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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	m	meter
cm	centimeter	min	minute
h	hour	mm^3	cubic millimeter
HRA	Rockwell hardness, A scale	N	Newton
HRC	Rockwell hardness, C scale	pct	percent
HV	Vickers hardness	wt pct	weight percent
kg	kilogram		

CORRELATING ABRASIVE WEAR TO ALLOY ADDITIONS IN LOW-ALLOY STEELS

By J. H. Tylczak[1]

ABSTRACT

The Bureau of Mines studied the effect of alloy additions on abrasive wear of low-alloy steels. A dry-sand, rubber-wheel abrasion test apparatus using ASTM G65-81 procedure B was used for the abrasive wear tests. Eighty-six material heat-treatment combinations were abrasion tested. Results of these tests were analyzed statistically using regression analysis to see if additions of Cr, Mn, Mo, Ni, Si, Al, Cu, and S were significant in affecting the abrasive wear rate of low-alloy steels. Regression analysis was also used to confirm hardness and C affect on the abrasive wear rate of these steels. It was found that for all the steels taken as a group, increased amounts of Mn significantly reduced the wear rate, while increased amounts of Mo and Si increased the wear rate. Analysis also confirmed previous research done by others, that increasing hardness and amounts of C reduced the wear rate. For the hardened steels taken as a class, only increasing amounts of C and Mn reduced the wear rate, while increases in Si increased the wear rate. In the class of unhardened steels, increases in C, Mn, and S reduced the wear rate, whereas increases in Mo increased the wear rate. The steels with the best resistance to wear were two hardened experimental steels similar to AISI 1055 and AISI 1078.

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INTRODUCTION

Low-alloy steels are inexpensive materials widely used in ore transport and mineral-processing equipment, such as ore chutes, truck beds, and bin walls. A simulation for the field condition of loose ore flowing over steel is the use of the well-known dry-sand, rubber-wheel abrasion test, in which loose sand abrades a test specimen. This test has become an ASTM standard (1)[2] for abrasive wear and was used for this work.

Research was designed to determine the effect of different alloy additions on sliding abrasive wear of low-alloy steels, and to optimize the composition of two types of low-alloy steels: one type with low (<0.3 pct C) carbon level to make it more easily weldable, and another type without a carbon limit. Other alloying additions investigated were Cr, Mn, Mo, Ni, Si, Al, S, and Cu. Whether or not chromium is useful in providing wear resistance in low-alloy steels was of particular interest because of U.S. dependence on imports for this strategic metal.

Most prior work in abrasive wear has been limited to studying variables individually. Research has established the effect of some of the variables studied. Khrushchov (2-3), using a pin-on-abrasive cloth test machine, documented that hardness affects wear. Larsen-Badse (4), using a similar machine, showed that wear resistance was proportional to material hardness and work hardening rate. Carbon has long been shown to affect wear. Haworth (5) reported in 1949 that carbon was the most important alloying element for abrasion resistance. Moore (6) found a square-root relationship of weight percent carbon with wear resistance in martensitic steels. Grinberg, Livshits, and Shcherbakova (7) studied the affect of Cr, W, and V. They found that increasing the amount of these elements, up to 5.9 Cr, 2.2 W, and 2.7 V, in ferrite did not increase the wear resistance for fully annealed steels.

The present work extends these past efforts to a multiple-variable study of abrasive wear.

EXPERIMENTAL PROCEDURE

TEST PROCEDURE

Abrasion tests were conducted on a dry-sand, rubber-wheel abrasion test apparatus in accordance with ASTM G65-81, procedure B. This test (fig. 1) consists of a rubber-coated wheel, a test specimen mounted on a pivoting load arm, and a sand nozzle that produces a sand curtain between the specimen and the rubber wheel. The sand used was AFS 50/70 test sand, shown in figure 2. This is a subangular quartzitic sand with 90 pct between 50 and 70 mesh (U.S. sieve sizes). The sand, acting as an abrasive, flows into the specimen-wheel interface. The wheel rotates against the specimen for a distance of 1,436 m with a force of 130 N. Specimens are weighed before and after the test. The weight loss is divided by the sample density to obtain its volume loss.

SPECIMENS

Test specimens included commercially purchased and laboratory-melted steels. Table 1 lists the analyzed composition and calculated carbon equivalents for the 43 steels investigated. The carbon contents ranged from 0 to 1.53 wt pct; the other alloying elements (Cr, Mn, Mo, Ni, Si, Al, Cu, and S) were within normally accepted ranges for low-alloy steels. Because the weldability of low-alloy steels is often of concern, calculations were made of the carbon equivalence (CE) (8), which is used to predict the susceptibility to cracking in the heat-affected zone. The CE values included in table 1 were calculated from the equation

$$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} + \frac{Si}{24}, \quad (1)$$

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

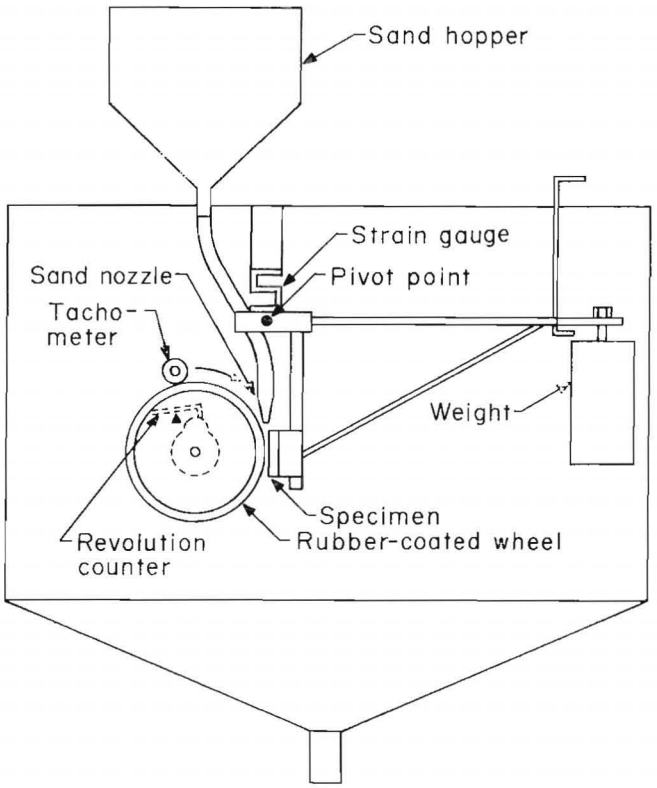

FIGURE 1.—Dry-sand, rubber-wheel abrasion test machine.

