SX 3CR12—a material for abrasion-corrosion control*

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SYNOPSIS

Although stainless steels have been used to a limited extent in the South African mining industry, the metallurgical development of 3CR12 has presented materials engineers with a viable alternative for certain materials-handling applications. The various types of wear involved in these operations are described, and an explanation is given of how 3CR12 is able to offer advantages, particularly in wet sliding applications. Certain applications result in various types of abrasive wear, and the performance of 3CR12 in these areas is described.

SAMEVATTING

Hoewel vlekvrye staal in 'n beperkte mate in die Suid-Afrikaanse mynboubedryf gebruik is, het die metallurgiese ontwikkeling van 3CR12 materiaalingenieurs 'n lewensvatbare alternatief vir sekere materiaalhanteringsgebruike gebied. Die verskillende soorte slytasie wat by hierdie werksaamhede betrokke is, word beskryf en daar word verduidelik watter voordele 3CR12 kan bied, veral wat natglywerk betref. Sekere gebruike veroorsaak verskillende soorte skuurslytasie en die werkverrigting van 3CR12 op hierdie gebiede word beskryf.

History

The stainless-steel industry in South Africa has been active in promoting the use of stainless steels in mining applications for more than ten years. Until fairly recently, all these efforts were concentrated on two alloys for abrasion–corrosion control – AISI 430 and 304 stainless steels. Type 304 has been used in the U.S.A. and Europe for coal-preparation and coal-handling equipment to a limited extent, and provides excellent life but at a high material cost. Since South Africa's stainless-steel producer is capable of producing high-quality type 430 plates, it was natural that this alloy was also introduced in such applications as coal chutes, coal-bunker liners, underground gold-ore cars, and gold-ore pass liners. Considerable success was achieved in these applications, but the problematic fabrication techniques required with type 430 severely restricted this alloy's application.

The advantages of corrosion-resisting alloys in corrosion–abrasion applications was recognized, and a detailed metallurgical investigation aimed at the development of a chromium-containing corrosion-resisting steel with excellent fabrication characteristics culminated in the South African-patented alloy, 3CR12[1].

Metallurgy

The chemical composition of SX 3CR12 is as follows (in percentages by mass):

C	0,025	Mn	0,50	Cr	11,6
N	0,015	P	0,025	Ni	0,6
Si	0,40	S	0,020	Ti	0,20

In the hot-rolled condition, 3CR12 has a duplex structure of ferrite and martensite (Fig. 1). The mechanical properties and corrosion resistance are subsequently optimized by an annealing treatment of 1 to 1½ hours at 700 to 750°C, by which time the structure consists of Fe–Cr ferrite and a few coarse, blocky Ti(C, N) precipitates distributed evenly throughout the matrix. In this condition, the alloy shows the optimum toughness and ductility, and good cold formability[2], which allows it to be fabricated with a minimum of skill. Typical properties are shown in Table I, while the structure is shown in Fig. 2.

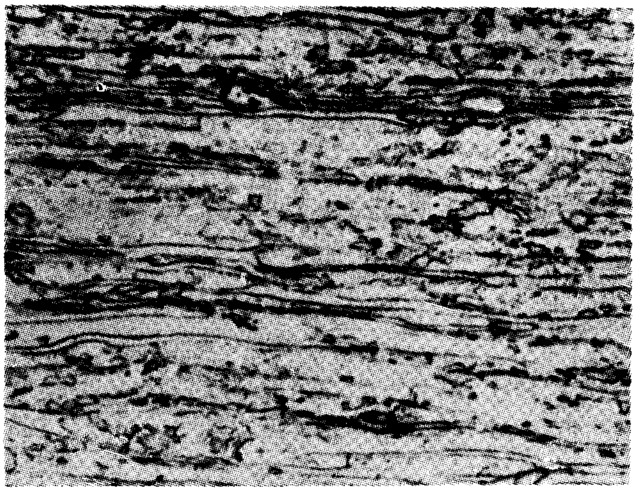

Fig. 1—Structure of 3CR12 in the hot-rolled condition, showing banded ferrite and martensite morphology

