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Improved wear- and corrosion-resistant steels*

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SYNOPSIS

The development of steels with improved abrasion-corrosion resistance for use in underground components in South African gold mines is described in terms of design, manufacture, and performance. Based on the concept of microstructural design, new compositions were formulated to provide the optimum structures and properties. Extensive laboratory tests were conducted, and an industrial melt was produced. The resultant materials were tested for fabricability and machinability, and various components were manufactured. According to the preliminary operational results, these alloys exhibited outstanding performance in wear-plate tests, and are very promising for general application in underground components.

SAMEVATTING

Die ontwikkeling van staalsoorte met beter skuur- en korrosiebestandheid vir gebruik in ondergrondse onderdele in Suid-Afrikaanse goudmyne word in terme van ontwerp, vervaardiging en werkverrigting beskryf. Daar is aan die hand van die idee van mikrostruktuurontwerp nuwe samestellings geformuleer om die optimale strukture en eienskappe te gee. Daar is uitgebreide laboratoriumtoetse uitgevoer en 'n industriële smelting voortgebring. Die resulterende materiale is vir fabriseerbaarheid en masjineerbaarheid getoets en daar is verskillende onderdele vervaardig. Volgens die voorlopige bedryfsresultate het hierdie legerings voortreflike werkverrigting in slytplaattoetse getoon en hou hulle groot belofte in vir algemene aanwending in ondergrondse onderdele.

Introduction

Abrasive–corrosive wear constitutes a major component of the costs of plant maintenance and replacement in the mineral-processing industry. Considerable effort has therefore been made by the Chamber of Mines Research Organization in the development of new engineering materials for use underground, and as part of a programme of work on the mechanization of mining operations in South African gold mines. In mineral-transportation networks in particular, the prevention—or, more realistically, inhibition—of failure through the progressive degradation of materials is a dominant factor in the implementation of new developments for the optimization of materials-handling procedures. In addition, there is a need for materials of more general usage in a wide range of applications in order, among other purposes, to obviate the necessity for diverse stockholding. This paper reports on the potential for significantly improved materials through the application of principles of (microstructural) alloy design.

The work described relates specifically to gold mining, where the extreme hardness of the quartzite matrix (900 to 1300 HV) implies that all the equipment used in mining and transporting the ore is subject to severe abrasive wear. In addition, the corrosive nature of mine water, combined with the high humidity and relatively high temperatures underground, produces an extremely aggressive operating environment.

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Conveying Systems

In recent years, the need has arisen to improve the performance and efficiency of both existing and new equipment, and in the latter case considerable effort has been directed at the mechanization of stoping operations in South African gold mines[1]. In one particular application, a prototype conveyor[2], Fig. 1, is employed to transport rock from the face. This consists of a number of pans, each 2 m long, extending to lengths of more than 80 m, which move the rock by the linear oscillatory movement of the pans. In this example, low-stress abrasion aggravated by corrosion was identified as the specific wear mechanism[3]. This equipment was selected for the initial evaluation of new materials since this would provide a guide to their performance under conditions of sliding wear, which are common in many components used in the mining industry.

Materials Selection Versus Alloy Design

Studies of the deterioration of materials used in gold mining have indicated that degradation processes vary widely from predominantly dry abrasion through to essentially pure corrosion. Logistical and operational considerations have formulated a need for a spectrum of materials utilization, ideally centred on a range of economical, general-purpose, abrasion- and corrosion-resistant materials.

In the search for a rapid evaluation of potential new alloys, as well as the characterization of current commercially available materials, a comprehensive, controlled experimental programme has already been carried out to establish a reliable laboratory wear test, through the correlation of results obtained in the laboratory with *in situ* tests[3].

