The performance, wear characteristics, and failures of austenitic manganese-steel castings used in crushing and rod milling*

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SYNOPSIS

Austenitic manganese-steel castings are very widely used in crushing and grinding in the gold-mining industry in South Africa. The service life of a casting in a short-head crusher is difficult to predict because there are no clear-cut criteria by which such a judgement can be made. The addition of molybdenum and zirconium to the castings for crushers failed to result in improved performance. The results of extensive tests with through-hardened steel castings were very disappointing, mainly because of a design factor in the bowl liner. The design of the bowl liner is an important determinant of the life and performance of these castings.

The extent to which the material in a crusher is reduced in size has profound effects on the consumption of metal and power, and on the effective life of a casting.

Tests on manganese-steel castings in an 8 ft by 12 ft rod mill provided data on the total consumption of metal, and on the variations in the pattern and rates of wear of liners over lengthy periods. Progressive changes in the wear profiles of the lifter bars and the other liner components showed unexpected features. There are clear indications that, whereas a set of lifter bars will at first lift the charge strongly with relatively little slippage, there is a later period characterized by more slippage and greater wear on all the liner components.

SAMEVATTING

Oustenietmangaanstaalgietstukke word in Suid-Afrika baie algemeen vir vergruising en maling in die goudmynbedryf gebruik. Dit is moeilik om die gebruiksduur van 'n gietstuk in 'n laekeëllasvergruiser te voorspel aangesien daar geen duidelike maatstawwe vir so 'n beoordeling bestaan nie. Die byvoeging van molibdeen en sirkonium by die gietstukke vir vergruisers het nie die werkverrigting daarvan verbeter nie. Die resultate van uitgebreide toetse met deurverharde staalgietstukke was uiters teleurstellend, veral vanweë 'n ontwerpfaktor in die bakvoering. Die ontwerp van die bakvoering is 'n belangrike determinant van die gebruiksduur en werkverrigting van hierdie gietstukke.

Die mate waarin die materiaal in 'n vergruiser verklein word, het 'n baie groot uitwerking op die metaal- en kragverbruik en op die effektiewe gebruiksduur van 'n gietstuk.

Toetse op mangaanstaalgietstukke in 'n staafmeul van 8 vt by 12 vt het data verskaf oor die totale verbruik van metaal en oor die variasies in die slytasiepatroon en -tempo van voerings oor lang tydperke. Progressiewe veranderinge in die slytasieprofiele van die ligstawe en die ander voeringbestanddele het onverwagte aspekte aan die lig gebring. Daar is duidelike aanduidings dat terwyl 'n stel ligstawe die lading aanvanklik sterk sal lig met betreklik min glipping, daar 'n later periode is wat deur meer glipping en groter slytasie van al die voeringdele gekenmerk word.

Introduction

In the South African gold-mining industry, the two most widely used abrasion-resistant materials for crushers and rotary mills are white cast iron and manganese steel. White cast iron was extensively used for lining the relatively small-diameter (6,5 ft or 1,95 m) tube mills that were installed in large numbers and that operate on the autogeneous principle, using pebbles as the grinding medium. Many of these mills are still in use. The low intensity of impact permits the continued use of white-iron liners. The later introduction of ball and rod mills of much larger diameter and characterized by much more severe impact forces made the use of manganese-steel liners essential.

In recent years, mills of up to 4,88 m in diameter have been installed both for autogeneous (or run-of-mine) milling and for pebble milling. Manganese-steel liners of either the lifter-bar and spacer-block type, or of the grid type are used. In this respect, the practice in the gold-mining industry of South Africa differs greatly from that in the U.S.A. and Canada, where the use of manganese-steel liners appears to be diminishing rapidly. In those countries, manganese steel is being replaced by more abrasion-resistant through-hardened alloy steels, and by alloyed white irons.

In South Africa, with its vast resources of manganese ore and a very extensive ferromanganese industry, austenitic manganese steel is still competitively priced in relation to its possible alternatives. In addition, the labour situation in the gold-mining industry makes it possible to accept a more frequent re-lining of mills than would be economic in North America. Nevertheless, the steady increase in the number of large-diameter high-capacity rotary mills may force significant changes in this practice.

For the wearing surfaces of crushers, particularly coarse crushers, manganese steel probably still remains the best material, mainly because of its extreme toughness.

This paper deals with the performance, wear characteristics, and failures of manganese-steel castings when they are used in two very different applications: dry secondary crushing, and wet rotary milling.

Short-head Crushers

The most widely used crusher in the gold-mining

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TABLE I

THE PERFORMANCE OF SETS OF MANTLES AND BOWL LINERS FOR NO. 3 4¼-FT SHORT-HEAD CRUSHER, WESTERN DEEP LEVELS GOLD MINING COMPANY LIMITED

Identity mark on castings		Mass loss in castings				Service life	Ore crushed		Consumption of liners	Power consumption			Remarks
Mantle	Bowl	Mantle		Bowl			Total	Feed rate	kg/t crushed	Total	kW .h/t crushed	Steel worn off	
		kg	%	kg	%	h	t	t/h		kW .h		g/kW .h	
Test 7	Set 8	396	55,0	397	52,4	315	54 590	173,3	0,01453	25 617	0,4693	30,9	
Stock	Set	400	53,3	422	57,2	306	49 173	160,7	0,01672	28 164	0,5725	29,2	Castings removed after visual examination at assessed end of useful life
Test 1	Set 6	457	63,9	462	60,5	404	60 208	149,0	0,01526	33 420	0,5551	27,5	
Stock	Set	460	61,5	472	62,9	401	58 609	146,2	0,01590	34 032	0,5807	27,4	
Test 15	Set 14					44	7 454	169,4		6 392	0,8575		Casting removed after premature failure of lug
Stock	Set	443	61,1	430	58,1	418	66 792	159,8	0,0131	33 236	0,4976	26,3	Castings removed after visual examination at assessed end of useful life
Test 13	Set 10	429	59,0	320	47,1	403	64 546	160,2	0,0116	30 732	0,4761	24,4	
Stock	Set	402	55,8	453	51,5	362	55 753	154,0	0,0153	31 544	0,5658	27,1	
Stock	Set	370	50,0	375	51,0	347	52 598	151,6	0,0142	29 268	0,5564	25,5	
Stock	Set	366	49,7	360	48,6	290	44 660	154,0	0,0163	25 600	0,5732	28,4	
Selected averages		414	56,6	410	54,4	361	56 325	156,5	0,01473	30 179	0,5385	27,4	

TABLE II

THE PERFORMANCE OF SETS OF MANTLES AND BOWL LINERS FOR NO. 4 4¼-FT SHORT-HEAD CRUSHER, WESTERN HOLDINGS GOLD MINING COMPANY LIMITED

Identity mark on casting		Mass loss in castings				Service life	Ore crushed		Consumption of liners	Power consumption			Remarks
Mantle	Bowl	Mantle		Bowl			Total	Feed rate	kg/t crushed	Total	kW .h/t crushed	Steel worn off	
		kg	%	kg	%	h	t	t/h		kW .h		g/kW .h	
Test 3	Set 4	460	64,2	527	73,7	308	39 426	128,0	0,025	42 416	1,08	23,3	One bowl-liner lug stripped, circumferential crack
Stock	Set	485	68,0	555	73,7	324	45 763	141,1	0,0227	44 310	0,97	23,5	All bowl-liner lugs stripped
Test 5	Set 2	476	62,9	554	76,4	329	51 228	155,7	0,0261	45 423	0,89	22,7	
Stock	Set	435	61,4	514	69,1	291	36 075	124,0	0,0263	39 198	1,09	24,2	Bowl liner worn through at centre line
Test 8	Set 16	411	58,0	487	67,2	298	36 419	122,2	0,0247	40 362	1,11	22,2	Bowl-liner lugs cracked at base
Stock	Set	429	58,8	505	68,2	316	32 457	102,7	0,0288	42 979	1,32	21,7	
Test 11	Set 12	456	62,9	519	69,1	321	40 449	126,0	0,0241	46 553	1,15	20,9	
Stock	Set	460	60,5	524	71,3	327	42 772	130,8	0,023	49 197	1,15	20,0	
Stock	Set	457	61,3	535	75,1	337	42 211	125,2	0,0235	44 767	1,06	22,2	
Selected averages		452	62,0	524	71,5	317	40 756	128,4	0,0242	43 912	1,09	22,3	

industry is the $4\frac{1}{4}$ ft* short-head, which consumes a considerable proportion of the austenitic manganese steel used by the whole industry. Two replaceable castings, the mantle and the bowl liner, are used in this type of crusher. Each weighs about 1 t, costs about R1000, and has a service life of only three to four weeks. In spite of the large tonnages of austenitic manganese steel that were used even then, it was not until 1953 that a very simple specification for this type of steel was formulated. A much more detailed specification was drawn up later, SABS 407/1975. Steel to this specification would incur higher production costs, some of which could legitimately be passed on to the purchaser. In the case of a very large mining house, this additional cost could amount to between half a million and one million rands a year.

*Where imperial measures are used in this paper, they refer to items of equipment that are supplied to that specified measure.