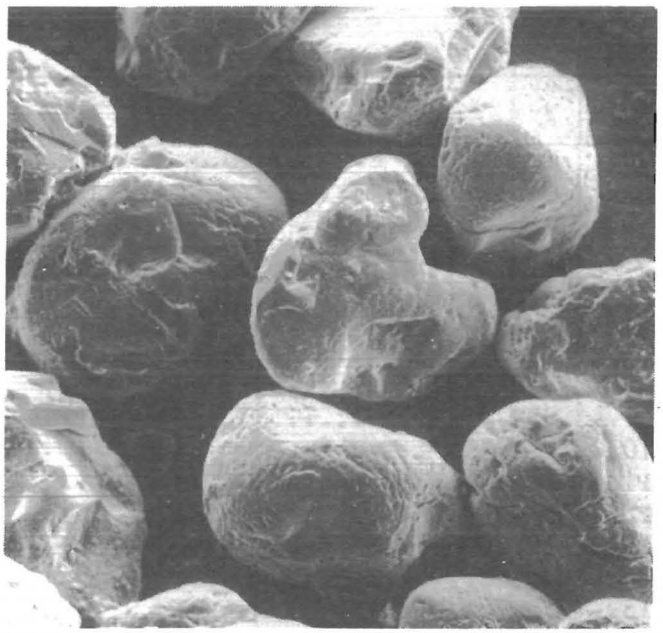

FIGURE 2.—Subangular quartzitic sand, minus 50 plus 70 mesh (X 100).

where elements are in weight percent. Because carbon is the most significant element in this equation, an attempt was made to develop a low-wear steel with a carbon limit set at 0.30 wt pct, rather than control CE to a set limit.

The laboratory-produced steels were melted in a 2-kg vacuum induction furnace or as 20-kg heats in an air induction furnace. These were initially hot forged, then hot rolled at a temperature of 1,100° C, with 25- to 30-pct reduction on each pass to a final thickness of 1.52 cm.

The specimens were fabricated into 2.5- by 7.6- by 1.3-cm bars and heattreated as required. Appendix table A-1 lists heat-treatment temperatures and the microstructures obtained. The steels were heated to around 860° C, based on similar alloys found in the Alloy Digest (9), held for 45 to 75 min, and quenched. The quenching media and resulting hardnesses are presented in table 2. It proved necessary to temper several of the steels after quenching because of their tendency to crack; the temper used was 1 h at 200° C. After this heat treatment, the 2.5- by 7.6-cm surfaces were wet surface ground to 1.3 cm thick by removing equal amounts of material from each side.

Hardness measurements were taken on the specimen surface and in the bottom of the wear scar with a Rockwell hardness tester using the A or C scale. These values, which are listed in appendix table A-1, were converted to Vickers hardness, using ASTM E140-79 (10) conversion tables, to provide a continuous linear scale. The unhardened steels were typically 10 Vickers points harder in the wear scar than on the nonworn surface because of work hardening caused by abrasion testing. In this case, the hardness in the scar was used as the specimen hardness because work hardening presumably occurred during the entire test over the entire volume of material removed. For the hardened steels, work hardening was negligible. But if the hardenability was so low that the hardness was substantially lower in the bottom of the wear scar than it was on the unworn surface, a correction was made. To approximate the mean hardness of the volume removed, the wear value used was a weighted average of three-quarters of the surface hardness plus one-quarter of the hardness at the bottom of the wear scar.