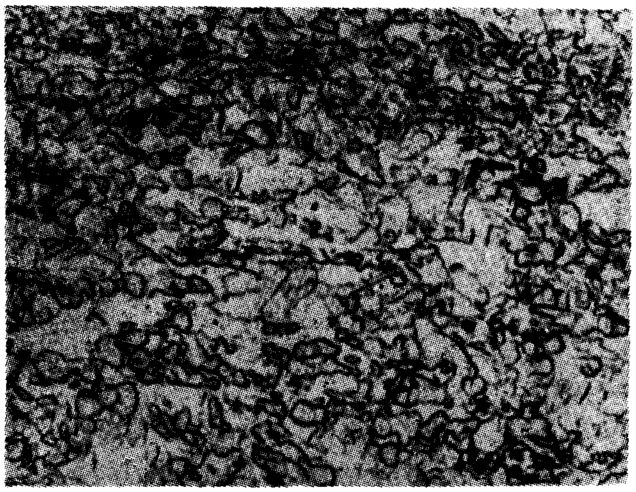

Fig. 2—Annealed 3CR12, with equiaxed grains of ferrite and small cuboid precipitates of titanium carbonitride

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TABLE I
TYPICAL MECHANICAL PROPERTIES OF 3CR12 AND STAINLESS STEELS

Property	3CR12	304	316
0,2 % proof strength, MPa ..	310	300	310
Ultimate tensile strength, MPa	520	600	600
Elongation, in 50mm	25	50	45
Hardness, VPN	165	155	160

Characteristics and Mechanisms of Abrasive Wear

There are three classic broad descriptions of wear processes: low-stress abrasion, high-stress abrasion, and gouging wear[3, 4]. The three mechanisms are sufficiently different to warrant totally different apparatus for the testing of wear rates, and good wear resistance in one test does not guarantee even fair resistance under other conditions[4, 5]. Furthermore, minor differences in the type of abrasive, or even its particle-size distribution, can change results drastically, so that engineers generally tend to rely on plant experience when selecting abrasion-resistant alloys[5].

Wear in chutes, which is sliding or low-stress abrasion (Fig. 3), is caused by hard rock (or slag in the case of coal chutes) sliding at speeds of between 0,3 and 4 m/s. Investigations by British Steel Corporation on wear in sinter and coke chutes[6] have shown that intrinsically hard materials, such as tungsten carbide, fusion-cast or extruded alumina, and plasma-sprayed chromium–vanadium carbides, show the lowest rates of wear. However, the Chamber of Mines of South Africa[7] has shown that there is little relationship between hardness and wear resistance in laboratory sliding-abrasion tests. Furthermore, at very high speeds, wear rates in materials of vastly different hardnesses (e.g., 450 VPN as against 18 VPN) are very much the same. This disparity illustrates an important feature of all wear processes – the number of variables involved is generally too great for any particular microstructural feature to be isolated as beneficial or detrimental in wear resistance.

Wear often takes place by ductile, as well as by brittle, fracture of small pieces of material. The ratio of ductile to brittle wear is affected by, among other factors, the toughness and ductility of the material. With 300 series austenitic stainless steels, e.g. 304 or 316, it could be expected that only ductile fracture would occur. However, significant work-hardening of the surface takes place (Fig. 4), and the appearance of α and ϵ martensite in a heavily-worked and slipped austenitic matrix causes a good deal of brittle fracture to occur. The stability of the austenite (controlled by chemical composition) can be used to vary the ratio of ductile to brittle wear. In two-phase materials in which one phase is austenite (such as quenched and tempered alloy steels), Allen *et al.*[7] were unable to conclude whether or not the retained austenite was advantageous.

