Improving The Efficiency Of Fine Grinding – Developments In Ceramic Media Technology

Curry D C[1]; Clermont B[2]
[1]*Technical Superintendent - Mineral Processing; Xstrata Technology*
[2]*R&D Project Manager – Comminution; Magotteaux International*

Abstract. The use of ceramic beads as grinding media within high intensity stirred mills (such as the IsaMill) is desirable to maximise the energy efficiency of these processing units. Using a ceramic media with properties tailored to high intensity stirred milling further increases energy efficiency and extends the practical operating range of these mills to coarser feed and product sizes. Historically, the economics of using ceramic media types in stirred mills in the minerals industry has not been attractive. Magotteaux International and Xstrata Technology cooperated in the testing and product development of a new ceramic media, known as Keramax MT1, designed specifically for the minerals industry. Comparative media consumption tests are described and show how the low wear rate and high efficiency of this new ceramic offers an economic alternative to existing media types. The paper proposes the sliding friction coefficient as a new tool in characterising stirred milling grinding media. The first application of this ceramic media will be regrinding a gold bearing, pyrite rich sulphide flotation concentrate in the industry's largest stirred mill; the M10,000 IsaMill.

1 INTRODUCTION

The high energy efficiency of stirred mills compared to ball mills is well understood within the industry. The use of tower mills as an energy efficient alternative to secondary and regrind ball milling became a standard flow sheet inclusion in the latter part of the previous century and is still common today. The modern high intensity stirred mills (such as the IsaMill) further extend the energy benefits of this technology by using higher agitation speeds and smaller media particles [1].

Media selection has a major influence on mill parameters such as energy efficiency, internal wear and operating costs. An inert grinding environment is beneficial to avoid mineral surface degradation and obtain downstream processing and cost advantages [2]. Ceramic media has a profound implication to these parameters and the availability of an economic ceramic media could give significant benefits to the users of IsaMills.

1.1 Grinding Media Types

To date, all IsaMill installations have taken advantage of the technology's ability to use a low cost, but relatively low quality grinding media such as silica sand, river pebble, smelter slag or fine primary mill scats (autogenous milling). Whilst the IsaMill produces high energy efficiencies compared to conventional milling when using these media types, these 'naturally occurring' materials handicap the technology in several ways. The energy efficiency is low compared to what is possible with higher quality media, such as ceramic based compounds. The angular shape and small grain size of the natural media types limit the size of media, and therefore size of feed that can be milled.

For example, sand media typically breaks down to its natural grain size when exposed to the high intensity milling environment. Generally sands have grain sizes finer than 5 mm. This limits the feed size that the mill can treat. From a mill wear perspective, it is preferable to use a higher SG media to increase media forces rather than larger, low SG media. The ideal media type for high intensity stirred mills has consistent, reproducible characteristics as shown below, and is further detailed by Lichter and Davey [3]:

- Definite initial charge PSD and top up size
- Chemical composition
- Hardness (related to chemical composition and grain size)
- High sphericity
- High roundness
- Competency (mechanical integrity)
- SG (as designed for machine operation /ore breakage requirements)

A media type that can be manufactured to the ideal qualities is therefore desirable. This reduces power costs and extends the benefits of the technology to treatment of coarser feed sizes. Despite this, the use of manufactured media such as ceramic beads has generally been uneconomic, as the combination of low consumption rate, high energy efficiency and low unit cost have not converged. This has limited the application of such energy efficient grinding technology such as the IsaMill, and restricted its application to regrind and ultra fine milling only.

1.2 Keramax MT1 Development

Magotteaux International has developed a ceramic grinding media specifically applicable to high intensity stirred milling in the minerals industry. In cooperation with Xstrata Technology, the performance and cost effectiveness of the Keramax MT1 grinding media has been tested and verified using laboratory, pilot and full scale IsaMills. The first industrial application combining Keramax MT1 and IsaMill technology will be commissioned late 2005.