TABLE 1. - Analysis of test materials

Sample	Alloy	Analysis, wt pct									CE[1]
		C	Cr	Mn	Mo	Ni	Si	Al	Cu	S	
1..	Ferro Vac. E.....	0.0	0.05	0.0	0.0	0.05	0.0	0.0	0.0	0.0	0.01
2..	Cor 99.....	.01	.00	.06	.00	.03	.02	<.01	.00	.013	.03
3..	Experimental steel	.09	1.12	.12	.09	.08	.19	.35	.02	.003	.36
4..	...do.....	.12	.93	.14	<.05	<.01	.23	.51	.02	.002	.35
5..	...do.....	.16	.26	<.01	.02	.11	.05	.04	.22	.027	.24
6..	...do.....	.17	.96	.35	<.05	.05	1.05	.65	.38	.009	.50
7..	AISI 1018.....	.18	.08	.43	.04	.15	.09	<.02	.34	.039	.31
8..	AISI 4620.....	.18	.20	.54	.21	1.71	.27	.04	.15	.016	.50
9..	USS "T1".....	.19	.50	1.33	.23	.20	.25	.02	.17	.030	.57
10..	USS "T1", Type B..	.19	.51	.88	.12	.08	.30	.03	.02	.013	.48
11..	Experimental steel	.20	1.3	1.05	.08	.21	1.97	.07	.01	.011	.75
12..	AISI 8620.....	.20	.43	.67	.13	.42	.27	.03	<.04	.019	.48
13..	Experimental steel	.21	>1.35	.08	.09	.51	.38	.17	<.01	.003	.69
14..	...do.....	.21	.11	.47	.06	.15	<.05	.43	.01	.028	.33
15..	...do.....	.21	.11	.48	.07	.14	1.78	1.44	.36	.032	.43
16..	...do.....	.23	1.37	.25	.08	.34	.12	.68	.35	.022	.61
17..	...do.....	.23	2.0	.45	.06	.24	.05	.06	.29	.026	.75
18..	...do.....	.27	1.64	.95	.04	.15	.14	.12	.36	.035	.80
19..	...do.....	.28	.11	.49	<.01	.15	1.32	.06	.39	.032	.52
20..	...do.....	.31	.85	.08	<.01	.08	.38	>.25	<.01	.002	.52
21..	REM 500.....	.33	.98	.61	.20	.14	.38	.03	.16	.004	.70
22..	Experimental steel	.37	.44	.24	<.01	.28	<.01	.068	.23	.033	.52
23..	AISI 4340.....	.40	.79	.71	.27	1.76	.27	<.02	.05	.009	.86
24..	AISI 4342.....	.42	.81	.80	.22	1.93	.32	.026	.09	.018	.91
25..	AISI 8740.....	.42	.50	.93	.21	.43	.28	.02	.15	.024	.77
26..	AISI 1340.....	.43	.02	1.93	.02	.05	.24	.01	.04	.022	.78
27..	AISI 4142.....	.44	1.05	.83	.12	<.1	.27	.055	<.04	.026	.83
28..	Experimental steel	.49	.27	.67	.00	.16	.17	.01	.21	.023	.69
29..	AISI 6150.....	.51	1.08	.83	.04	.16	.29	.02	.08	.012	.90
30..	Experimental steel	.54	.28	.80	.03	.10	<.01	.03	.32	.024	.76
31..	AISI 1060.....	.59	<.1	.53	<.1	.13	.18	<.02	.22	.026	.73
32..	Experimental steel	.60	.01	.01	<.01	.12	.02	.073	<.01	.016	.61
33..	AISI 5160.....	.61	.80	.76	<.1	.11	.24	<.02	.12	.032	.93
34..	Omegalloy 61.....	.85	<.1	.40	<.1	<.1	<.01	NA	<.04	NA	.94
35..	Experimental steel	.87	.17	.55	.03	.06	<.02	<.02	.29	.027	1.03
36..	...do.....	.90	.37	.97	.11	.11	.18	.03	.38	.024	1.20
37..	Experimental steel	.92	.05	.02	<.01	.33	.04	.14	<.01	.021	.93
38..	...do.....	.93	1.30	.43	<.01	.03	.69	.08	.05	.023	1.30
39..	...do.....	.94	.83	.04	.01	.30	.07	.19	.04	.020	1.14
40..	...do.....	.96	.79	.17	.03	.28	<.01	.37	.18	.023	1.18
41..	AISI 52100.....	1.05	1.7	.34	.06	.18	.26	<.02	.12	.016	1.49
42..	W1.....	1.07	<.1	.30	<.1	<.1	.20	.04	<.04	.008	1.15
43..	Experimental steel	1.52	.05	.38	<.05	.08	<.05	<.05	.28	.025	1.63

NA Not available. [1]Carbon equivalency.

The steels also were examined metallographically for differences in microstructure that might explain the differences in wear. (Typical grain size was found to be finer than ASTM grain size 8.)

ANALYSIS TECHNIQUES

The effect of element additions and hardness on wear of each specimen were analyzed by a multiple linear regression (MLR) program. The MLR program produced

TABLE 2. - Dry-sand, rubber-wheel abrasive test data

Sample	Alloy	Condition	Hardness, HV	DSRWAT[1] wear mm^3	Coefficient variation, pct	Sample	Alloy	Condition	Hardness, HV	DSRWAT[1] wear mm^3	Coefficient variation, pct
1....	Ferro Vac. E.....	R	70	187.8	1.3	26....	AISI 1340.....	R	269	57.3	0.04
2....	Cor 99.....	R	93	166.0	1.5			WQ	640	38.5	5.3
3....	Experimental steel	R	112	170.9	1.4	27....	AISI 4142.....	A	172	95.0	5.0
4....	...do.....	R	116	155.6	2.6			R	192	86.7	1.3
5....	...do.....	R	118	148.7	4.3			OQ, T	556	44.3	1.8
6....	...do.....	R	159	120.3	2.3	28....	Experimental steel	R	214	64.4	1.5
7....	AISI 1018.....	R	139	129.6	.98			WQ	653	37.2	2.1
8....	AISI 4620.....	R	190	141.3	2.8	29....	AISI 6150.....	A	192	80.4	3.8
		A	135	134.6	2.1			R	346	83.0	2.4
		WQ	426	76.2	2.0			OQ	610	32.7	2.5
9....	USS "T1".....	RQ	243	104.4	1.3	30....	Experimental steel	R	216	52.6	3.7
		WQ	434	74.2	3.1			WQ	718	24.1	1.3
10....	USS "T1", Type B..	RQ	283	121.5	2.8	31....	AISI 1060.....	A	176	84.3	6.1
11....	Experimental steel	R	346	99.4	.66			R	227	60.4	4.6
		WQ, T	458	73.0	.5			WQ	708	32.1	3.4
12....	AISI 8620.....	A	133	137.7	3.6	32....	Experimental steel	R	170	75.3	7.8
		R	170	121.7	2.0			WQ	725	40.7	.82
		WQ	434	67.6	2.7	33....	AISI 5160.....	A	208	76.8	5.2
13....	Experimental steel	R	322	110.6	2.7			R	306	51.3	8.4
		WQ	424	70.0	1.6			WQ	709	39.6	3.0
14....	...do.....	R	145	128.3	5.2	34....	Omegalloy 61.....	RQ	801	29.8	5.3
15....	...do.....	R	187	113.7	4.3	35....	Experimental steel	R	312	40.5	1.9
16....	...do.....	R	170	95.3	4.5			WQ	842	24.1	.98
		WQ, T	423	74.4	2.6	36....	...do.....	R	346	36.2	.55
17....	...do.....	R	307	103.0	.06			OQ	817	25.2	1.4
		WQ	512	63.7	3.30	37....	...do.....	R	230	47.3	2.3
18....	...do.....	R	404	95.3	2.1			WQ	861	26.2	2.7
		WQ	513	60.5	4.2	38....	...do.....	R	384	37.3	1.3
19....	...do.....	R	212	119.5	1.7			OQ	820	32.1	3.0
		WQ	456	82.6	3.9	39....	...do.....	R	340	43.4	3.8
20....	...do.....	R	216	103.4	.93			OQ	766	33.8	.4
		WQ	453	60.8	6.4	40....	...do.....	R	333	38.8	4.7
21....	REM 500.....	A	176	136.6	3.0			OQ	766	33.9	2.0
		RQ	505	64.6	2.3	41....	AISI 52100.....	A	184	89.2	2.8
22....	Experimental steel	WQ	511	47.8	.11			R	346	39.3	1.35
		R	148	97.6	.23			OQ, T	720	35.2	4.7
23....	AISI 4340.....	WQ	595	46.6	6.2	42....	W1.....	R	158	99.9	3.3
		R	170	113.1	2.1			A	176	82.9	4.2
24....	AISI 4342.....	OQ	530	54.3	6.7			WQ	800	29.1	2.5
		R	184	102.4	2.1	43....	Experimental steel	R	298	47.5	.6
25....	AISI 8740.....	WQ	633	42.0	1.9			WQ	832	28.3	5.7
		A	165	97.0	1.2						
		R	254	97.6	.4						
		WQ	591	39.4	4.5						

[1]Dry-sand, rubber-wheel abrasion test.