The first phase of the testwork described here was a comparison of the performance of castings that had

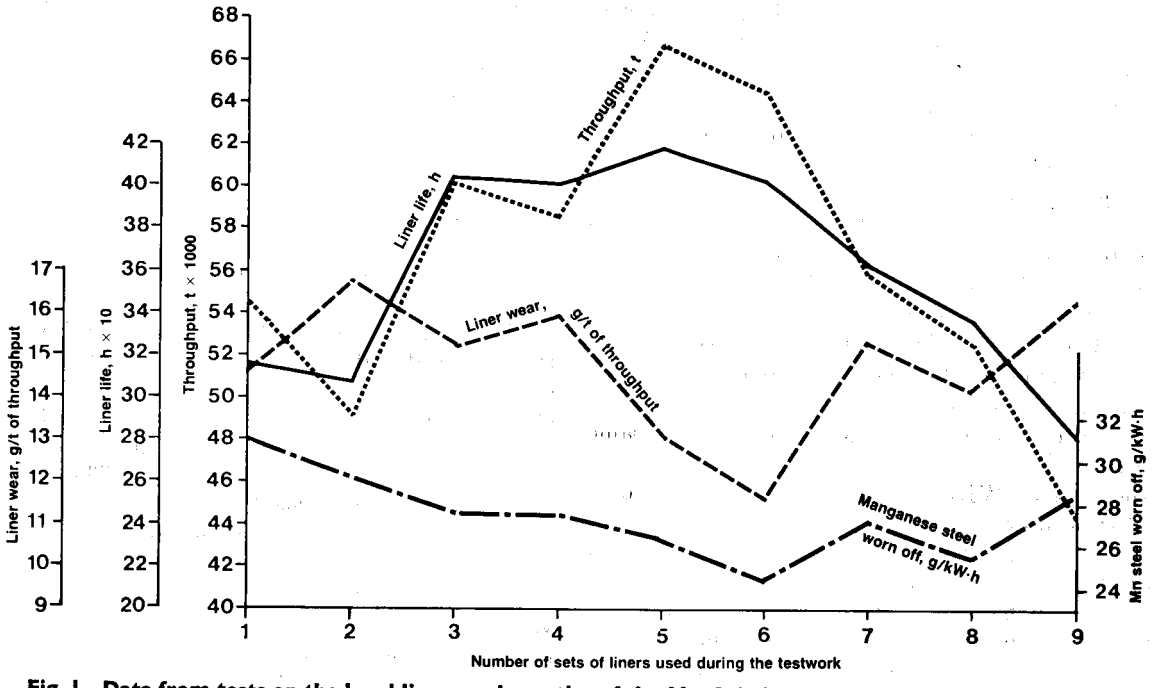

Fig. 1—Data from tests on the bowl liners and mantles of the No. 3 $4\frac{1}{4}$ ft short-head crusher at Western Deep Levels Gold Mine

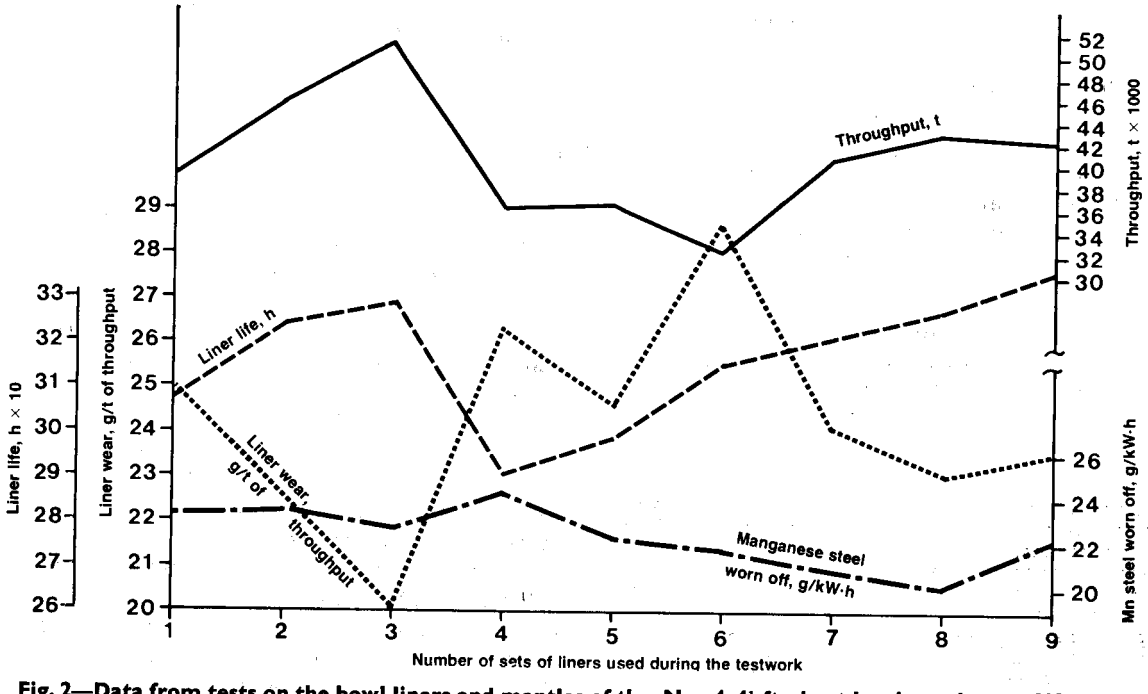

Fig. 2—Data from tests on the bowl liners and mantles of the No. 4 $4\frac{1}{4}$ ft short-head crusher at Western Holdings Gold Mine

been produced in strict compliance with SABS 407/1975 (their production was closely monitored) and that of line-of-production castings. Tests were carried out on crushers in the reduction plants of two gold mines, Western Deep Levels (WDL) and Western Holdings (WH). The procedure involved the fitting of sets of test castings (a bowl liner and a mantle) with alternating sets of stock castings.

As shown in Tables I and II, no significant differences in performance were found between the test castings and the stock castings. Very disturbing are the fairly wide fluctuations in the amount of rock crushed and in the lives of the sets of castings, particularly at WDL (Figs. 1 and 2).

Undoubtedly, a major factor in these large variations is the absence of an unambiguous criterion of the end of the service life of a casting. The decision to change the castings is inevitably highly subjective and dependent on imponderables such as the day of the week. In this regard, the test procedure in which test sets and stock sets were alternated showed that, despite fluctuations in performance, the results obtained by the use of the two sets of castings did not differ significantly.

At an early stage in the study it became obvious that there was a marked difference in the average size-reduction ratio effected at the two mines. For the same size of product, the size-reduction ratio was 9,34 at WH, and 3,24 at WDL. The size-reduction ratio of 5 to 5,5 that is recommended by the manufacturers highlights the great difference between the crushing operations at the two mines. Table III gives averaged performance figures that emphasize the differences resulting from the size-reduction ratios at the two mines. It is clear that, in spite of the much higher percentage utilization of metal in the castings at WH, the large size-reduction ratio results in a lower service life for the castings, higher consumption of metal, and double the consumption of power per ton of rock crushed.

In collaboration with a steel foundry, the National Institute for Metallurgy decided to investigate means of extending the service life of castings. Following a patent claim by Hadfields Ltd that an improvement of up to 50 per cent in abrasion resistance could be secured by the addition to austenitic manganese steel of small amounts of zirconium, eight sets of castings were produced with a zirconium content of 0,1 to 0,125 per cent. As shown in Tables IV and V, no significant improvements in performance were obtained.

TABLE III

AVERAGED DATA FOR THE PERFORMANCE OF NINE SETS OF CASTINGS IN 4¼-FT SHORT-HEAD CRUSHERS

	Western Deep Levels	Western Holdings
Size reduction effected	3,24 to 1	9,34 to 1
Tons fed to crusher	56325	40756
Service life of castings, h	361	317
Percentage utilization of metal in castings: bowl liner	54,4	71,5
mantle	56,6	62,0
Consumption of metal in castings:		
g per ton of ore fed	14,73	24,2
g per kW .h of power supplied	27,4	22,3
Power consumed, kW.h per ton crushed	0,5385	1,09

The addition of molybdenum has been claimed to bring about significant improvements in the performance of austenitic manganese-steel castings. A report from Climax Molybdenum Co.[1] proposes a double-cycle heat treatment, involving heating of the casting to 1050°C followed by water quenching. The casting is then subjected to a tempering treatment (described as 'Pearlitizing') at 600°C and is then heated to between 950 and 980°C and water-quenched.

It was agreed that four sets of castings should be produced with a molybdenum content of 1,2 per cent. These castings were subjected to double-cycle heat treatment, which is intended to produce finely dispersed complex carbides throughout the austenitic matrix. As shown in Fig. 3, the structure obtained appeared to be quite satisfactory, and the hardness values determined on the castings were within the range 241 to 269 HB. It is clear from Tables IV and V that no improvement in performance was obtained from the castings containing molybdenum.

Finally, it was decided to produce test castings of through-hardened steel to the following composition: carbon 0,26 to 0,34 per cent, manganese 1,5 per cent, chromium 0,6 per cent, and molybdenum 0,5 per cent. These were water-quenched and tempered to give hardness values in the range 400 to 450 HB. The performance of these castings was decidedly inferior to that obtained from the other castings that were tested, as is shown in Tables IV and V. No castings broke up while in service at WDL under the less-severe crushing conditions prevailing at that mine, but Fig. 4 shows a bowl liner that cracked. The crack was initiated at the base of the lug by localized stresses and propagated in three directions. Under the more severe conditions at WH, the bowl liner in both sets of castings fractured during service after lives of 162 hours and 216 hours, as against an average of 317 hours for the other castings that were tested. Curiously enough, although the hardness of these castings was very similar to that developed during service by the austenitic manganese-steel components, the consumption of steel was considerably higher — 35 g/t compared with an average of 25 g/t for the other castings. From Fig. 5 it is clear that the damage occurred mainly in the annular recess of the bowl liner, almost certainly from cracks initiated at the lugs.

