in the analysis, one for copper and one for nickel smelting.

Smelter models, based on thermodynamics, require information about both the chemical and mineral composition of the concentrate fed to the smelter. The mill to melt methodology generates information about the concentrate in terms of mineral mass flows which are readily converted to elemental flows.

A model of the smelting energy requirements can best be done on a case-by-case basis because there is variation in the equipment units employed at different smelters. To simplify the analysis, without loss of accuracy, it is sufficient that a case study should focus on modelling equipment units within a smelter that satisfy both of the following criteria:

- the greedy energy consumers, and
- the mineral-dependent equipment units.

Equipment units satisfying these two criteria are the most influential when making decisions about the concentrator-smelter interface and therefore the most important for the mill to melt optimisation.

An important consideration for smelter modelling is the inclusion of different energy sources. A smelter may have separate inputs of multiple fossil fuel types as well as electricity.

This case study includes different sources and expresses the model output as a common energy unit of kilowatt hours (kWh).

A MILL TO MELT CASE STUDY

The route chosen to prove that the concept of linking concentrator and smelter process and energy models is feasible involved developing a case study using real ore. The ore used in this proof-of-concept phase was a copper-nickel sulfide ore from an operating site in Canada. This ore is treated to produce both nickel and copper products. The smelter models used in this case study were based on the equipment units in the actual smelters which process these copper and nickel concentrates.

As with many base metal concentration process routes, the ore is subjected to two sequential stages of grinding and separation, as shown in Figure 1. When the smelters are included, there are four energy-intensive stages to be analysed in order to minimise overall energy consumption and the resulting GHG emissions of the operation.

In the example presented here, the effect on overall energy consumption of using varying amounts of energy in the second (or regrinding) stage is examined. The primary grinding energy is held constant and two levels of energy are applied in the regrinding stage. Laboratory tests and the corresponding mineralogical analyses of the products provide the information needed to model the grinding and flotation stages.

As Figure 2 shows, as the energy input to the regrinding of the rougher concentrate is increased the subsequent separation process is able to achieve a higher grade of flotation product at a given recovery of the target metal.

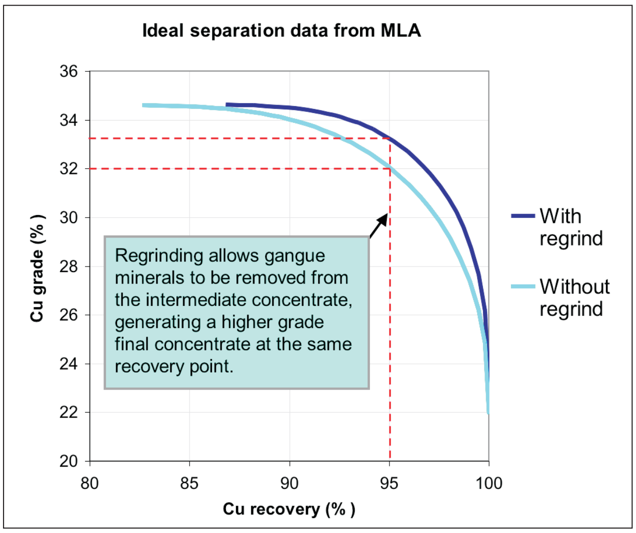

FIG 2 - Effect of grinding energy on separation performance of the ore.

This shift in behaviour occurs because the comminution stage breaks the mineral grains in the rock apart, allowing the now separate grains of gangue mineral to be removed in the subsequent flotation stage. Removal of the gangue minerals in the concentrator means that energy is not spent removing it in the smelter. The question which the mill to melt methodology will allow us to answer is whether this will lead to a net reduction or net increase in energy consumption across the concentrator – smelter production chain.

In Figure 3 and Figure 4 the effect on smelting energy requirements of increasing the amount of energy input to comminution, in this case to regrinding, is shown.

Note that the calculations for the smelter models include only the energy consumed by the concentrate-dependent, high energy consuming units (Somanathan and Tripathi 2008; Tripathi and Mackey 2009). For this case study, the relevant units were:

- nickel smelter – the electric smelting furnace; and
- copper smelter – the concentrate dryer, the production of industrial oxygen and compressed air for smelting/ converting, the electric slag cleaning furnace.

These smelting units have been modelled assuming:

- the same concentrate moisture applies to the concentrate with/without regrind;
- the same smelter operating temperature for concentrate with/without regrind; and
- the concentrate is smelted at the typical smelting rate applicable at the case-study smelters, ie for the purposes of the energy model the smelter production rate was unconstrained by the concentrate production rate.

The energy data shown in Figures 3 and 4 indicate that the energy required to smelt the concentrates is reduced if regrinding is included in the mineral concentration stage. It is particularly interesting to note that the reduction in smelter energy consumption as a result of regrinding in the concentrator is many times larger than the energy consumed regrinding. The positive impact of regrinding on the total energy consumption is highlighted by the summary of the energy data presented in Figure 5 and Table 1.