NOTE.--A Annealed. R Hot rolled (assumed for purchased commercial steels). OQ Oil quenched.
RQ Received in hardened condition. WQ Water quenched. T Tempered.

F values that could be used in hypothesis testing to determine which of the independent factors were significant. Prior to running the MLR on the composition and wear results, the element additions and hardnesses were plotted versus wear. Using these plots, transformations were performed on carbon and hardness to linearize them with respect to wear. Inverse, natural-log, and square-root transformations were attempted. The transformed data were used along with the element additions that were not transformed for the MLR. The data also were separated into hardened and unhardened steels. A MLR was run on the nine elements additions versus wear for these two conditions. The regression was performed by the forward stepwise method (11).

The optimization routine consisted of abrasion testing a variety of commercial low-alloy steels, then optimizing the composition through the rotating simplex method of optimization, or self-directing optimization (SDO) (12-13). The process was repeated with a new optimized alloy composition until the change in wear was judged insignificant for the new alloy compared with the wear data for the previous one. An example of this technique is given in appendix B.

RESULTS

GENERAL

Forty-three different steels were tested. Because more than one heat treatment was used on many of the steels, 86 alloy heat-treatment combinations were evaluated. Table 2 shows the wear results. The range of wear loss was from 188 mm^3 to 24.1 mm^3. The alloy with the least wear resistance was Ferro Vac E,[3] which is pure vacuum-arc-melted iron having no alloy additions. The best wear resistance was shared by hardened experimental steels, samples 30 and 35. Sample 30 is similar to AISI 1055; sample 35 is similar to AISI 1078. Both have relatively high carbon levels, making them difficult to weld. Among the 19 commercial steels tested, sample 34, which is Omegalloy 61, and sample 42, which is tool steel W1, gave the lowest wear with values of 29.8 and 29.1 mm^3, respectively. The best nonhardened steel was sample 36, an experimental high-carbon manganese steel with a wear of 36.2 mm, which was better than many of the hardened steels. Among the steels with carbon content limited to 0.30 wt pct, sample 18 had the least wear, 60.5 mm. However, the other elemental additions resulted in a CE of 0.80, which is rather high for a weldable alloy.

The best wear resistance was obtained with alloys having a martensitic structure. Figures 3 and 4 show the microstructures of samples 30 and 35, which are both martensitic. Other hardened specimens that were almost as abrasion resistant, such as samples 31, 33, 38, and 41, showed a second phase, either pearlite or cementite. The microstructure of the best low-carbon steel, sample 18, also was martensitic. The typical microstructure of the nonhardened steels, as shown for sample 36 in figure 5, was fully pearlitic. In contrast, the alloy with the worst wear resistance, pure-iron Ferro Vac E, was ferritic, as shown in figure 6.

ANALYSIS INCLUDING ALL SAMPLES

Relationships between wear volume and alloying elements (C, Cr, Mn, Mo, Ni, Si, Al, Cu, and S) on hardness of each sample were analyzed statistically using MLR. Prior to the MLR analysis, hardness values were transformed to inverse hardness and carbon to the square root of carbon because these transformations gave the best linear correlation with wear. Hypothesis testing showed, with a 99.5-pct confidence level, that alloying elements and hardness affected the wear. All individual factors also were tested for their significance. Inverse hardness and square root of the carbon level were found significant at the 99.5-pct

[3]Reference to specific products does not imply endorsement by the Bureau of Mines.

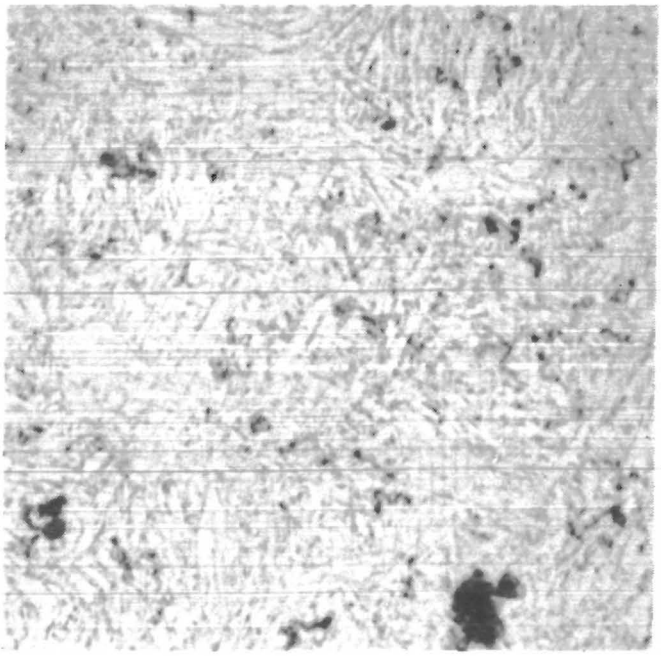

FIGURE 3.—Fully hardened martensitic steel sample 30 (X 1,500).

