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THE TESTING OF STEEL FOR WEAR BY ABRASIVES

BY

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A

THESIS

submitted to the faculty of the

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in partial fulfillment of the work required for the

Degree of

METALLURGICAL ENGINEER

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Approved by Chas Y Clayton

Professor of Metallurgy.

NOT FOR PUBLICATION

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

The testing of metals for wear resistance means that an apparatus must be developed for the specific type of wear one is studying. We can justly say with Boeghold (1) that, "A universal wear test can be placed in the same category as the perpetual motion machine." Materials that withstand one type of wear may or may not be or any value in another type.

Boeghold (2) gives the following list of more common methods by which metallic parts are destroyed by wear:-

TYPE OF WEAR	EXAMPLE
1. Unlubricated sliding surface contact	Brake shoe on car wheel
2. Lubricated sliding surface contact	(Plain bearing (Piston against cylinder
3. Rolling unlubricated	Car wheels on track
4. Rolling lubricated	Roller and Ball bearings
5. Crushing non-metallic abrasives	Rock crushing jaws
6. Abrasion by non-metallic dry	Steam shovels
7. Abrasion by non-metallic wet	Pumps handling wet sand
8. Crushing non-metallic abrasives wet	Wet Grinding Ore
9. Soft material against steel, lubricated, where soft material is continually renewed	Copper wire drawing
10. Soft material against steel, unlubricated, where soft material is continually renewed	Flyers used in Silk Spinning

(1) Proc. A.S.T.M.- Vol.29, 1929, Part.II, P.125.
(2) Loc. Cit. P.116.

The tests herein reported were conducted with the idea of finding a steel which would give improved wear as roll shells in the comminution of ores. Types 5, 6, 7 and 8 of the above classification come under this category. Not only must the wear be considered, but also the physical properties. It is desirable to have a steel of such Tensile and impact values that no failure by breakage would occur until the shell was worn very thin. The ideal condition being to wear the shell down to zero thickness, but such cannot be accomplished.

Economic aspects of the case also bear considerable relationship to the thickness of the shell before discard. Thus a cheaper shell need not wear as thin before breaking as a more expensive composition.

Felix Robin (3) studied wear by measuring the loss of weight of a specimen after holding it under a known pressure on a revolving disc covered with emery paper. He studied the effect of the nature of the abrasive, the speed of revolution of the disc, and the influence of pressure on the specimen. His study of the effect of the different alloys on wear is very interesting, but has very little to do with the subject in hand, due to the fact that the hardness of the materials he used was far beyond any that could possibly be used in roll shells.

J.M.Blake (4) studied the effect of wet grinding

(3) Felix Robin, "Report on the Wear of Steels"- Iron & Steel Institute Carnegie Scholarship Memoirs - Vol.II, P.1, (1910)
(4) J.M.Blake "Wear Testing of Various Types of Steels"-Proceedings, Amer.Society for Testing Mats. Vol.28, PartII, P.341,(1928)

on materials and described the Fahrenwold machine, which is a wet grinding machine in which the pressure, time, speed, abrasive, and moisture can be accurately controlled. It is quite a bulky piece of apparatus and Blake does not give conclusive proof that it gives results that are reproducible in the field.

Hall (5) used a small jaw crusher and used different liners in the jaws. He measured his wear by loss in weight per unit surface per ton of ore crushed. He only listed low carbon steel and manganese steel.

The testing of the wear on automobile tire chains was developed by Parker (6). He held the chain against a grinding wheel and measured the number of revolutions required for the removal of a given amount of material.

Others (7) have studied the wearing qualities of different steels for special purposes but they need not be considered for this report.

The work proposed called for the development of a machine not too complicated, yet of sufficient accuracy to allow reproducibility of results and also ~~to and also~~ to give us some idea as to the resistance of different compositions of steel to

(5) J.H.Hall, "Wearing of Twelve Percent Manganese Steel," Proc. Amer. Soc. for Testing Mats. Vol.28,PartII, P.326, (1928)
(6) W.H.Parker, "The Wearing Qualities of Tire Chains", Proc. Amer. Soc. for Testing Mats. Vol. 28, Part II, P.352 (1928)
(7) See Bibliography.

abrasive wear. Consequently an abrasive wear testing machine, based somewhat on Robins idea, was developed.

TESTING APPARATUS

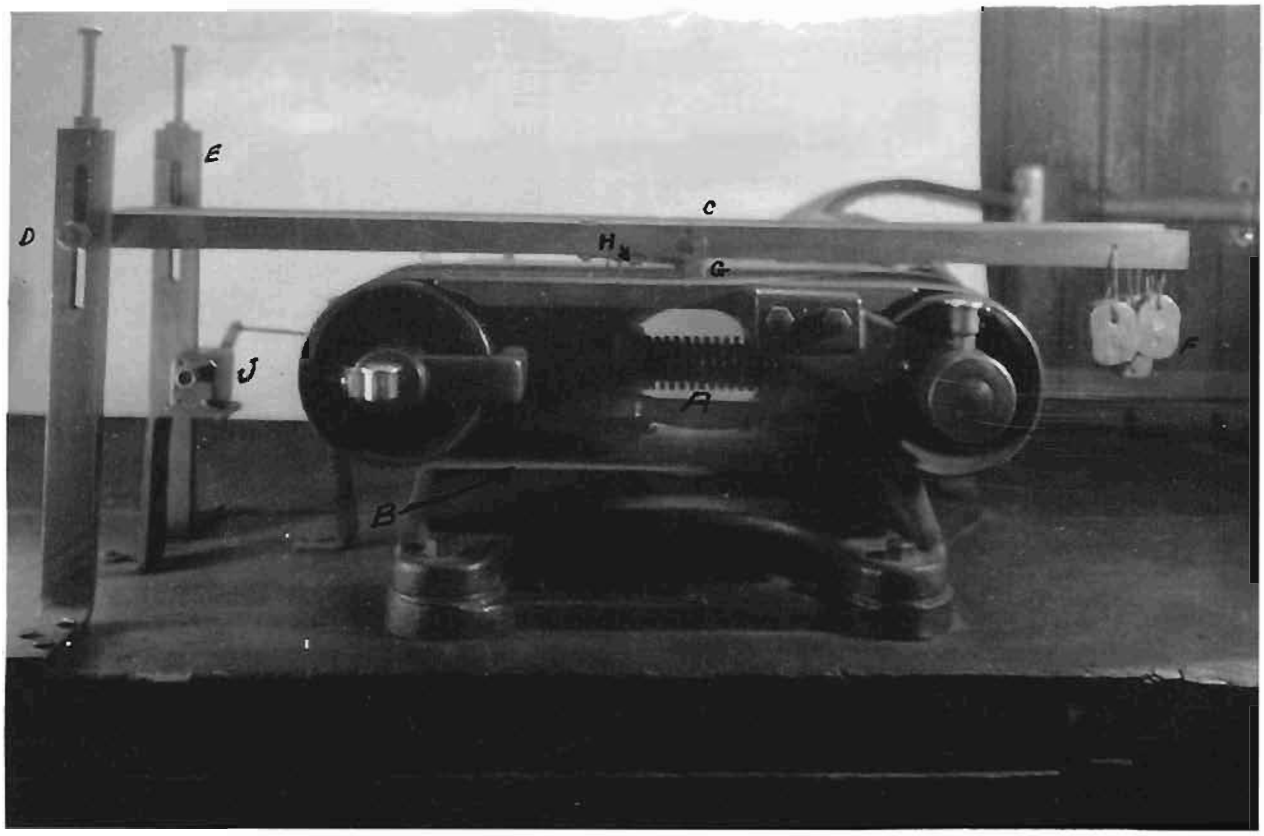

Fig.I. Wear Testing Apparatus.

The testing apparatus (Fig.1) consists of a small motor driven belt grinder:- (A) using a 4" wide abrasive belt. (B) The type of belt used is grit.100 - Metalite adamite cloth made by the Behr-Manning Abrasive Co. of Troy, N.Y. This type of belt was picked arbitrarily because it appeared to be best suited for the work intended. The grit is firmly held on the belt and is not fine enough to clog up and not coarse enough to break out easily.

Because of the width of the belt, 4 specimens can be run at the same time. These specimens are held on the belt my means of four levers (C) supported at one end by a rod (D), which is in turn held firmly by an adjustable rack (E). The other end of the rod is weighted with lead (F) so as to give a pressure of 5 pounds per square inch on the face of the specimen.

The specimens are held in place by a small box shaped holder (G) fastened to the lever. One side of this box is left open so that the specimen can easily be placed into it. A small sliding piece (H) with a lip shaped to form the other side of the box is then pressed firmly against the specimen and held tightly by a screw.

The specimen itself is 1 cm x 1 cm x 1.2 cm. It was so chosen so that 4 specimens could be obtained from the broken halves of a standard Charpy Impact test specimen, thus saving the expense of extra machining.