Annealed 3CR12 has a hardness of about 170 VPN, only slightly more than that of mild steel; its toughness and ductility are much the same as those of mild steel, and,

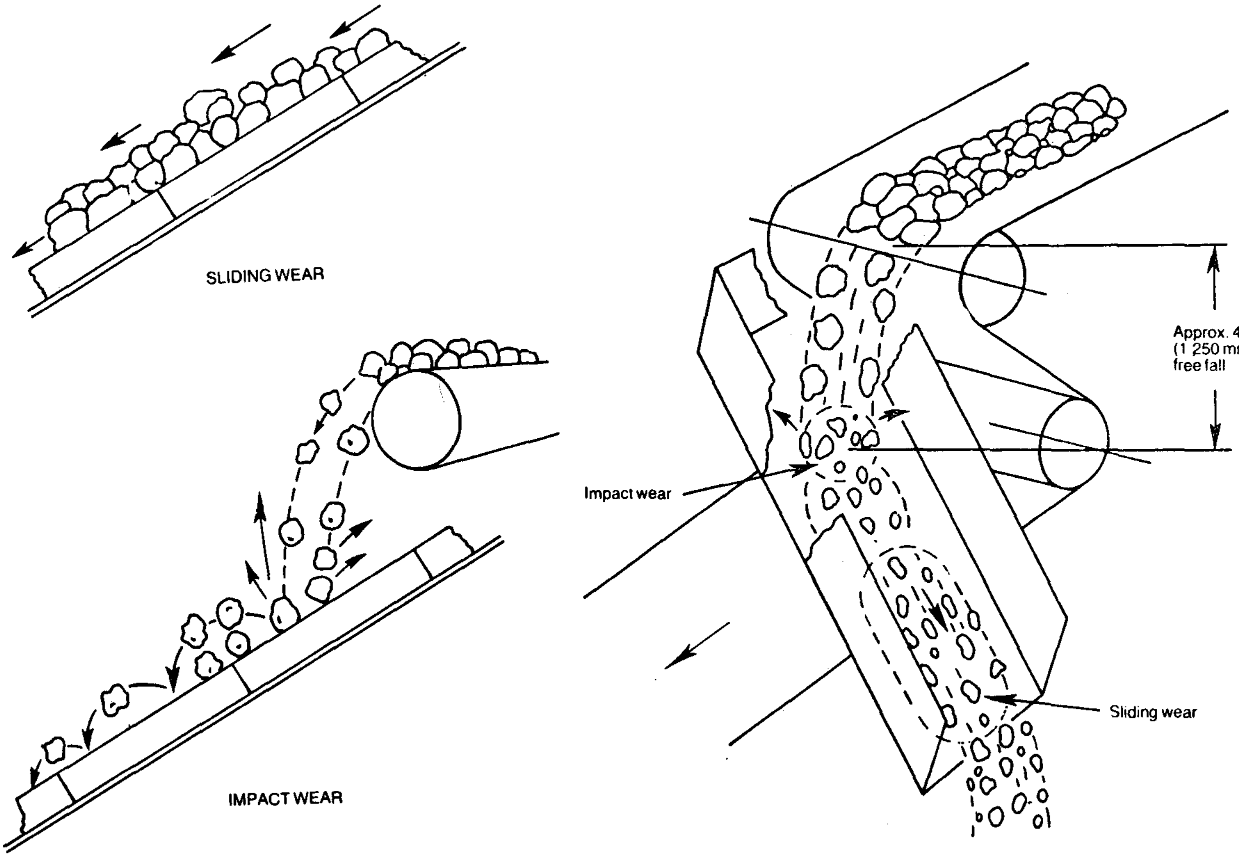

Fig. 3—Types of wear[6]