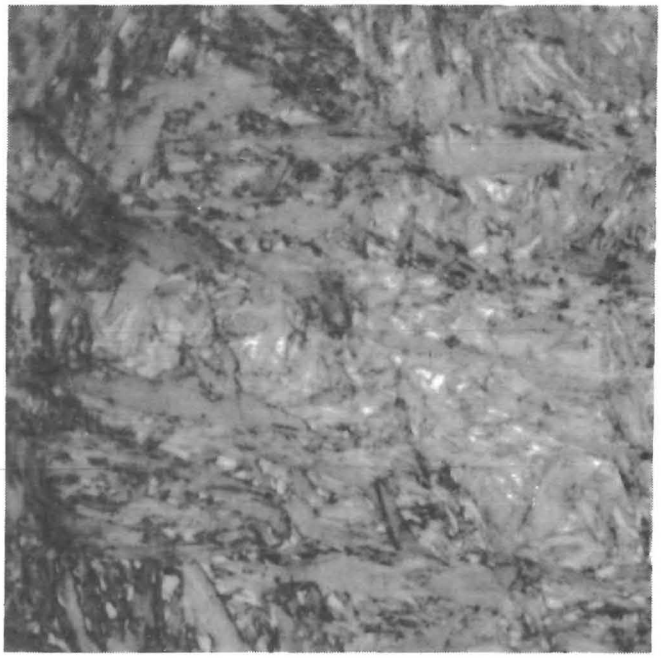

FIGURE 4.—Fully hardened martensitic steel sample 35 (X 1,500).

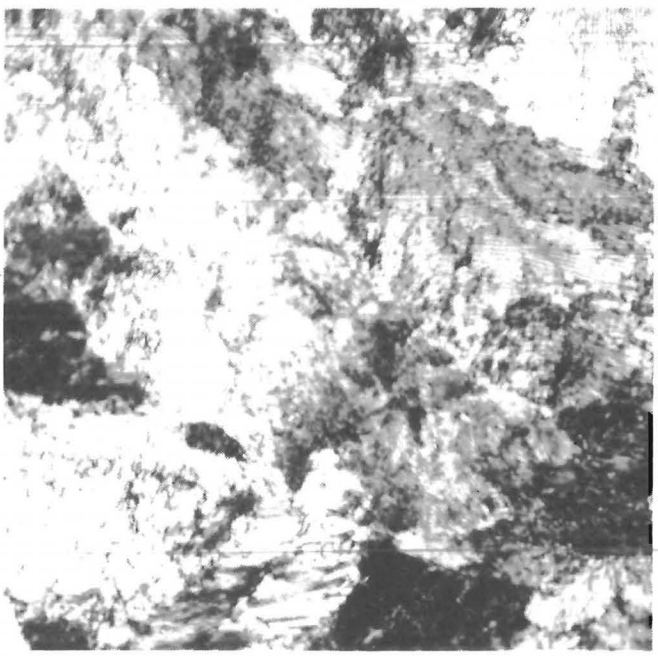

FIGURE 5.—Sample 36 showing fully perlitic structure (X 1,900).

FIGURE 6.—Sample 1 showing ferritic structure of pure iron (X 100).

confidence level. Three elements (Mn, Mo, and Si) were significant at the 95-pct confidence level; the other elements evaluated (Cr, Ni, Al, Cu, and S) did not show a significant effect on wear. Although dependent on carbon and other alloying additions, the justification for using hardness for an independent variable is that it is greatly affected by heat treatment. This is indicated by the correlation between inverse hardness and the square root of the carbon content, which was only 0.49.

The MLR program produced the following equation to predict wear (ASTM G65-81, procedure B):

$$\text{Wear} = 67 + 10{,}900(\text{HV})^{-1} - 54(\text{C})^{1/2} - 9.2(\text{Mn}) + 74(\text{Mo}) + 11(\text{Si}), \quad (2)$$

where elements are in weight percent, and wear is in cubic millimeters. The numerical values of the coefficients in equation 2 and subsequent equations should not be considered exact, but they show that increasing hardness, carbon, and manganese decreases the wear of low-alloy steels. Excluding any effect of Mo and Si on hardness through heat treatment, Mo and Si increase wear. The correlation of the data with equation 2 was 0.89.

To demonstrate the effects of significant wear factors, the data were fit to a higher order equation using the two most significant factors identified by MLR analysis, namely, hardness and carbon. The equation used was

$$\text{Wear} = A + Bx + Cx^2 + Dx^3 + Ey + Fy^2 + Gy^3 + Hxy, \quad (3)$$

where X is Vickers hardness number,

Y is wt pct carbon,

and A, B, C, D, E, F, G, and H are coefficients.

After fitting the hardness and carbon data to equation 3, a pseudo-three-dimensional graph was plotted (fig. 7).

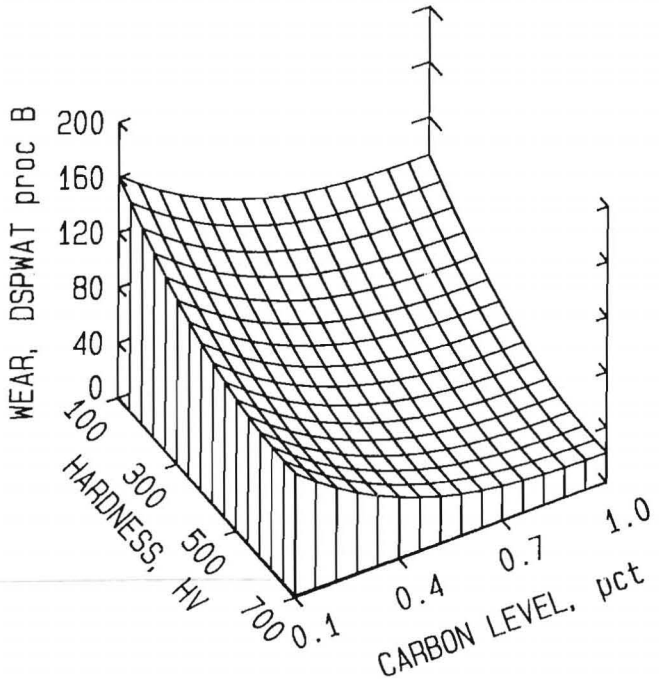

FIGURE 7.—Effect of hardness and carbon on wear.

This graph shows that increasing the hardness decreases the wear, and increasing the carbon content to 0.7 to 0.8 pct also results in a minimum in wear. The coefficient of determination fit of the data from all the specimens to this equation was 0.97.

The MLR program also was run with the data separated into two categories: hardened martensitic steels and nonhardened pearlitic and ferritic steels. Separate analysis of each category allowed the effects of structure and hardness to be separated from the effects of composition. Since the effect of hardness is well established, the hardness term was eliminated from these analyses.