The revolutions of the belt are counted by means of a Veeder (J) counter, which is run by a cam attached to the idler wheel. It is to be noted that the counter is not attached to the driving wheel because of a slippage of the belt when loaded.

TABLE NO.I [redacted] TREATMENTS

A - 2000 - 3 hrs. air; 1700 - 6 hrs. air; 1425 - 6 hrs. slowly.

B - 2000 - 3 hrs. air; 1425 - 6 hrs. slowly.

C - 1750 - 6 hrs. air; 1625 - 6 hrs. slowly; 1100 - 6 hrs. slowly.

D - 1750 - 6 hrs. air; 1425 - 6 hrs. slowly.

A1 - 1800 3 hrs. air; 1200 - 3 hrs. air.

B1 - 1800 - 3 hrs. air; 1450 - 3 hrs. slowly.

C1 - 1800 - 3 hrs. air; 1450 - 3 hrs. slowly; 1200 - 3 hrs. air.

E - 1700 - 3 hrs. air; 1425 - 5 hrs. slowly; 1300 - 5 hrs. furnace.

F - 1725 - 12 hrs. air; 1625 - 12 hrs. air; 1225 - 15 hrs. slowly.

G - 1625 - 12 hrs. air; 1200 - 12 hrs. slowly.

H - 1625 - 6 hrs. slowly; 1475 - 5 hrs. oil; 1125 - 5 hrs. slowly.

K - 1725 - 12 hrs. air; 1625 - 12 hrs. air; 1100 - 12 hrs. slowly.

L - 1800 - 1 hr. furnace; 1100 - 1 hr. slowly.

M - 1800 - 3 hrs. air; 1000 - 3 hrs. slowly.

N - 1850 - 4 hrs. air; 1200 - 4 hrs. slowly.

O - 1900 - 4 hrs. air; 1550 - 4 hrs. Fur. Cool - 1200 - 4 hrs. slowly.

P - 1800 - 3 hrs. air; 1450 - 3 hrs. Cool 1 M.V./hr. - 1200 - 4 hrs. slowly.

R - 1800 - 3 hrs. air; 1750 - 3 hrs. air - 1450 - 3 hrs. slowly.

S - 1800 - 3 hrs. air; 1450 - 3 hrs. cool - 30 deg./hr.

T - 1750 - 3 hrs. air.

U - 1750 - 3 hrs. air; 1000 - 3 hrs. slowly.

All temperatures are given in degrees Fahrenheit.

CALIBRATION OF WEAR MACHINE

The only calibration that was done was to determine the length of time to run a test and to see how closely results could be duplicated with this given time, all other variables such as type of abrasive, speed of belt, and pressure, being kept constant. With any good abrasive cloth it is common knowledge that its greatest cutting efficiency is at the beginning of use. As the small cutting edges of the grain are dulled, the efficiency gets poorer and poorer, until finally the grains are so dull that they are actually pulled out of the glue holding them. This pulling action starts at the very first, but is not noticeable until the grains are sufficiently dull to cause friction, which softens the glue.

Another factor that is equally important is the clogging up of the cloth by the chips of material ground out. The finer the grain, the more important this item becomes. Friction then heats the glue and allows the grains to be pulled out. The coarser grained cloths are less subject to this action than those of finer grain.

In choosing a cloth for this work, care was taken to have a grain sufficiently fine to avoid excessive pulling out and yet not fine enough to clog when run a reasonable length of time. This grain was arbitrarily picked as 100X and was found to give excellent results.

Time was first used as an indicator of the length of run for each test, but it was soon discovered that the results could not be checked with any reasonable accuracy. There is a certain amount of slippage of the belt on the driving pulley which is not constant. Timing was therefore discarded as an indicator of length of run.

With this idea of slippage in mind, a veedor counter run by a cam was attached to the idling pulley, which would indicate the actual movement of the belt irrespective of the slippage.

Tests were then run by determining the weight lost in grams per square centimeter of specimens after each 1000 revolutions of the idle pulley. The average of 4 separate specimens is plotted in Fig. 2. There is a straight line relationship of wear to revolutions up to 2500. Above this figure the factors mentioned above begin to prominently assert themselves and the curve leaves the straight line tangentially. If this test were run far enough, it is expected that the curve will approach a horizontal line. Therefore 2500 revolutions, which means a belt travel of 604 feet, was adopted as our standard length of run.

Another variable, which was investigated, was the ability of the machine to check results. Consequently 24 specimens taken from a carbon roll shell and 24 specimens from a chrome molybdenum roll shell were run, giving 24 tests on each composition. The results of these tests are given in Tables 2 and 3. The average deviation from the average is below 10% in both cases. This was considered sufficiently accurate for the purpose of the test.

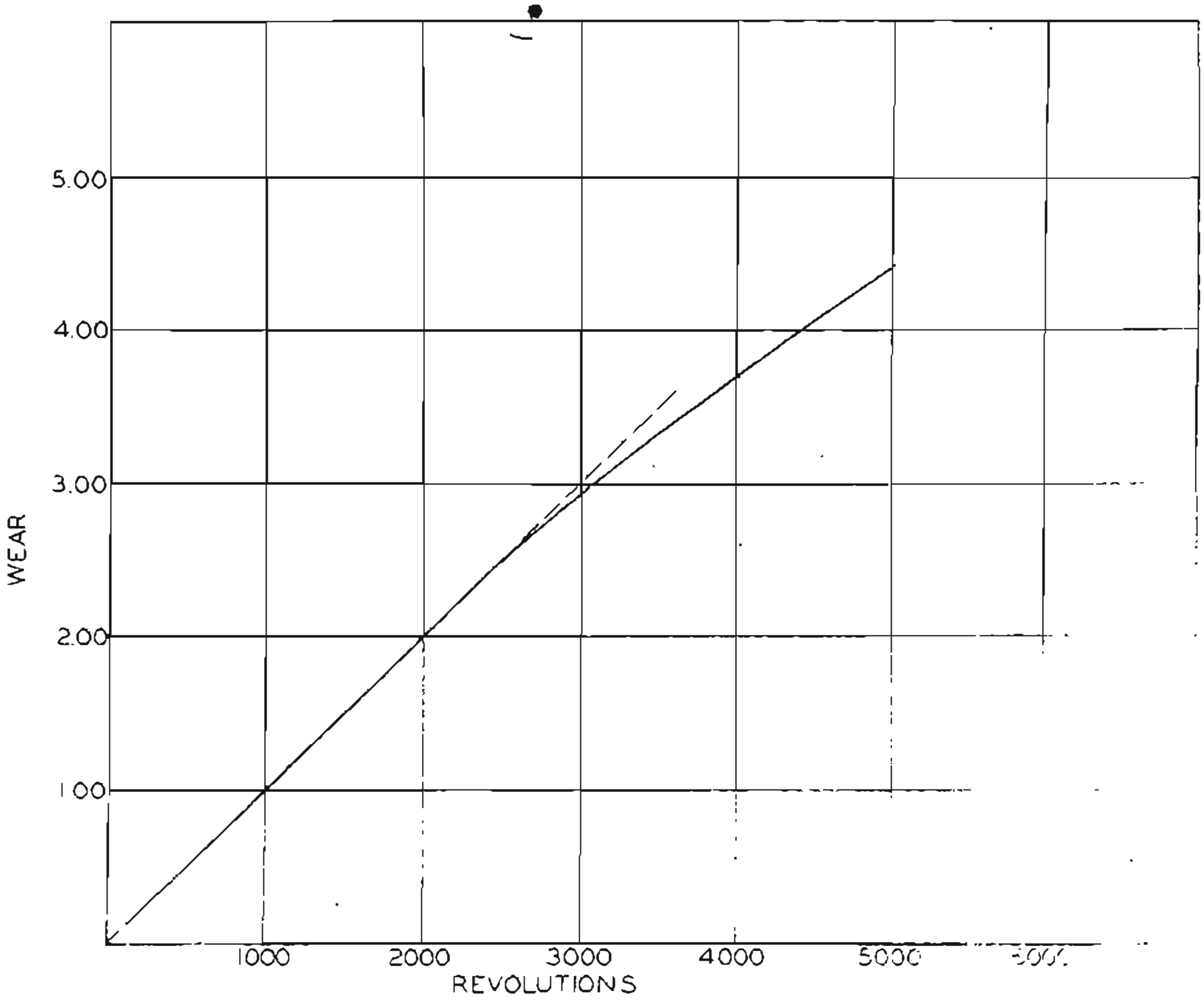

Fig. 2. Wear Vs. Revolutions. Plotted to determine the standard length of run.

TABLE NO. II

ACCURACY OF TEST

	C.	Mn.	P.	S.	Si.	Cr.	Mo.
Composition -	.59	.89	.033	.027	.30	1.19	.21

Treatment - 1725 Deg.F. - 12 hrs. - air
1625 Deg.F. - 12 hrs. - air
1225 Deg.F. - 12 hrs. - C. S.