In the first instance, excellent resistance against gouging wear can be obtained by the use of high-chromium mar-

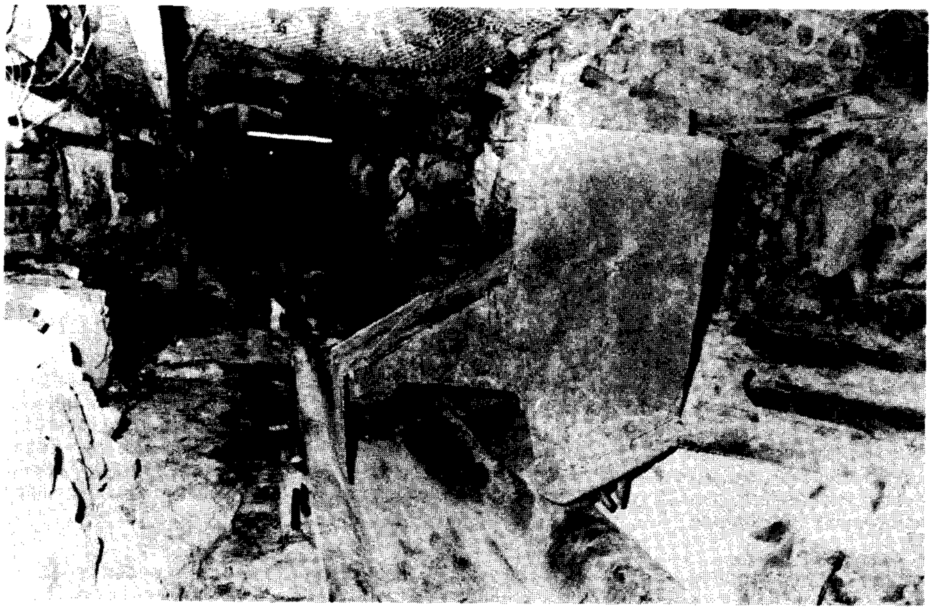

Fig.1—A prototype conveyor operating in a dip gully

tensitic white irons, but their relatively high degree of brittleness, even during transportation[4], limits their potential for use in stope areas. Material hardness, of course, is of importance in determining abrasion resistance, and Richardson[5] has shown that, before any significant improvement in abrasion resistance can be achieved, the material should have at least half the hardness of the abrasive medium. For use with quartzitic materials therefore, a minimum surface hardness of about 500 HV is a prerequisite.

Secondly, it is generally accepted that resistance to both crack initiation and crack propagation is desirable for good abrasion resistance and, indeed, Zum Gahr[6] has reported that, beyond a certain hardness level, material toughness becomes the property that controls resistance to abrasive wear. Studies of a wide range of existing steels[7,8] have indicated that a Charpy impact energy of at least 30 J is a minimum requirement for appropriate abrasion resistance. This level of toughness is also considered to be the minimum acceptable in mining applications, where rugged demands for transportation and day-to-day service preclude the use of more brittle materials.

Thirdly, the high corrosivity of the stoping environment is anathema for many structural alloys, and it is frequently observed that corrosion processes are accelerated by abrasion. For this reason, adequate corrosion resistance in metallic materials dictates a minimum chromium content of around 10 per cent (consistent with acceptable material and production costs).

Finally, of course, desirable fabrication characteristics and realistic financial considerations contribute to an unenviable exercise in materials selection.

A wide range of materials is obviously readily available for use in abrasion–corrosion applications, including polymers, ceramics, surface-treated steels, coatings, high-chromium cast irons, and transformable austenitic stainless steels. However, none of these materials has yet proved adequate in meeting the combination of requirements, as defined above, for more general-purpose use in gold-mining environments. In consequence, an alternative approach through microstructural design has been developed, in which new alloy compositions are formulated to provide the necessary operational (and economic) benefits.

Alloy Design

A wide range of materials, including stainless, transformable, and martensitic steels, has been studied extensively by the Chamber of Mines Research Organization in its search for improved resistance to abrasion and cavitation erosion. This work identified important desirable microstructural features. These are rarely found in existing commercial steels, and in the present study developments were based on the high-strength, high-toughness martensitic steels initially formulated by Thomas *et al.*[9–11]. These steels were thought to go some way towards meeting the needs of the mining industry, but they had neither the required corrosion resistance, nor had they been made on any commercial scale.