2 CERAMIC GRINDING MEDIA OVERVIEW

Two manufacturing processes may be distinguished in the production of ceramic media commonly used in fine grinding for non-contaminating applications:

- Sintered ceramic beads obtained by a cold forming of ceramic powder and by firing in high temperature kilns.
- "Fused" ceramic formed by electric fusion of oxides. The majority of these ceramic beads are named "zirconium silicate".

Ceramic beads are usually classified according to their chemical composition and physical properties such as bulk density, hardness and fracture toughness. The bulk density has a large influence on the mill power draw. Hardness and fracture toughness could give an indication of the bead's wear resistance.

The zirconium oxide beads are the highest quality grinding media with the highest initial cost. Keramax MT1 beads have been developed as an economic ceramic media for the mineral processing industry.

2.1 Keramax MT1 Properties

Keramax MT1 is a high density alumina grinding media with consistent microstructure to provide high resistance to wear and high energy efficiency. The media features a smooth bead surface which is 'pearl' like to touch. The surface properties suggest that the energy loss in grinding due to friction could be far lower than with other media and that the life time of the internal mill wear components will be increased.

Some low unit cost alumina media types have previously been tested in the IsaMill; both at laboratory and full scale. The consumption rate of these media types was very high (higher than silica sand) due to inconsistencies throughout the bead cross section. Some beads were very soft in the centre and others had air inclusions. The microstructure of MT1 is consistent throughout the cross section.

Table 1: Summary of ceramic bead compounds

Ceramic Beads	Chemical Composition
Alumina	$Al_2O_3 \geq 85\%$ - SiO_2
Yttrium stabilized zirconium oxide	ZrO_2 (95%) - Y_2O_3 (5%)
Cerium stabilized zirconium oxide	ZrO_2 (80%) - CeO_2 (20%)
Magnesium stabilized zirconium oxide	ZrO_2 (97%) - MgO (3%)
Zirconium silicate	ZrO_2 (69%) - SiO_2 (31%)
Aluminum silicate	Al_2O_3 (34%) - SiO_2 (62%)

Table 2: Summary of ceramic bead physical properties

Ceramic Beads	Bulk Density	Hardness (HV)	Fracture Toughness (K1C)
Alumina	2.0 – 2.1	1500-1700	3 - 5
Yttrium stabilized zirconium oxide	3.6 – 3.8	1300-1400	13
Cerium stabilized zirconium oxide	3.9 – 4.0	1100-1200	13
Magnesium stabilized zirconium oxide	3.2 – 3.4	900-1100	6
Zirconium silicate	2.2 – 2.4	600-800	3
Aluminum silicate	1.7 – 1.8	800-900	3

Table 3: Keramax MT1 compound

Ceramic Bead	Chemical Composition
Keramax MT1	Al_2O_3 (79%) – SiO_2 (6,5%) – ZrO_2 (14%)

Table 4: Keramax MT1 physical properties

Ceramic Bead	Bulk Density	Hardness (HV)	Fracture Toughness (K1C)
Keramax MT1	2.3 – 2.4	1300-1400	5 - 6

Table 5: Keramax MT1 cross sectional hardness

Location	1	2	3	4	5	6	7	8	9	10	Ave	SD
HV	1308	1301	1308	1351	1322	1294	1366	1322	1396	1294	1326	34