This leads to a consideration of the types of fracture that were encountered during the testwork. The brittle fracturing of lugs was observed three times at WDL. Views of a typical fracture are shown in Figs. 6 and 7. In each case, the plane of fracture through the lug was between 46 and 47 degrees from the vertical, through the zone on the underside of the lug on which the U-bolt had exerted pressure. There was no distortion of the metal as a result of the fracture, and, as is clear from Fig. 7, the two halves could be fitted together perfectly. In these crushers, packing is not inserted between the mating faces of the bowl and the bowl liner. For this reason, the fit depends on the accuracy of grinding of the faces of the bowl liner to the angle specified by the manufacturers. No tolerance is specified on the drawing

TABLE IV

THE PERFORMANCE OF SETS OF MANTLES AND BOWL LINERS FOR NO. 3 4¼-FT SHORT-HEAD CRUSHER, WESTERN DEEP LEVELS GOLD MINING COMPANY LIMITED

Identity mark on castings		Mass loss in castings				Service life	Ore crushed		Consumption of liners	Power consumption			Remarks
Mantle	Bowl	Mantle		Bowl			Total	Feed rate	kg/t crushed	Total	kW.h/t crushed	Steel worn off	
		kg	%	kg	%	h	t	t/h		kW.h		g/kW.h	
A. Castings of manganese steel containing zirconium compared with stock sets													
Stock	Set	461	62,2	459	62,2	370,4	55 792	150,6	0,0165	30 420	0,5452	30,2	Castings removed at assessed end of useful life
Test 3Z	Set Z2	532	70,9	523	68,2	414,4	63 007	152,0	0,0167	36 632	0,5814	28,8	Zig-zag cracks in mantle and crack in bowl when bowl removed
Stock	Set	514	68,4	534	68,6	404,6	60 789	150,2	0,0172	34 108	0,5611	30,7	Castings removed at assessed end of useful life
Test Z1	Set 8Z	404	54,6	407	54,8	331,4	50 887	153,6	0,0159	27 468	0,5398	29,5	Cracks in mantle
B. Castings of through-hardened steel compared with stock sets													
Stock	Set	439	58,6	438	57,8	369,1	59 499	161,2	0,0147	28 440	0,4780	30,8	Castings removed at assessed end of useful life
Test TH13	Set TH14	426	52,9	526	68,3	296,9	46 742	157,4	0,0204	27 352	0,5826	34,8	Mantle and bowl developed large cracks
Stock	Set	428	57,8	491	65,4	373,4	58 250	156,0	0,0158	33 568	0,5763	27,4	Castings removed at assessed end of useful life
Test TH9	Set TH16	452	54,7	564	72,3	311,1	48 700	156,5	0,0209	27 380	0,5622	37,1	
C. Castings of manganese steel containing molybdenum compared with stock sets													
Test M01	Set M08	454	57,5	464	63,6	363,1	56 685	156,1	0,0162	30 972	0,5464	29,6	Castings removed at assessed end of useful life
Test M07	Set M04	400	54,1	394	54,0	303,6	47 656	157,0	0,0167	26 748	0,5613	29,7	
Stock	Set	370	49,9	477	63,7	330	51 076	154,8	0,0166	29 320	0,5740	28,9	

TABLE V

THE PERFORMANCE OF SETS OF MANTLES AND BOWL LINERS FOR NO. 4 4¼-FT SHORT-HEAD CRUSHER, WESTERN HOLDINGS GOLD MINING COMPANY LIMITED

Identity mark on castings		Mass loss in castings				Service life	Ore crushed		Consumption of liners	Power consumption			Remarks
Mantle	Bowl	Mantle		Bowl			Total	Feed rate	kg/t crushed	Total	kW.h/t crushed	Steel worn off	
		kg	%	kg	%	h	t	t/h		kW.h		g/kW.h	
A. Castings of manganese steel containing zirconium compared with stock sets													
Test Z5	Set 4Z	441	59,9	496	67,4	329,9	42 963	130,2	0,0218	46 448	1,0811	20,2	Castings removed at assessed end of useful life
Stock	Set	505	70,8	609	81,0	310,4	39 141	126,1	0,0285	48 901	1,2494	22,8	Bowl liner broken into 3 pieces
Test Z7	Set Z6	415	59,0	462	62,8	308,3	36 170	117,3	0,0243	44 759	1,2375	19,6	Castings removed at assessed end of useful life
Stock	Set	424	58,1	585	79,2	320,7	37 618	117,3	0,0268	45 578	1,2116	22,1	Castings removed at assessed end of useful life
B. Castings of through-hardened steel compared with stock sets													
Test TH7	Set TH8	364	45,8	458	61,2	162,3	18 316	112,9	0,0449	22 262	1,2154	36,9	Bowl badly broken up. Indications of fast wear rate
Stock	Set	464	62,3	565	74,9	355,6	42 032	118,2	0,0245	50 850	1,2098	20,2	Bowl liner broken
Test TH11	Set TH6	378	47,7	553	71,8	215,6	26 670	123,7	0,0349	29 616	1,1105	31,4	Bowl liner broken
C. Castings of manganese steel containing molybdenum compared with stock sets													
Stock	Set	360	46,5	450	70,0	342,4	45 488	132,9	0,0178	47 830	1,0515	16,9	1 lug broken off bowl
Test M03	Set M06	499	69,8	518	73,8	307,7	39 719	129,1	0,0256	46 164	1,1623	22,0	Bowl liner broken
Stock	Set	499	65,4	498	70,6	330*	45 075*	136,6	0,0221*	52 196	1,1580*	19,1	*Hour meter out of order, tonnages etc. based on estimated life
Test M05	Set M02	470	60,6	534	72,8	332,0	45 440	136,9	0,0221	48 739	1,0726	20,6	Cracks round base of 4 lugs

*Estimated

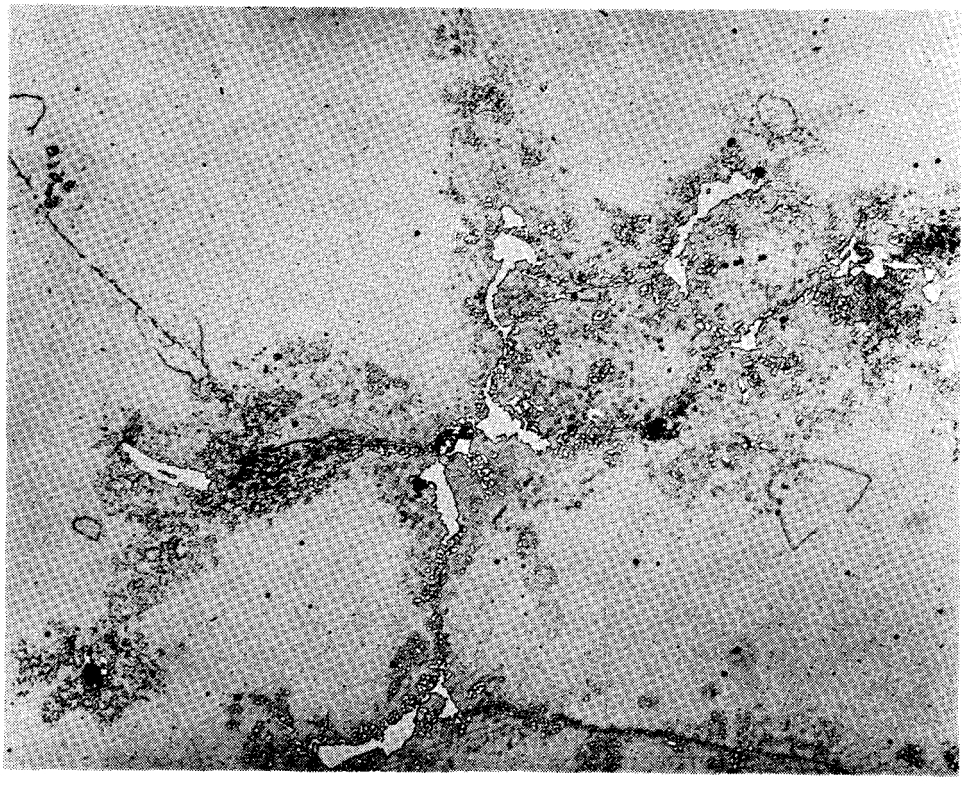

Fig. 3—Photomicrograph of section of austenitic manganese steel containing 1,2 per cent molybdenum after double-cycle heat treatment (X350)

Fig. 4—A bowl liner of through-hardened steel from the Western Deep Levels Mine. The liner cracked but did not break up. When removed from the crusher, it had had a service life of 296,9 hours, during which 46 742 tons of ore had been crushed

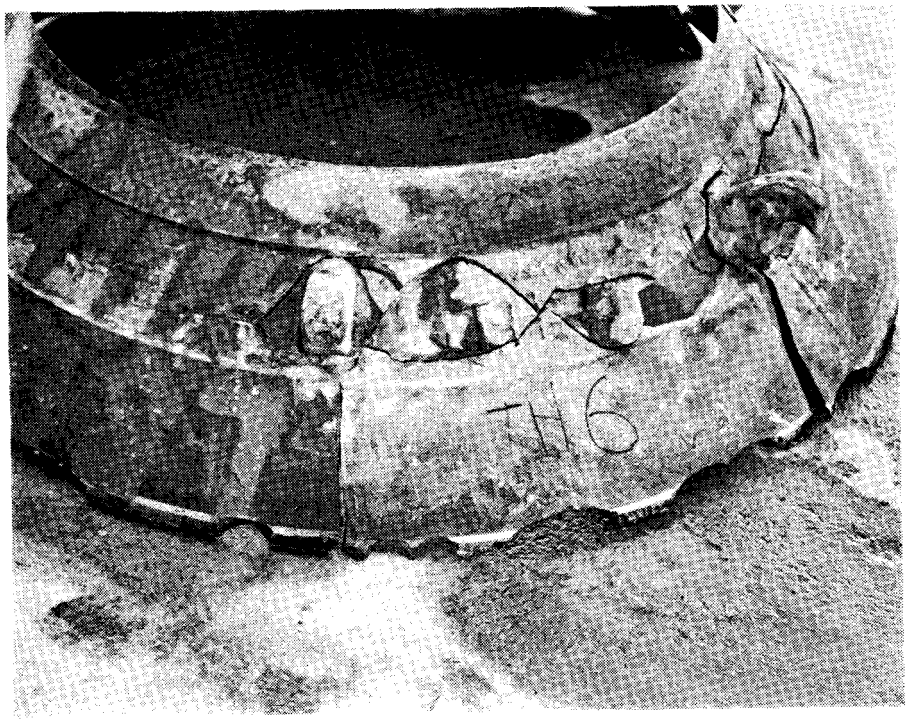

Fig. 5—A bowl liner of through-hardened steel from the Western Holdings Mine. The broken pieces were refitted after the liner had been removed from the crusher to show the fracture pattern. The liner had a life of 215,6 hours, during which 26 670 tons of ore had been crushed. The utilization of metal was 71,8 per cent

for the angle of grinding. The breaking of the lug by what appears to be shear forces may be due to uneven wear in the bowl, or to inaccurate grinding of the mating faces on the bowl liner.