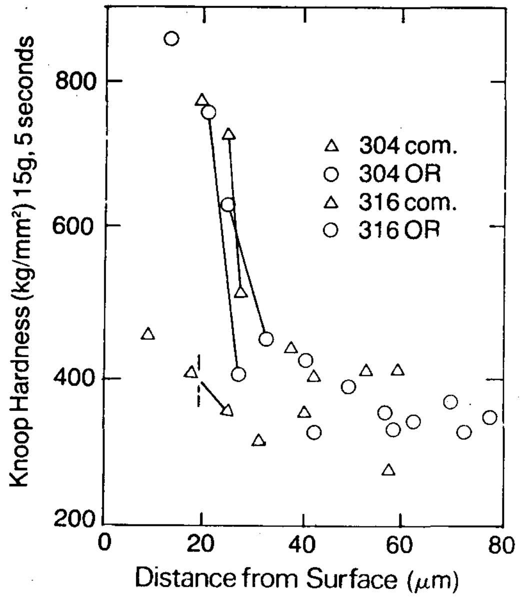

Fig. 4—A hardness traverse across an austenitic stainless-steel surface exposed to gouging wear[3]

indeed, its wear rate under dry sliding conditions is similar to that of mild steel and of type 304 austenitic stainless steel according to laboratory tests. Under these conditions, mild steel is certainly the most economical material for chute applications. Nevertheless, 3CR12 chutes in chromite mines and in an eastern Transvaal asbestos mine, have a life many times that of mild-steel chutes. It can only be assumed that extraneous factors are present.

The situation in the case of high-stress or impact abrasion (Fig. 3) is quite different. In instances where abrasive material falls under gravity onto metal surfaces, or in crushing or grinding equipment, the rate of metal loss is very high. Traditionally, 13 per cent manganese steel has been used in these applications. This alloy is fully austenitic in the heat-treated condition, but transforms readily to martensite under impact loads, to increase the hardness to about 500 VPN. A major advantage of Hadfields manganese steels, as well as of the chromium and molybdenum variations, is that the material is exceptionally tough[8]. A distinction must be made that, while 13 per cent manganese steels show very good service in high impact areas, more brittle materials show better resistance once the kinetic energy of the abrasive material has been reduced somewhat. Under erosion conditions, manganese steel has little merit, and should not be specified at all (Figs. 5 and 6).

Austenitic stainless steels are also able to undergo extensive hardening under impact loads. However, testing under erosion conditions using dry silica and alumina abrasive failed to show any resistance to impact erosion[9]. An interesting result of that investigation was that aluminium (50 VPN) behaved better than mild steel, Hadfields manganese steel, or hard martensitic steels and cast irons. It was claimed that toughness was of overriding significance.

Fully ferritic 3CR12 does not work-harden to any significant extent. Under impact-loading conditions, the impact toughness of 3CR12 will obviously determine its behaviour. In the absence of any macro-defect that would lead to cracks above a critical CTOD, and hence brittle fracture, micro-defects are likely to form. Carbides are traditionally microstructural features inherently prone to cracking in ferritic materials. In 3CR12, the blocky, cubic Ti(C,N) precipitates are indeed brittle and hard (1200 VPN), and often initiate both stable and unstable cleavage cracks in ferrite grains. Furthermore, the occurrence of any angular precipitates at the grain boundaries will generally assist in the formation of brittle cracks. These carbides are sometimes found in 3CR12