TABLE 1

Summary of energy consumption in the concentrator – smelter process chain with and without regrinding.

	Without regrinding	With regrinding	% energy saving from using regrinding
Total energy consumed per tonne of ore in feed (kWh/t)	55.7	50.9	8.6%
Total energy consumed per tonne of metal produced (kWh/t)	3910	3461	11%

As the data in Table 1 show, in this case study the introduction of a regrinding stage in the concentrator results in an estimated reduction of 11 per cent in the total energy consumption per unit mass of metal.

To assist in comparing various process operating points it may be useful to calculate the ratio of the net increase in regrinding energy to the resulting net reduction in smelter energy requirements. This ratio, termed the *mill to melt energy dividend* (E_{MM}) is calculated as follows:

$$E_{MM} = \frac{\text{Net smelter energy saving with regrinding}}{\text{Energy consumed in regrinding}} \quad (1)$$

For the current study, the E_{MM} value calculated for the two process strategies shown in the case study is 12 which indicates the energy invested in regrinding is returned twelve-fold by the resulting reduction in energy consumption in the smelter. The E_{MM} value may be a useful indicator of the relative benefits of regrinding in the concentrator.

The methodology has the potential to allow mining companies to optimise the use of energy across concentrator and smelter processes, reducing the carbon footprint of their operations. This proof of concept work indicates that the approach to integrating concentrator and smelter mass and energy models in the mill to melt methodology is worth investigating further.

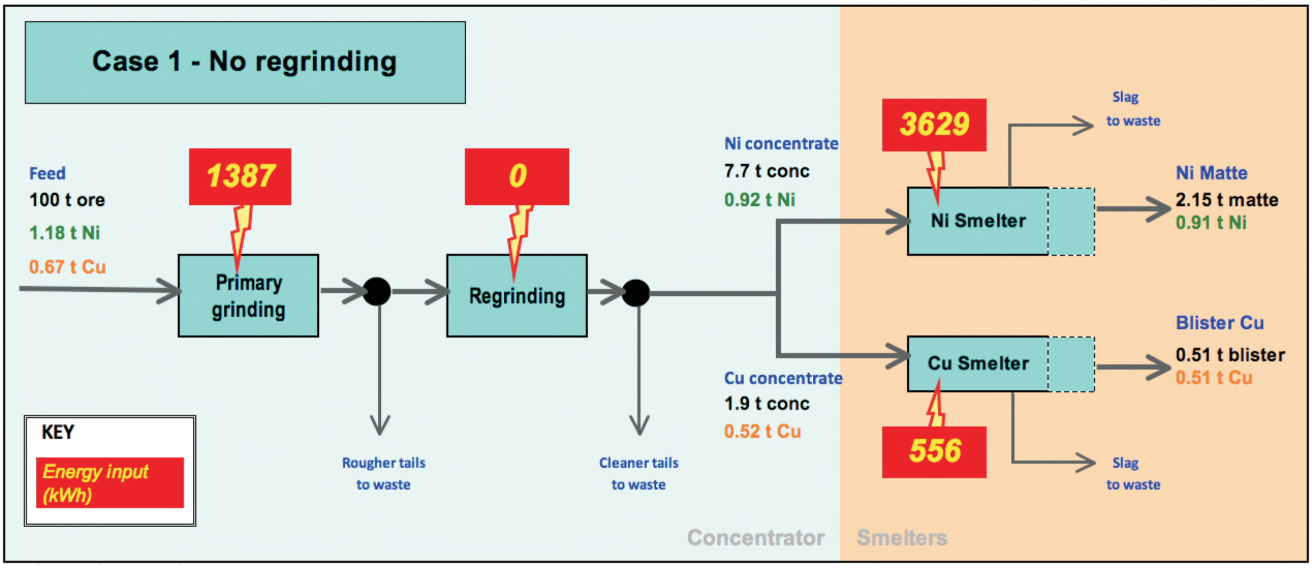

FIG 3 - Mass and energy flow diagram for Case 1 – no regrinding energy.