The other failures of bowl liners encountered were all associated with the annular recess. As shown in Figs. 8 and 9, this is a design feature of the bowl liner that allows for the provision of six supporting lugs and for the procedure for grinding the two surfaces of the bowl liner to fit against the bowl. As shown in Fig. 9, this involves the provision of an annular recess in the bowl, 90 mm wide and 6 mm deep, that is mechanically unsupported. When the section of the metal at the annular recess is worn to below a certain thickness, a ductile material such as manganese steel will initially deform plastically and belly out into the recess. With a further reduction in the thickness of the metal, cracks begin to form at the sides of the lugs and circumferentially at the top and/or bottom of the recess. Under the severe crushing conditions at WH, it is comparatively rare to find a worn bowl liner in which one or more lugs do not show cracks around the base, or in which the lugs have not torn out of place. Typical failures are shown in Figs. 10 and 11. This type of failure is naturally associated with a high percentage utilization of metal in the bowl liner.

Obviously, this design feature limits the percentage utilization of metal that is possible during service. It also constitutes a major source of cracks and precludes the adoption of through-hardened steel castings.

Fig. 6—A lug of a bowl liner that was tested at the Western Deep Levels Mine. Brittle fracture occurred, and the line of the crack is clearly visible. The bowl liner had a life of 44 hours, during which 7454 tons of ore had been crushed

Failure of the mantle is a much less frequent occurrence, although, as with the bowl liner, the contact is between ground metal and ground metal. On occasions, relatively small zig-zag cracks were observed in the mantle, but the only serious damage to a mantle at WDL occurred when the manganese-steel castings containing zirconium were tested. As shown in Fig. 12, very severe zig-zag cracks developed during service in this particular mantle.

These zig-zag cracks appear to be shear-type cracks, and there is possibly a parallel between such cracks in the mantle and the shear-type fractures of lugs that were observed in the bowl liners on the same crusher. During crushing, there are powerful components of forces acting to push the mantle down over the conical head on the gyratory shaft. If there are worn areas on the head, or a lack of concentricity on the interior surface of the mantle (leaving some areas not solidly backed by the conical head), then shear stresses may be set up. This appears to be the most probable cause of the zig-zag cracks.

Rod Mill

In the gold-mining industry of South Africa, liners

Fig. 7—The fracture surface of the lug shown in Fig. 6

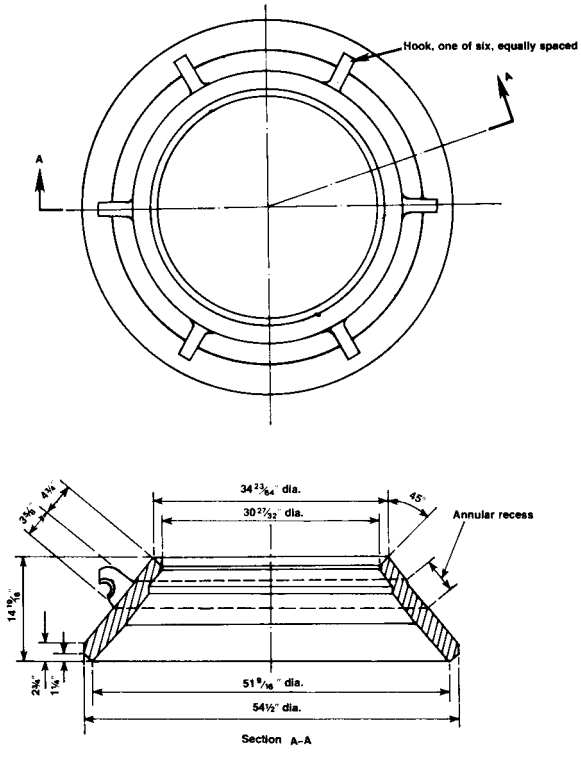

Fig. 8—Plan view showing position of lugs on bowl liner

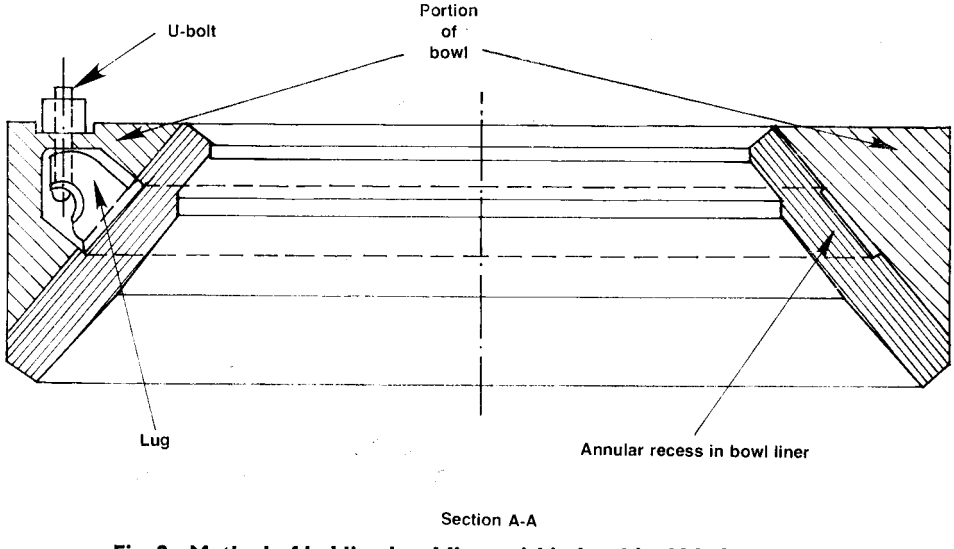

Fig. 9—Method of holding bowl liner within bowl by U-bolts and lugs

Fig. 10—A bowl liner from the stock set tested at the Western Holdings Mine. Two lugs have broken off and the others are cracked at the base. The liner had a life of 311,6 hours

Fig. 11—A bowl liner from set No. 1 tested at the Western Holdings Mine. A lug has broken off and a crack has appeared in the groove running round the circumference. The liner had a life of 308 hours, during which 39 426 tons of ore were crushed. The utilization of metal was 73,7 per cent

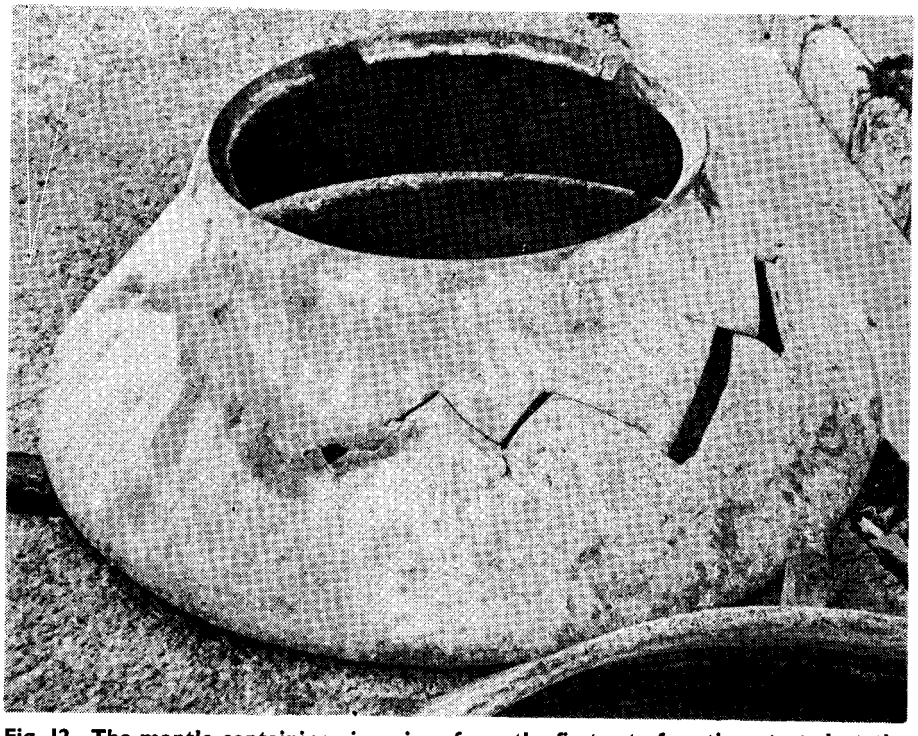

Fig. 12—The mantle containing zirconium from the first set of castings tested at the Western Deep Levels Mine. Very severe zig-zag cracks are apparent. The mantle had a life of 414 hours, during which 63 000 tons of ore were crushed. The utilization of metal was 70,9 per cent

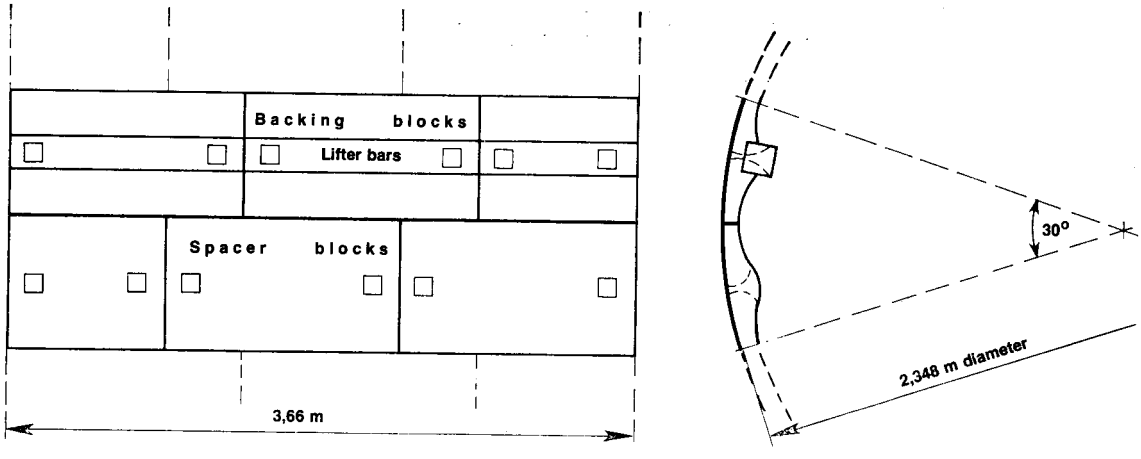

Fig. 13—Schematic diagram showing one line of backing blocks and lifter bars, and one line of spacer blocks

of austenitic manganese steel are widely used for rotary mills of all types. The liners are of two main types: the grid type, which is relatively light and is designed to hold steel balls or pebbles within the grids; and the type in which spacer blocks alternate with lifter bars that are superimposed on backing blocks.

