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RECENT ADVANCES IN AUTOGENOUS GRINDING

by

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Autogenous grinding has been used in a variety of ways for a number of years. In this talk, I shall outline the economic incentives and technical details of different autogenous-grinding systems that are in use around the world. I shall also describe some of the research work being conducted at the South African National Institute for Metallurgy on the scale-up and control of autogenous grinding.

However, before I get down to detail, I need to define a few terms.

DEFINITION OF TERMS

The term *autogenous grinding* can be applied to all types of grinding in which the ore itself is used as the grinding medium. The term *semi-autogenous grinding* is used when steel grinding media are used to supplement the grinding. A circuit consisting of a rod mill and a pebble mill could therefore be regarded as a semi-autogenous grinding system. However, the most attractive form of autogenous grinding is that which is used on coarse ore (i.e., after primary crushing only). This is called *primary grinding* in North America, because it is normally followed by a second stage of grinding (in a ball mill or pebble mill). South Africans call it *run-of-mine milling* because the rocks produced by the blasting procedure used in the gold mines are small enough to be conveyed, stored, and fed direct to an autogenous mill.

Figure 1 illustrates the common forms of autogenous grinding. A ball-mill circuit is usually similar to the pebble-grinding circuit shown in Figure 1, except that all the ore is crushed fine. Compared with pebble grinding, ball grinding, because of its higher capacity, may be more economical despite the cost of the balls[1]. The real savings come when the crusher plant is eliminated. A normal crushing plant has at least two stages of crushing as well as screens and intermediate storage for the fine ore. This plant can cost about 70 per cent of the associated milling plant[2] and consequently its elimination can result in a substantial saving in capital and operating costs. I therefore confine my discussion to the direct milling of coarse ore.

COST COMPARISON OF VARIOUS GRINDING SYSTEMS

The incentive for the use of autogenous grinding is obviously a reduction in capital (no crusher plant) and operating costs. However, detailed cost comparisons at the design stage are usually not disclosed, and a comparison of operating plants is often complicated by the new and old systems in use. Old plants usually have many small units, while new plants use large milling with consequent economies of scale and a reduction in the number of conveyors, pumps, etc. In addition, the use of larger units makes automatic control more economical.

Grinding costs are usually expressed in cents per ton of material processed. This is convenient for bookkeeping at a particular mine, but rather confusing when the costs at various mines are compared. The nature of the ore determines the amount of energy required for adequate liberation, and this varies from mine to mine. The cost per kilowatt of operating power provides a better basis for the comparison of grinding systems. Allowance must still be made for changes in milling efficiency and in the abrasive characteristics of the ore.

Cost comparisons are also influenced by the scale of operation. As the labour cost is far more important in a small mill, where a certain minimum number of people are required irrespective of throughput, the elimination of crusher plant is much more significant at small capacities, and there is a trend towards the use of a single autogenous or semi-autogenous mill under these circumstances. A small phosphate mine in Rhodesia has even eliminated the primary crusher. Blasting in the open pit of this mine is designed to produce a suitable coarse ore, and oversize rocks are removed on a grizzly. Also, the cost of labour varies from country to country. Therefore, the cost comparison given below should be used only as an illustration of how savings can be achieved.

Consider a grinding installation of 5MW capacity. This mill could handle 12 000 t of ore per day, which would require 9,5 kW.h/t (at 95 per cent availability). This power could be produced by a single semi-autogenous mill 9,7m (32ft) in diameter. Alternatively, two fully autogenous mills or two ball mills could be used. The combination of crusher and ball mill could use less power, but, when the power used by the conveyors, screens, etc. is included, the power is virtually the same. Table 1 shows approximate capital and operating costs for the three grinding systems. It is assumed that the fully autogenous system uses 20 per cent more power, and the semi-autogenous system 10 per cent more power, than that used by the ball-milling system. Two large single-stage ball mills are used, after the design of the Bougainville plant.

