



Materials selection in the mining industry: Old issues and new challenges

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Synopsis

The historical development of materials engineering in the mining industry is briefly reviewed, and some of the factors currently influencing the industry in South Africa are discussed. Material usages in various parts of the mining operation are surveyed. The predominant mechanisms in the degradation of materials in mines are wear, corrosion, and fatigue. The issue of corrosion-abrasion is considered, but it is concluded that abrasive wear predominates in most rock-handling and comminution applications and that, in general, little economic benefit is to be gained in those applications by the use of existing corrosion-resistant alloys. However, alloys with a measure of corrosion resistance find profitable application elsewhere in the mining environment. The use of other engineering materials such as polymers, ceramics, aluminium, and various ferrous alloys may be economically viable in a variety of niche situations. Identification of the most cost-effective material in each case calls for a systematic approach and some patience.

Introduction

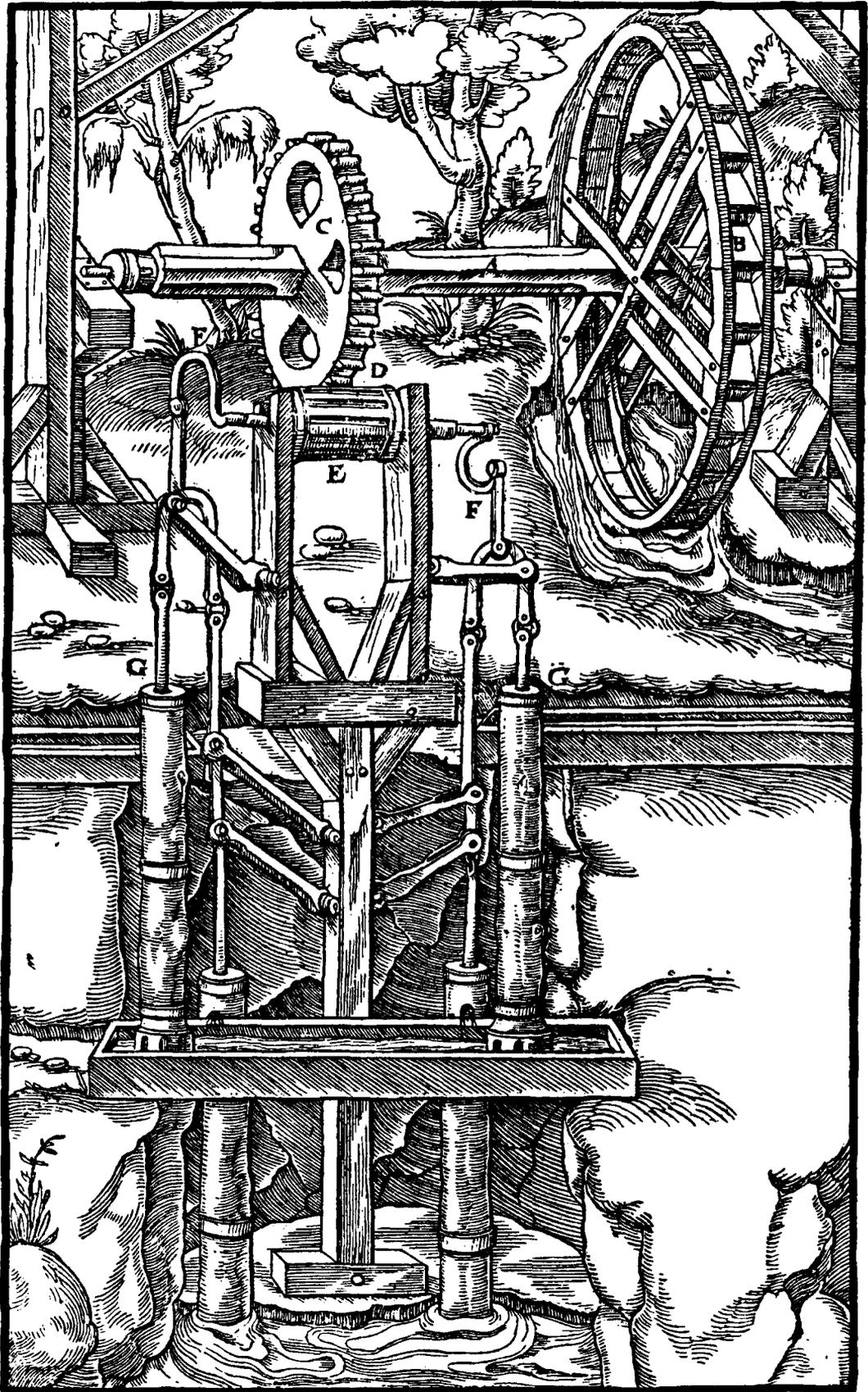
In 1550, Agricola, in his famous book *De Re Metallica*, pointed¹ out that 'a learned and experienced miner differs from one unskilled and ignorant in the art.... What wonder then if we find the incompetent miner suffers loss, while the competent one is rewarded by an abundant return on his mining?'. Even in Agricola's time, mining had a reputation for being tough on men and equipment, and it required then, as now, a certain amount of daring, both on the part of the personnel who must engage the rock at first hand, and on the part of those who must venture their own and their shareholders' capital on a project that has by no means a certain outcome. However, the probability of economic success can be raised by careful attention to detail. Readers are referred to Agricola's book for interesting discussions of the environmental, economic, and health and safety issues in the mining industry of 440 years ago. That industry was not as unmechanical as many people might suppose. The mines were ventilated by fans powered by water-wheels, pumps removed excess water, iron tools or fires were used to break the ground, wagons and wheelbarrows

of various designs were used to move the ore horizontally, and buckets and hoists lifted it up the shaft. A diagram from Agricola's book depicting a relatively advanced mechanism to pump water out of a pit is reproduced in Figure 1. The device was manufactured from wood, iron, and leather¹.

Once on the surface, the ore was generally crushed in stamp mills and then ground between water-operated millstones. Although by 1897 the stamp mill had been joined by a few other inventions, it was still dominant, while the principle of the millstones still applied for fine grinding². Wood, iron, leather, and clay were the materials in common use in the mines of Agricola's time, and this was still broadly true by the end of the nineteenth century, although 'iron' had expanded by then to include various forms of steel and cast iron. The Frenchman Alphonse Karr said in 1849, '*Plus ça change, plus c'est la même chose*' (the more things change, the more they are the same), and he might just as well have been referring to the mining and metallurgy of his century. However, significant changes occurred in the twentieth century. For example, the reduction process was revolutionized by the general introduction of crushers and tube mills, a large variety of mechanized and labour-saving equipment has been developed, and increasing use is being made of more sophisticated materials.