TABLE VI

DETAILS OF THE FEED AND THE PRODUCT, ROD MILL A

Particle size, mm	> 25	> 19	> 12,5	> 6,3	< 6,3
Feed, %	0,9	36	33,9	11,0	18,2
Particle size, mesh	> 48	> 100		> 200	< 200
Discharge, %	67,4	10,8		6,8	15,0

Tests were carried out on an 8 ft by 12 ft rod mill at Free State Saaiplaas Gold Mine in the Orange Free State. The feed to the mill is the crushed and screened fraction smaller than 19 mm, and the mill works in open circuit. Details of the feed and discharge are given in Table VI. There are twenty-four rows of liners on the inner surface of the shell of the mill, of which twelve are backing blocks with superimposed lifter bars, and twelve are spacer blocks. The general arrangement is shown in Fig. 13. The lifter bars fit into slots 121 mm wide and 26 mm deep in the backing blocks, and project about 40 mm above the ridges of the backing

TABLE VII

THE PERFORMANCE OF ROD MILL A, FREE STATE SAAIPLAAS MINE
THE INDIVIDUAL COMPONENTS WERE REMOVED FOR MEASUREMENT AT WEEKLY INTERVALS

Test component	Lifter bars						Backing blocks			Spacer blocks		
Set no.	1			2			1*			1*		
Unit position no.†	1	2	3	1	2	3	1	2	3	1	2	3
A. Liners conforming to SABS specification 407/1975												
Mass — as installed, kg	74,1	74,5	38,8	75,1	76,6	39,3	138,4	145,2	75,0	98,3	176,5	179,8
Mass — after removal, kg	46,6	43,0	24,3	33,0	25,1	14,0	113,1	114,2	56,3	53,6	101,4	76,3
Loss of metal during service, kg	27,5	31,5	14,5	42,1	49,5	25,3	25,3	31,0	18,7	44,7	75,1	103,5
Utilization of metal, %	37,1	42,0	37,4	56,0	66,3	64,3	18,3	21,3	24,9	45,5	42,6	57,6
Ore fed to mill, t		138 477			182 921			321 398			321 398	
Service period, h		1698,32			2239,97			3938,29			3938,29	
Power consumption, kW .h		373 695			472 444			846 139			846 139	
Power consumption per ton of ore milled, kW .h		2,70			2,58			2,63			2,63	
Metal worn off per ton of ore milled, g		0,53			0,64			0,23			0,70	
B. Liners not claimed to conform to SABS specification 407/1975 (stock castings)												
Mass — as installed, kg	74,0	74,1	37,3	75,2	75,1	40,1	144,3	144,3	79,0	97,1	177,5	180,0
Mass — after removal, kg	36,4	30,1	18,3	33,1	27,4	16,7	117,8	108,8	60,7	50,0	78,5	71,2
Loss of metal during service, kg	37,6	44,0	19,0	42,1	47,7	23,4	26,5	35,5	18,3	47,1	99,0	108,8
Utilization of metal, %	50,8	59,4	50,9	56,0	63,5	58,4	18,4	24,6	23,2	48,5	55,8	60,4
Ore fed to mill, t		166 708			177 075			343 783			343 783	
Service period, h		2045,94			2192,79			4238,73			4238,73	
Power consumption, kW .h		408 566			449 578			858 144			858 144	
Power consumption per ton of ore milled, kW .h		2,45			2,54			2,50			2,50	
Metal worn off per ton of ore milled, g		0,60			0,64			0,23			0,74	

*N.B. One set each of backing and spacer blocks used for 2 sets of lifter bars.
†Position nos.: 1 inlet section, 2 centre, 3 outlet section.

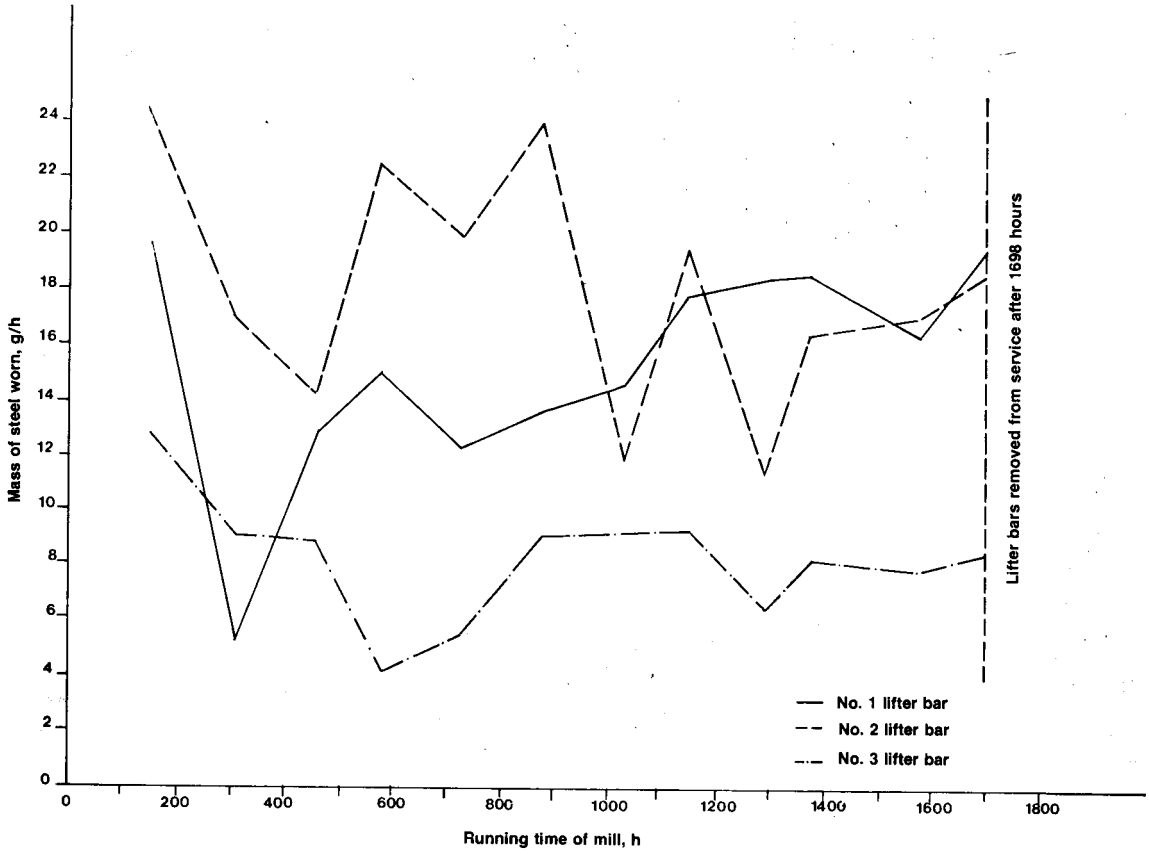

Fig. 14—Rate of wear of steel versus running time: first set of lifter bars (specification: SABS 407/1975)

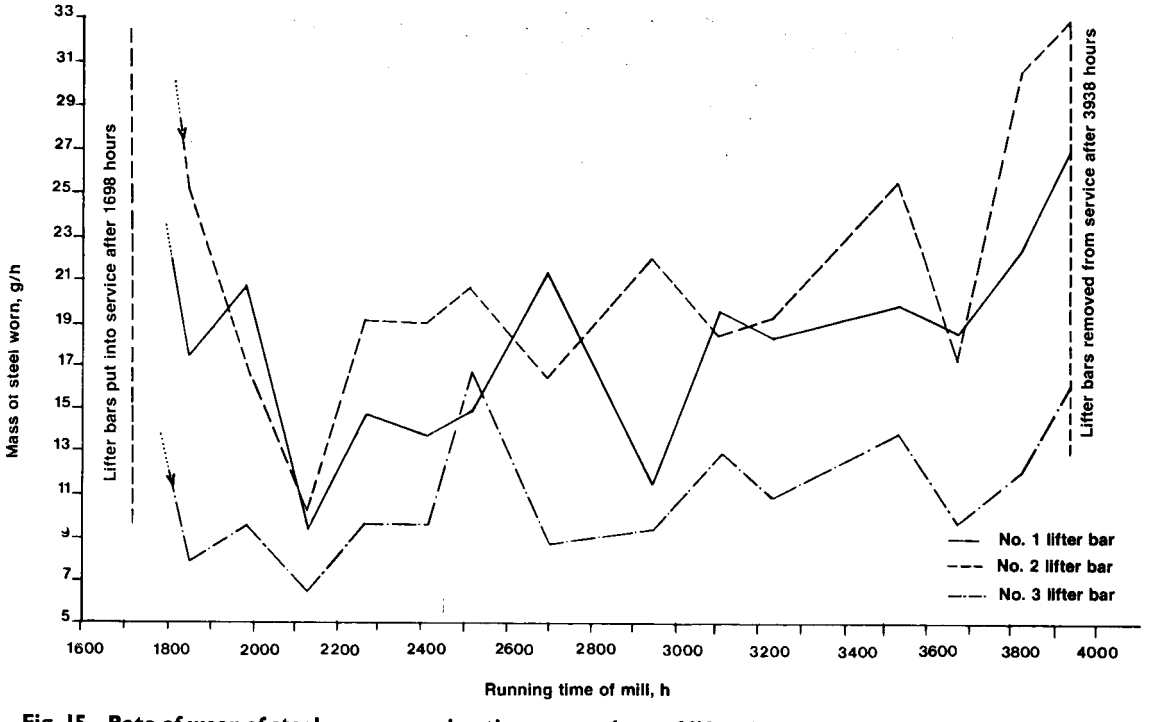

Fig. 15—Rate of wear of steel versus running time: second set of lifter bars (specification: SABS 407/1975)

blocks. The usual practice is to remove and replace all the lifter bars about half way through the life of the other components of the shell liners. There are twelve liner plates on both the feed end and the discharge end, and each liner plate is bolted to the end plates of the mill.