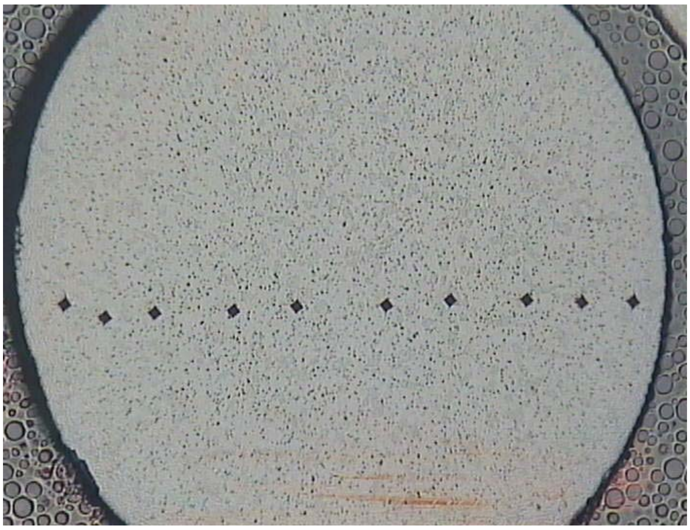

Figure 1: Keramax MT1 cross section – hardness measurement points 1-10, left to right

3 SURFACE PROPERTIES OF GRINDING MEDIA

Grinding media selection is usually focused around the parameters listed in 1.1. In testing of MT1 during product development, it was found that grinding efficiency was greater than other media types of similar size, shape factors and SG. In fact, grinding efficiency was better than could be predicted with stress intensity calculations. Of significance was the power trend that occurred during test work under the conditions of media-water and media-slurry. In all other media types ever tested by Xstrata Technology (including ceramics), an IsaMill will draw more power when operating with a media-water system than with a media-slurry system (ie motor power would always decrease when slurry was introduced to a mill operating with grinding media and water – in a start up situation for example). With MT1, the reverse occurs. It was hypothesized that slurry 'lubricates' a typical media charge as the frictional loss between media particles in motion is lower in the presence of fine feed slurry than media on media interaction in the presence of only water. Further to this, and considering the unique reverse trend with MT1, it was proposed that the media on media interaction of MT1 in a water environment resulted in minimal frictional loss, compared to what now would be considered an abrasive slurry environment with slurry being fed to the mill.

The appearance of the MT1 surface and observing how easily the media flows certainly supported the theory of lower frictional loss. Xstrata's Discrete Element Method (DEM) model was used to verify the sensitivity to energy distribution and power draw of surface friction coefficients.

3.1 Media Surface Sliding Friction Coefficient

Surface rolling friction (μ_r) does not have a measurable effect on energy distribution, shaft torque or media velocity and force, so was fixed at μ_r = 0.005 which is consistent with other DEM simulation work [4].

Two sliding friction coefficients (μ_s) were used in this simulation to illustrate the difference between media of mid and low μ_s. These were μ_s = 0.01 and 0.30 which compare well to measured μ_s of < 0.10 for MT1 and > 0.30 for silica sand and river pebble. All other media parameters were held constant.

Figure 2 shows the steady state flow patterns of media at a cross section near a disc surface, located at the shaft mid-point along the axial direction of the IsaMill. The colour represents the velocity of particles. Figure 3 shows the steady-state force distribution of the same media with colour representing total forces acting on media particles. The simulations use a mono-sized media charge of 4 mm diameter, in a 4 litre chamber and ignore the effect of slurry, so physical interactions are solely a function of media specification.

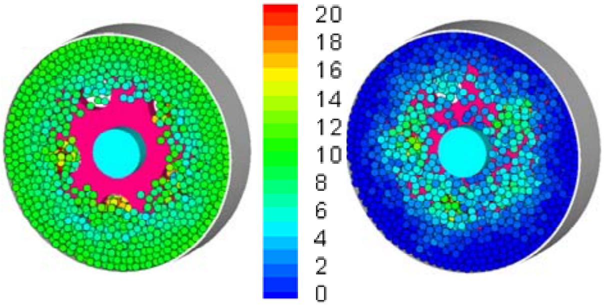

Figure 2: Snapshots of flow with left μ_s = 0.01, right 0.30 (units are 0.198 ms^{-1})