In this paper we offer a summary of the current state of the use of materials in the mining and extractive-metallurgical industry in Southern Africa. In order to do this meaningfully, we examine aspects of the current environment in which our mines operate, the individual activities that make up the mining process, and some issues and challenges regarding the use of materials. Although we have tried to survey the field as broadly as possible, it is inevitable that the topics with

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A—UPPER AXLE. B—WHEEL WHOSE BUCKETS THE FORCE OF THE STREAM STRIKES. C—TOOTHED DRUM. D—SECOND AXLE. E—DRUM COMPOSED OF RUNDLES. F—CURVED ROUND IRONS. G—ROWS OF PUMPS.

Figure 1—A medieval water-pump, constructed from wood and iron (reproduced from reference 1)

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which we are not familiar receive less attention than they perhaps deserve. We apologize in advance for omissions and urge our colleagues in the industry to send us any additional information or contrary opinions that they may have.

Intrinsic and extrinsic factors

A casual glance through the records of any mine or its suppliers will reveal that mining consumes large quantities of engineering materials, which are used as structural items, wearing components, or plant. In particular, it is interesting to note that the larger part of this demand is for the replacement of existing material. The belief that some cost savings can be achieved by the application of greater effort in the selection of appropriate materials has been extant³ in the South African mining industry since at least 1969. Unfortunately, it seems there has been only a modest improvement in the situation since then. Approximately R10 billion were spent⁴ on 'consumables' in 1990 by the gold and coal mines who are members of the Chamber of Mines (COM). Our study of the figures provided by the COM, aided by the venerable guide of the Department of Mines⁵, indicates that the materials component of this amounted to about R3.9 billion. This component comprised all items of hardware listed that were judged to be susceptible in principle to metallurgical wear-and-tear, and which were therefore likely to represent the replacement or refurbishment of existing equipment. Clearly, the situation will deviate in detail for the mining of other minerals, but the general trends will be similar.

The situation is summarized in Figure 2. Electricity at R1763 million and explosives at R460 million represent large fractions of the overall R10 billion (Figure 2a). The motivation for a reduction in the energy consumed and the further development of non-explosive methods of cutting or breaking rock or ore will therefore be obvious. (Non-explosive mining has the further advantage that it avoids the large and sudden releases of elastic energy that accompany the fracture of rock by blasting.) With regard to the materials consumed (Figure 2b), it is evident that a few categories are prominent. Timber and generic iron and steel, for example, each made up 16 per cent of the total. Also significant were piping and pumps, at nearly 13 per cent; scrapers, haulages, and loaders and winches, at 7 per cent; and reduction (which includes liners and balls for mills), at about 7 per cent. Examination of the data shows that the pumps and piping required to move water and slurries around gold and coal mines are together responsible for as much expenditure as are explosives. Evidently, the wear-and-tear of pumps and piping is responsible for a significant fraction of the costs in the mining industry. In slurry or dense-medium pipelines, wear of the impingement erosion type is considered⁶ to be a greater nuisance than corrosion. However, either phenomenon presents a potential opportunity for improvement as a result of changes in materials and designs.

The replacement of items involves both a material and a manpower cost and, if the replacement must be made down the mine itself, there are additional logistical problems and costs associated with the movement of items to and from the working areas. However, even these costs may be far less than the additional expense due to unplanned outages⁷. The

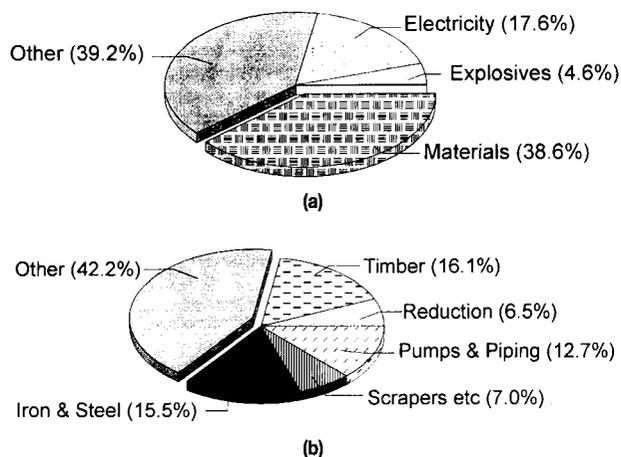


Figure 2—Breakdowns for gold and coal mines affiliated to the Chamber of Mines for 1990

(a) Items consumed
(b) Materials consumed

question arises as to whether a cost saving could not have been achieved by the initial selection of some other, longer-lasting, material of construction. Most mining companies are aware of this, and have devoted some attention to the issue of whether they can save money by doing things differently. The most public efforts to optimize the use of materials have been in the gold-mining industry. The reasons are partly historical in so far as the industry is over a hundred years old, it has been well-studied, and it is comparatively large. However, it is also important to remember that this industry, more than any other, has had to endure extremely difficult conditions. It should only be necessary to remind the reader of, *inter alia*, the depths of our gold mines, the notable hardness of the quartzite mined, the volatility of both the gold price and the labour required to tram the ore to the skip, the constant pressure of inflation, the falling grades (down from an average of 13.3 to 5.2 g/t in 25 years⁸), and the rising costs of energy and labour. Although the industry is still the biggest in the world, it is sobering to note that the 40-odd tonnes of gold produced in May 1995 was the lowest⁸ production in any month since 1956. Naturally, the gold mines, like other mines, exist primarily to generate an income for their shareholders. In the past, it was possible in some cases to increase income by the expedient of increasing production. However, since this is now often inadvisable or difficult, it is worth noting instead that the amount spent on the replacement of materials that have worn out is similar in magnitude to the financial value of the recent decreases in production. Clearly, both incremental and revolutionary measures to save on the materials consumed should be eagerly sought as an alternative means to increase profit. For similar reasons, potential cost-saving measures should also be sought at platinum, coal, diamond, and base-metal mines.

Aware of the severity of the challenges facing it, the industry has responded with a variety of technological strategies⁹. At the stope itself and in the adjacent regions, systems such as non-explosive cutting of the rock, trackless mining, continuous scrapers, longwall mining, hydro-powered machinery, backfilling, and better roof-support systems have been proposed, and have been either

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implemented or prototyped. The environment within our increasingly deeper gold mines, in particular, is now cooled with chilled water and water-ice slurries. The shafts providing ingress and egress are of greater depth, and must last longer. Deeper shafts require stronger mine ropes and lighter conveyances. Once brought to the surface, the ore must be crushed and milled more cheaply, and the valuable content extracted in a manner that is effective, secure, economic, and environmentally acceptable. Materials engineering apparently plays only a small part in all of this at present.

Two factors underpin any attempt to save on the cost of the materials consumed. The first is that the actual mechanisms by which the existing materials become degraded must be identified before meaningful substitutions or design changes can be made; the second, that the cost-life benefits of substituting one material for another must be carefully considered. Neither issue is trivial. The most common causes of material failure in general (non-mining) activities are corrosion, fracture and fatigue, wear, and environmentally-assisted cracking, perhaps in that order. Fatigue failures are not uncommon in mining, and occur wherever reciprocating or rotating equipment is used. Fatigue cracking of ventilation-fan impellers, grinding mills, stacker-reclaimers, bucket-wheel excavators, and walking draglines have been recorded in South Africa^{7,10-12}. However, most investigators of the South African and other mining industries agree that abrasion, corrosion, and corrosion-abrasion are more significant than fatigue and fracture^{6,13-17}. Since wear appears to be the greatest of the materials problems, we shall term it the *wear issue* and isolate it for consideration. Although corrosion is a problem too, it will not be isolated for specific attention, since it has been extensively reviewed by Slabbert¹⁸, the Chamber of Mines¹⁹, and Andrew²⁰.