	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.
Physical Properties -	135,500	60,000	74,000	13.0	27.0	4.77

Specimen No.	Brinell	Wear
II A1	255	2.59
II A2	255	2.64
II A3	267	2.42
II A4	261	2.30
II B1	267	2.53
II B2	269	2.48
II B3	271	2.53
II B4	258	2.37
II C1	267	2.60
II C2	269	2.58
II C3	275	2.48
II C4	267	2.47
II D1	262	2.54
II D2	277	2.53
II D3	270	2.56
II D4	266	2.56
II E1	275	2.53
II E2	271	2.68

TABLE NO.II ACCURACY OF TEST (Continued)

Specimen No.	Brinell	Wear
IIE3	269	2.61
IIE4	258	2.47
IIF1	277	2.65
IIF2	273	2.46
IIF3	273	2.63
IIF4	255	2.67
Ave.	267	2.538

TABLE NO.III

ACCURACY OF TEST

	C.	Mn.	P.	S.	Si.
Composition -	.73	.74	.037	.041	.25

Treatment - 1625 - 12 hrs. - air cool
1200 - 12 hrs. - C. S.

	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.
Physical Properties -	117,500	47,500	58,250	13.0	17.8	2.24

Specimen No.	Brinell	Wear
III A1	215	2.63
III A2	214	2.97
III A3	212	2.52
III A4	204	2.84
III B1	207	2.54
III B2	204	2.48
III B3	207	2.60
III B4	210	2.52
III C1	207	2.54
III C2	207	2.38
III C3	210	2.53
III C4	212	2.63
III D1	217	2.54
III D2	212	2.70
III D3	215	2.58
III D4	214	2.45
III E1	216	2.76

TABLE NO.III ACCURACY OF TEST (Continued)

Specimen No.	Brinell	Wear
III E2	215	2.58
III E3	215	2.64
III E4	214	2.50
III F1	217	2.77
III F2	217	2.74
III F3	217	2.64
III F4	214	2.65
Ave.	212.1	2.613

MATERIALS TESTED

Both castings and forgings of Carbon steels, Manganese, Manganese Molybdenum, Molybdenum, Chrome-Molybdenum, Nickel-Chrome-Molybdenum, Nickel-Chrome, steels, with varying carbon and alloy additions, heat treated with varying treatments to give special micro structures and varying Brinell hardness, were used. The tensile properties, Charpy Impact, Brinell hardness and wear results are given for each type of material and are listed in the attached tables.

It will be noted that the tensile properties of a number of the castings are not given. These were experimental heats cast from a high frequency induction furnace, using a very limited amount of metal, not allowing the use of sufficient risers, etc. to obtain sound castings. The Brinell and wear figures in these cases are the only ones which may be considered accurate.

Other tests where only Brinell and wear are given, treatment and physical properties being missing, are small samples obtained from large castings by Mr. Alan Kissock of the Climax Molybdenum Co. and tested on our machine.

Wear was plotted against Brinell hardness for each type alloy and each composition of steel used of that alloy. Each type alloy is kept on a separate chart. The numbers on each curve refer to the specific composition, which may be found listed as "Heat No." in the tables. All compositions are plotted where it was possible to obtain a sufficient number of points to give proper identification to the results. The plotting of the carbon steels was eliminated because of the few points obtainable. It was considered easier to draw deductions from the table itself.

CARBON STEELS

Heat. No.	C.	Mn.	Si.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
6-9228	.24	.64	.23	as forged	75000	38000	45000	30.7	55.7	44.10	119	3.23
5-6578	.64	.27	.20	annealed	85000	20000	35000	19.0	28.5	2.63	141	2.90
G6233-1	.77	.72	.22	G	113000	39000	54500	8.7	10.0	3.62	197	2.42
G6254-1	.74	.75	.20	G	100000	34000	50000	4.2	3.5	2.24	199	2.39
MPD705	.89	.30	.20	annealed	78500	33000	40000	28.2	51.7	9.80	129	2.75
4-8795	1.32	.12	.16	"	83000	33000	48000	20.0	34.4	4.22	144	2.20
5513	.76	.69	.25	G	109500	42000	51500	15.2	28.5	3.63	193	2.89
8550	.74	.77	.28	G	125000	41000	54500	5.7	8.5	3.22	218	2.58
8770	.78	.71	.19	G	119500	40000	52500	12.5	18.1	3.22	207	2.57
8778	.78	.71	.19	G	128000	49000	60000	10.0	15.2	2.24	226	2.40
9705	.74	.79	.17	G	109000	32000	45500	12.7	18.5	2.24	187	3.06

CASTINGS

Heat. No.	C.	Mn.	Si.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
KE1459	2.20	.68	.09	B-1	73500	51000	57500	1.2	1.2	3.88	253	.872
				C-1	65500	49000	55000	1.0	.8	1.08	248	.863
1" P.P.	2.99		.50								430	.54
1" Chill Slug	3.49	.49	1.93								477	.84
2" F.P.	3.87	.27	.80								512/ 550	.45

CARBON MANGANESE - FORGINGS

Heat. No.	C.	Mn.	Si.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
E3010	.52	1.58	.20	A-1	98000	51000	53000	25.0	49.5	24.52	171	3.18
				B-1	113000	60000	61500	19.2	39.4	9.80	204	2.97
				C-1	105000	50000	57000	22.2	45.4	12.26	187	3.09
E3011	.56	1.50	.20	A-1	99500	51000	53500	23.0	45.7	12.26	171	2.94
				B-1	114000	57000	62000	18.2	36.9	7.16	208	2.52
				C-1	107000	51000	54000	21.0	39.1	10.80	189	2.78
E1405	.82	2.43	.18	A-1	131000	80000	93000	7.7	8.5	3.63	252	2.68
				B-1	123000		71000	11.0	8.9	1.41	213	2.91
				C-1	112000	59000	61000	17.2	29.2	5.49	205	2.53
E1908	.92	1.56	.43	A-1	152000		85000	9.2	15.2	6.43	280	1.98
				B-1	109000	65000	67500	22.7	47.2	10.24	192	3.14
				C-1	107000	60000	64000	24.0	46.9	12.57	185	3.29
EE1408	1.28	2.13	.25	A-1	145000		88000	2.0	3.1	2.24	302	1.76
				B-1	112000	64000	68000	9.7	8.9	2.65	206	2.81
				C-1	111000	65000	67500	16.2	28.9	4.20	203	2.26
EE1394	.76	1.49	.19	A	112000	50000	58000	11.0	25.5	4.12	192	3.12
				B	123500	53000	59000	9.0	11.1	1.08	223	2.65
				C	116000	45000	52000	12.2	17.8	2.24	206	2.59
				M	153000		86000	9.5	14.8	4.65	285	1.75
EE1396	.93	1.67	.20	A	111000	48000	57000	15.2	42.2	4.70	195	3.22
				B	117000	58000	61500	10.2	11.1	2.24	213	2.65

CARBON MANGANESE - FORGINGS (Continued)

Heat. No.	C.	Mn.	Si.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
				C	105000	50000	57000	18.7	32.5	6.18	184	3.03
				M	168500		122000	3.2	3.9	1.16	321	1.26
EE1319	.64	1.65	.27	A	101500	51000	55000	22.5	46.0	10.79	183	3.28
				B	121000	54000	61000	12.5	22.7	2.07	214	2.66
				C	117000	54000	59000	11.7	30.5	2.64	213	2.57
				D	128000	51000	60000	10.5	17.6	1.66	227	2.27
				L							262	1.74
EE 1314	.60	1.52	.20	A	104500	51000	54000	20.0	36.3	3.06	193	3.09
				B	122000	54000	61000	7.2	7.8	1.66	218	2.87
				C	110000	68000		3.2	3.1	1.08	221	2.39
				D	121000	57000	62500	8.2	10.4	1.16	204	2.73

CASTINGS

Heat. No.	C.	Mn.	Si.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EE1465	2.15	2.70	.32	B-1	86000	77000	82000	.5	1.9	1.08	293	.830
				C-1	89500	78000	85000	1.2	2.4	1.08	285	.976