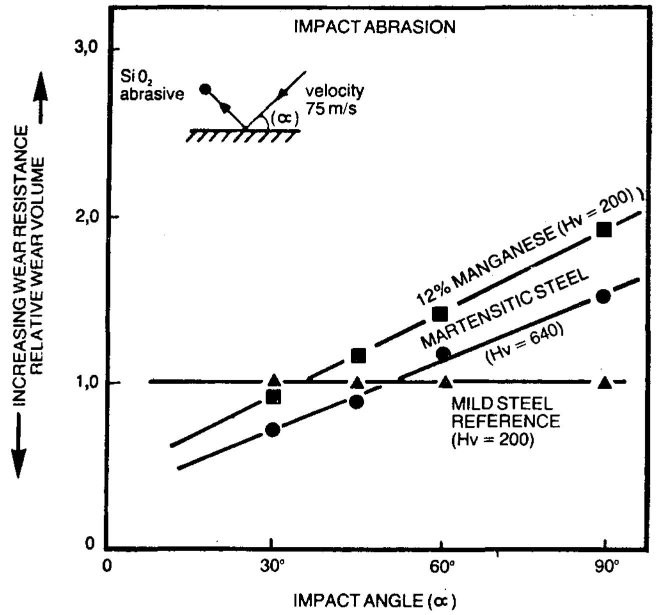

Fig. 5—Effect of impact angle on the wear of mild steel, martensitic steel, and manganese steel[3]

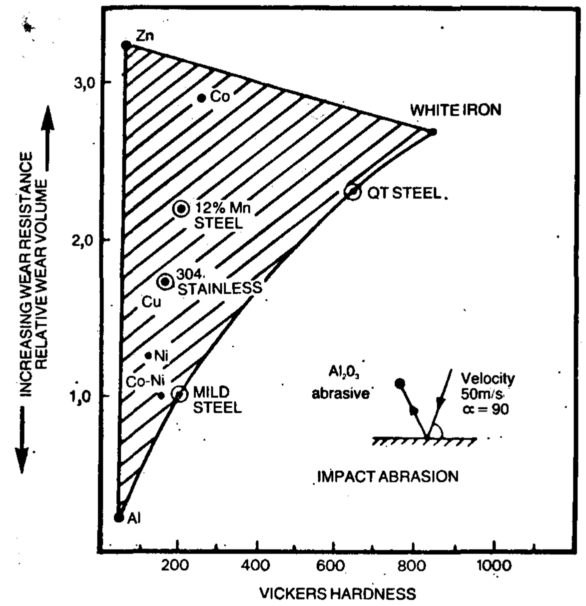

Fig. 6—The role of hardness in wear under impact-loading conditions[8]

structures that have been incorrectly heat-treated, or in the heat-affected zone of weldments[10]. In duplex ferritic–martensitic structures, such as in heat-treated 3CR12, it has been found that tough, low-carbon martensite is able to arrest growing cracks. This suggests that heat-treated 3CR12-type alloys provide some impact resistance, and indeed the Chamber of Mines is pursuing research along these lines.

In a test on a particular prototype, namely a skip liner in a West Rand gold mine, 3CR12 proved a very suitable material in the side and bottom areas, but in the back wall of the skip, where a significant degree of impact abrasion occurred, 3CR12 was worse than mild steel. In skips of other designs, however, 3CR12 has shown improved life over rubber, mild steel, and abrasion-resistant alloy steels. Coal chutes at the SASOL II plant were lined in 3CR12 after the inferior slideability of rubber lining had created problems. However, in splitters and some chutes, where a significant amount of impact occurred, 3CR12 showed excessive wear rates. Here, a change in the design of the splitters, involving a reduction in the impingement angle of the coal, was necessary to ensure that the impact erosion of the 3CR12 liners was limited.

The Role of Corrosion and Synergy

It is quite obvious that abrasion under dry conditions is an exceptionally complex occurrence, and the introduction of a corrodent to an abrasive environment compounds the complexity. Indeed, the number of variables involved in descriptions of abrasion–corrosion wear would tend to make even complicated laboratory experiments inappropriate. The Materials Engineering Laboratory of the Chamber of Mines is to be complimented on the extensive laboratory and field testing being undertaken on an extremely wide range of alloys for materials-handling applications in mechanized gold mining. The correlations obtained so far between laboratory and field studies are sufficiently encouraging to give a good indication of the usefulness of many alloys.