ANALYSIS OF HARDENED STEELS

For the hardened steels, the best fit was found by using inverse carbon. There was very little difference between an inverse and square-root fit for carbon in equation 4. The difference was too slight to attribute to any physical meaning. For the MLR, the C and Mn were significant at the 99.5-pct confidence level and Si at the 95-pct level. None

of the other alloy additions showed any significant effect. The multiple correlation fit of the hardened steels was 0.78. The equation predicting the wear rate for ASTM G65-81, procedure B, for hardened steels, is

$$\text{Wear} = 21 + 11(C)^{-1} - 7.1(Mn) + 8.5(Si), \quad (4)$$

where elements are in weight percent, and wear is in cubic millimeters.

ANALYSIS OF UNHARDENED STEELS

For the unhardened steels, the best fit was found by using square root of carbon. Using MLR, carbon was found significant at the 99.5-pct confidence level, and Mn, S, and Mo at the 95-pct level. In this case, the multiple correlation fit was 0.85. The equation for wear for the unhardened steels is

$$\text{Wear} = 190 - 120(C)^{1/2} - 24(Mn) - 500(S) + 95(Mo), \quad (5)$$

where elements are in weight percent, and wear is in cubic millimeters.

For unhardened steel, carbon is useful in decreasing wear, probably by increasing the amount of work hardening that occurs during wear. Manganese also is useful, probably by hardening the ferrite. Sulfur, although not considered desirable, probably is a solid solution strengthener. Molybdenum increases the wear, possibly by combining with some of the carbon.

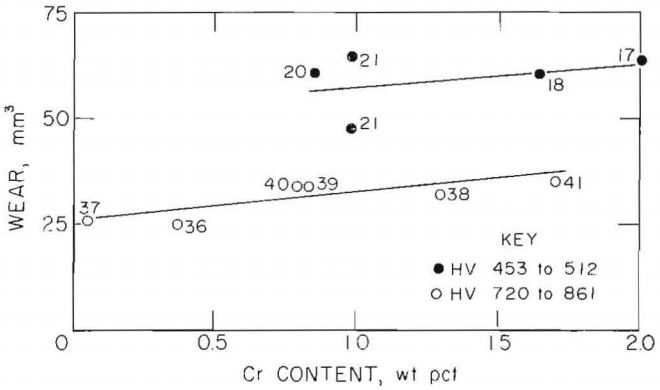

FIGURE 8.—Effect of chromium on wear resistance of hardened low-alloy steels.

EFFECT OF CHROMIUM

Because of the Bureau's concern for the supply and conservation of chromium in the United States, the effect of this element on wear is emphasized. The results from hypothesis testing, as shown in equation 2 for all the low-alloy steels, equation 4 for the hardened steels, and equation 5 for nonhardened steels, do not show chromium to be significant in affecting wear.

A simplified linear analysis of the effect of chromium on wear of hardened steels was made on two groups of specimens. The results can be interpreted from figure 8. Five samples (17, 18, 20-21) with moderate hardness, HV 453 to 512, and medium C, 0.23 to 0.33 wt pct, showed an increase in wear with up to 2 wt pct Cr. Six very hard samples (37-41), HV 720 to 861, containing 0.90 to 1.05 wt pct C, showed that Cr was deleterious because it increased the wear.

CONCLUSION

Steels with the least wear were found to be hardened high-carbon steels containing 0.55 to 1.0 wt pct C. These steels had enough alloying additions, 0.6 to 1.0 wt pct Mn, along with a sufficient carbon level, to provide full hardening in small specimens. Sulfur, in small amounts, also decreased the wear for the unhardened steels. Other alloy additions were not significant in reducing wear. The best steels tested were hardened experimental steels that fell within the specifications for AISI 1055 and 1078.

Carbon was found to reduce the wear of both hardened and nonhardened steels. Manganese decreased wear in all of the steels because it strengthens ferrite and increases the hardenability of the

steels, thus reducing wear in hardened steels.

Other alloy additions may be useful for other purposes. A plain carbon steel has limited hardenability; therefore, additional alloying elements may be necessary to increase the depth of hardening. Chromium and molybdenum, despite being shown as generally detrimental to the wear resistance of steels, would probably be added in order to increase the hardenability.

Molybdenum and silicon were shown to increase wear. Molybdenum, being a carbide former, probably combines with carbon that might otherwise strengthen the steel. The reason that silicon increases abrasive wear of steel is still undetermined.

This work suggests that the best abrasive wear resistance in a low-alloy steel is obtained by--

1. Making the steel as hard as practical.
2. Having a high carbon level, at least up to 0.7 to 0.8 wt pct. It increases hardness in hardened steels, and improves work hardening in nonhardened steels.
3. Using a fairly large amount of manganese. It is useful in reducing wear in nonhardened steels, within the limits tested of 0 to 2 wt pct Mn.
4. Adding other alloying elements to adjust other properties. For example, add Ni for toughness and Cr and Mo for hardenability.