Several workers have tried to estimate the relative importance of wear and corrosion, the extent to which they are coupled, and what they cost the industry. Work by Ball and others^{15,16,21,22} has shown that, under some circumstances, the simultaneous effects of abrasion and corrosion are synergistic. This observation has been widely interpreted as indicating that materials having reasonable combinations of corrosion and wear resistance should significantly outperform the mild steel or alloyed steel so frequently used in mining. We term this hypothesis the *corrosion-abrasion issue* and shall return to it. Finally, there has been an unprecedented surge of interest around the world in what are termed advanced materials. The interest is partially driven by the belief that only incremental improvements are possible in traditional engineering materials, and that entirely new materials must be developed if revolutionary advances are to be made. Some of the so-called advanced materials proposed for use in mining and other industries include metal-matrix composites (MMCs) and intermetallic compounds. We shall return later to the *advanced materials issue*.

Mining activities and their associated materials problems

At the face

In Agricola's time, miners released the ore from the face by either chopping it out with iron tools or shattering the rock with fires. The latter was avoided where possible since it

necessitated evacuation of the mine for several hours. Today the world's hard-rock mines tend to use pneumatic drills (Figure 3) or hydraulic drills and explosives to achieve the same ends. Both the steel drills and their hard cutting ends have been the subject locally of ongoing development efforts. Mines in which the rock is softer have now been extensively mechanized in the industrialized world, with machines such as cutters being used to rip out the valuable component in mines and quarries. Hard metals (tungsten carbide-cobalt composites) and hard-facing coatings figure prominently in the working end of this type of equipment for ripping and cutting.

It would be extremely useful if the non-explosive rock-breaking techniques could be broadly extended into the gold-mining industry. However, quartzitic gold ore is very hard, and the equipment used in coal or other soft-rock mines is unsuitable. One attempt to overcome this problem is embodied in the impact ripper, the development of which started at the Chamber of Mines Research Organization (COMRO), and which is being carried on by Gold Fields²³. This is a sharp tool, with a hardness of at least 450 Hv, that is impacted at a shallow angle against the rock to break out lumps. However, the tips of these rippers are subjected to very high localized stresses, and those made of tool steels are said to last only from 2 to 7 hours apiece. The tool material is removed by a combination of gouging abrasion and spalling, and an extreme combination of hardness and toughness is required. About half a dozen impact rippers are currently being operated²³ in gold mines.

Other non-explosive technologies that are being investigated in South Africa for hard-rock mining include diamond sawing or wire cutting²⁴, and water-jet cutting²⁵. In one version of the latter technique, a stream of water loaded with steel shot or some other abrasive is directed at great speed against the rock face, where it abrades a slot. The speed of cutting, the cost of the abrasive medium, and a method to break out the rock between the slots are the key parameters in both diamond sawing and water-jet cutting. In the latter case, the shot can possibly be recovered by some magnetic means for subsequent re-use. However, the rate of attrition of the shot then becomes very important. Abrasive jet cutting is widely used in the dimension-stone industry for the cutting of softer rocks.

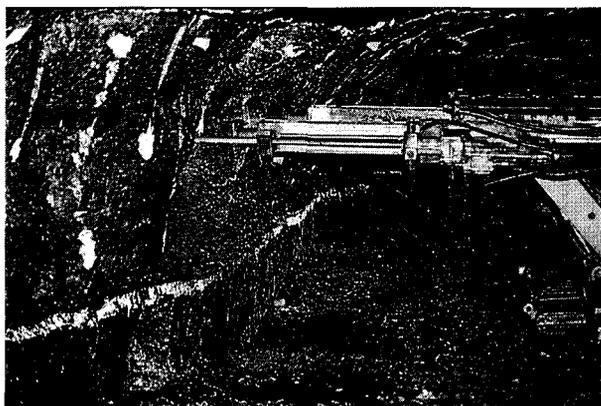


Figure 3—A modern drill used to prepare the face for blasting (Randfontein Estates 1991)

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Traditionally, the roof of a stope has been supported by wooden pack supports and, while this solution is still widely used some distance from the face, a variety of other methods have come into use. Fast-acting hydraulic pit props are preferred for close-in support, and these are made of cast steel, martensitic stainless steel, or duplex stainless steel (2205). In a recent development, spun-cast pipes of a high-strength nickel-free, manganese duplex stainless steel developed at the University of the Witwatersrand have been produced for this application²⁶. There is a renewed interest in the backfilling of disused parts of mines with tailings. The backfill not only supports the roof, but also reduces the volume of space to be cooled and ventilated. The technologies for the support of the hangingwall are undergoing continuing development.

Movement of material from workface to stockpile

The predominant type of wear in this zone is caused by impact and sliding abrasion (Figure 4). The occurrence of the former inhibits the widespread use of the harder, more brittle, martensitic steels and cast irons. Agricola's miners used wooden chutes, wheelbarrows, and buckets, but today mild steel lined with abrasion-resistant steel plate is the norm for hoppers, as well as for components such as loader buckets, bulldozer blades, and shovel teeth. Layers of hard facing are frequently applied by thermal deposition to protect the more exposed parts of the steel substrate. Popular hard-facing choices for mining environments include high-chromium irons, alloy steels, or mixtures containing chromium and tungsten carbide. In some countries, Hadfield manganese steel is deposited thermally onto steel for wear resistance, and may also be used in the cast form for scrapers. Where impact is less severe, as in chutes for example, alumina tiles, chromium carbide overlay plate, and a cast composite of silicon carbide particles bonded with silicon nitride have often been found to work well. However, many chutes are made of mild steel only, although the grizzlies above their surge bins may be made of a medium-carbon abrasion-resistant steel. Experience in South Africa, Australia, and the United Kingdom has shown that the corrosion-resistant material 3CR12 performs well in some of these applications, provided that the amount of impact of the rock is low and that a significant element of corrosion exists²⁷. Applications in which 3CR12 has proved cost-effective include ore hoppers, decking, and other components of conveyor systems, open-grid flooring, and wagons for wet coal^{27,28}. The material should also be considered for cases where the slidability of the ore is important, and this is one of the reasons for its use in the trucks of the Vryheid-Richard's Bay coal line.