CHROME MOLYBDENUM - FORGING

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
P4385	.59	.89	.30	1.19	.21	F	135500	60000	74000	13.0	27.0		268	2.54
EE1324	.58	.52	.48	1.89	.34	A	120000	78000	84000	20.5	51.7	24.70	224	3.18
						B	116000	75000	81000	20.5	52.5	23.76	211	3.10
						C	106000	66000		22.5	47.5	18.01	187	3.13
						D	114000	69000	77000	19.2	50.0	24.23	215	3.24
EE1330	.96	.22	.56	1.99	.28	A	137000	78000	83000	16.2	28.5	9.42	253	2.89
						B	139000	93000	101500	15.0	30.2	6.69	256	3.13
						C	110000	63000	66000	22.0	52.8	20.94	193	2.98
						D	136500	72000	80000	8.2	15.9	3.63	251	2.93
						L							304	2.00
EE1331	1.24	.90	.51	2.12	.27	A	133000	72000	78000	14.2	22.7	4.70	250	2.92
						B	143500	84000	95000	11.7	18.5	1.66	261	2.71
						C	117000	63000	69000	19.7	38.8	10.30	211	2.42
						D	141000	78000	84000	7.2	16.7	3.22	240	2.60
						L							304	1.77
EE1332	1.81	.86	.42	2.37	.30	A	141000	66000	73000	7.5	10.4	2.24	248	2.17
						B	156500	96000	105000	1.7	3.9	2.24	311	2.08
						C	114500	71000		15.5	20.6	6.69	224	1.77
						D	129000	80000		5.0	9.3	2.24	279	1.72
						L							294	1.12

CHROME MOLYBDENUM - FORGING (Continued)

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treat-ment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EE1333	2.02	.60	.48	2.14	.28	A	121000	75000	80000	8.7	8.1	2.24	255	1.52
						B	133500			.7	.8	1.08	346	1.26
						C	110000	70000		8.7	10.8	1.08	236	1.45
						D	127000	75000	80000	3.2	3.9	1.08	291	1.39
S-1308	.71	.79	.24	1.48	.23	1800-Air 1750-Air 1475-OS	96500	50000	59000	26.5	60.4	20.87	166	3.06
7/8" Forged	.78	1.00		1.10	.32								640	1.19
S-3336	.65	.87	.25	1.39	.27	1800-Air 1750-Air 1100-OS	162500	80000	94000	8.2	13.4	Unnotched 136.88	285	2.09
S3335	.71	.79	.24	1.48	.23	1800-Air 1750-Air 1100-OS	171000	95000	110500	10.0	25.8		345	1.97

CHROME MOLYBDENUM - SAND CASTINGS

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	YIELD Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EE1309	.60	62.	.31	2.19	.34	A							193	3.16
						B							196	3.03
						C							222	2.82
						D							228	2.78
EE1318	.76	.60	.35	1.92	.34	A							192	3.06
						B							206	2.97
						C							256	2.34
						D							218	2.83
EE1322	1.24	.58	.20	2.10	.25	A							198	2.96
						B							218	3.08
						C							224	2.95
						D							313	2.81
EE1323	1.58	.52	.42	1.97	.31	A							225	1.97
						B							247	2.18
						C							259	1.70
						D							233	2.14
EE1329	2.10	.19	.56	2.37	.25	A							286	1.34
						B							291	1.36
						C							261	1.29
						D							320	1.30
EE1418	1.44	.61	.43	2.54	.80	A-1	71,000					1.55	354	1.30

CHROME MOLYBDENUM - SAND CASTINGS (Continued)

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
						B-1	72,000					2.53	256	1.81
						C-1	53,000					4.20	248	1.94
EE1420	2.00	.54	.14	2.50	.34	A-1	83,000					3.22	338	1.28
						B-1	49,500					3.06	241	1.23
						C-1						3.22	239	1.66
EE1421	2.20	.53	.10	2.53	.39	A-1	64,000					1.08	345	1.04
						B-1	41,000					1.66	257	1.21
						C-1	52,500					2.24	254	1.24
1" Chill	.79	.73	.24	2.16	.30	C					6.3		279	2.36
2" F.P.	3.42	.25	1.20	1.10	.37								512/555	.56

MANGANESE MOLYBDENUM - CASTINGS

Heat. No.	C.	Mn.	Si.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EE1428	1.47	1.55	.20	.80	A-1	49000					6.02	240	1.52
					B-1						1.66	318	1.38
					C-1	59000					2.24	224	1.87
EE1426	1.63	1.97	.21	.35	A-1	67500					1.08	308	1.34
					B-1	63500					1.08	241	1.39
					C-1	53000					2.24	233	1.47
EE1427	1.99	1.92	.22	.35	A-1	42000					3.06	323	1.09
					B-1	49500					2.64	272	1.08
					C-1	48500					1.66	251	1.11
EE1464	2.25	.64	.28	.36	B-1	85000	61000	68000	.5	1.9	1.08	269	.692
					C-1	73000	62000	70000	1.2	1.9	2.24	187	1.32
EE1461	2.20	2.33	.14	.41	B-1	67500			.7	3.1	1.08	252	.597
					C-1	63000			.7	3.1	1.08	331	.553
E7922	1.83	.96	.57	.36	B-1	84000		66000				241	1.48
					C-1							229	1.59
E7955	2.12	1.15	.49	.41	B-1							269	1.05
HF2-86	2.09	1.02	.38	.35	B-1	65000	37000	52500	1.5	1.2	Unnotched 5.36	222	1.14
					C-1	69500	30000	47000	1.5	1.2	3.94	228	.93
HF3-77	1.70	1.13	.45	.30	C-1	59000	30000	50000	.5	1.9	3.48	178	.99

MANGANESE MOLYBDENUM - FORGINGS

Heat. No.	C.	Mn.	Si.	Mo.	Treat- ment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EB1407	.84	1.79	.23	.36	A-1	150000	91000	107000	10.0	15.6	5.20	292	2.26
					B-1	134000	50000	58000	10.0	15.6	3.65	247	2.29
					C-1	129000	57000	64000	11.5	18.1	3.06	236	2.63

CARBON MOLYBDENUM - CASTINGS AND FORGINGS

Heat. No.	C.	Mn.	Si.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
E3164	1.52	.69	.26	.29	R	103000	47000	58000	10.5	11.9	3.06	197	2.22
E3089	1.62	.63	.21	.34	N	110000					1.08	321	1.66
					O	111000		60000	3.5	4.3	1.08	225	2.30
					P	98500		47500	5.0	5.5	1.08	194	1.40
					R	97500	40000	46000	3.5	4.3	1.08	212	1.43
E3088	1.74	.63	.25	.35	N	116000		92000	.7	.8	1.66	308	1.65
					O	111000		58000	2.5	3.1	3.65	228	1.88
					P	92000		51500	3.7	3.9	1.66	205	.88
					R	94500	32000	45000	3.0	2.4	1.08	207	1.25
2"F.B. Chill	2.35	.58	.89	.48	as cast							503	.59
"	3.65	.21	.56	.32	"							522/ 589	.42
"	"	"	"	"	1450 Deg.F annealed							470	.47
"	3.23	.41	.85	.57	as cast							477/ 555	.38

CASTINGS

Heat. No.	C.	Mn.	Si.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
E7968	2.39	.62	.57	.51	B-1			68500				286	.80
					C-1							242	.71
E7994	2.27	.69	.61	.35	B-1	72000		62000				269	1.06

NICKEL CHROME MOLYBDENUM FORGINGS
NICKEL CHROME FORGINGS

Heat. No.	C.	Mn.	Si.	Ni.	Cr.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
EE1391	.60	.57	.67	2.68	1.10	.29	A	156500	82000	96000	13.0	35.7	18.04	288	2.79
							B	158000	70000	110000	15.2	36.0	9.80	288	2.88
							C	133000	80000	85000	18.0	43.7	16.09	250	3.09
							M	187500		170500	10.7	30.2	6.69	363	2.46
EE1392	.92	.58	.20	2.90	1.13	.25	A	195000		145000	6.0	8.9	4.70	363	2.36
							B	138000	62000	70500	15.0	30.2	9.42	253	2.47
							C	131000	60000	69000	18.0	39.7	12.26	236	2.79
							M	189000		165000	2.0	2.4	2.24	404	1.88
8/1317	.32	.70	.19	2.35	.62	.31		114000	75000	91500	13.2	33.1	6.69	226	3.08
E2431	.50	.55	.16	1.89	1.00		H	129500	102000	110000	20.0	58.6	44.11	243	2.89
7-1136	.52	1.08	.22	1.32	.42		A-1	119000	75000	83000	20.0	50.0	14.69	229	3.10
							B-1	124000	60000	66000	17.5	36.0	8.00	224	2.41
							C-1	120000	55000	60000	19.0	39.4	10.30	218	2.87

CASTINGS

Heat. No.	C.	Mn.	Si.	Ni.	Cr.	Mo.	Treatment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
E2682	.49	.43	.28	1.72	.98		H	122000	90000	99000	8.0	15.6	26.00	235	3.02
5264	.55	.77	.36	3.21	.92		T							600	.80
							U					12.0	.25	350	1.62

MISCELLANEOUS COMPOSITIONS

CASTINGS

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treat- ment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
2" N	2.87	.10	.28	2.82		as cast							512/ 555	.68
						1450 Deg.F slow							375	.87
Hatfield's Mn.	1.20	12.05	.21			1950 Deg.F water							160	1.11

FORGINGS

Heat. No.	C.	Mn.	Si.	Cr.	Mo.	Treat- ment	Tensile Strength PSI	Elastic Limit PSI	Yield Point PSI	Ext. %	Con. %	Charpy Impact Ft.Lbs.	Brinell	Wear Gms/ Sq.In.
"	"	"	"			"							177	1.13

DISCUSSION

It appears that three variables may be considered to effect wear resistance;—

1. Composition of the steel,
2. Hardness,
3. Condition or Micro-structure of the steel.

These variables are dependent one on the other. Hardness is a function of the composition and micro-structure. Micro-structure for any given heat treatment would be a function of the composition.