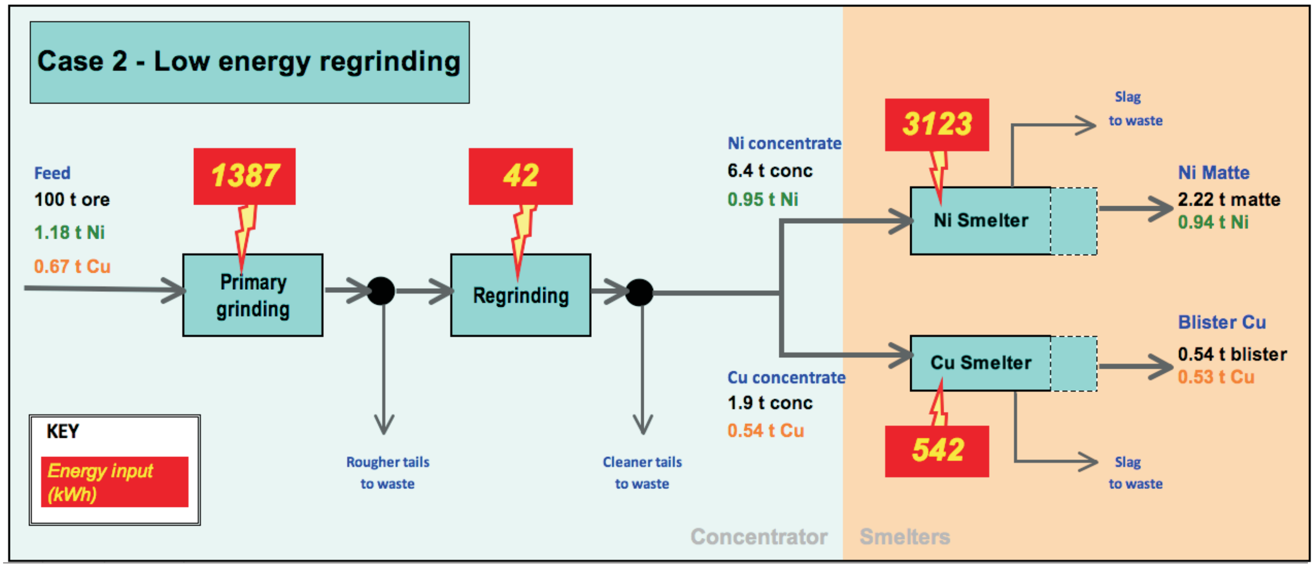

FIG 4 - Mass and energy flow diagram for Case 2 – low regrinding energy.

FUTURE STEPS

Having shown that the concept of using concentrator and smelter process and energy models together to reduce energy use across the entire metal production chain is feasible, the next step is to develop the methodology further and to test its applicability to a range of ore types.

An important aspect of the ongoing flotation modelling work in mill to melt will be to optimise the flotation performance of ore particles after regrinding. The scope of the initial proof-of-concept work did not include flotation optimisation studies but there is potential for greater rejection of gangue after regrinding when optimisation is included in next phase of work. This has the potential to further reduce the total energy requirements.

The integration of the concentrator and smelter models is a key step which will allow the mill to melt methodology to be used in energy and GHG footprint minimisation studies.

With the addition of a small increment of complexity, the smelter energy modelling could be enhanced by the inclusion of mineral-dependent operating temperature calculations. In this scheme, the smelter operating temperature would be permitted to fall/rise to reflect the relative ease/difficulty of smelting particular minerals. This would more closely approach the real operation and would demonstrate the disproportionate energy savings that are achievable by selective rejection of problematic gangue species at the concentrator stage.

In some case studies, where the smelter and concentrator are geographically separated, the mill to melt approach could be expanded to include the logistics chain between the concentrator and smelter, because the impact of transport energy, per tonne of metal, is also dependent on concentrate grade.

Note that this paper has focused on one particular sustainability indicator, namely specific energy consumption. We acknowledge that changes in one area have the potential to influence other key sustainability indicators such as water use. The purpose of this case study was to demonstrate how changes in operating philosophy, implemented as a result of adopting a wider view of an integrated processing system, could result in net gains in terms of energy reduction. The further work described above could also eventually be expanded to include other key environmental sustainability indicators, depending on the context of the work.

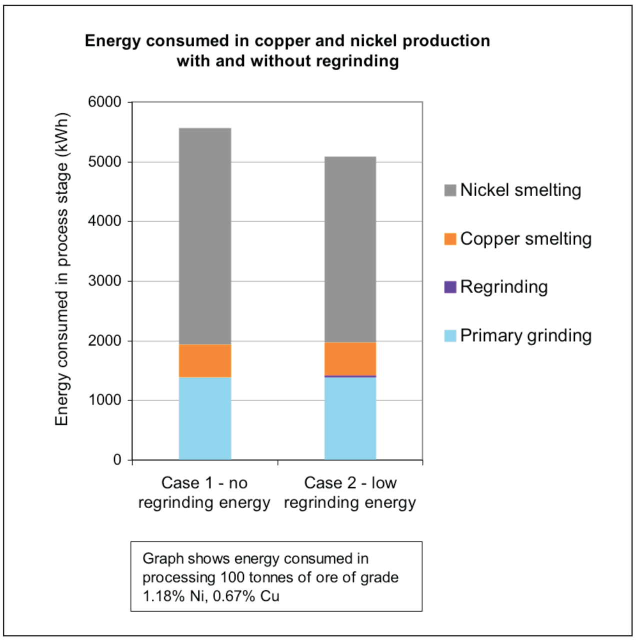

FIG 5 - Graph showing the relative contributions to the total energy consumed in the concentrator to smelter process chain.

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