Table 1 shows a case where the operating cost of a semi-autogenous mill is the same as that of a ball-grinding plant despite the elimination of the crusher plant. This is due to the higher power consumption and liner wear in the mill. However, the capital is almost halved. [illegible]

TABLE 1

Comparison of grinding systems for a production of 12 000 t/d

	Ball	Autogenous	Semi-autogenous
Power, MW	5,0	6,0	5,5
Number of mills	2	2	1
Bulk density of load, kg/l	4,4	2,4	3,0
Size of mill (diameter x length), m	5,2x5,6	8,5x3,8	9,7,4,3
Capital ($\$ \times 10^6$)			
Crushing	6,3		
Grinding	8,9	10,8	8,0
	15,2	10,8	8,0
Operating cost ($\$ \times 10^6$)/a			
Power (at 2c per kilowatt-hour)	0,8	1,0	0,9
Steel	0,7		0,7
Labour	0,3	0,2	0,2
Liners, pumps, etc.	1,0	1,0	1,0
	2,8	2,2	2,8

Data for Calculations

Cost of large semi-autogenous mill : $\$2 \times 10^6$.

Installed price : 4 x mill price.

Scale factor : 0,7

Therefore, the price of 2 units = 1,23 x price of equivalent large unit.

Mill price $\propto \left(\frac{\text{Power}}{\text{Load density}}\right)^{0,7}$, peripherals being constant.

Cost of crusher plant = 70% of milling plant[2].

The semi-autogenous plant appears to be the most attractive for a new mine under current circumstances, where interest rates are high and capital difficult to raise. This type of grinding is less susceptible to variations in ore quality, which is a desirable feature for a plant that is starting up. However, fully autogenous grinding, or the use of a smaller ball load, should be considered when a second mill is installed. A popular way of expanding the capacity of a semi-autogenous plant is to install a second stage of grinding (ball or pebble grinding), which does not require duplication of the primary conveyor systems. This arrangement is not very suitable for small plants, where both mills would have to be stopped for maintenance or breakdowns, resulting in lower availability.

The use of fully autogenous grinding seems desirable in the long term because the additional capital is recovered rapidly by the lower operating cost. It would seem prudent to design mills for semi-autogenous grinding (which have stronger shells and larger motors) to allow for flexibility. The availability of extra power is also an advantage if an autogenous mill becomes over-filled, because if a mill stops in this condition, the motor may trip when it is restarted.

DESIGN OF AUTOGENOUS GRINDING SYSTEMS

I shall now describe the autogenous grinding systems that are used in Sweden, South Africa, and North America with the aid of photographs that I myself took.

Coarse-ore Stockpile

The first stage in an autogenous-grinding system is the coarse-ore stockpile, which is usually designed to have a capacity of one to two days' supply and could allow for a mining week of six days. The product from the primary crusher is usually elevated on a conveyor and distributed over a line to produce an elongated conical stockpile. In many cases, this stockpile is in the open, but this can cause problems when there are heavy thunderstorms or freezing conditions that affect the withdrawal points underneath the stockpile. The provision of a roof allows the entry of bulldozers to move the 'dead' portion of the stockpile should the mining be held up. An alternative method of storing coarse ore, which is adopted by some mines in South Africa, is the use of large concrete silos.

The ore usually becomes segregated into coarse and fine portions, with the coarse rocks rolling away from the discharge point. If the delivery of rock is held up for a considerable period, this pattern is reversed and an inverted cone develops. The proportions of coarse and fine material have a marked influence[3] on the performance of an autogenous mill, and several feeders are usually placed below the stockpile to provide some control of feed quality. Large vibrating feeders are normally used, but, where the ore is wet, drum or apron feeders may be preferred.

Mill Design

The design of the mill itself also varies. The typical North American design evolved out of the dry Aerofall design, which requires a large trunnion opening for the air. The large-diameter, short-length mill proved to be very suitable for the production of the coarse product required by the iron ore industry for primary magnetic separation. The autogenous mills that are used in Sweden and in South Africa evolved out of a pebble-mill design, with length almost twice the diameter. This type of mill produces a finer product, which may be desirable for certain applications. In North American practice for a fine grind, a short-length mill is used followed by a pebble mill or ball mill with intermediate classification. It is claimed that two-stage milling is more efficient (fewer kilowatt-hours per ton for a given product), but the use of two mills in series may not be economical in small plants, where a single large mill can be used.