The private railways that serve the South African mining industry are another, sometimes overlooked, part of the mineral-transportation system. It has been reported that, in 1993, South Africa's underground railroads shifted a greater tonnage than Spoornet's surface railroad system (220 Mt versus 196 Mt)²⁹. A survey conducted by Mintek some years ago found that severe corrosion of the rails occurred in some environments, and an attempt to develop a more corrosion-resistant steel for rails was launched. The resultant steel alloy showed promise in laboratory tests³⁰, and subsequent testing in underground environments revealed that a small



Figure 4—The surface of a load-haul-dump truck's bucket in service in a gold mine, showing gouging and material removal

benefit could result from its use there under alternate wet and dry conditions³¹. Rails are obviously an area to which materials engineering could contribute in principle, and it may be worth mentioning that 3CR12 testpieces were found to have suffered significantly less attack than the other steels examined.

The transportation of ore on surface by rail or tipper truck requires attention as to the most effective use of energy. For example, on an open-cast mine, haulage costs can contribute up to 40 per cent of the total mining costs³². Efforts to reduce these costs are directed towards increasing the payload efficiency of the mode of transport, decreasing the costs of wear and tear, and improving the grade of the material transported. Preliminary work with aluminium has proved very successful and, although the pans of the trucks must still be lined with rubber for wear resistance, there is an overall saving in tare weight and an increase in payload³². Polymer linings have been successfully used in Australia, and have the particular advantage that they permit ready emptying out of buckets and trucks.

Lifting of material up a shaft

Since the lifting of material up a shaft requires expenditure of energy in proportion to the mass lifted and, perhaps more importantly, the carrying capacity of a shaft is often the bottleneck that limits material movement, the use of aluminium in mine cages and skips has increased in an attempt to increase the payload efficiency. A change to aluminium can save 9 t of the 15 t of a three-deck man cage³², and 3 t of the 12 t of a skip³³. Approximately one-third of mine cages are now made of aluminium alloys³⁴. However, aluminium has poor wear resistance, and the skips must be lined with rubber, mild steel, or abrasion-resistant steel.

An alternative strategy to improve the payload of skips would be to increase the strength of the steel rope used. At present, the down-shaft masses of the ropes are a significant fraction of the total mass lifted and, if a reasonable payload is to be lifted, this factor limits the maximum depth of a single shaft. The wire used in these ropes can have a tensile strength of more than 2000 MPa, but wires of the higher strengths may be susceptible to strain aging. Some work to resolve this problem has been reported by Haggie Rand³⁵

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and, in 1993 after carefully controlled aging, wire with a breaking strength of 2300 MPa was made into rope for use at President Steyn mine. Finally, although it is not strictly a materials issue, we should not overlook the other obvious way to improve the payload: selection of the material to be hoisted so that as much waste as possible stays underground. In this respect proposals have been made to combine selective mining with underground crushing of ore in high-energy attritor mills and pumping the resultant slurry to surface for the extraction process. However, wear of the components of such attritor mills would be very high if they were made from most of the materials known at present.

A shaft is a vital and very expensive part of a mine's infrastructure, and some attention has therefore been devoted to the question of which materials should be used within it for structural purposes. Wood was used historically, but steel, in some cases painted, is the material of choice today. However, severe corrosion of unprotected steel buntons has been known to occur (Figure 5). Hot-dip galvanized steel and 3CR12 have also been considered^{17,36,37}. Testwork conducted on site has shown that both 3CR12 and aluminium can potentially offer improved service lives in principle³⁸, provided that they can be obtained in the appropriate product form, while evaluation by JCI of galvanized and duplex (galvanized and painted) steelwork has been so successful that that organization has reportedly standardized on these systems for its mines^{20,37}. In extremely corrosive areas such as at the bottom of deep, wet shafts, type 304 has occasionally been used but, as for 3CR12 and aluminium, the use of type 304 has significant first-cost implications. Damage to coated materials caused by the spillage of material and the development of corrosive conditions within poultices of sediment on the upper surfaces of structural members remain problems.

Crushing and milling

Wooden stamp mills shod with iron were used for many centuries (Figure 6) and, if further comminution was required, two hard millstones were harnessed to a water wheel. Curiously, although Agricola was very precise about materials and processes in general, he did not disclose what the millstones were made of, and merely revealed that they were of a very hard material. Today, the mantle and liners of

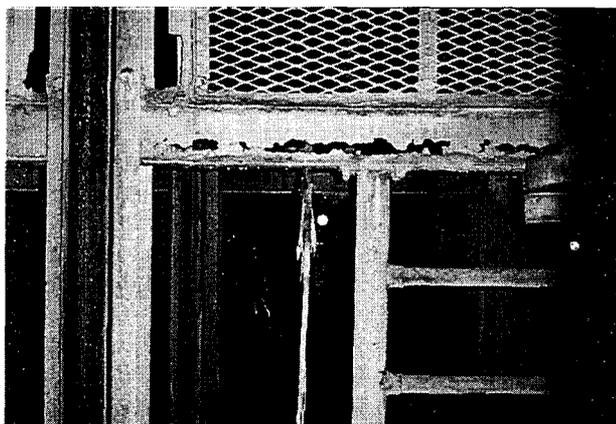


Figure 5—Severely corroded structural steelwork in the shaft of a gold mine

gyratory crushers and jaw crushers, or the mantle and bowl of short-head crushers, are usually made of some variation of Hadfield's manganese steel (also widely known as austenitic manganese steel, AMS), which, as is well-known, has a high work-hardening rate under conditions of impact^{39,40}. Unfortunately with quartzitic ores, the abrasion removes this hardened layer almost as fast as it is formed. Improvements in the life of crusher components have been reported to result from the use of hard facing with high-chromium white-cast iron (HCWCI), or from the use of HCWCI liners⁴¹.

The materials used in tube mills vary widely, and are largely determined by the processes operating in the mill. The older, autogenous tube mills of approximately 2 m diameter that were previously in widespread use in the South African gold-mining industry were often lined with white-cast iron, a material that can withstand low stress or sliding abrasion well, but is too brittle for severe impact conditions. However, the use of the Osborne bar-liner system allowed for the retention of rock pebbles to form an effective lining layer⁴⁰. The larger diameters and different operating conditions of many modern mills dictate that the liners must have significant resistance to high-energy impacts. Cast grids of AMS in which pebbles become lodged have therefore become popular, and are used in about half the gold-mine mills in South Africa⁴². However, low-alloy steel liners³⁹ and rubber liners⁴³ are also widely used in the mining industry throughout the world, although to a lesser extent in South Africa. Some years ago, Mintek extensively investigated materials for both the liners and the lifter bars of mills for quartzitic gold ore^{44,45}. Liners of HCWCI or rubber were found to provide long life, but not at sufficiently low a cost to be viable. Surprisingly, mild steel used in conjunction with lifter bars was found to provide a reasonable life (Table 1).



A—MORTAR. B—UPRIGHT POSTS. C—CROSS-BEAMS. D—STAMPS. E—THEIR HEADS. F—AXLE (CAM-SHAFT). G—TOOTH OF THE STAMP (TAPPET). H—TEETH OF AXLE (CAMS).