Two complete sets of liner components were purchased for the test. One set was supplied to the SABS specification 407/1975, and the other was obtained from a foundry that, at the time the set was purchased, was not authorized to use the SABS mark. The latter set is referred to in this paper as 'stock manganese-steel castings'. The total mass of all the components in the lining was determined before they were fitted to the mill, and again after their removal.

TABLE VIII

CHANGES IN RELATIVE WEAR RATES OF SHELL-LINER COMPONENTS OVER 4100 HOURS OF RUNNING TIME

Component	Time over which observations were made* h	Actual length of service h	Relative wear rate
First set of lifter bars			
Lifter bars	0 to 1170	1170	0,96
	1170 to 2040	870	1,38
Spacer blocks	0 to 1280	1280	0,53
	1280 to 2040	760	0,83
Backing blocks	0 to 1300	1300	0,23
	1300 to 2040	740	0,62
Second set of lifter bars (installed after 2040 hours)			
Lifter bars	2040 to 3190	1150	1,07
	3190 to 4100	910	1,23
Spacer blocks	2040 to 2900	860	0,40
	2900 to 4100	1200	0,54
Backing blocks	2040 to 3080	1040	0,16
	3080 to 4100	1020	0,32

*These periods are demarcated by vertical arrows cutting the curves in Fig. 18.

Test Procedure

The procedure adopted for weekly measurements involved the removal of a line consisting of three backing plates and three lifter bars, and an adjoining line of three spacer blocks. Each component was unbolted from the shell of the mill, was lifted out through the manhole, and (after careful cleaning) was weighed and measured. Each line represents one-twelfth of the total lining, and progressive changes in the mass of the whole lining were approximated by multiplication of the recorded changes in the mass of the components by 12.

An assessment was made of the possibility of carrying out similar measurements on the end-liner components, but no satisfactory procedure could be found. Thus, no measurements for end liners are given in this paper. For much of the testwork, measurements had to be made very quickly so that the mill would be shut down for as short a time as possible. In the later stages, the mill was shut down for longer periods in a programme designed to minimize peak power demand, and more extensive measurements could be carried out.

The values in Table VII relate to changes in the mass of the individual liner components under test, the utilization of the metal in the castings, power consumption, and tonnage milled. Figs. 14 and 15 show the variation in the rate of wear of steel in the different lifter bars against the running time of the mill. It is clear that the lowest rate of wear is found on the No. 3 lifter bar, and, in general, the highest rate of wear is found on No. 2 lifter bar. The strange feature of these two diagrams is the marked variations in the rate of wear from one week to the next. Variations of up to 50 per cent are shown in

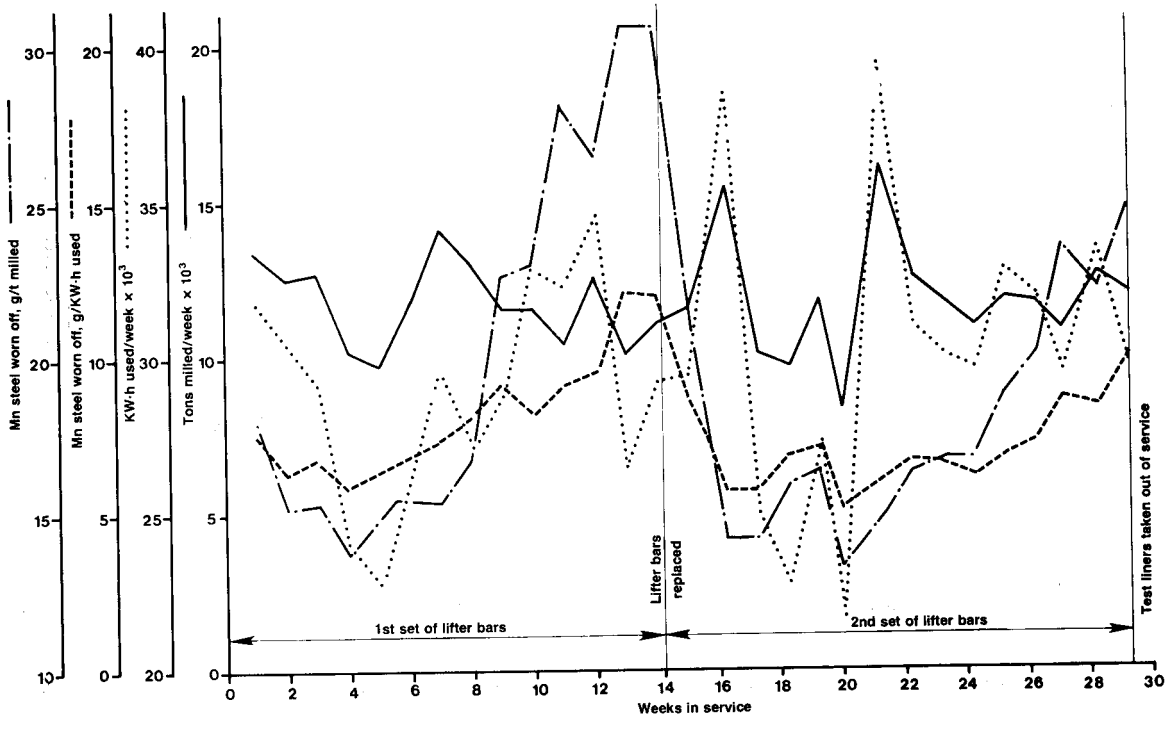

Fig. 16—Test of stock manganese-steel liners at Free State Saaiplaas Gold Mine (A rod mill)

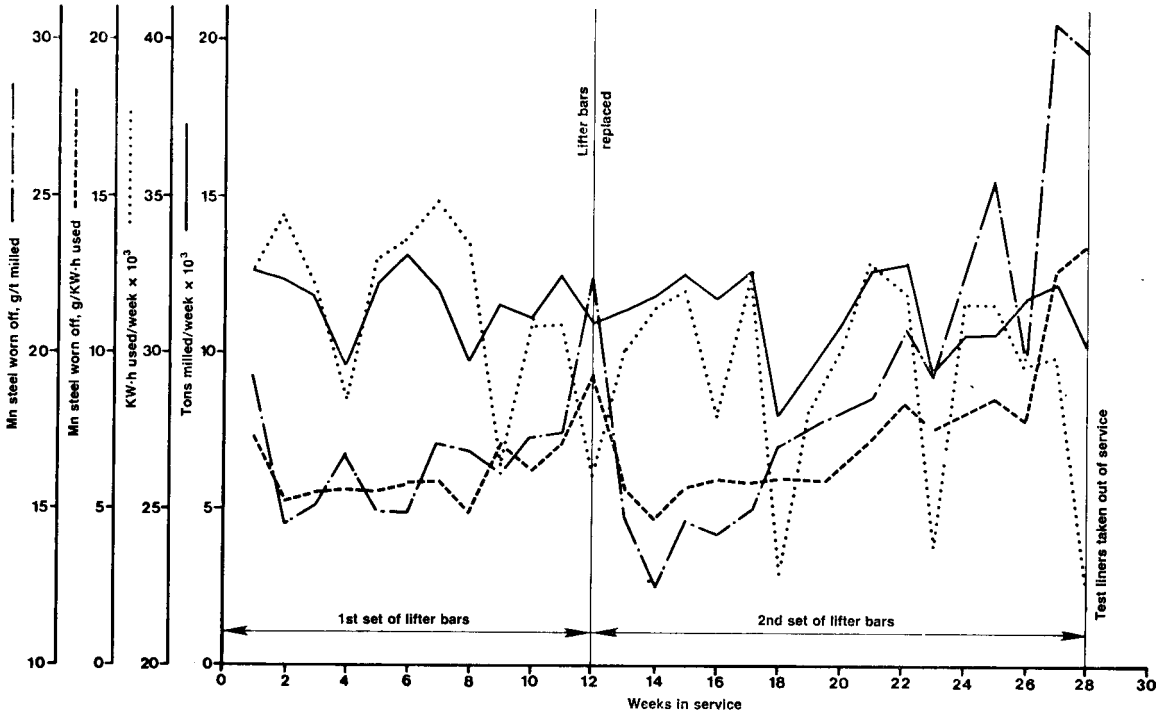

Fig. 17—Test of manganese-steel liners cast to conform to SABS 407/1975, at Free State Saaiplaas Gold Mine (A rod mill)

Fig. 14, and of up to 40 per cent in Fig. 15. The rate of feed to the mill does vary, but not sufficiently to explain these changes in the wear rate.

As shown in Table VII, the metal worn off per ton milled is 0,55 to 0,64 g in the lifter bars, half that in the backing blocks, and rather higher in the spacer blocks. Adjustment of the measured figures gives the amount of metal worn off all the shell liners as about 19 g/t. If the total mass of all the liner components originally fitted to the mill is taken as 19 611 kg, the total consumption of steel is 60 g/t. At the present price of manganese steel in South Africa, the costs of liners are about 6 cents per ton milled.

The total steel consumption of the liners in the 8 ft by 12 ft rod mill is 60 g/t when highly-abrasive quartzitic gold-bearing rock from the Orange Free State is being treated. This compares favourably with the 50 to 53 g/t reported as average figures by Norman[2] for fifteen high-tonnage plants in the U.S.A. and Canada (these include taconite-ore grinding plants).