Microstructure

In these alloys, the desired microstructure is essentially a fine-grained austenite that has been transformed to dislocated lath martensite surrounded by continuous films of retained austenite. A fine grain size promotes both strength and toughness.

The toughness of the lath martensite is also important, and appears to be influenced by two factors: the presence of internal twinning[11–13] and the martensite packet size[14,15]. The extent of twinning in martensite is significantly influenced by composition and by the effect of alloying elements in lowering the martensite transformation temperature (M_s). The corresponding loss in toughness at lower M_s values appears to be associated with a restriction of slip during deformation. A fine martensite packet is desirable since the average fracture direction must change on crossing a packet boundary. Control of twin density and lath structure can be achieved through appropriate manipulation of the chemical composition and processing procedures, as will become apparent.

The importance of maintaining thin, continuous interlath films (approximately 5 to 10 nm thick) of retained austenite for improved toughness in high-strength martensitic steels has been noted by a number of authors[9,13–16]. It has been suggested[16] that the presence of this phase along the martensite lath boundaries serves to interrupt the crystallographic alignment of laths within a packet, thus preventing trans-packet cleavage. Best combinations of strength and toughness in medium-carbon martensitic steels seem to result from volume fractions of retained austenite of about 5 per cent.

Carbide size and distribution are also important. A fine, intra-lath dispersion of carbides has been shown to be beneficial to strength, toughness, and abrasion resistance[9–11]. Coarse, inter-lath carbides, however, can be very detrimental to mechanical properties, as exemplified in the phenomenon of tempered martensite embrittlement[17].

Another desirable microstructural feature is, if possible, the absence of inclusions. While the precise relationship of cleanliness to steel quality is still not fully understood, cleaner steels generally result in improved properties, providing benefits both in fabrication and in service[18].

Chemical Composition

The first step towards improved martensitic steels was an increase in the chromium content to provide improved corrosion resistance. Additional benefits of this alloying addition are solid-solution strengthening of the martensitic matrix and the inhibition of coarsening of the Fe_3C precipitates.

The potential deleterious effect of chromium on toughness, through the promotion of substructural twinning in the martensite, was obviated by a reduction in the carbon content. This carbon level provided adequate hardness, and had the further benefit of maintaining a relatively high M_s temperature. This latter effect facilitated carbon partitioning during transformation, which chemically stabilized the retained austenite.

Nickel additions were also employed to provide further austenite stabilization, as well as improved corrosion resistance and fracture toughness (in chromium-containing steels).

Experimental

Two Fe–Ni–Cr–C alloys (A and B) of different chromium content were prepared by vacuum melting and casting into 5 kg ingots, and were then hot-rolled to plate. The alloys are currently the subject of patent applications, and the precise compositions and optimum heat-treatment parameters cannot be disclosed at this time.

Determinations of the mechanical properties and wear testing were conducted on the materials in the quenched and tempered condition. Laboratory wear data were obtained from experiments carried out in the Department of Materials Engineering at the University of Cape Town. Microstructural information was obtained from the use of light microscopy, and scanning (SEM) and transmission (CTEM) electron microscopy.

As indicated in the Introduction, a meaningful and reproducible laboratory testing procedure has been developed for the evaluation of material performance in abrasive–corrosive environments[3]. In this test, which uses synthetic mine water of pH 6,5 at 30°C, controlled-abraded surfaces are exposed to corrosion for timed periods. Such laboratory tests have been correlated with a programme on a prototype conveyor operating underground in a stope in a gold mine[3]. In this rig, sections approximately 500 mm by 300 mm were cut from the bases of several shaker pans, and were replaced with similar-sized panels of high-density polyethylene mounted on a backing plate. Samples of materials under test were fitted to present a surface 75 mm by 50 mm flush with the sliding quartzitic rock. (Polyethylene was chosen to ensure a constant exposed sample surface, because of its slightly higher wear rate, and to eliminate any effects of galvanic corrosion between test samples[3].)