Figure 6—A medieval wooden stamp mill with iron-shod shafts (from reference 1)

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However, the best cost-life performance was found to be provided by AMS grids and cast-iron liners, owing primarily to the low cost of these materials. Interestingly, the work cited clearly demonstrated that the most economically useful reduction in the wear of liners was actually achieved by a design change (the introduction of lifter bars). This indicates how closely intertwined are the materials-selection and mechanical-design processes.

The wear rate of ferrous grinding media, where used, is about five times greater than that of liners, and can make up a greater cost item than the electric power consumed by a mill. Accordingly, it has been the subject of several investigations. Some of the results are summarized in a publicly available report⁴⁶. A variety of materials have been tried as grinding media. However, in South Africa, cast semi-steel balls are used predominantly. These balls, of which about 80 kt are said to be produced annually in South Africa⁴⁷, have a carbon content of about 1.6 per cent. Trials conducted more than ten years ago demonstrated that a heat-treated version of these balls would last 27 per cent longer⁴⁸; however, this potential improvement has yet to be widely implemented. Micro-alloying of the semi-steel has also been investigated, and small improvements seem possible by this route. With regard to more expensive materials, HCWCI balls have been found not to be cost-effective in the milling of quartzite, but may wear at up to seven times more slowly in applications in which less abrasive materials, such as Black

Mountain (copper) ore, Merensky reef, cement, or coal, are milled^{46,49} (Figure 7).

The storage and movement of ore on the surface requires bins and chutes. The need to eliminate blockages and promote the free flow of materials in these has led to several installations of ultra-high-molecular-weight polyethylene (UHMWPE)⁵⁰. This material works well in various specific instances, provided that the angle of impact of the rock is low, and depending on the type of material that must flow down the chute or sides of the bin. Elsewhere on the surface, chutes are lined with alumina, cast basalt, composite alumina-polyurethane, chromium carbide weld overlays, andesite lava-cement, quenched and tempered steels, or corrosion-resistant steels^{27,51-53}. The alloy 3CR12 has also been reported to offer some resistance to hang-ups, compared with mild steel²⁷. However, AMS, which is commonly used to line bins and chutes, does not have outstanding wear properties in sliding abrasion.

Concentration and extraction

As this is a diverse topic, we confine ourselves here to examples drawn from dense-medium separation (DMS), cyclones, the carbon-in-pulp (CIP) process, and electrowinning.

Dense media are used in coal, diamond, and iron-ore operations to effect a separation on the basis of density. The liquids, generally based on slurries of Fe₃Si (commonly described as 'ferrosilicon', 'fezzi', or 'fesi') or magnetite, are very abrasive. Although the density of these media is obviously the primary process variable, the viscosity is also very important. It is known that the shape of the particles in the medium has an influence on this. In particular, slurries made of atomized ferrosilicon are less viscous at a given density than those made of milled ferrosilicon. Accordingly, producers such as Samancor have developed atomized grades⁵⁴, which are available at a slightly higher price. In South Africa, these grades are used for the concentration of iron ore and chromite, while the milled grade is used in the diamond industry. A survey conducted in the mid 1980s found that Nihard cast iron was a popular choice for the pumps and impellers required to move DMS slurries around, although rubber linings and other types of cast iron were also used⁶. Piping used at that time included mild steel, rubber-lined mild steel, and HDPE. An interesting feature of Fe₃Si powder is that small variations in its composition can lead, in ways that are not yet fully understood, to rather large changes in its resistance to corrosion and abrasion, and in its magnetic susceptibility. Since the consumption of ferrosilicon can represent a significant cost-item on diamond mines, these three properties are very important.

Although also used in DMS plants, cyclones are more generally used to effect a separation of water-borne particles on the basis of size and density, as well as to de-water slurries. Since the slurry pumped through a cyclone generally consists of angular, freshly milled particles, it is very abrasive. Consequently, although the cyclone itself is usually made of mild steel, its interior is often lined with rubber, alumina, or cast basalt. However, some of the cyclones used to process iron ore and coal are cast from HCWCI⁵⁵. The problem of wear is also severe at the spigots, where in some cases a longer-lasting and reproducible cross-section is

Table 1

Results of a liner-evaluation programme conducted in a run-of-mine (ROM) mill⁴⁴

Material	Expected life days	Cost per block 1990 rands	Cost per liner location per year 1990 rands
Mild steel	563	847	549
Cast iron	420	315	274
Rubber	421	1049	909
AMS grids	384	289	274
HCWCI	917	1136	452

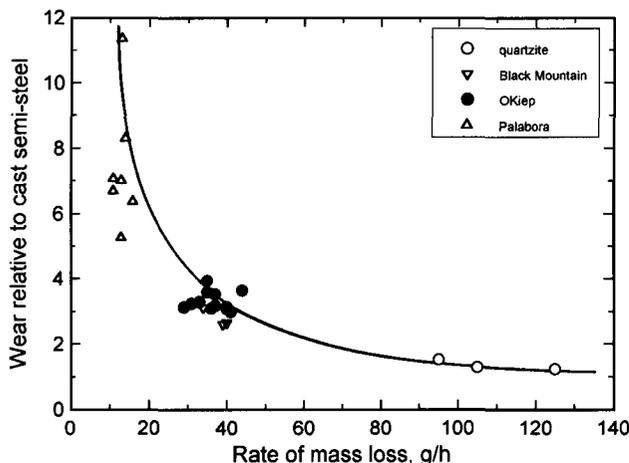


Figure 7—The effect of rock type on the relative wear rate of HCWCI grinding balls

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essential to maintain consistent operation. As a result, advanced ceramics⁵¹ and the Alanx ceramic-metal composite^{56,57} have been tested in these applications.

New plants in the gold-mining industry are based on the CIP extraction process. Gold-laden cyanide solution is mixed with particles of activated carbon, onto which the gold is adsorbed. The carbon particles are then separated, and the gold is eluted with a fresh cyanide solution. Solutions of hydrochloric acid are also used in the plant to strip organic compounds from the carbon. The use of this new technology has ensured a market for highly corrosion-resistant nickel-based materials such as alloy C276²⁶.

Items in the mining industry that are sometimes overlooked are the anodes and cathodes used in the electro-winning or refining processes in the base-metal industries. Here, it is essential to ensure the lowest electrical costs and the longest life of these items, while retaining convenient operation. Unfortunately, many metals are conveniently plated out of a sulphuric acid solution, so that corrosion of the anodes and cathodes is a serious problem. The local situation for the lead anodes used for electrowinning has been investigated by Missio and Bell⁵⁸, and some improvements seem possible. Dimensionally stable anodes (DSA) based on titanium are known to give long life but, as they are expensive, they have not found universal application. Other materials used in these applications include stainless steel and graphite. Composite cathodes made of stainless steel and copper are also produced and, although these dissimilar materials can be brazed together, some suppliers offer explosive welding or even laser welding⁵⁹ to effect a join.