The amount of steel worn off at the Saaiplaas mine is 7,7 g per kilowatt-hour of power supplied. Norman[2] quotes a range of 23 g/kW.h for coarse abrasive ore to less than 1 g/kW.h for soft limestone. It is surprising that the figure for Free State Saaiplaas is in the lower part of this range.

If the comparable Free State Saaiplaas figures are taken, the consumption of steel rods is 460 g per ton fed and 180 g per kilowatt-hour of power supplied. In relation to similar rod mills treating jasper, magnetite, and taconite, Nass[3] quotes figures of 410 g per ton milled and 100 g per kilowatt-hour of power supplied. The figures are comparable with those obtained in this investigation.

Figs. 16 and 17 show the changes in the mass of the manganese steel worn off all the shell-liner components during the test period of over twenty-nine weeks. Closely parallel to these are the changes in the mass of manganese steel that is worn off per kilowatt-hour of power supplied. Apparently unrelated to these are the other two variables plotted: tons per week, and total power supplied per week. It is evident that, for all the shell-liner components, the amount of manganese steel worn off per ton fed rises fairly steeply during the latter part of the life of a set of lifter bars. This suggests that, in the early life of a lifter bar, the rate of wear is rapid but is confined mainly to the bar itself. When the protrusion of the lifter bar above the backing block is reduced, there is less lift of the charge and more slippage occurs, and there is more general wear over the whole interior surface of the lining.

Fig. 18 shows the rates of wear (mass per unit area against hours of running time in the mill) for lifter bars, spacer blocks, and backing blocks. In each case, the rate of wear is highest on the lifter bars, but for any given set there is a fairly marked increase in the rate of wear of all three components after about 1200 hours of running. An attempt was made to express the relative wear rates by calculating the angle of slope of the graphs over the two periods mentioned above, and the results are shown in Table VIII. These values emphasize the marked increase in the rates of wear during the second part of the period, although the increase is less marked during the period after the installation of the second set of lifter bars. The factors definitely appear to confirm the suggestion that there is more lift and less slippage of the charge after the installation of new lifter bars, the wear being concentrated on the bars. At

a later period, when the bars are worn down, more slippage of the charge occurs with greater wear over the components of the entire lining.

Wear Profiles

When the first and second sets of lifter bars were removed from the mill at the end of their useful life, the height of each bar was measured at 50 mm intervals along its length. The readings obtained are shown in Fig. 19, together with a comparable set of measurements obtained for the two sets of lifter bars from the stock manganese-steel castings. The first feature that emerges strongly is that the most severe wear occurred on the No. 2 lifter bar in each of the four sets. This bar was worn down to a level below that of the No. 1 and No. 3 lifter bars. The abrasion profile on No. 1 lifter bar, especially noticeable on the first and second sets, is peculiar. There is evidence of pronounced wear on the first 100 to 200 mm length from the inlet end, and less wear towards the middle of the bar. Then, on the final 600 mm of the bar, there is a zone of increasing wear, where the bar is only half as thick as at the centre. This is the end of the bar that points towards the discharge end of the mill.

The same pattern is evident in the remaining set of two lifter bars from the stock manganese castings, but the height of the region near the centre of the first bar is not as pronounced. In addition to showing the greatest wear, both the No. 2 lifter bars show a marked depression at the centre.

The longer shut-down period for the mill during the life of the last set of lifter bars made it possible for progressive wear profiles to be determined at weekly intervals throughout the service life of each of the lifter bars of the second set. These changes in profile are shown in Fig. 20. Although the thickness of the No. 2 lifter bar in this set was at first appreciably greater than those of the No. 1 and No. 3 bars, it is obvious that rapid wear occurred on this bar, and, after a comparatively short period, the No. 2 lifter bar was worn to a greater extent than the others. This pattern persisted to the end of the service lives. In addition, the wear on a length 100 mm to 200 mm in from the inlet end of the No. 1 lifter bar was very rapid, as is shown in Fig. 19. Tests on a portable hardness tester showed that the developed hardness at the inlet zone of the No. 1 lifter bar was not very high. As the steel rods have to be slightly shorter than the internal length of the mill, the impact sustained by the first 100 to 200 mm of the liners may not be sufficient to harden them in this region. The feed smaller than 19 mm enters the mill at the rate of 70 to 80 t/h and some of it presumably flows down over the feed end-plates and comes into direct contact with the inlet ends of the No. 1 lifter bars. This would cause fairly rapid erosion of this relatively unhardened portion of the bar. The severe wear on the No. 2 lifter bar is not easy to explain unless there is some flexing of the centre portion of the steel rods. This could be due to the inlet ends of the steel rods being pushed above the horizontal by the presence of a high proportion of coarse material in the feed.

Table IX shows the total masses of the mill-lining components before their installation and after they had been removed from the mill, together with data on the consumptions of metal and power. The averaged

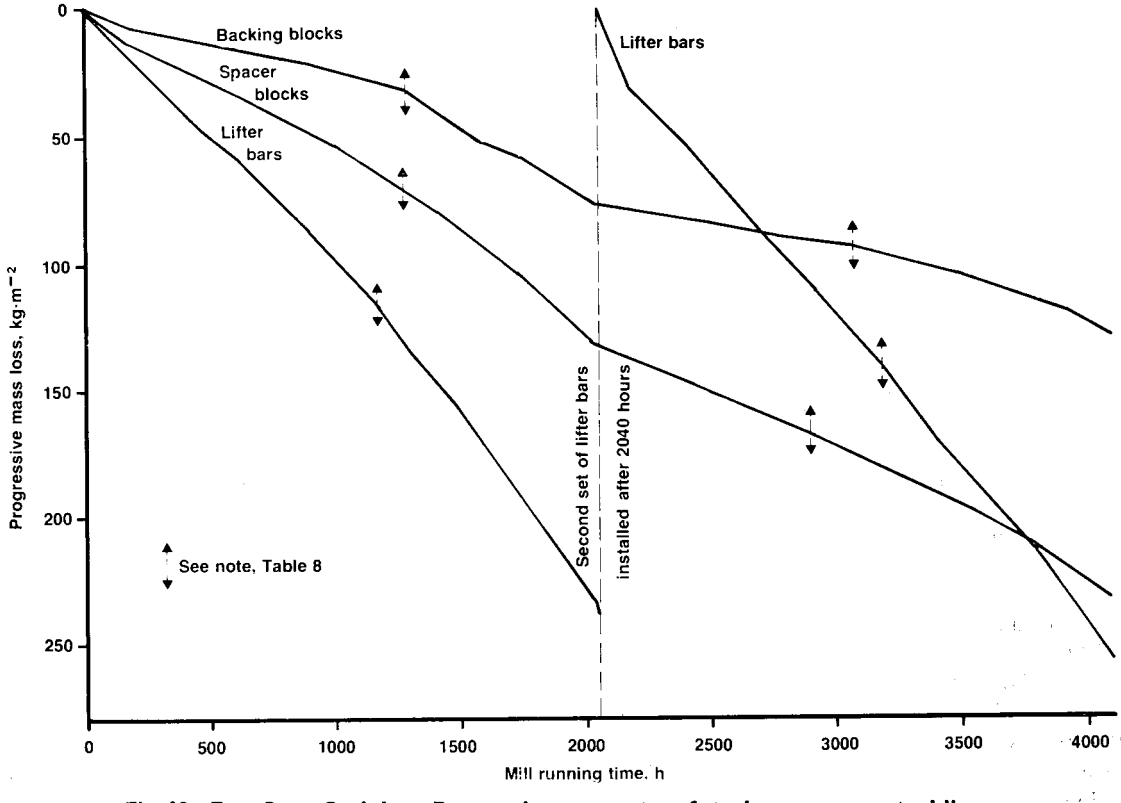

Fig. 18—Free State Saaiplaas. Progressive wear rates of stock manganese-steel liners