The design of the mill is also influenced by the availability of suitable manufacturing facilities. Large-diameter, short-length mills are machined in a vertical boring machine, in which the height is limited, necessitating flanged sections. Long mills are usually machined in a horizontal lathe, which limits the diameter.

A further consideration is the transportation of the mill to the site. Because of bridges and tunnels, large-diameter mills may have to be sectioned for transportation. Large vertical boring machines are not available in South Africa, and consequently the mills of 9,7m diameter must be imported from the U.S.A. However, mills with diameters of up to 6m and lengths of up to 12m, which are almost comparable with 9,7m mills, can be manufactured in South Africa.

The inlet trunnion in a mill must be large enough to accept coarse ore. Most mills are supported on the trunnions, and the surface area available on the trunnion for mill support also influences its design. A casting is used for the trunnion and a portion of the mill end, and, in many mills, cracks have developed in the casting, resulting in significant loss of production while the casting was being replaced. This problem has been overcome in larger mills by the use of slipper bearings on the shell[4]. This eliminates castings completely, the mill ends being made of a much-lighter metal. The two new autogenous mills in South Africa (Deelkraal and Elandsrand) are both of this type. A second advantage of the shell-mounted bearing is the elimination of pulp lifters and their effect on pulp level in the mill. Figure 2 compares the bearings used in mills.

Mill Liners

The types of liners used in Sweden, South Africa, and North America also vary.

In North America, massive shell liners and lifter bars of manganese steel are used. The life of the shell liner is influenced by the height of the adjacent lifter bar, and, in order to obtain maximum utilization of the lifter bars without adversely affecting the life of the shell liners, the lifter bars are replaced in alternate rows. This method ensures that at least one lifter bar in two is more than 50 per cent of its full height. A combination of lifter bar and shell liner is used in some places to minimize the time required for relining. The use of massive steel liners necessitates the use of a crane in the mill, which may have a limited reach in a long mill. The optimum relationship between lifter height and spacing has been investigated on a pilot scale[5], but plant practice has tended towards high lifters to minimize down-time.

Swedish autogenous mills are fitted with rubber shell liners and lifters[6]. The amount of rubber consumed in these mills is about twice that of manganese steel by volume, necessitating thicker sections. However, as the density of rubber is only one-eighth that of steel, large sections can be man-handled. The Swedes use very high lifters (400mm) to minimize down-time. Alternate rows of lifters are replaced every six months, resulting in a mill availability of up to 98 per cent. The replacement of heavy manganese-steel liners and lifters takes more time and is required more often, giving an availability of 90 to 95 per cent. In addition, the risk of injury to the relining crew is minimized by the use of rubber liners. Other advantages of rubber liners are a reduction in the noise level and in the shattering of rocks on the mill shell. The operating cost for a mill with rubber liners is similar to that for a similar mill with liners of manganese steel. The advantages outlined above make this type of lining very attractive provided there is a local source of supply.

The lining system used in South Africa, which can be described as a semi-autogenous shell liner, consists of a manganese-steel grid bolted on top of a backing plate. Ore pebbles and balls become wedged in the grid, and only the edge of the grid is worn. This liner is used without any lifters because most autogenous mills in South Africa are run at 91 per cent of critical speed to maximize capacity. At this speed, a lifter can cause centrifuging of part of the charge and a reduction in power and mill stability. However, experiments on the use of a lifter in conjunction with a grid liner are in progress.

Grates and Classification

Tapered holes or slots with a minimum dimension off about 13mm are commonly used for the grate at the discharge side of a mill. It has been found that the use of rubber grate sections minimizes plugging of the holes with chips of ore. The discharge is usually passed through a trommel, shaking screen, or grizzly to protect the pump and prevent blockages of the cyclone by chips or balls. These back-up screening devices make it possible for the mill to continue operating when a grate section fails. The oversize is usually returned to the mill on conveyors (see Figure 1).

The use of a shaking screen on the mill discharge permits the recovery of pebbles from the mill for use in a secondary milling stage. A polyurethane screen with relatively small apertures (say 3mm) can be used as a final screen to minimize wear on pumps and cyclones. The circulating load of screen oversize gives an indication of the accumulation of hard components or a 'critical size' in the mill load.