Overall factors

Structural

Ideally, the structure of a mine should last without maintenance for the useful life of the mine, and then should fall apart the next day! The available options include the use of mild steel with an ordinary paint layer if it is accepted that frequent maintenance will be required; the use of a well-selected heavy-duty paint system⁶⁰, possibly over a hot-dip galvanized layer³⁷; the use of a hot-dipped galvanized layer on its own; or the use of a corrosion-resistant material such as 3CR12. The coated solutions are obviously economically effective only in less-abrasive, chiefly architectural or load-bearing applications. Both stainless steel and aluminium sheeting may provide cost-effective long life as roofing or side walls for mine and metallurgical buildings, depending on the nature of the atmospheric corrosion at the site. The situation with regard to structural work in shafts has already been discussed. Specialized advice and a careful analysis of the cost-life benefits is recommended for these installations⁶¹.

Piping

As mentioned here and elsewhere^{6,62}, the replacement of piping is another of the infrastructural costs that is very significant. There are two aspects to this: the replacement of piping used to convey slurries, and of piping used to transport liquids. Of the two, a survey conducted in the mid 1980s found that mining personnel regarded materials difficulties associated with the transportation of slurries as the greater problem⁶. The situation has probably not changed much in the intervening years, and there has been some discussion on these issues^{21,63}. Low-carbon steel piping is still

predominant in the conveyance of slurries, since it offers excellent toughness and reasonable wear and corrosion resistance at a low cost, and can be lined with rubber or polyurethane for service in corrosive waters^{6,63}. However, many other materials have been considered for piping or linings for piping to convey slurries, including heat-treated steel, martensitic stainless steels, high-density polyethylene, polyvinyl chloride, polyurethane, rubber, basalt, alumina, HCWCI, and the COMRO 1210 alloy⁶³⁻⁶⁷. Another solution on offer is an induction-hardened pipe consisting of martensite at its bore, with a smooth transition to ferrite-pearlite at the outside pipe wall. Lives of up to eight times that of mild steel have been claimed⁶⁸, although this improvement has not been confirmed in field trials⁶⁹.

With all the options available for slurry piping, there has been some discussion regarding the best choice. It is worth mentioning that the findings of laboratory tests may differ strongly from plant experience, especially with regard to the ranking of the polymers. One reason is that the abrasion of polymers is more strongly affected by the morphology of the abrasive particles than is the abrasion of metals. Therefore, for example, while laboratory testing with rounded abrasive particles may find that UHMWPE wears at a lower rate than steel, plant experience may be the reverse, apparently on account of the sharp, angular nature of the particles resulting from comminution. Furthermore, conditions in slurry or other hydraulic-transportation pipelines vary significantly from one site to another. For example, while many workers have reported that corrosion (including bacterial corrosion and stray-current corrosion⁷⁰) is responsible for some portion of the total material loss in slurry pipelines, and that the use of corrosion-resisting alloys can extend operating lives by amounts varying from tens of per cent^{21,71} to an order of magnitude^{27,72}, others who have investigated apparently similar quartzitic slurries or ash-disposal pipelines have found that little or no improvement in life was gained from the use of stainless steels^{64,73}. Some of these differing results can be partially explained by reference to the test technique used; it is inevitable in a closed-circuit slurry testing system that the abrasive medium will become degraded, rounded, and smaller. This will tend to cause a reduction in the amount of true abrasive wear during the course of the testwork and a concomitant increase in the importance of corrosion. Where this explanation fails, the availability of the oxygen used by the corrosion process could be investigated, since mass transfer of oxygen has been shown to control the corrosion component in the wear of slurry pipelines⁷⁴. With confusing results such as these, there is evidently no substitute for *in situ* testing.

The pumping equipment used to move slurries is also subject to wear. Nihard and HCWCI are reputed to be the best options for slurry pumps⁵⁹. Alumina impellers have been found to work well^{51,75,76}, but these must be protected from tramp iron or other conditions that may cause severe impact. An order-of-magnitude improvement in life over rubber-coated units has recently been claimed for an alumina impeller operating in a gold mine⁷⁶.

Of course, much of the piping in use does not convey slurry, but is used to transport mine waters of varying corrosivity⁷⁷. Several studies have been conducted to determine the best material options for such piping. Cruise⁶² found that mild steel and aluminium coated-pipes were not robust enough to survive the underground environment,

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especially nearer the stoping regions, and that either low-carbon steel or polyvinyl chloride appeared to be the most cost-effective option in this case. Polyethylene and GRP piping have also found their niches⁶⁹. Although the alloy 3CR12 offers excellent general corrosion resistance, it is susceptible to pitting and crevice attack when immersed in waters of too high a chloride content, or too low a pH. The effect of water chemistry on the pitting and crevice of 3CR12, and on the corrosion of metallic pipelines in the mining industry in general, has been extensively investigated, and the results are available in the literature⁷⁸⁻⁸¹.

Mintek has undertaken a number of piping-exposure programmes lasting up to two years for various clients. For example, Enright⁸² monitored the performance of a variety of piping materials in the chilled-water circuits of two mines, one in Gauteng and the other in the Free State. The averages of two years of water-quality monitoring are shown in Table II. It is evident that, while both waters were loaded with dissolved salts, that of the Free State mine was particularly aggressive. The results of the programme indicated that, after two years, there was substantial corrosion inside the mild-steel and galvanized piping. Alloys with 9 to 12 per cent chromium exhibited marginal performance, with the experimental 927 alloy showing severe pitting along weld heat-affected zones (HAZ), while the alloys Fe-12% Cr-10% Mn and 3CR12 were not attacked in the Gauteng mine but were attacked in the Free State mine. More highly alloyed stainless steels were not attacked at either site. A typical view of the large pits that developed in the alloys containing about 12 per cent chromium is shown in Figure 8. This and other exposure programmes highlighted the sometimes erratic control of the pH in reticulation systems, and the large benefits that accrue when the water is kept consistently neutral.

Table II
Average quality of the chilled water in two representative mines

Characteristic	Gauteng mine	Free State mine
pH	7.6	5.0
Conductivity, mS/m	140	787
Cl ⁻ , ppm	100	1848
SO ₄ ²⁻ , ppm	462	1380



Figure 8—The development of large pits in a 12 per cent Cr pipe used to convey mine water

Discussion

The wear issue

Even a casual visitor to a mine cannot fail to be impressed by the abrasive nature of the rock mined. Indeed, the amount of material removed from mining equipment by various types of wear is the major factor limiting the life of that equipment. Naturally, there has been a consistent effort to find materials that wear less rapidly than, say, mild steel, and that would offer cost savings. It is widely believed that, the harder the material, the better its wear resistance. This is true in a general sense but wear is a complex phenomenon, and austenitic steels such as Hadfield's manganese steel, and even type 304, will, if they harden during wear, out-perform many hardened steels in certain types of wear^{16,22,83}. Some other materials, such as UHMWPE, remain soft during use but will out-perform martensitic steels in slurry applications, provided that the abrasive medium is rounded rather than angular⁸⁴. Nevertheless, martensitic steels or hard-faced steels, with Vickers hardnesses in the range 300 to 600 Hv, are most frequently punted as a solution for excessive wear. However, quartzite in particular, at between⁸⁵ 840 and 1200 Hv, is so much harder than most ferrous materials that martensitic alloys are frequently found to offer little or no cost benefit⁷². Put another way, quartzite is so hard that the difference in wear rates between hard and soft steels does not compensate for the increased cost of the hard alloy. Of course, there is a greater prospect for enhanced cost-life benefits for martensitic alloys in other mines in which the rock is softer. However, we should not exclude the possibility that metallic materials hardened by a constituent other than martensite may offer a partial solution. The M₇C₃ carbide phase, for example, has a hardness⁸⁵ of between 1300 and 1800 Hv and is a major constituent of chromium carbide hard-facing deposits and HCWCI. Another hard compound that has been found experimentally to confer wear resistance on iron-base alloys is the FeCr sigma phase⁸⁶.