Wear appears to depend principally on hardness, two types of which are to be considered: Intrinsic and Conferred. Intrinsic hardness is that hardness inherent in the metal itself. Conferred hardness is that hardness which is given the metal by heat treatment.

Intrinsic hardness is dependent primarily on composition. It is that hardness that gives wearing qualities to babbitt and other bearing metals. In steels of the type being studied, it is believed to be due to the amount, size, hardness, distribution, and composition of carbides in the steel. It is not shown exactly by any hardness test, but may be estimated to some extent by the carbon content of the metals considered with the amount of alloying elements present, as will be shown later.

Conferred and Intrinsic hardness are at best relative terms. Certain compositions cannot, under any heat treatment, be softened beyond a certain Brinell, whereas others can, by proper manipulation, be obtained with much lower Brinell figures. A highly alloyed steel, such as high speed steel, may not be annealed much lower than between 200 and 250 Brinell, the higher figure being considered very good, whereas an exceedingly low carbon steel can be annealed below 100 Brinell. On the other hand, high speed steel may be heat treated to give a Brinell of over 600, where the carbon steel may not be changed but very few points under any treatment so far conceived, without the use of carbonization. The Brinell number, being a relative measure of hardness, is influenced both by intrinsic and conferred hardness. The lowest Brinell figure obtainable in any given composition is predominantly influenced by the intrinsic hardness of the piece. However, the conferred hardness will predominantly influence the higher figures. Both these terms are used in this paper as being readily distinguishable, and they are, when studied collectively.

Figure 3, a chart of Wear Vs. Carbon Content at a 240 Brinell and Fig. 4, at 280 Brinell, show that increasing the carbon increases wear resistance. Wear appears to be quite variable, with increase of carbon up to approximately 1.30% carbon. Above this figure it appears as a more or less straight line relationship. Carbon has approximately the same influence on all compositions. That is, if we draw an imaginary line through the points of each composition plotted on each chart, they will be more or less parallel. This applies, of course, to carbon content of 1.30% and above.

Carbon has a greater influence on wear resistance than any other element investigated. Its combination with the other elements and the reason for this influence will be considered later. With the lower carbon contents, this influence is not so well defined. Especially is this true of the Carbon-Manganese steels.

A study of these two charts in combination with the charts of Wear Vs. Brinell for each type composition may now be considered more fully.

CARBON STEELS - (Results Not Plotted.)

The best wear results obtained were from castings. A chilled casting of 3.87% carbon and a Brinell of 512/550 gave a wear of .45. A lowering of the carbon to 2.99% and the Brinell to 420 gave .54, which is comparable to .45. However, lowering the carbon to 2.20% and the Brinell to about 250, gives a wear of .87, which is double that of the highest carbon material. This material, on the other hand, is machinable where the others are not.

Increasing the carbon content increases the resistance to wear. A 1.32% carbon and a Brinell of 144 has a wear of 2.20, whereas a .74% to .78% carbon, a regular roll shell composition with Brinells of around 200 to 225, has a wear of 2.40 to 3.06. A .24% carbon with a Brinell of 119 gives the poorest

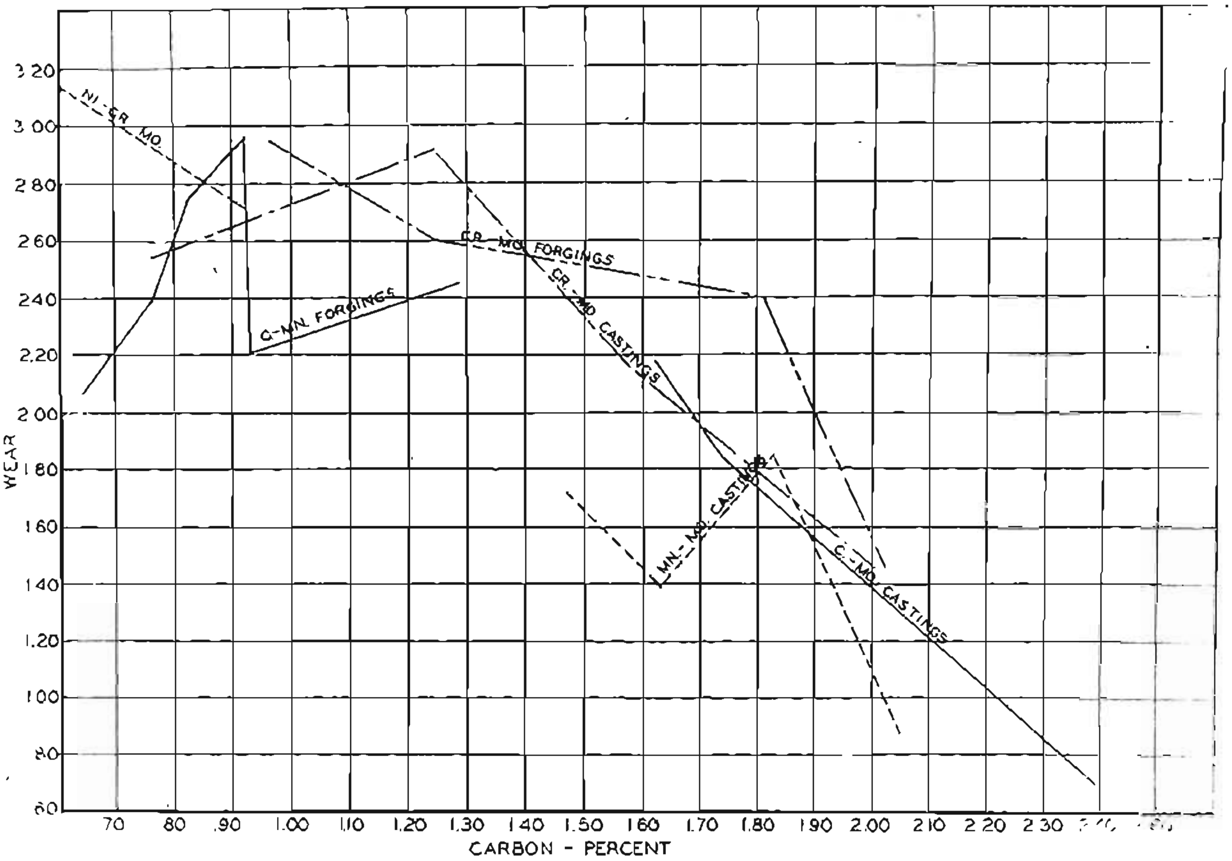

Fig. 3 - Wear Vs. Carbon Content at 240 Brinell Hardness.