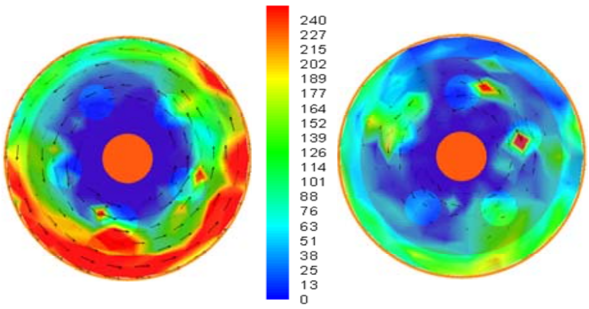

Figure 3: Snapshots of force distribution with left μ_s = 0.01, right 0.30 (units F = mg)

The velocity in both cases is highest near the disc hole meaning that the disc surface properties and holes are responsible for 'lift' of the media. Media with low sliding friction move to the periphery and have higher velocity. Media with high sliding friction stay closer to the shaft and possess lower velocity. The transfer of energy between the disc and media for particles with low sliding friction is more efficient.

Particles with low sliding friction have much larger forces than those with high sliding friction. Grinding should consume less energy when media types having low sliding friction coefficients are used.

Figure 4 shows the resultant torque acting on the IsaMill shaft for the two different media types. The IsaMill took longer to reach steady state with the low μ_s media but the stable torque was 14,000 torque units compared to 21,000 torque units with the higher μ_s media. In this case, the IsaMill operating with the higher μ_s would consume 50 % more power than the lower μ_s case. Again, this demonstrates that an IsaMill operating with a low μ_s media charge would have better energy efficiency.

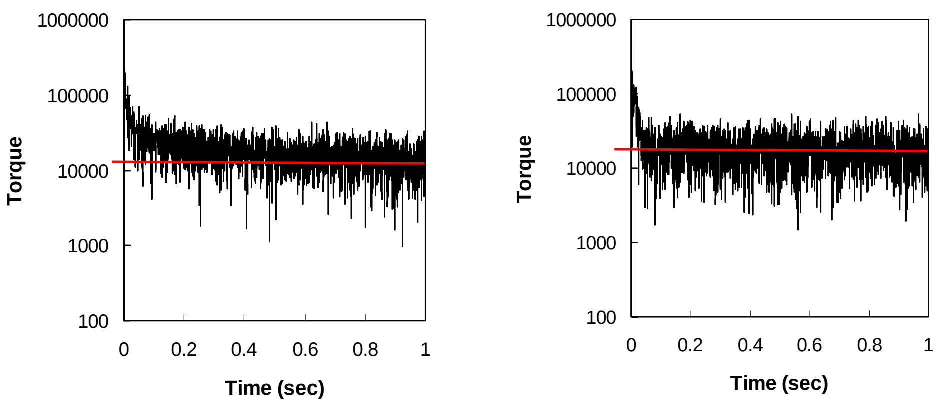

Figure 4: Total torque for left μ_s = 0.01, right 0.30 (units are 3 x 10^{-6} Nm)

4 TEST WORK

4.1 Laboratory

The aim of laboratory tests was to obtain comparative results of different grinding media in terms of relative consumption rate and grinding efficiency. Combining the energy and consumption data produces a kg/t consumption figure for each media type. This would present the first evaluation of the economic potential of MT1 in IsaMilling applications.

Tests were performed in Netzsch LME4 (IsaMill M4) machines at both Magotteaux's Belgian facility and Xstrata's Brisbane laboratory. This section describes test work performed on a gold bearing pyrite concentrate from the Eastern Gold Fields region of Western Australia.