After the laboratory trials, a small (4 t) industrial melt (alloy USCO-A) was prepared by the Union Steel Corporation of Vereeniging. In the absence of large-tonnage vacuum-melting facilities, techniques of electroslag melting were used to reduce impurities. This alloy was cast into three ingots, each 450 mm in diameter, and then hammer-forged to a diameter of 150 mm. Surface defects were removed to produce a final bar diameter of 130 mm.

This material was subjected to an extensive range of heat treatments and formability and machining tests[19]. The forming limit line and workability index were determined from the fracture strain of compression specimens. This proved a simple, but effective, method for the evaluation of formability. Machinability was assessed by the subjection of the material to an actual turning operation. The parameters considered were tool life, tool forces, chip formation, and surface finish under various machining conditions. In addition, sections of the industrial alloy were used in the manufacture of various underground components: a hammer tool, a hammer collet, and a rock-drill tie-rod.

Results

In the preliminary study, both laboratory alloys were given the same heat treatment. This produced a fine prior austenite grain size (approximately 30 μm and 40 μm in alloys A and B respectively). In this condition, alloy A gave a Charpy impact value at room temperature of 67 J (minimum) with a bulk hardness (HV 30) of 530; while alloy B gave values of 30 J and 560 VPN. The industrial alloy (USCO-A) in the quenched and tempered condition produced comparable properties (47 J and 500 VPN) despite an increased grain size (about 100 μm).

The general appearance of the lath martensitic microstructure of these alloys is shown in Figs. 2 and 3. CTEM (Figs. 4 and 5) clearly illustrate that the desired lath structure was produced, with limited internal twinning. Interlath films of retained austenite and an extremely fine dispersion of cementite precipitates were also observed in all the alloys.

The cold-workability index for the annealed industrial alloy is given in Table I, together with values for some other commercial steels. Although comparison with the results of other studies is difficult (since there is some doubt as to the exact condition of the material tested), such results can be used in ranking the performance of the experimental composition under consideration here. On this basis, alloy USCO-A appears to have superior

Fig. 2—General structure of alloy A (optical)

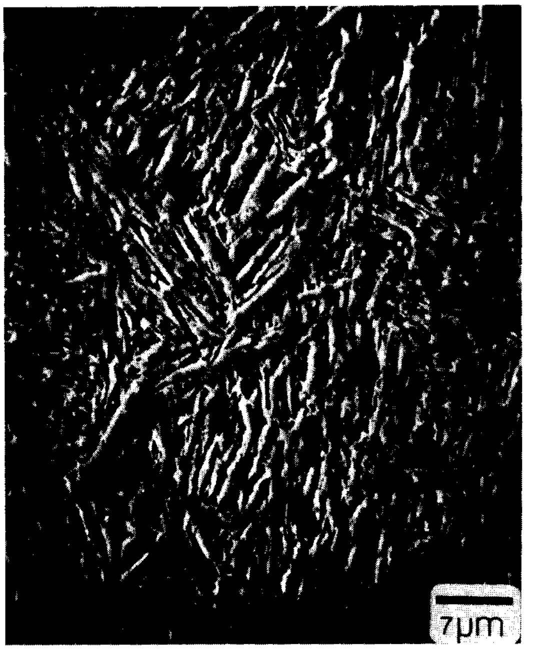

Fig. 3—Martensite morphology of alloy B (SEM)

Fig. 4—Desired microstructural features of alloy A (CTEM)