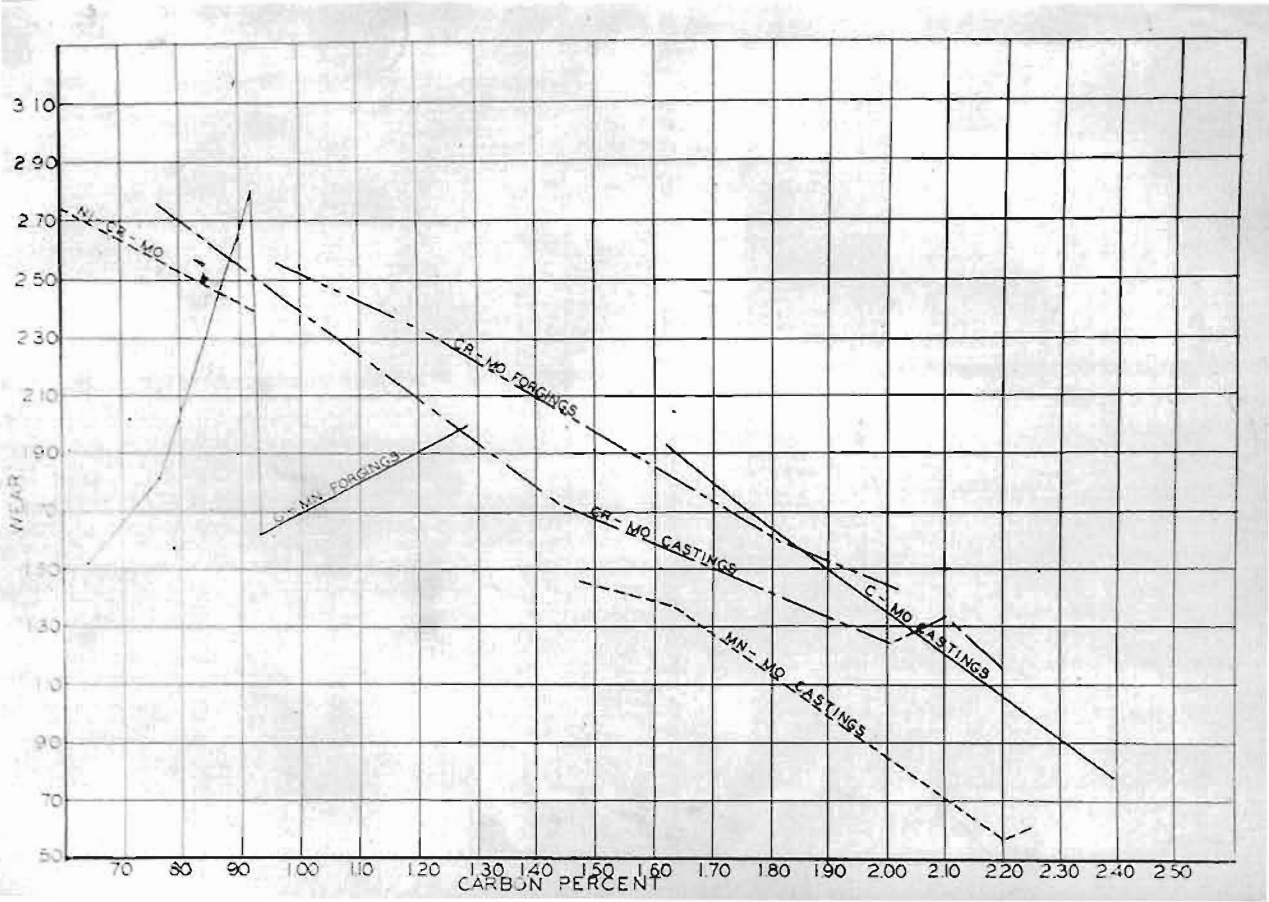

Fig. 4 — Wear Vs. Carbon Content at 280 Brinell Hardness.

wear of 3.23. In these forgings the carbon is not high enough to be of any real benefit in wear resistance.

A carbon of 2.00% or better gives excellent wear resistance, even with a Brinell hardness of around 250. This carbon content, however, calls for castings, as it is not a practical proposition to forge it successfully. Chilled cast iron has excellent wear resisting possibilities, its extreme brittleness being its only drawback.

CARBON - MANGANESE STEELS -(Fig.5)

The addition of Manganese, in the amounts investigated, to high carbon castings has little or no effect on the wear resistance. The figures given for EE1465, a 2.15% carbon, Manganese 2.70%, with Brinell of about 288 gave an average wear of .90. This compared to a straight carbon casting of 2.20% carbon, Brinell of 250 and wear of .87 does not give any advantage to the Manganese casting. Hatfield's Manganese steel of 1.20% carbon and 12.05% Manganese with Brinell of 160-177 gave a wear of 1.11-1.13. This type of steel, of course, is used extensively in the crushing of products and gives excellent results, especially where impact is to be considered. No Manganese chill castings were available for test.

The addition of Manganese with carbon up to 1.28% to the forging compositions gives no advantage in wear resistance. At low Brinells, below 220, wear resistance is not particu-

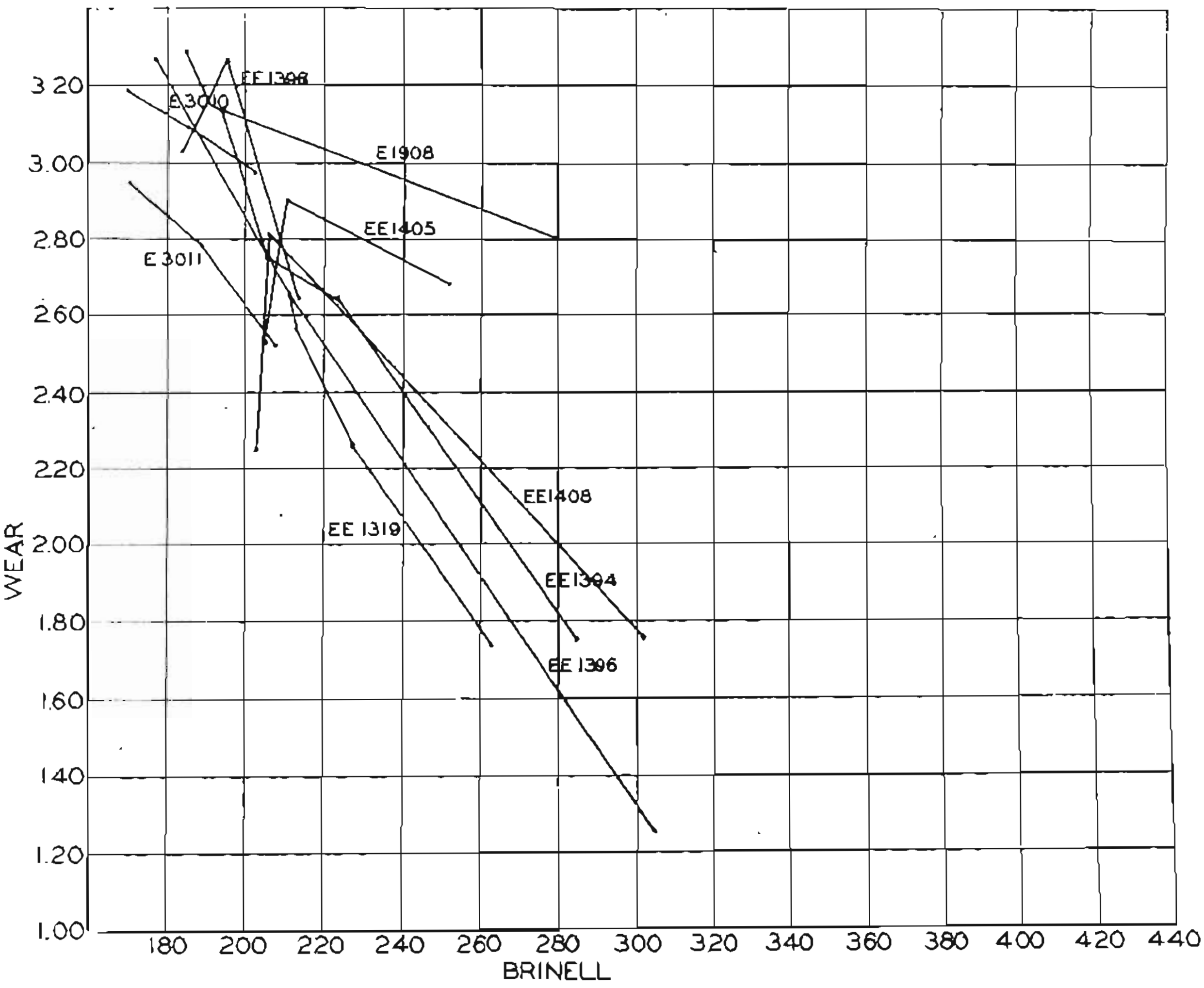

Fig. 5 - Wear Vs. Brinell Hardness for Carbon Manganese Steel Forgings.

Brinell being relatively flat. This is especially true with Brinell above 240. As the carbon content increases, this flattening is more pronounced. Conferred hardness, therefore, has very little effect on the resistance of this material. Intrinsic hardness gained by the use of carbon, Manganese and Molybdenum, appears to have a greater influence.

The physical properties of the cast material are not exceedingly good. Tensile strengths of 60,000 PSI to 80,000 PSI may be taken to be accurate, the lower values recorded are due to the flaws obtained in casting, as was explained previously. The extension and contraction are about normal for castings of this sort. The impact value is exceedingly low, even when the specimens were broken unnotched. It is thought, however, that these physical properties are sufficient when backed up properly for roll shells and other crushing implements, where no heavy impact will be encountered.

CARBON - CHROMIUM - MOLYBDENUM STEELS - (FIG. 7 and 7A)

The addition of Chromium and Molybdenum to steels gives good wearing qualities. The higher carbon cast compositions are comparable somewhat to the Manganese Molybdenum castings, although the figures obtained are higher. A carbon content above 1.40 seems to be necessary for good resistance. Hardness has a greater influence on wear of steels of this composition than it had on the Manganese Molybdenum castings.