The simplified test procedure is described below:

- Media is pre-conditioned in water before testing on slurry to simulate a conditioned charge. Media is dried, weighed and re-loaded in the mill. (Note the MT1 media charge did not lose any mass after 60 minutes of grinding in water).
- Pyrite concentrate slurry with a F_{80} = 170 µm is pumped through the LME4 in a single pass of ± 10 minutes. Energy, flow rate and pulp density are measured during this time.
- A sample is taken for particle size analysis using a Malvern Microsizer.
- This process is repeated a minimum of three times to produce size /energy data pairs.
- The test rig is then placed in closed circuit with the slurry stock, and operated for a further 60 minutes to maximise the accuracy of energy measurement and media consumption.
- The loss in mass is measured at the end of the test. Dividing this mass by total net energy, gives a g/kWh media consumption rate.
- A size value (eg P_{80}) is plotted against its respective energy value and a measurement of grinding efficiency is obtained (a Signature Plot).

The consumption rates of different media types on the pyritic concentrate, under identical grinding conditions are shown in Table 6. Keramax MT1 exhibited the lowest consumption rate, giving a relative wear ratio of 1. The relative wear ratios of the other media types are shown in the right hand column.

The size distribution of the media types (with exception of the nickel slag) were not representative of fully conditioned charges; most media types only had particles in the -4 +3 mm range as this was how they could be ordered from the suppliers. The absence of -3 mm media would lead to inefficient grinding to ultra fine sizes. Because of this, a coarser target product size was selected where all media types could produce a product of acceptable efficiency. A P_{80} = 47 μm was selected, as it met the above criteria for the narrowly sized media charges, and also presented as the only data point produced for Alumina 2 (due to a pump failure during testing, more data points were not produced for this media type). Therefore, the energy efficiency of all media types are compared at a P_{80} = 47 μm and shown in Table 7. All tests were performed in open circuit.

The next best media to MT1 required 50% additional energy to produce the same product size. Significantly, this media was an Australian silica sand which required less energy than the two alumina ceramic media types. The silica sand was however, coarser than either of the alumina media which would result in higher wear rates of internal mill components, so maintenance costs would need to be evaluated.

Using the available media consumption and energy data, the media consumption per tonne of concentrate treated can be calculated and is shown in Table 8.

It is clear that MT1 has economic potential in IsaMill applications, as the consumption per tonne milled in this test is at least an order of magnitude less than the next best media. The higher energy efficiency also has capital cost benefits, as a lower installed power can be selected to optimise project economics. For example, Table 9 shows the net power requirement for this concentrate type to treat an arbitrary 250 t/h. Once a specific project's power cost is factored in, the relative performance of MT1 further improves. Based on this outcome, further work at pilot scale was planned.

Table 6: Grinding media consumption rates - per unit energy

Media Type	Consumption Rate (g/kWh)	Relative Consumption
MT1 (-4 +3 mm)	15	1.0
Alumina 1 (-4 +3 mm)	128	8.5
Alumina 2 (-4 +3 mm)	295	19.7
Australian River Pebble (-4 +3 mm)	200	13.3
Australian Silica Sand (-6 +3 mm)	781	52.1
Ni Slag (-4 +1 mm)	1305	87.0

Table 7: Grinding media energy efficiency from F_{80} = 170 μm to P_{80} = 47 μm

Media Type	Specific Energy (kWh/t)	Relative Energy
MT1 (-4 +3 mm)	7.6	1.0
Alumina 1 (-4 +3 mm)	13.1	1.7
Alumina 2 (-4 +3 mm)	12.4	1.6
Australian River Pebble (-4 +3 mm)	27.9	3.7
Australian Silica Sand (-6 +3 mm)	11.2	1.5
Ni Slag (-4 +1 mm)	17.8	2.3

Table 8: Grinding media consumption rates - per tonne treated

Media Type	Consumption Rate (kg/t)	Relative Consumption
MT1 (-4 +3 mm)	0.11	1
Alumina 1 (-4 +3 mm)	1.68	15
Alumina 2 (-4 +3 mm)	3.66	32
Australian River Pebble (-4 +3 mm)	5.58	49
Australian Silica Sand (-6 +3 mm)	8.77	77
Ni Slag (-4 +1 mm)	23.23	203