The simplest mechanism by which corrosion increases wear rates is the oxidation of a surface of a non-adherent corrosion product (e.g., an oxide, sulphate, or nitrate), which is rapidly worn away in the next cycle of abrasion, exposing fresh metal to become oxidized once again. This process is illustrated in Fig. 7. In these circumstances, the severity of corrosion can be so great that abrasion is of secondary importance. Some preliminary tests by the Chamber of Mines have shown that stainless steels as a group behave better than alloy steels under certain corrosion–abrasion conditions (Fig. 8). In other situations, notably in high-stress impact abrasion–corrosion applications, the mechanism of wear by abrasion or impact damage is dominant, and stainless steels are of limited use.

General corrosion of a surface tends to create roughening of the surface, which increases friction, thereby reducing the velocity of rock sliding over the metal surface, perhaps even causing some galling, and resulting in a modest increase in metal loss. A corrodent that causes intergranular corrosion of the metal could be expected to severely increase the rate of metal loss, since whole grains of the metal are pulled out during abrasion. In such instances, the grain size of the metal can play an important role in corrosion–abrasion wear. A corrodent that causes stress–corrosion cracking of the metal could drastically affect wear rates. Under high-stress impact abrasion, the presence of cracks in a metal would tend to aggravate brittle fracture of small pieces of the metal, or of the entire section, and rapid failure would ensue. The rates of sliding-abrasion wear would not change as drastically, however, although cracks would tend to tear open and reach a critical length in a shorter time.

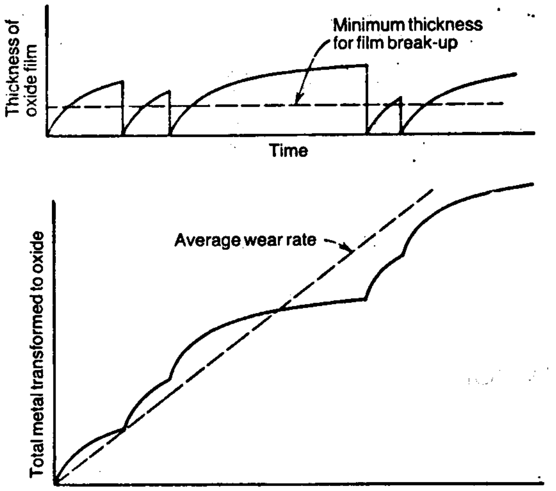

Fig. 7—The formation of an oxide film, and its effect on wear rate

The presence of copious quantities of an aqueous corrodent would restrict temperature rises due to sliding-friction abrasion, and thus keep the metal surface cooler, and, in the case of bcc or hcp metals, more brittle. This could lead to accelerated wear rates.

Certain types of corrosion can be precluded from this discussion. Pitting or crevice corrosion generally occurs only under stagnant conditions, and is unlikely to occur on wearing surfaces. Frettage is obviously a possible complication, but can be ignored in most cases. Erosion under wet conditions is obviously a prime example of the synergistic action of corrosion and abrasion, and pumps, valves, and piping that handle corrosive slurries have to be made of materials capable of combating both forms of metal wear acting cojointly. In such instances, hard-facings using ceramics or carbides on tough, ductile substrates can usually offer a solution, although failure of the coating by spalling can lead to catastrophic results. Rubber and other soft, tough materials can be employed in these cases.

Conclusion

Experience with 3CR12 material under abrasion–corrosion conditions has been largely restricted to actual plant applications. With a few notable exceptions, the alloy has performed remarkably well. The corrosion resistance of 3CR12 in gold-mine waters, waters in coal-washing plants, and brackish waters in platinum, phosphate, and asbestos mining operations is such that the corrosion portion of abrasion–corrosion wear has been