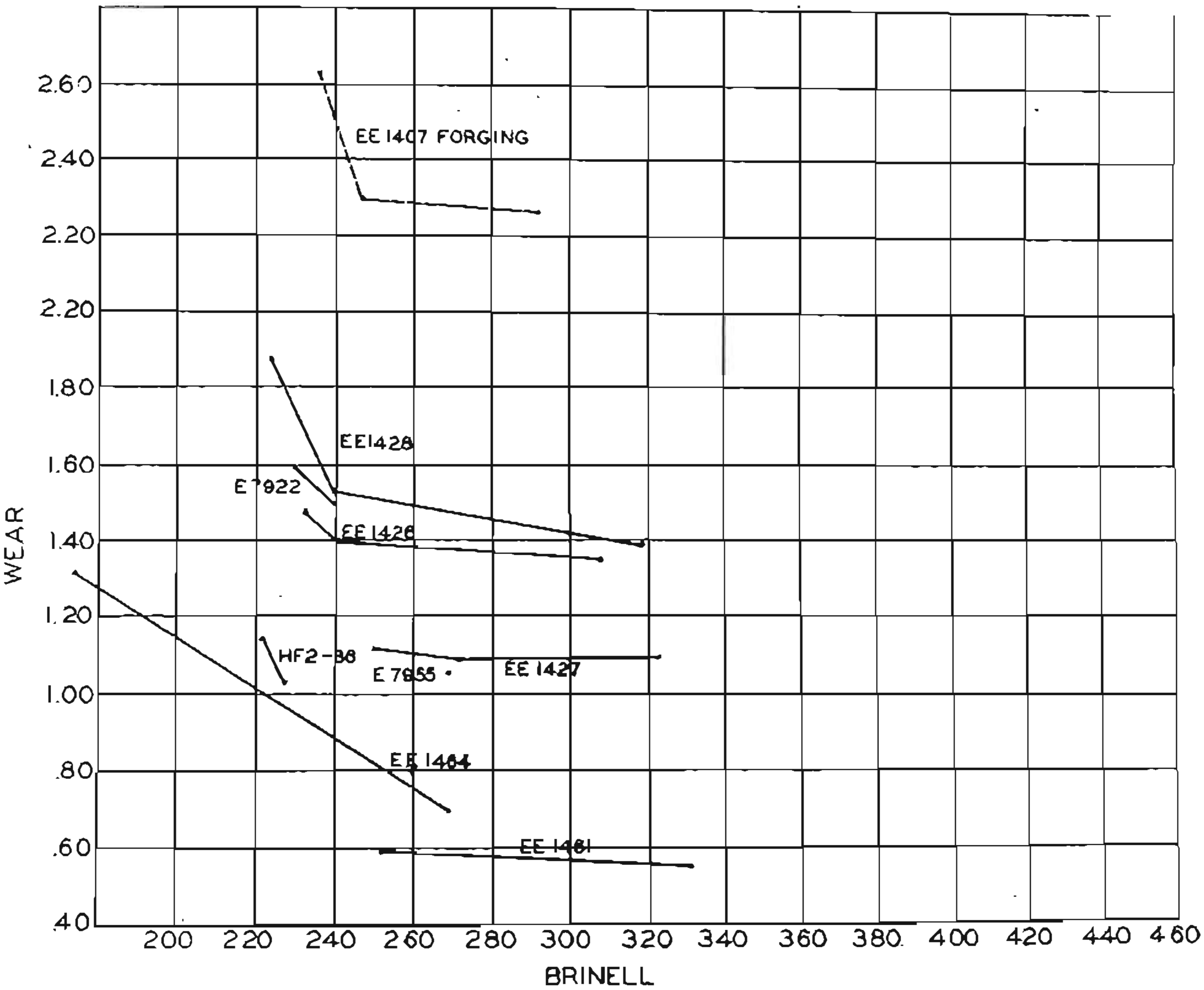

Fig. 6 – Wear Vs. Brinell Hardness for Manganese Molybdenum Steel Forgings.

Brinell being relatively flat. This is especially true with Brinell above 240. As the carbon content increases, this flattening is more pronounced. Conferred hardness, therefore, has very little effect on the resistance of this material. Intrinsic hardness gained by the use of carbon, Manganese and Molybdenum, appears to have a greater influence.

The physical properties of the cast material are not exceedingly good. Tensile strengths of 60,000 PSI to 80,000 PSI may be taken to be accurate, the lower values recorded are due to the flaws obtained in casting, as was explained previously. The extension and contraction are about normal for castings of this sort. The impact value is exceedingly low, even when the specimens were broken unnotched. It is thought, however, that these physical properties are sufficient when backed up properly for roll shells and other crushing implements, where no heavy impact will be encountered.

CARBON - CHROMIUM - MOLYBDENUM STEELS - (FIG. 7 and 7A)

The addition of Chromium and Molybdenum to steels gives good wearing qualities. The higher carbon cast compositions are comparable somewhat to the Manganese Molybdenum castings, although the figures obtained are higher. A carbon content above 1.40 seems to be necessary for good resistance. Hardness has a greater influence on wear of steels of this composition than it had on the Manganese Molybdenum castings.

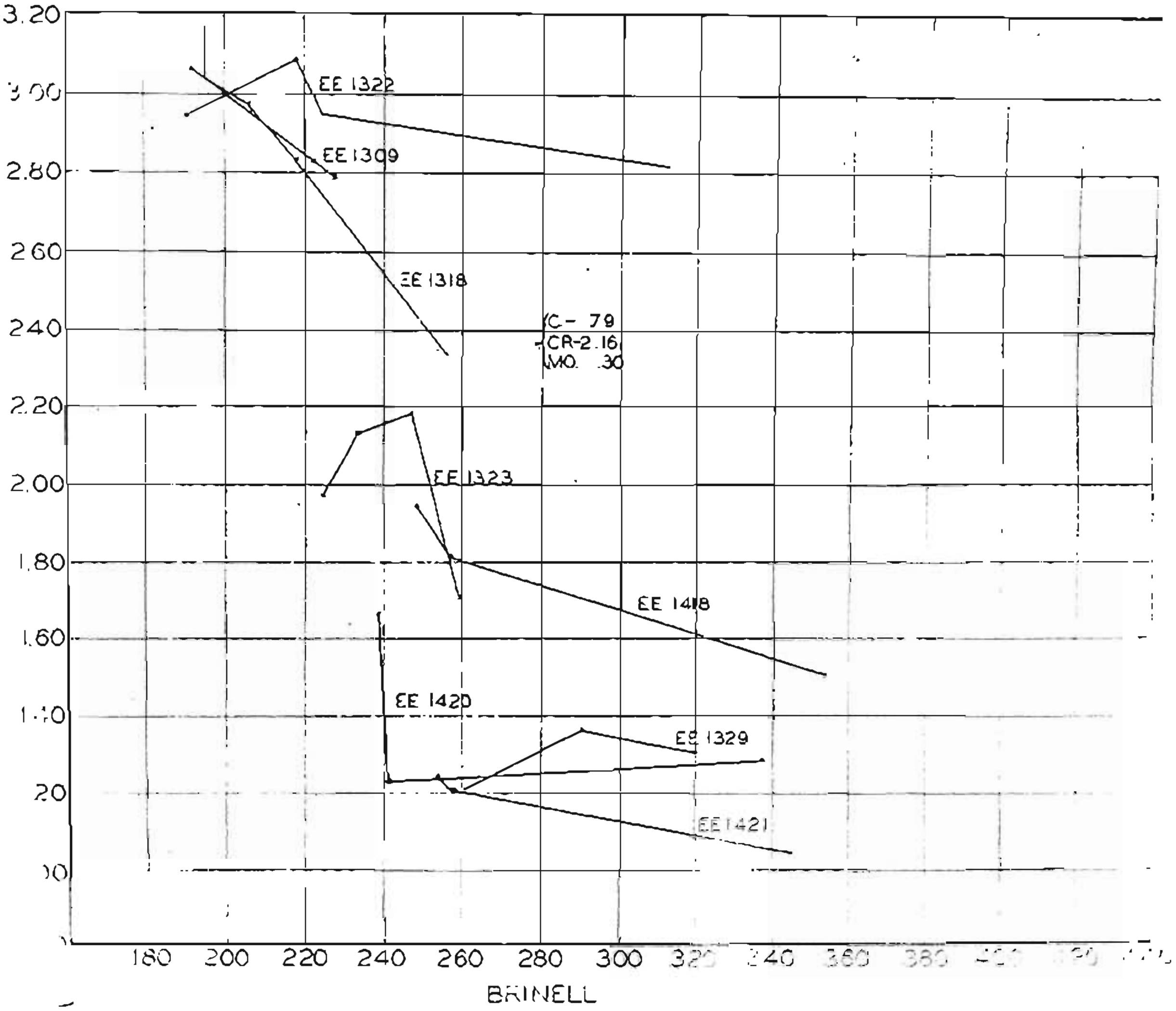

Fig. 7 - Wear Vs. Brinell Hardness for Chrome - Molybdenum Steel Castings.