Besides alleviating the overall problem of wear, the successful development of a significantly more wear-resistant material may permit the more extensive application of novel methods of comminution such as high-pressure grinding rolls or stirred ball mills. These techniques can produce a finer grind than conventional equipment (and hence, in some cases, have an increased yield), but their use is at present somewhat constrained by the exceedingly high rates of wear that afflict the working parts.

The corrosion-abrasion issue

The corrosion-abrasion issue was introduced earlier in this discussion. The environments in which mining equipment and structural members are used vary from purely abrasive, for example a jaw crusher, to purely corrosive, for example a pipeline carrying untreated saline water. Of course, there are various classes of wear too, and materials differ in their ability to withstand the various types. In between the extremes of material degradation by wear and that by corrosion, lies a spectrum of applications that are exposed to some degree of simultaneous wear and corrosion¹³. It is widely believed that corrosion and abrasion operate together synergistically in these applications, a view promoted by Postlethwaite⁸⁷ in the 1970s and taken up by others in the 1980s^{14,15,22,71,73,85,88,89}.

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Published examples of instances in which the use of corrosion-resistant alloys extended the life of components under laboratory or prototype conditions abound. For example, Allen, Protheroe, and Ball¹⁵ recorded the surprising result that the wear performance of a variety of alloys tested in a prototype shaking conveyor system was more strongly correlated with their corrosion resistance than with their mechanical properties. In a similar vein, work at the University of Minnesota and elsewhere in the USA has consistently demonstrated that, in laboratory test situations, the process of corrosion is responsible for a significant proportion of material loss in comminution^{71,85,89}. In these situations, stainless steels or HCWCI were found to significantly outperform low-carbon steel and the proprietary wear-resistant alloys. The explanation given was that, while it takes from 20 to 60 seconds to form a protective film on low-carbon steel exposed to mixed wear and corrosion⁸⁹, the rate of film formation on alloys of high chromium content (more than 20 per cent) is so high that they remain passive even while they operate in a ball-mill environment⁸⁵. Since the rate of corrosion while the film is forming may be several orders of magnitude higher than on a passive surface, this can cause a very significant acceleration of material removal during continuous abrasion⁸⁵. The results of these types of work were interpreted as indicating that a compromise alloy, which would be cheaper than standard stainless steels but would still retain adequate resistance to corrosion and abrasion, could be developed for general mining use.

The desired properties of the hypothetical new alloy were outlined by Protheroe *et al.*⁹⁰ in 1982. Some of the most important constraints were that it should not have a high price, but that it should contain about 12 per cent chromium and be capable of developing a surface hardness of about 500 Hv. The search for this alloy, funded in most cases by COMRO, became an important activity in the 1980s at a number of organizations^{14,83,91,92}. Although dual-phase alloys (martensite laths surrounded by a continuous film of austenite) had originally been envisaged, a variety of experimental, predominantly martensitic, stainless steels eventually emerged from the test programme, together with an austenitic alloy⁸³. About 60 t of experimental plate materials were manufactured for the programme in the United Kingdom¹⁴, and smaller quantities were produced at USKO in Vereeniging⁹¹ and by Iscor. Laboratory testing of these alloys under simulated corrosion-abrasion conditions indicated that up to five times the performance of mild steel could be obtained, but the alloys could be susceptible to pitting attack under immersed conditions¹⁴. A commercially available variation of type 420 martensitic stainless steel was later added to the list of candidate materials.

A quantity of experimental martensitic tubing that was produced from this last material by the company TOSA was tested on a mine⁶⁹, but the results have not been published. However, a comprehensive evaluation of some of the experimental alloys in rock handling was undertaken, the results of which are in print¹³. Applications in the stope (scraper scoops), at the bottom of a shaft (measuring flask), and in a reduction plant (discharge chutes) were selected for testwork. Mines that were known to experience corrosive conditions were incorporated in the test programme. However, no advantage was found in the applications tested for the corrosion-resistant alloys over the Hadfield's type and abrasion-resistant comparators used (Figure 9), and it was

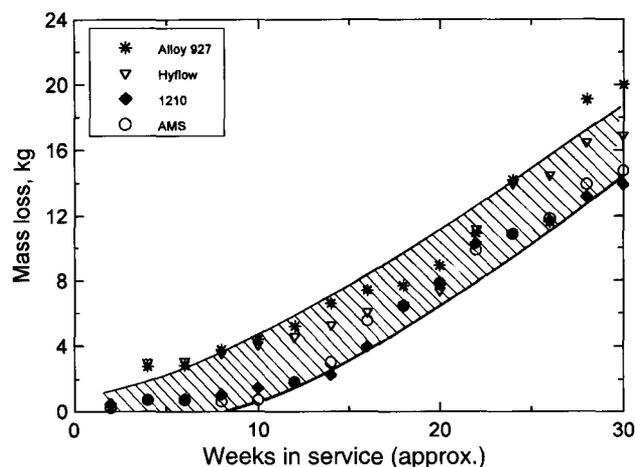


Figure 9—The wear of experimental alloys and a Hadfield's comparator in the measuring flask in a gold mine

finally concluded that the experimental alloys offered few advantages for use in quartzitic mining environments. Apparently, the prior laboratory testwork from which the compositions of the experimental alloys had been developed had not fully simulated the real situation¹³. The programme on the development of these alloys did not survive the cut-back in COMRO's activities. Mintek and other organizations have, however, continued with their own investigations into improved materials. A certain amount of the experimental COMRO plate material is in storage at Mintek, and is available for further study by interested parties.

The failure of the experimental corrosion-resisting alloys to exhibit better performance than the comparators may initially appear very puzzling, and certainly flies in the face of what may have been expected from the laboratory testwork undertaken in corrosion-abrasion situations. One explanation for the poor performance of the experimental 12 per cent chromium alloys could be that they formed corrosion-resistant films no more quickly than the comparators did, and that the material loss was therefore dominated by the high transient corrosion rates immediately following the exposure of abraded surfaces. However, an alternative explanation may be that the impact and attrition events in a mine are significantly more energetic than those in the laboratory simulations, and more damaging on account of the angular nature of the freshly broken rock. The same explanation for the difference between laboratory and plant experience was offered by Dodd and his co-workers in 1985⁹³, in that case referring to testwork with grinding balls and grinding circuits.