MILL CONTROL

The strategy for mill control depends upon the type of produce required. The first objective is to maintain the maximum power that is consistent with milling efficiency. This ensures maximum throughput. If an autogenous mill is required to produce a coarse product (as in most North American applications), the mill load should be maintained at about 35 per cent of the mill volume. If the load is allowed to rise higher, the power may increase, but the capacity can decrease because the rocks are cushioned and the grind becomes finer. If the mill is producing a fine product in a single stage, it can be operated at maximum power to ensure maximum productivity. In general, however, control of the feed rate does not have a marked effect on the size distribution in the product because the level in the mill varies accordingly.

The sizing of the product and the mill capacity depend upon the size distribution in the feed[3] and the competency (compressive strength) of the larger rocks (larger than 150mm). If the larger rocks shatter, the rate of wear of the intermediate-sized rocks may limit the capacity of the mill, resulting in a fine grind and low capacity. The addition of large steel balls (100mm and 125mm) can overcome this problem, but operating costs, including liner wear, are increased.

The maintenance of a fixed power (or maximum power) only, by the control of the feed rate to a mill can result in changes in the size of the product of up to 50 per cent of a specified product size. This applies to both fully autogenous and semi-autogenous milling. These changes seem to be caused primarily by variation of the size distribution in the feed. If the feed becomes finer, the mill can accept more ore, the feed rate increases, and the product becomes coarser. If the feed contains a higher proportion of competent rocks, the mill tends to fill up, the feed rate decreases, and the product becomes finer. Therefore, the design of the coarse-ore stockpile and its withdrawal points forms a vital part of mill control.

The pulp density in a mill is usually controlled by fixing the ratio of water to the dry solids feed rate. Recent tests at the South African National Institute for Metallurgy[7] have shown that pulp density has a marked effect on mill performance in that it influences the rate of wear of the rocks and can be used to control the size distribution in the product within

V ENCONTRO NACIONAL DE TRATAMENTO DE MINÉRIOS

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Mecanismos de fragmentação

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Tamanho crítico

certain limits. The application of these findings to the automatic control of autogenous grinding is being investigated.

The grindability of an ore (as determined by the Bond or similar test) may vary significantly in an ore-body. The competency of the rock also varies, although it may not be directly related to grindability; for example, very hard rock may have weak planes that result in poor competency[8]. One can measure these phenomena on laboratory[9] or pilot-plant scale[7] in order to assess possible control problems in a plant. The blending of hard and soft components of the ore-body is beneficial if this is possible, but it may be difficult in an open-pit mine, where one large shovel can deliver up to 30 000 t of ore per day. Although variations in ore hardness also affect a ball-grinding circuit, an autogenous-grinding circuit tends to be more sensitive to these changes, particularly in the case of a hard ore with weak planes.

The load volume in large-diameter, semi-autogenous mills must be maintained above a certain level (about 25 per cent) if the large balls that are used in these mills (100mm and 125mm) are not to do severe damage to the liners. This limitation can be a problem if very soft ore enters the plant, when the feed rate to the mill may rise to the point where the downstream equipment (pumps, secondary mills, concentrate launders, etc.) reach the limit of their capacity. The Lornex plant in British Columbia keeps a stockpile of hard ore for these occasions.

PREDICTION OF PLANT PERFORMANCE

The incentive for the use of autogenous grinding lies primarily in the elimination of crushing plants. This means that one must be able to predict whether an ore is suitable for autogenous grinding before a grinding plant is built. Some plants have used ball grinding for the first phase, followed by autogenous grinding when the capacity of the mine was expanded. This approach is the safest and allows representative samples of coarse ore to be tested. However, because full-scale tests are very expensive, the preliminary tests are usually conducted in pilot-plant mills with a diameter of about 1,8m. This size of mill requires a feed rate of about 1 t/h or less, meaning that ore can be transported from the mine (which is often in a remote area) to an established pilot plant.