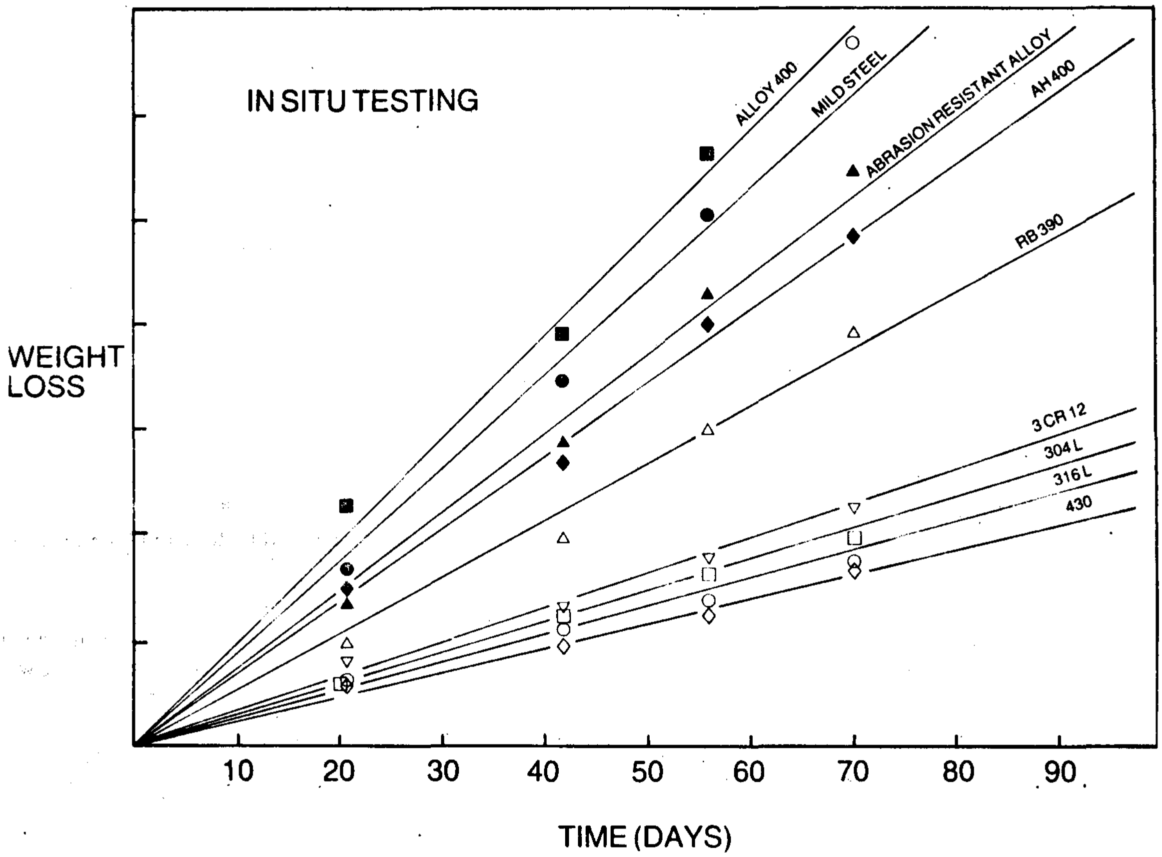

Fig. 8—Wear *in situ* of various materials under wet sliding-abrasion conditions[7]

largely overcome. This in turn restricts abrasion to some extent, and leads to longer life. The potential for corrosion-resisting steels in both wet and dry abrasion applications in the mining industry is very large, and, after more than three years of testing in a large number of diversified applications, the alloy known as 3CR12 has shown significant merit as a cost-saving material.

Of course, materials selection often boils down to economics, and to justify its added cost, 3CR12 must provide a life many times that of mild steel. On the other hand, certain applications in materials handling are so specialized that special ceramic or other hard materials must be utilized, but there is a large 'grey' area where abrasion-resisting steels are at a considerable disadvantage because of the corrosion that occurs at the same time as abrasion. More details of experiences with 3CR12 in materials-handling applications in the mining industry are available on request.

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