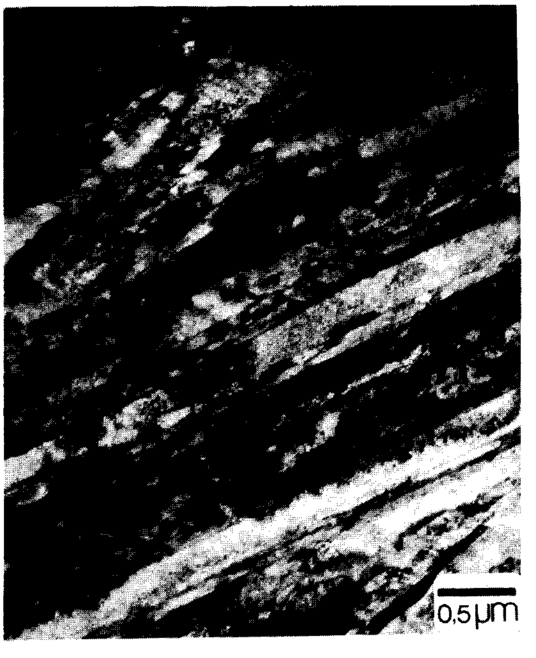

Fig. 5—Regions of lath martensite in alloy B (CTEM)

cold-formability characteristics, particularly when compared with other medium-carbon steels (such as AISI 1040).

In the evaluation of the hot formability, the power requirements for the forging of cones from cylindrical slugs were monitored. The hot-forming characteristics were assessed by comparison with reference material EN3. The average results for USCO-A and 3CR12 are given in Table II, from which it can be seen that the apparent hot strength of this alloy under severe deformation conditions was approximately three times that of mild steel and 3CR12. Nevertheless, the general forging of the components was successful (with generous soaking times) using starting and finishing temperatures of 1150 and 900°C respectively.

The machinability of these alloys was found to depend critically on the annealing heat treatment and the tool grade and geometry[19]. Under finishing conditions, all the alloys exhibited well-broken chip formation and, under the given test conditions, all the experimental alloys were found to be adequately machinable. Further detailed, quantitative information is available elsewhere[19].

TABLE I

COMPARATIVE WORKABILITY INDICES

Material	Workability index	Reference
1040 steel annealed	0,38	20
1020 steel as received hot-rolled	0,32	21
3CR12: As cast	0,46	22
50% hot reduction	0,31	22
USCO-A annealed	0,43 ± 0,03	

TABLE II

RELATIVE POWER REQUIREMENTS FOR HOT FORGING

Alloy	Power required for alloy / Power required for EN3
3CR12	0,9 ± 0,15
USCO-A	2,9 ± 0,22

TABLE III

RELATIVE-DRY ABRASION RESISTANCE OF MATERIALS

Material	RAR
Alloy B	1,99
Alloy A	1,79
Quatough	1,70
Abrasalloy	1,43
Roqlast AH 400	1,36
AISI 304	1,30
Wearalloy 400	1,27
Benox	1,24
AISI 316L	1,17
3CR12	0,99

Wear Tests

Laboratory dry-abrasion tests were conducted (at the University of Cape Town) by a pin-on-disc technique[23], with mild steel as the reference material. The relative dry-abrasion resistance (RAR) of the experimental alloys and some commercial materials are presented in Table III. It can be deduced from these results that, under dry conditions, the abrasion resistance of martensitic materials is superior to that of both ferrite–pearlite structures and stainless steels. It is also clear that the new experimental alloys are superior to existing materials.

The pin-on-disc technique was also employed in the determination of relative wet-abrasion resistance (RWR), with mine water as the corrosive medium. This test has been shown to provide excellent agreement with the results of site tests underground[24]. The correlation for commercial materials is illustrated in Fig. 6, which shows that the performance of the corrosion-resistant materials (3CR12, 430, 316, and 304) is superior to that of the abrasion-resistant steels (Abrasalloy and Roqlast AH 400). The laboratory test data for alloys A and B are included for comparison. On this basis, it would be predicted that alloy A is significantly better than currently used materials, but only marginally superior to Quatough. However, the results obtained for alloy A in the form of pan inserts in an underground prototype conveyor system (RWR 2,70) are much more promising. Alloy B, which has a higher chromium content than A, appears even better, and should provide an exciting new material for mining applications involving sliding wear, for which it was designed.