The use of autogenous milling may be a significant factor in the design of a new mine. However, because the acquisition of representative samples for testing in an autogenous mill is difficult, pilot-plant tests are usually conducted on ore from an underground adit. A comparison of the compressive strength and grindability of drill cores from different sections of the ore-body gives an indication of possible variations in autogenous-grinding performance. A small-scale test has been developed to assess the semi-autogenous grinding characteristics of drill cores[8]. The compressive strength and frequency of fractures in drill cores have also been used to assess the suitability of rock at depth[6]. However, pilot-plant tests are usually necessary for plant design.

The relationship between full-scale performance and pilot-scale performance has been tested at the South African National Institute for Metallurgy[7], and it seems that pilot-scale tests can match full-scale performance provided that the grate area is scaled down proportionately. The level of the pulp in a mill has a marked effect on its performance, and this is influenced by the grate area and the arrangements for the removal of pulp. A test of the competency of the rocks has also been developed, which exposes weak planes in the rock that might not be apparent in smaller-scale tests[8].

SUMMARY

Autogenous grinding of coarse ore, with or without the addition of steel balls, is a very economical way of grinding in that it eliminates secondary and tertiary crushing, with the associated screens, conveyor, and labour. A semi-autogenous grinding system may be most suited to the requirements of a new mine because the capital investment is minimized and this form of grinding does not rely on the competency of the larger rocks.

The use of very large grinding units and autogenous mills with diameters of up to 10,4m have resulted in lower costs, but cracking of the castings in the mill ends have caused expensive shut-downs. In addition, the use of large-diameter mills may cause shattering of the larger rocks. Long mills with moderately large diameters have proved suitable for single-stage autogenous or semi-autogenous grinding, but the choice of mill size is often influenced by the availability of manufacturing facilities and transportation.

The design of coarse-ore stockpiles (or bins) influences the control of a mill in that variations in the size distribution of the feed have a marked effect on the size of the product. The product size cannot be controlled by the feed rate because the level in the mill alters accordingly. However, pulp level and pulp density do affect mill performance, and these variables can be used to control the size of the product within certain limits. The addition of steel balls can increase capacity and make the product coarser.

Various types of mill liners, grates, and peripheral equipment that influence mill availability and operating cost are discussed.

In prediction of full-scale performance from pilot-plant tests, good correlations have been obtained, but the testing of ore at depth remains a problem.

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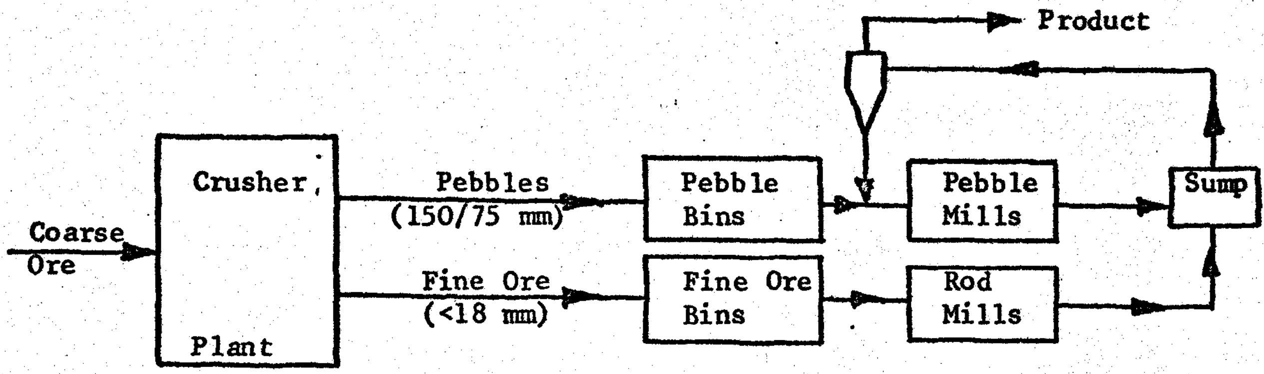
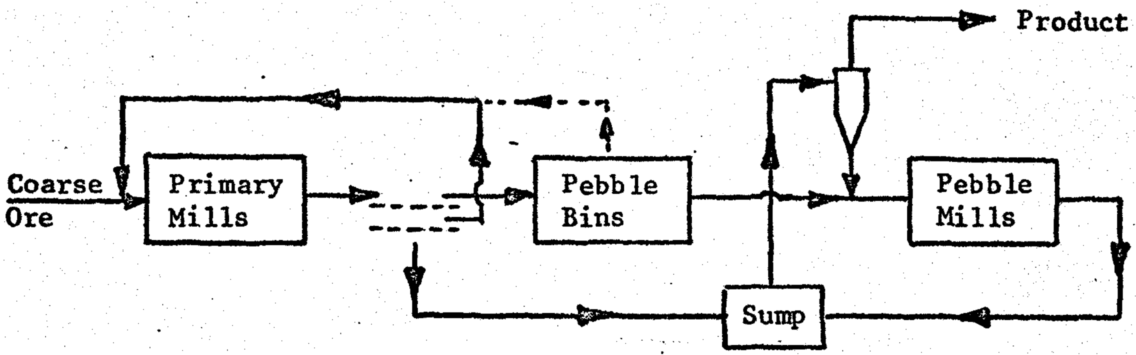
FIGURE 1 - COMMON AUTOGENOUS GRINDING SYSTEMS