Table 9: IsaMill net power requirement – illustration at 250 t/h treatment rate

Media Type	Net Power (MW)
MT1 (-4 +3 mm)	1.9
Alumina 1 (-4 +3 mm)	3.3
Alumina 2 (-4 +3 mm)	3.1
Australian River Pebble (-4 +3 mm)	7.0
Australian Silica Sand (-6 +3 mm)	2.8
Ni Slag (-4 +1 mm)	4.4

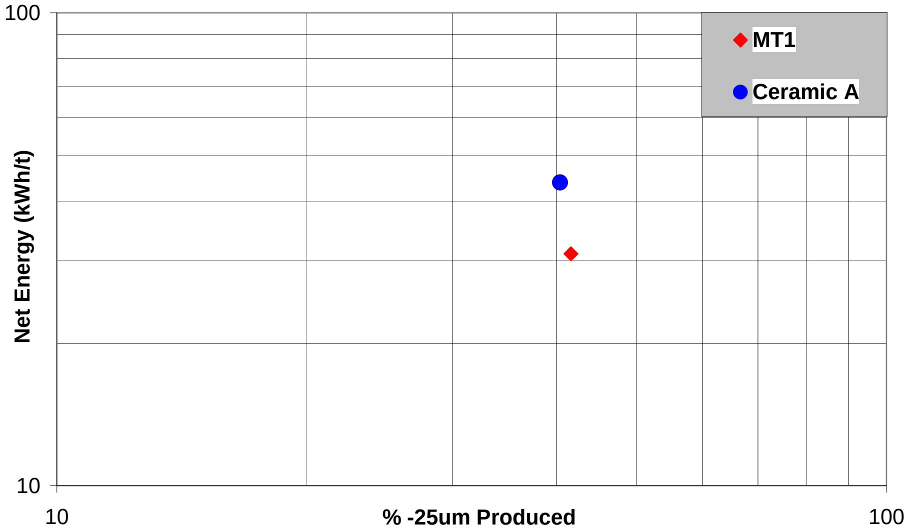

Figure 5: Specific energy vs size

4.2 Pilot

Pilot testing was conducted at a South African platinum concentrator treating MF2 tail (ie secondary ball mill /flotation circuit tailing) on UG2 ore in the Western Limb of the Bushveld Igneous Complex near Rustenburg. This site was selected because a full scale IsaMill is already operating in cleaner circuit regrind on silica sand which would permit full scale verification of the pilot results. Also, the M100 pilot IsaMill (55 kW) was located near this site which is an ideal mill for this work.
Four media types were selected, however only two were able to grind the extremely hard chromite in the plant tail. The two media types that failed to grind the feed were a silica sand and alumina ceramic (both having SG = 2.6 t/m^3). Neither of these media types are available in coarse enough sizes to break the chromite in the feed. 'Ceramic A' was of similar SG to MT1.

The simplified test procedure is described below:

- Equivalent volume of media is loaded into the IsaMill.
- The power draw is recorded, and maintained by pumping fresh media in with the feed slurry.
- Media consumption is calculated by recording the mass added during the test and by measuring the mass variation of the load before and after each test.
- Composite samples are taken every day for particle size analysis.
- All the operating conditions such as slurry flow rate, pulp density and mill speed are identical for each test.
- Each media type was tested for 5 days to generate sufficient data.
- The IsaMill was running in a continuous mode in a single pass operation.

Figure 5 plots the operating points of the IsaMill with the two media types during the test (specific energy against % passing 25 μm). Table 10 summarises the consumption and specific energy data per % -25 μm produced.

Ceramic A required 46 % more energy to produce the same product size, whilst consuming over 400 % more media in the process.

During the MT1 test, some media was crushed in the gland seal area of the mill which had worn during the Ceramic A test. The seal arrangement was subsequently modified to a similar design as the full scale mills. However, it was suspected that the observed 20 g/kWh consumption rate was high. This could be confirmed during full scale tests.