Although the data have not yet been quantified, the hammer tool was successfully fabricated from alloy B and has exhibited very good impact properties in operation.

Service trials on the hammer collet and rock-drill tie-bolt have not yet been completed. Nevertheless, their manufacture, involving forging and extensive machining, was carried out without any problems.

Summary and Conclusions

(1) The solutions to materials problems in the transportation of minerals in gold-mining applications require the optimization of complex combinations of desired features, including abrasion resistance, corrosion resistance, ease of fabrication, and economy.

(2) Microstructural design for the development of optimum combinations of properties shows considerable promise for the future provision of improved materials for use in the mining industry.

(3) There are indications that the most satisfactory combinations of properties for abrasion and corrosion resistance in engineering applications can be achieved

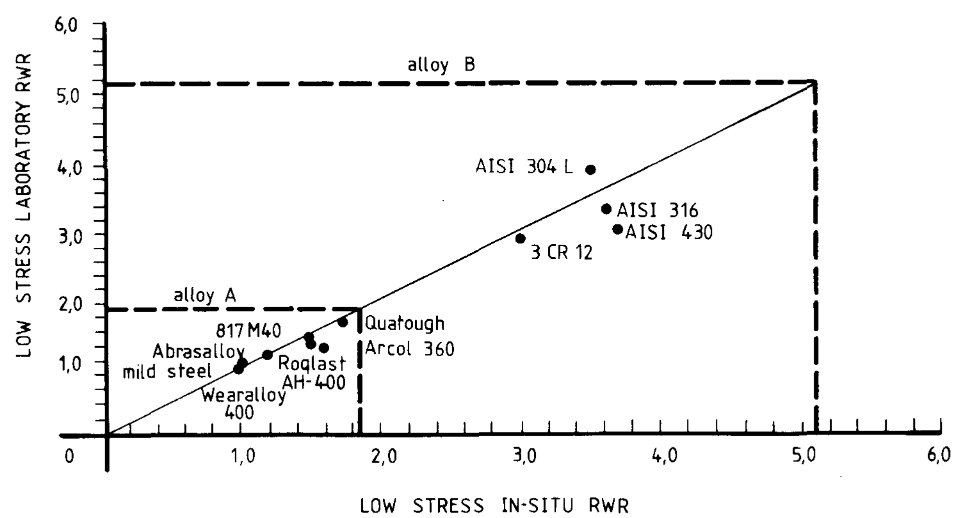

Fig. 6—Correlation between laboratory and *in situ* relative abrasion and corrosion resistance (RWR) based on data from reference 3

by the appropriate manipulation of chemical compositions, and fabrication procedures. A concept of microstructural design was therefore employed in the development of a series of alloys with a hardness of more than 500 VPN and an impact toughness of more than 30 J.

(4) The outstanding results of alloys A and B in tests on a prototype conveyor prove that these steels have potential widespread applications in skips, chutes, and other conveying systems in many general mining operations, which are subject to sliding wear and/or corrosion.

(5) Similar mechanical properties can be obtained in commercial alloys by the use of electro-slag remelting (ESR) techniques. The workability and machinability are sufficient also for the production of a wide range of components for the mining industry.

(6) Alloys A and B were designed primarily to have a microstructure that would optimize hardness and toughness properties for abrasion resistance. Alloy B, which combines abrasion and corrosion resistance, provides a potentially superior material for this application. However, high chromium contents have disadvantages, and a lower chromium content, such as in alloy A, could be preferable. Although the performance of alloy A appears to be inferior on the basis of the current tests, this could be improved by an increase in its corrosion resistance (for example, by being alloyed with copper, molybdenum, or more nickel). However, in other applications where corrosion resistance is less dominant, its performance is likely to be superior to that of alloy B.

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Coal-mining wastes

The 2nd International Symposium on the Reclamation, Treatment and Utilization of Coal Mining Wastes is to be held in Nottingham (England) from 7th to 11th September, 1987.

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