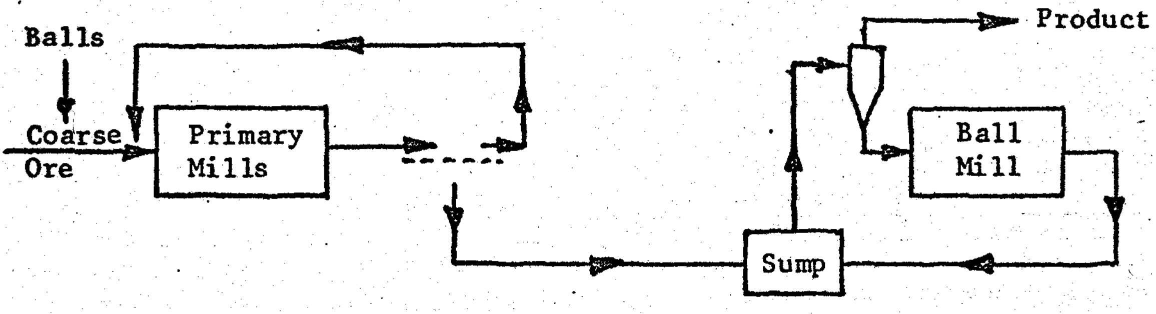
PEBBLE GRINDING



FULLY AUTOGENOUS PRIMARY AND SECONDARY GRINDING



SEMI-AUTOGENOUS PRIMARY AND SECONDARY GRINDING



SINGLE-STAGE AUTOGENOUS OR SEMI-AUTOGENOUS GRINDING

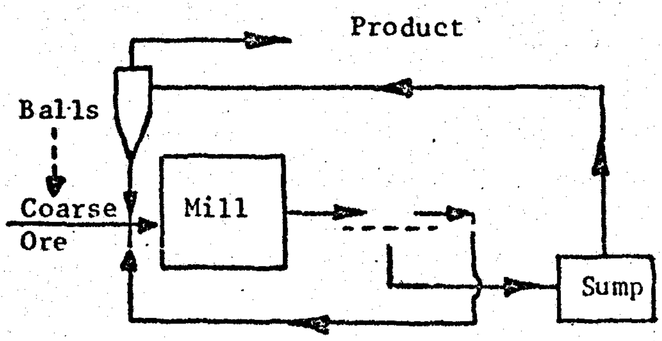
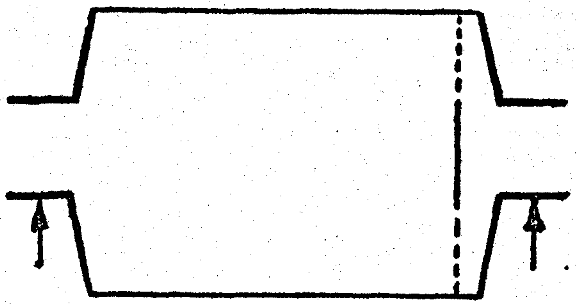


FIGURE 2 - MILL SUPPORT SYSTEMS

CONVENTIONAL TRUNNION BEARINGS



SHELL MOUNTED SLIPPER BEARINGS