However, while the use of corrosion-abrasion resistant alloys seems of negligible utility in the highly abrasive environments of quartzitic rock-handling and comminution, it may still be worth exploring further in the area of slurry transportation, as well as in corrosion-abrasion applications in coal and other mines where the rock is softer.

Advanced materials

There has been an active interest worldwide in the so-called advanced materials, of which a fully comprehensive definition seems unlikely. The term *advanced material* appears to encompass composite materials of most kinds,

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intermetallic compounds, the newer ceramics, shape memory alloys, and some modern polymers. In general, most of these materials are not yet in widespread (tonnage) production. An exception is a particulate reinforced MMC in which the continuous phase is an aluminium alloy, with the dispersed phase being up to 20 per cent Al_2O_3 or SiC by volume. One version of the product is Duralcan™, which possesses good stiffness and resistance to low-stress abrasion and has been used to a limited extent in products as diverse as tennis rackets, bicycle frames, cylinder liners, drive shafts, and automobile brake rotors^{94,95}. The use of materials of this type offers potential savings in mass, and in principle should help reduce transportation costs in mines while simultaneously overcoming the poor wear resistance of aluminium.

Unpublished work conducted at Mintek some years ago investigated the performance of Duralcan and certain experimental MMCs in various low- and high-stress abrasive environments. The microstructure of one of these aluminium-matrix composites is shown in Figure 10. In this case, the hard particles consist of the mineral zirconia, and make up about 40 per cent of the material by volume. Improved wear resistance of experimental aluminium-matrix composites was confirmed in quartzitic slurries under low-stress conditions (Figure 11), but it was found that, under high-stress conditions such as those that might be expected in rock-handling, both the experimental MMCs and the Duralcan material performed no better than ordinary aluminium, which in turn performed worse than mild steel.

More success has been achieved with composite materials of other types. For example, a proprietary ceramic-matrix composite, Alanx™, consisting of about 70 per cent silicon carbide, 21 per cent Al_2O_3 , and 9 per cent aluminium, has provided excellent performance in components such as hydrocyclones, slurry pumps, valve parts, and chute linings⁵⁷. In certain laboratory slurry tests, the product was found to last an order of magnitude longer than materials such as Stellite or alumina. Elsewhere, alumina tiles set in polyurethane are currently out-performing the traditional hardened steel liners used previously as impact plates for ore chutes in headgears. It is said that steel liners last about six weeks, whereas composite-alumina impact plates have lasted more than three years in several Free State gold mines. A similar composite material is Poly-Cer, a tradename of Skega,

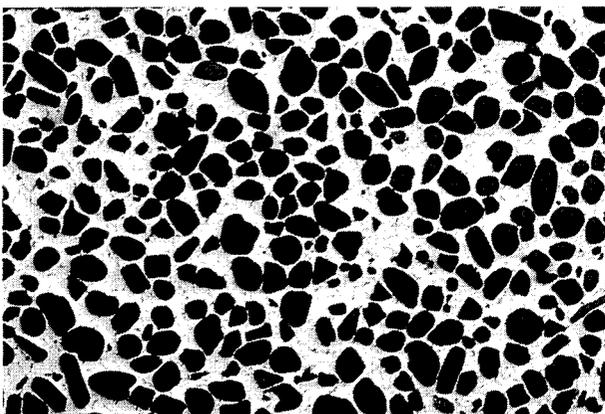


Figure 10—The microstructure of an experimental aluminium-zirconia composite (the aluminium being the continuous phase)

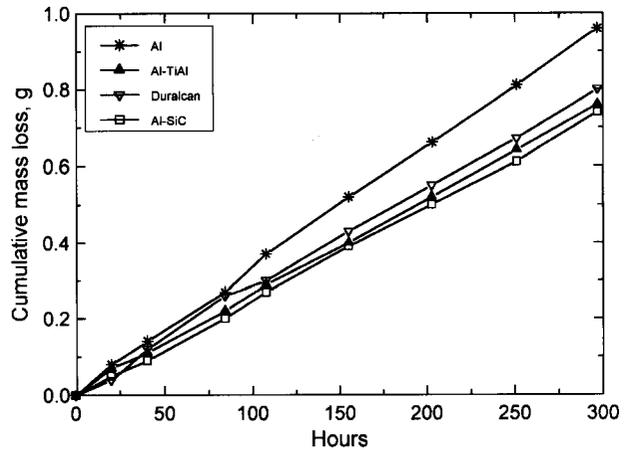


Figure 11—The loss in mass of experimental aluminium-matrix composites in quartzitic sand tumbled in a mill of 700 mm diameter

which contains alumina rods in a rubber matrix⁹⁶. In both cases, the purpose of the organic backing material is to absorb forces generated by impacts, while the alumina provides the resistance to abrasion. The opposite situation prevails for composite Polymet lifter bars for mills, which are made of rubber capped with a piece of wear-resistant steel. There are several advantages arising from the use of a rubber liner and lifter, including a reduction in the amount of locked-up gold in a mill. However, while this kind of lifter bar has apparently found some use in Canada, it is less popular in South Africa⁴³.

Conclusions

Equipment operating in mining environments is susceptible to a significant amount of wear and corrosion, and the cost of material degradation represents a sizable proportion of the overall operating costs of a typical mine. A reduction in these costs will normally lead to a greater profit. Various strategies have been explored in order to achieve this, but the relative merits of a low first-cost approach versus a low lifetime-cost approach remain debateable. It should be recognized that a low first-cost (even if the material is inferior or unsuitable) often predominates in the cost-life equation. Mild steel is now considerably cheaper in real terms than in the past, and remains the generic first choice. However, the true cost of downtime and skilled engineering staff to replace worn-out items must also be considered in the analysis. Unfortunately, this is sometimes under-emphasized since the occurrence of downtime and the necessity to employ a strong technical services complement are often taken as a given factor. A relatively sophisticated in-house costing system is required so that these expenses can be correctly attributed to appropriate material selection.

In general, the quartzitic rock of gold mines is extremely abrasive and, although martensitic alloys are sometimes used, other materials, including mild steel, are frequently found to be more cost-effective. However, martensitic steels are more useful in other types of mining where the broken rock is not as hard. In general, it can be said that, besides mild steel, there is no single material that can be applied generally to mining environments. Materials such as AMS, quenched and tempered steel, polymers, galvanized steel,

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ceramics, MMCs, stainless steels, and concrete all have applications. It takes systematic work, and a degree of patience, to determine which one provides the best cost-life benefits in each niche. The factors are complex, and the optimum solutions are mine-dependent. However, the relevant information has not yet been extensively collated or shared. A collaborative programme, undertaken on behalf of the various mining houses by a full-time team, and with a focus on practical applications, may be required before substantial progress is achieved.

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