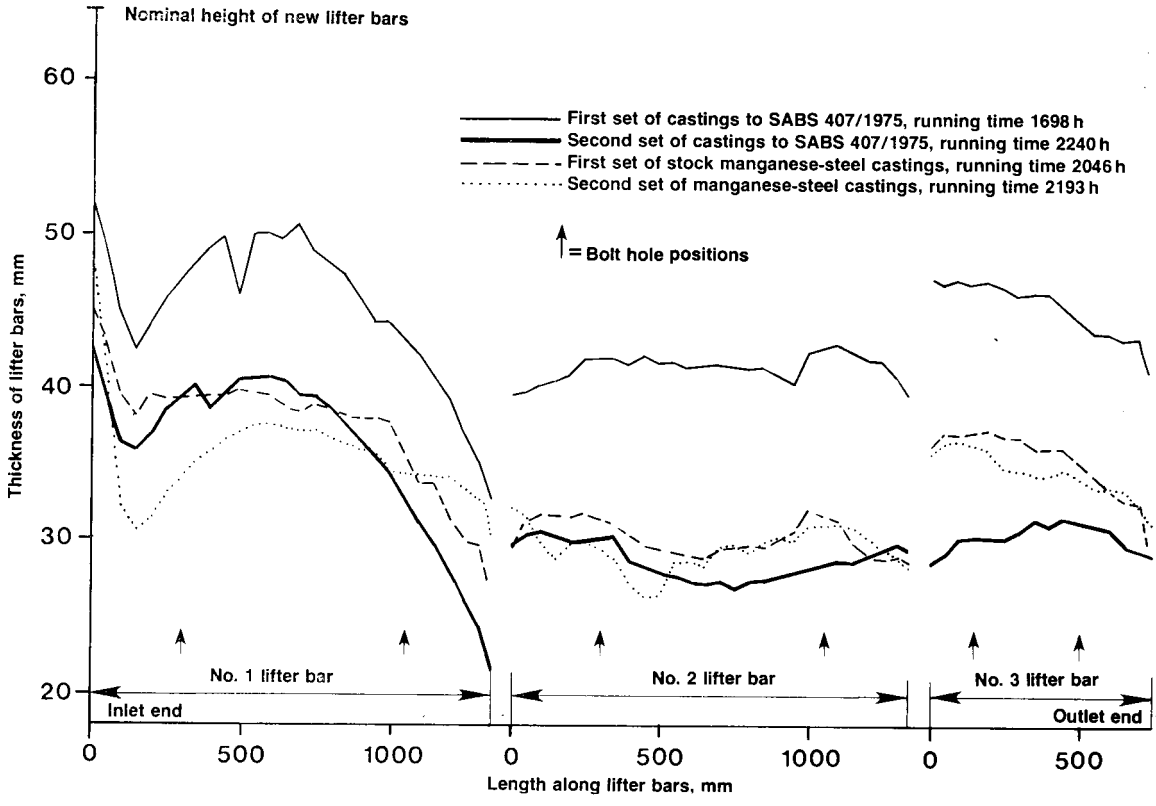

Fig. 19—Final wear profiles of lifter bars after their removal from service

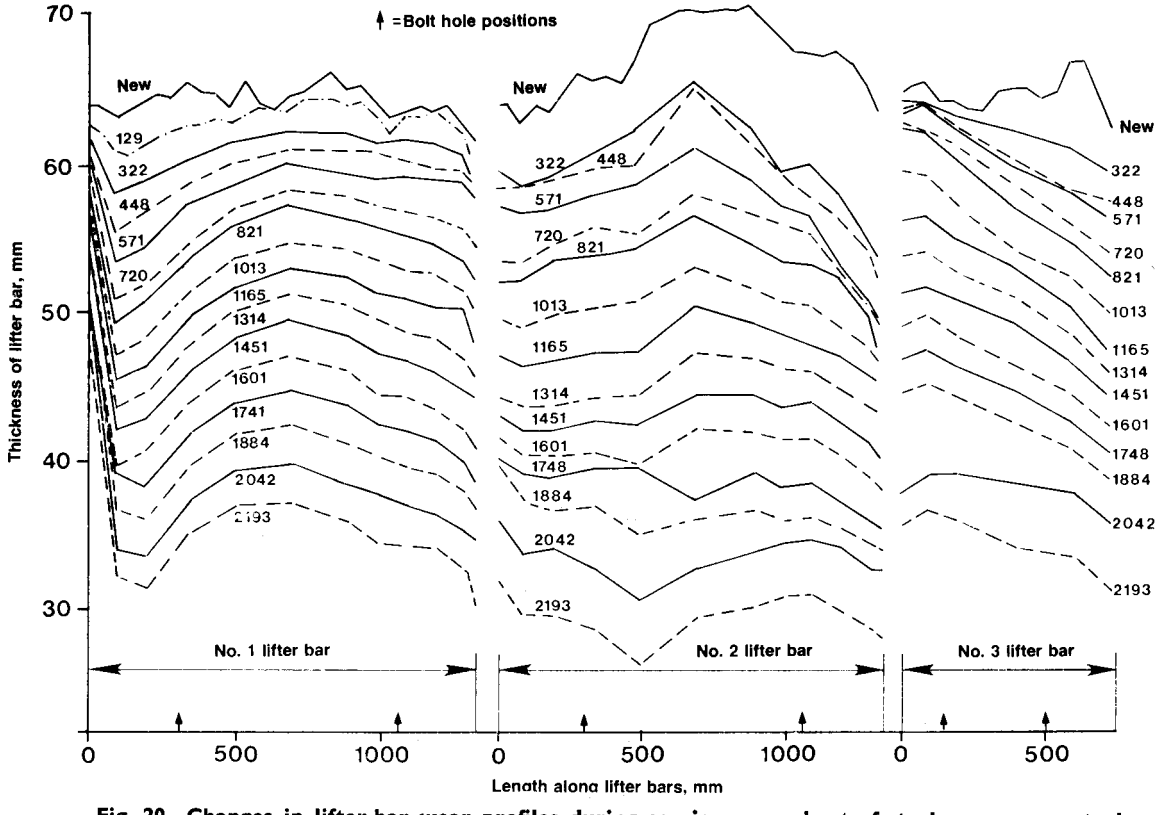

Fig. 20—Changes in lifter-bar wear profiles during service: second set of stock manganese-steel castings (the values on the graphs refer to hours of service)

TABLE IX

THE PERFORMANCE OF SETS OF CASTINGS OF SHELL-LINER COMPONENTS TESTED IN THE 8 FT BY 12 FT ROD MILL

Liner component	Mass of components		Metal worn off	Utilization of component	Ore fed to mill	Metal worn off		Power consumption			
	Installed	Taken out						Total kW.h supplied	kW.h/t fed to mill	Metal worn off g/kW.h	Weighted average
	kg	kg	kg	%	t	g/t (of feed)	Weighted average				
Components supplied to SABS 407/1975 for manganese-steel castings											
Spacer blocks	5424,6	3141,9	2282,7	42,1	321 398	7,10		846 139	2,63	2,70	
Backing blocks	3885,1	2358,8	1526,3	39,3		4,75				1,80	
Lifter bars											
1st set	2027,5	1135,9	891,6	44,0	138 477	6,44	7,07	373 695	2,69	2,39	2,69
2nd set	2186,2	804,7	1381,5	63,2	182 921	7,55		472 444	2,58	2,92	
Totals	13523,4	7441,3	6082,1		321 398			846 139			
Averages				45,0		18,92			2,63	7,19	
Stock component castings of manganese steel											
Spacer blocks	5492,7	3017,6	2475,1	45,1	343 783	7,20		858 144	2,50	2,88	
Backing blocks	3989,3	2424,6	1564,7	39,2		4,55				1,82	
Lifter bars											
1st set	2013,5	1004,8	1008,7	50,1	166 708	6,05	6,78	408 566	2,45	2,47	2,72
2nd set	2156,1	834,2	1321,9	61,3	177 075	7,46		449 578	2,54	2,94	
Total	13651,6	7281,2	6370,4		343 783			858 144			
Averages				46,7		18,53			2,50	7,42	

TABLE X

CONSUMPTION OF MANGANESE STEEL AND OF POWER IN CRUSHING AND GRINDING

Crushing		Grinding	
$4\frac{1}{4}$-ft short-head crusher		8 ft by 12 ft rod mill	
Manganese-steel mantle and bowl liners		Manganese-steel shell liners	Carbon-steel rods 90 mm dia.
Western Deep Levels	Western Holdings		
Grams of steel worn off per ton of ore fed			
14,7	24,2	19	460
Grams of steel worn off per kW.h of power supplied			
27,4	22,3	7,9	180
Power consumption (kW.h per ton of ore fed)			
0,54	1,09	2,65	

figures for the components that were individually measured are in good agreement with the final data presented in Table VII.

Comparison between Short-head Crushers and Rod Mill

Data obtained from the tests on the consumption of manganese steel and of power in the short-head crushers and in the rod mill are shown in Table X. In terms of the manganese steel worn off during the tests, the figures for both crusher liners and rod-mill liners are very similar, lying within the range 15 to 24 g/t. The masses of steel worn off per kilowatt-hour of power supplied are also similar for the crushers, but the figure obtained for the rod-mill lining is by far the lowest (8 g as against 22 g to 27 g for the crushers). Power consumption is within the range 0,54 to 2,65 kW.h per ton of ore fed. The table emphasizes the very high ratio of the consumption of steel used as grinding medium (rods or balls) to steel worn off the lining. In this rod mill, the ratio was 22 to 1. The rods used at the Free State mine are the normal hot-rolled (1,0 per cent carbon) steel products 90 mm in diameter. They cost 25 cents per kilogram as compared with about R1 per kilogram for manganese-steel castings. The ratio of the cost of the rods to the cost of the total mass of manganese-steel liners that is installed in the mill is 2,1 to 1.

At present prices for electric power in South Africa, the total steel costs are almost three times the cost of the power required for each ton of ore fed to the mill.

Conclusions

For crushing the hard, very abrasive quartzitic ore from the Witwatersrand gold fields, manganese steel maintains its position as the best material. This is mainly due to its toughness, and despite its comparatively low resistance to abrasion.

For relatively small size-reduction ratios, manganese steel is not often damaged. All else being equal, a large size reduction greatly reduces the life of the castings: they become worn more quickly, power consumption is higher, and there is increased consumption of metal per ton of ore fed. In addition, because of the design of the bowl liners in common use in South Africa, mechanical damage is liable to occur, particularly cracking around the lugs and circumferential tears along the annular recess.

The addition of molybdenum to manganese-steel crusher castings and double-cycle heat treatment did not improve the performance to an extent commensurate with the probable increase in cost that would be incurred. The use of crusher castings of through-hardened steel resulted in serious mechanical failures of the castings, which were seriously aggravated in coarse crushing.

The manganese-steel castings used in wet grinding in the 8 ft by 12 ft rod mill are of much simpler design than the bowl liner and mantle castings. In addition, the castings in the rod mill are securely bolted to the shell, and the lifter bars are backed firmly against the backing blocks. No fracture of a casting was observed during the course of the testwork, although fairly serious distortion took place in some of the discharge-end liner plates. Overall wear of the shell liners in the rod mill (in terms of grams per ton of feed) was very similar to that found in the castings in the $4\frac{1}{4}$ ft short-head crushers, but there were wide fluctuations in the rate of wear throughout the life of a set of lifter bars. The consumption of metal per ton of feed was low when new lifter bars were installed, but it rose rapidly towards the end of the life of the bars. This suggests that much of the wear is due to the slippage of the charge in the mill. Curiously enough, wear of the shell liners in relation to the power supplied (grams per kilowatt-hour) was significantly lower than that obtained in the short-head crushers.

The wear profiles for the lifter bars, determined at weekly intervals, showed that the most severe wear occurs on the second (or middle) lifter bar. Wear on the lifter bar at the feed end gives an anomalous pattern for which there is no easy explanation.

Acknowledgements

Grateful acknowledgement is made of the wholehearted cooperation and assistance freely given by the staff and operators at Western Deep Levels, Western Holdings, and Free State Saaiplaas gold mines. Without this the testwork would have been impossible.

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