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APPENDIX A

TABLE A-1. - Heat treatment and structure of test materials

Sample	Alloy	Condition	Heat treatment and temperature	Measured hardness		Structure
				Surface	In scar	
1.....	Ferro Vac, E.....	R	As received.....	HRA22	NA	Ferrite.
2.....	Cor 99.....	R	...do.....	HRA34	HRA33	Ferrite, grain size 7.
3.....	Experimental steel	R	1,100° C working temp.....	HRA41	NA	Fine ferrite and a little pearlite.
4.....	...do.....	R	...do.....	HRA42	HRA42	Fine ferrite and 10 pct pearlite.
5.....	...do.....	R	...do.....	HRA54	NA	Ferrite and 10 pct pearlite.
6.....	...do.....	R	...do.....	HRA51	NA	Ferrite and some pearlite.
7.....	AISI 1018.....	R	As received.....	HRB76	NA	Ferrite and pearlite, grain size 8 to 9.
8.....	AISI 4620.....	R	1,100° C rolling temp.....	HRA55.5	NA	NA.
		A	Heat to 840° C; hold for 3 h; furnace cool..	HRA46	NA	NA.
		WQ	Heat to 840° C; WQ.....	HRC43	HRC44	Martensite.
9.....	USS "T1".....	RQ	As received.....	HRA61	NA	NA.
		WQ	Heat to 900° C; WQ.....	HRC45	HRC43	NA.
10.....	USS "T1", Type B..	RQ	As received.....	HRA46	HRA64	Unresolved.
		WQ	Heat to 900° C; WQ.....	HRC45	HRC43	NA.
11.....	Experimental steel	R	1,100° C working temp.....	HRA68	NA	NA.
		WQ, T	Heat to 900° C; WQ; temper at 200° C.....	HRC46	HRC46	Martensite.
12.....	AISI 8620.....	A	NA.....	HRA45	HRA46	Ferrite and pearlite, grain size 8.
		R	As received.....	HRC53	HRC53	Bainite and ferrite, grain size 7.
		WQ	Heat to 860° C; WQ.....	HRC44	HRC44	Fine martensite.
13.....	Experimental steel	R	1,100° C working temp.....	HRA67	NA	NA.
		WQ, T	Heat to 700° C; WQ; temper at 150° C.....	HRC43	HRC44	0.005-in layer of ferrite plus fine martensite and 10 pct ferrite.
14.....	...do.....	R	1,100° C working temp.....	HRA48	HRA49	Fine ferrite and 10 pct pearlite.
15.....	...do.....	R	...do.....	HRA56	HRA56	Fine ferrite and 15 pct pearlite.
16.....	...do.....	R	...do.....	HRA53	NA	NA.
		WQ, T	Heat to 900° C; WQ; temper at 200° C for 1 h	HRC44	HRC43	Martensite.
17.....	...do.....	R	1,100° C working temp.....	HRA66	NA	Bainite and ferrite.
		WQ	Heat to 900° C; WQ.....	HRC51	HRC47	Martensite.
18.....	...do.....	R	1,150° C working temp.....	HRA70	HRA71	Fine ferrite and a 2d phase, possibly austenite.
		WQ	Heat to 860° C; WQ.....	HRC50	HRC50	Martensite.
19.....	...do.....	R	1,150° C working temp.....	HRA59	HRA58	Fine ferrite and 10 pct pearlite.
		WQ	Heat to 950° C; WQ.....	HRC46	HRC48	Martensite, grain size 6.
20.....	...do.....	R	1,100° C working temp.....	HRA59	NA	NA.
		WQ, T	Heat to 700° C; WQ; temper at 150° C.....	HRC47	HRC43	0.004-in layer of ferrite plus martensite and 15 pct austenite.
21.....	REM 500.....	A	Heat to 730° C; hold 2.5 h; air cool.....	HRA54	NA	NA.
		RQ	As received.....	HRC50	NA	NA.
		WQ, T	Heat to 700° C; WQ; temper at 150° C.....	HRC50	HRC50	0.004-in layer of ferrite plus 2-phase unresolved mixture.
22.....	Experimental steel	R	NA.....	HRA49	HRA49	Ferrite and 40 pct pearlite.
		WQ	Heat to 860° C; WQ.....	HRC56	HRC55	NA.
23.....	AISI 4340.....	R	As received.....	HRA53	NA	Decomposed pearlite.
		OQ	Heat to 810° C; OQ.....	HRC51	HRC53	NA.

NA Not available.

TABLE A-1. - Heat treatment and structure of test materials--Continued

Sample	Alloy	Condition	Heat treatment and temperature	Measured hardness		Structure
				Surface	In scar	
24.....	AISI 4342.....	R	As received.....	HRA55	NA	NA.
		WQ	Heat to 840° C; WQ.....	HRC57	NA	Martensite.
25.....	AISI 8740.....	A	Heat to 1,550° C; hold for 3 h; furnace cool	HRA52	NA	NA.
		R	1,100° C rolling temp.....	HRA61	NA	Bainite, grain size 7.
		WQ	Heat to 840° C; WQ.....	HRC55	HRC54	Fine martensite and 30 to 40 pct retained austenite.
26.....	AISI 1340.....	R	As received.....	HRA63	HRA63	Unresolved pearlite and 5 pct ferrite.
		WQ	Heat to 820° C; WQ.....	HRC58	HRC56	Fine martensite.
27.....	AISI 4142.....	A	Heat to 820° C; furnace cool.....	HRA54	HRA54	Pearlite and ferrite, grain size 9.
		R	As received.....	HRA56	HRA56	Fine pearlite and spherical cementite in ferrite.
		OQ, T	Heat to 860° C; OQ; temper at 200° C.....	HRC53	HRC53	Fine martensite.
28.....	Experimental steel	R	1,100° C working temp.....	HRA58	HRA59	Fine pearlite and 15 pct ferrite.
		WQ	Heat to 810° C; WQ.....	HRC58	HRC58	Fine martensite.
29.....	AISI 6150.....	A	Heat to 850° C; hold for 3 h; furnace cool..	HRA56	HRA56	Pearlite.
		R	1,000° C working temp.....	HRA67	HRA68	Bainite.
		OQ, T	Heat to 860° C; OQ; temper at 150° C.....	HRC55	HRC58	Martensite and some bainite.
30.....	Experimental steel	R	1,100° C working temp.....	HRA59	HRA59	Pearlite.
		WQ	Heat to 850° C; WQ.....	HRC62	HRC60	Martensite.
31.....	AISI 1060.....	A	Heat to 840° C; hold for 3 h; furnace cool..	HRA53	HRA54	Pearlite and ferrite, grain size 8.
		R	As received.....	HRA59	HRA60	Pearlite and ferrite, grain size 7.
		WQ	Heat to 820° C; WQ.....	HRC61	HRC59	Martensite and some pearlite.
32.....	Experimental steel	R	1,100° C working temp.....	HRA53	HRA53	Pearlite and 30 pct ferrite.
		WQ	Heat to 860° C; WQ.....	HRC65	HRC41	Fine martensite.
33.....	AISI 5160.....	A	Heat to 820° C; furnace cool.....	HRA57	HRA58	Fine pearlite.
		R	As received.....	HRA66	HRA66	Pearlite, grain size 8.
		WQ	Heat to 860° C; WQ.....	HRC61	HRC59	Martensite.
34.....	Omegalloy 61.....	RQ	As received.....	HRC65	HRC63	Martensite, grain size 4.
35.....	Experimental steel	R	1,100° C working temp.....	HRA66	NA	Pearlite.
		WQ	Heat to 850° C; WQ.....	HRC66	HRC64	Martensite.
36.....	...do.....	R	1,100° C working temp.....	HRA60	NA	Pearlite.
		OQ	Heat to 850° C; OQ.....	HRC65	HRC63	Martensite.
37.....	...do.....	R	1,100° C working temp.....	HRA60	HRA61	Pearlite.
		WQ	Heat to 810° C; WQ.....	HRC66	HRC65	Martensite and some pearlite.
38.....	...do.....	R	1,150° C working temp.....	HRC40	HRC39	Pearlite.
		OQ, T	Heat to 860° C; OQ; temper at 150° C.....	HRC65	HRC64	Martensite and some fine, round carbides.
39.....	...do.....	R	1,100° C working temp.....	HRA66	NA	Pearlite.
		OQ, T	Heat to 860° C; OQ; temper at 150° C.....	HRC63	HRC62	Fine martensite and a little pearlite.
40.....	...do.....	R	1,050° C working temp.....	HRC36	HRC35	Pearlite.
		OQ, T	Heat to 860° C; OQ; temper at 150° C.....	HRC63	HRC62	Martensite.
41.....	AISI 52100.....	A	Heat to 780° C; hold for 3 h; air cool.....	HRA55	NA	Decomposed pearlite.
		R	1,000° C working temp.....	HRA67	HRA68	Fine grain pearlite and maybe graphite.
		OQ, T	Heat to 790° C; OQ; temper at 200° C.....	HRC61	NA	Martensite and some round carbides.
42.....	W1.....	R	As received.....	HRA51	HRA51	Spherodite.
		A	Heat to 820° C.....	HRA54	HRA52	Ferrite and small, round cementite.
		WQ	Heat to 860° C; WQ.....	HRC64	HRC64	Martensite and some cementite.
43.....	Experimental steel	R	1,100° C working temp; soak after 16 h.....	HRA66	HRA66	NA.
		WQ	Heat to 800° C; hold for 20 min; WQ.....	HRC67	HRC64	NA.