4.3 Full Scale

At the time of writing this paper, two full scale IsaMill tests with MT1 at different sites were underway. The sites agreed to perform full scale testing, based on the encouraging results from the laboratory and pilot test work. It is planned to publish the test results in the future, however the following conclusions can be made:

- The laboratory energy determination and media consumption rate tests scale up accurately.
- MT1 consumption in the UG2 ore test was inflated due to crushing of media. The actual consumption is < 10 g/kWh in the full scale test.

Table 10: Specific energy and media consumption rate

Media Type	Specific Energy (Per % -25 μm)	Consumption Rate (g/kWh)
MT1 (-3.5 +1.8 mm)	74	20
Ceramic A (-3.4 +1.7 mm)	108	81

Table 11: Kumtor – relative consumption and motor power draw @ P_{80} = 12.5 μm

Media Type	Relative Consumption	Relative Motor Power
MT1 (-2.2 +1.8 mm)	1.0	1.0
Ceramic B (-2.4 +1.4 mm)	4.6	1.3
Australian River Sand (-2.4 +1.2 mm)	9.2	2.2

5 FIRST INDUSTRIAL APPLICATION

The first application of MT1 and large scale IsaMilling is at Centerra Gold's Kumtor operation in the Kyrgyz Republic. Kumtor is the largest gold operation in Central Asia producing over 500,000 oz pa. MT1 media and the large M10,000 IsaMill enabled the highest energy efficiency possible on a small foot print. Due to the variation in (pyritic) rougher concentrate mass pull, a high intensity stirred mill with good turn down was required; the IsaMill is designed to operate between 1.3 and 2.6 MW power draw by varying the amount of media inside the mill.

The IsaMill will process an existing regrind mill product to ultra fine sizes of P_{80} < 12.5 μm.

Several media types were evaluated, including ceramics and silica sand. The lower energy efficiency of silica sand would have required the additional capital cost of a second mill. The media evaluation is summarised in Table 11.

6 CONCLUSION

Historically ceramic type grinding media has not been economically viable for mineral processing applications with high speed stirred mills such as the IsaMill, due to high operating costs. The availability of an economic ceramic media will provide considerable benefits to the users of IsaMills, and allow the energy benefits of the technology to be applied at coarser grind sizes.

Keramax MT1 ceramic grinding media was tested on various mineral concentrates and offers very high energy efficiency and extremely low consumption rates. The surface properties of MT1 contribute to the high energy efficiency of IsaMilling with this media type. DEM simulations explain the more efficient distribution of energy when using a grinding media with low sliding friction coefficient.

MT1 offers the design metallurgist a way of lowering capital and operating costs for large scale stirred milling projects. The foot print of IsaMill installations can be decreased because of the lower installed power requirement and smaller media handling system.

The Kumtor gold project will be the first to demonstrate the effectiveness of combining a high efficiency grinding media with large scale stirred milling.

REFERENCES

1. Gao, M., Young, M. & Allum, P. (2002) *IsaMill Fine Grinding Technology And Its Industrial Applications At Mount Isa Mines.* 34th Annual Meeting Of The Canadian Mineral Processors, Ottawa, Canada.

2. Pease, J. D., Curry, D. C. & Young, M. F. (2005) *Designing Flotation Circuits For High Fines Recovery.* AusIMM /SME Centenary Of Flotation Symposium, Brisbane, Australia.

3. Lichter, J. & Davey, G. (2002) *Selection and Sizing of Ultrafine and Stirred Grinding Mills*. SME Mineral Processing Plant Design Symposium, Vancouver, Canada.

4. Yang, R., Jayasundara, C., Yu, A. & Curry, D. (2004) *Numerical Simulation of the Flow of Grinding Medium in IsaMill*. 8th ICBMH Conference, Wollongong, Australia.