NA Not available.

NOTE.--A Annealed. WQ Water quenched. RQ Received in hardened condition.
OQ Oil quenched. R Hot rolled (assumed for purchased commercial steels). T Tempered.

APPENDIX B

The self-directing optimization (SDO) technique was used for the optimization. In this technique, a simplex is created that continually directs itself toward an optimal composition. To do the optimization, you first need n + 1 tests, one more test than the number of independent components that you are trying to optimize. The composition of the new material to test is calculated by the rule: Twice the average of the "n" best points minus the worst point, for each independent component. The data for the material with the worst test results are now eliminated. A test is now done with the new composition. You now have n + 1 test again, so the next optimized composition can be calculated with the new best "n" test materials minus the worst of this group. This can be repeated until there is no improvement through several optimization runs, or until time or money runs out.

An example of this SDO technique based on data from this report follows. Using just four independent variables, C, Cr, Mn, and Mo, it will be shown how the composition of an unhardened steel can be optimized. First five abrasion tests are run, letters A-E. The composition of the alloy was then set up as a matrix shown in table A-1. The composition for the new alloy is calculated using the rule of twice the average of all but the worst point, minus the worst point.

TABLE B-1. - Example data for self-directed optimization

	Analysis, wt pct				Wear, mm^3
	C	Cr	Mn	Mo	
Alloy:					
A.....	~~0.18~~	~~0.08~~	~~0.43~~	~~0.04~~	~~121~~
B.....	.20	.43	.67	.13	114
C.....	.40	.79	.71	.27	113
D.....	.44	1.05	.83	.12	86.7
E.....	1.07	.05	.30	.05	99.9
Av.....	.53	.58	.74	.14	NAp
2X (Av).	1.06	1.16	1.47	.28	NAp
Less alloy A	.18	.08	.43	.04	NAp
New alloy, F	.88	1.08	1.04	.25	(83)

NAp Not applicable.

New alloy, F, is obtained for the next test. After conducting the wear test on this alloy, we see that some improvement has taken place. Using this specimen in the set of data and eliminating A, the optimization procedure is repeated in table B-2.

TABLE B-2. - Second iteration from sample optimization example

	Analysis, wt pct				Wear, mm^3
	C	Cr	Mn	Mo	
Alloy:					
B.....	~~0.20~~	~~0.43~~	~~0.67~~	~~0.13~~	~~114~~
C.....	.40	.79	.71	.27	113
D.....	.44	1.05	.83	.12	86.7
E.....	1.07	.05	.30	.05	99.9
F.....	.88	1.08	1.04	.25	83
Av.....	.70	.74	.72	.17	NAp
2X (Av).	1.40	1.48	1.44	.35	NAp
Less alloy B	.20	.43	.67	.13	NAp
New alloy, G	1.20	1.92	.77	.22	39

NAp Not applicable.

With the result from this step, alloy G, an alloy with considerably higher chromium, is made and tested. The wear in this case is considerably better, at 39. Going through the optimization one more time, with alloy G in the new set of data and B removed is shown in table B-3.

TABLE B-3. - Third iteration from sample optimization example

	Analysis, wt pct				Wear, mm^3
	C	Cr	Mn	Mo	
Alloy:					
C.....	~~0.40~~	~~0.79~~	~~0.71~~	~~0.27~~	~~113~~
D.....	.44	1.05	.83	.12	86.7
E.....	1.07	.05	.30	.05	99.9
F.....	.88	1.08	1.04	.25	83
G.....	1.20	1.92	.77	.22	39
Av.....	.90	1.03	.74	.16	NAp
2X (Av).	1.80	2.05	1.47	.32	NAp
Less alloy C	.40	.79	.71	.27	NAp
New alloy, H	1.40	1.26	.76	.05	32

NAp Not applicable.

This technique does not promise improvement each time, but the new alloy should be better than the alloy eliminated, and the trend should be toward an optimum alloy.

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