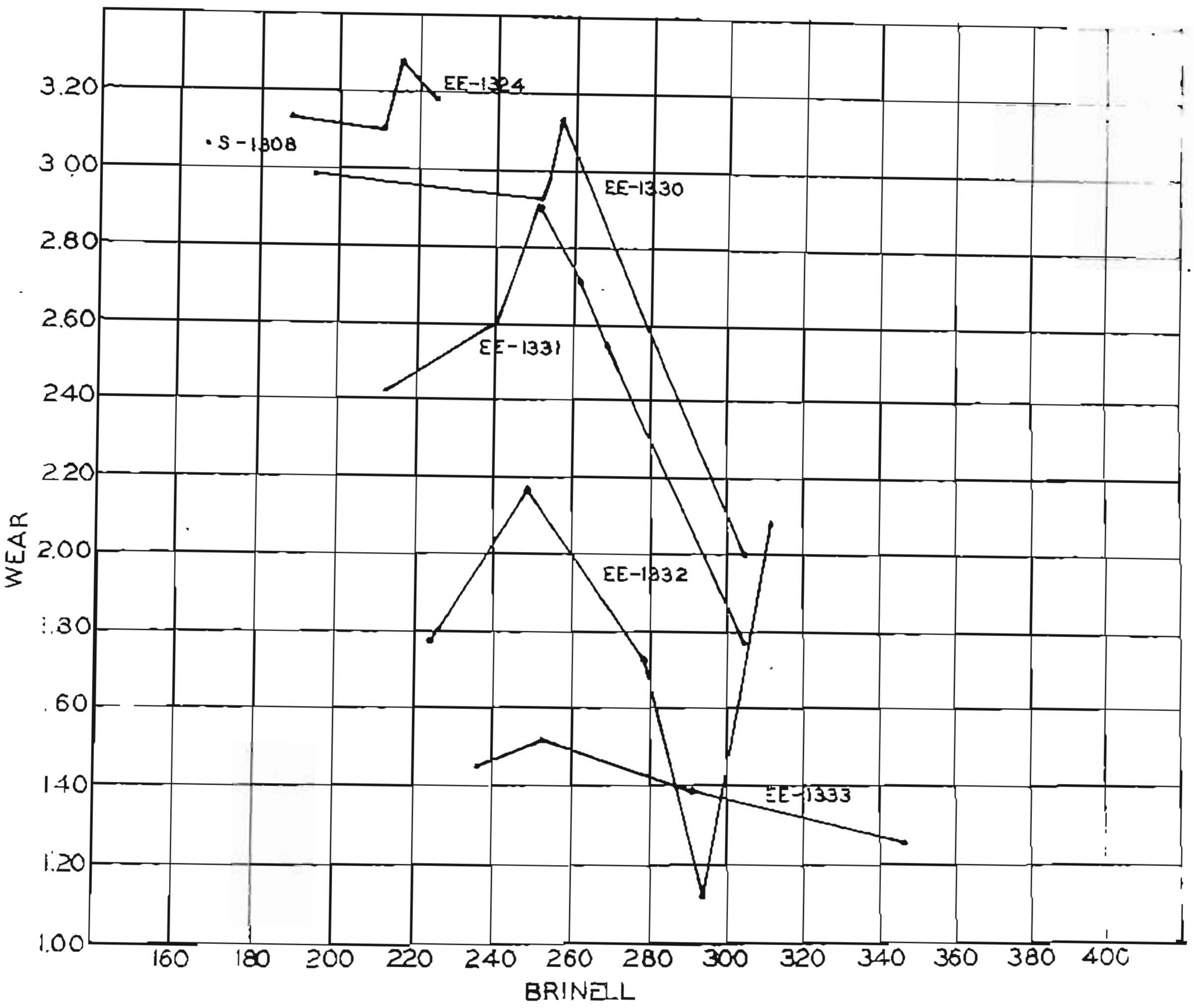

Fig. 7A – Wear Vs. Brinell Hardness for Chromium Molybdenum Steel Forgings.

The forged material of this composition is not a particularly good wear resister with the lower carbon contents, but above 2.00% it gives promising results. Increasing hardness increases the resistance of these lower carbon materials which are forgable.

The physical properties of both the castings and forgings are considered to be sufficient.

NICKEL CHROME AND NICKEL CHROME MOLYBDENUM - (FIG.8)

Forgings of these compositions are not good wear resisting materials with the carbon contents studied. Increasing the Brinell hardness improved the wear considerably in the Nickel Chromium composition, but not enough to give it good wearing qualities. Nickel as an alloying element does not improve the wear resistance.

CARBON - MOLYBDENUM - (FIG. 9)

Castings with carbon contents above 2.00 percent are very good. Increasing the hardness above 400 Brinell gives the best wear results obtained. However, the ductility of this material is so low that early breakage in roll shells is feared. Carbon contents low enough for forgings were not studied.

CARBON - CHROME

Carbon Chromium castings appear to have good possibilities. Only one composition was tried and very good results were obtained. However, one test cannot decide in favor of such a

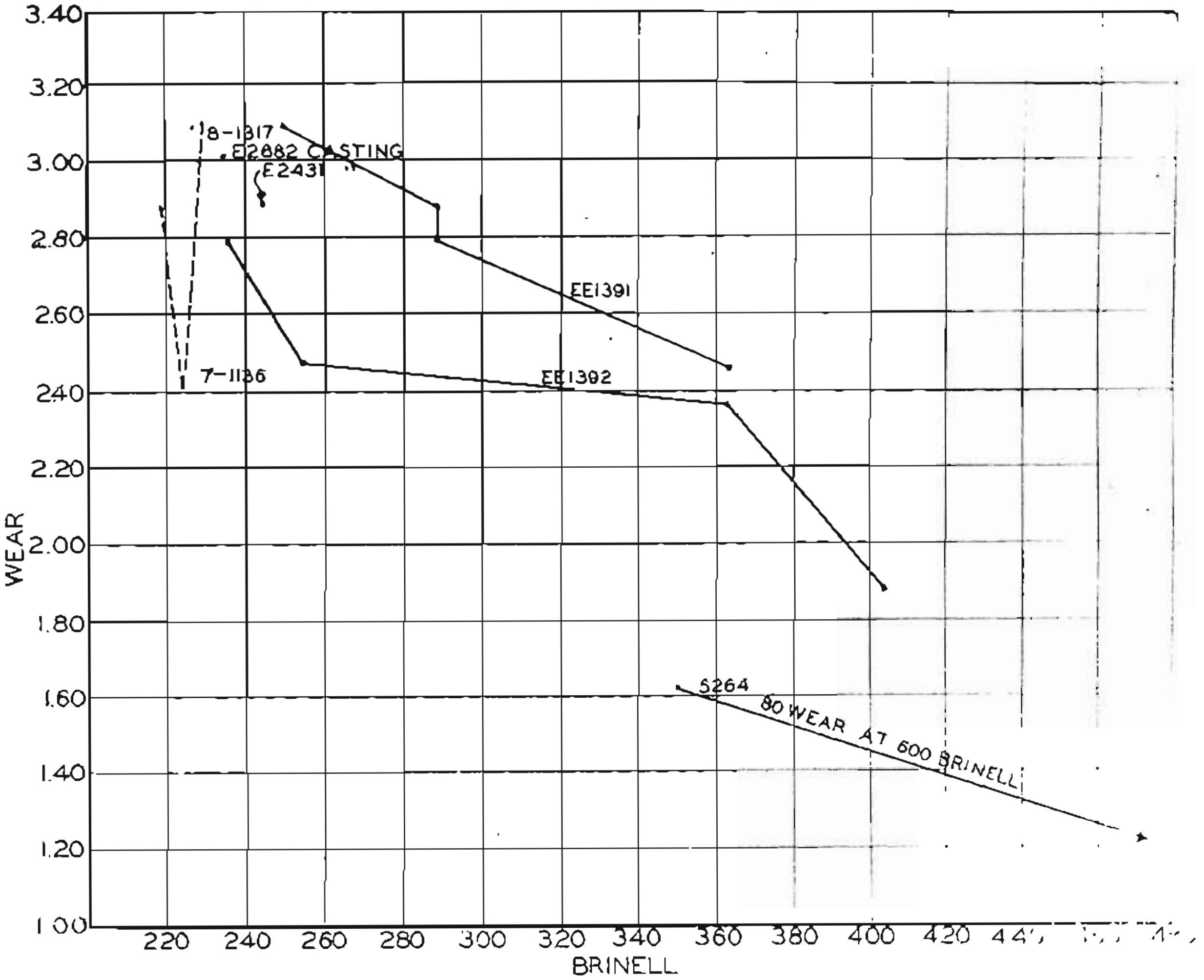

Fig. 8 - Wear Vs. Brinell Hardness for Nickel Chromium and Nickel Chrome Molybdenum Steel Forgings.

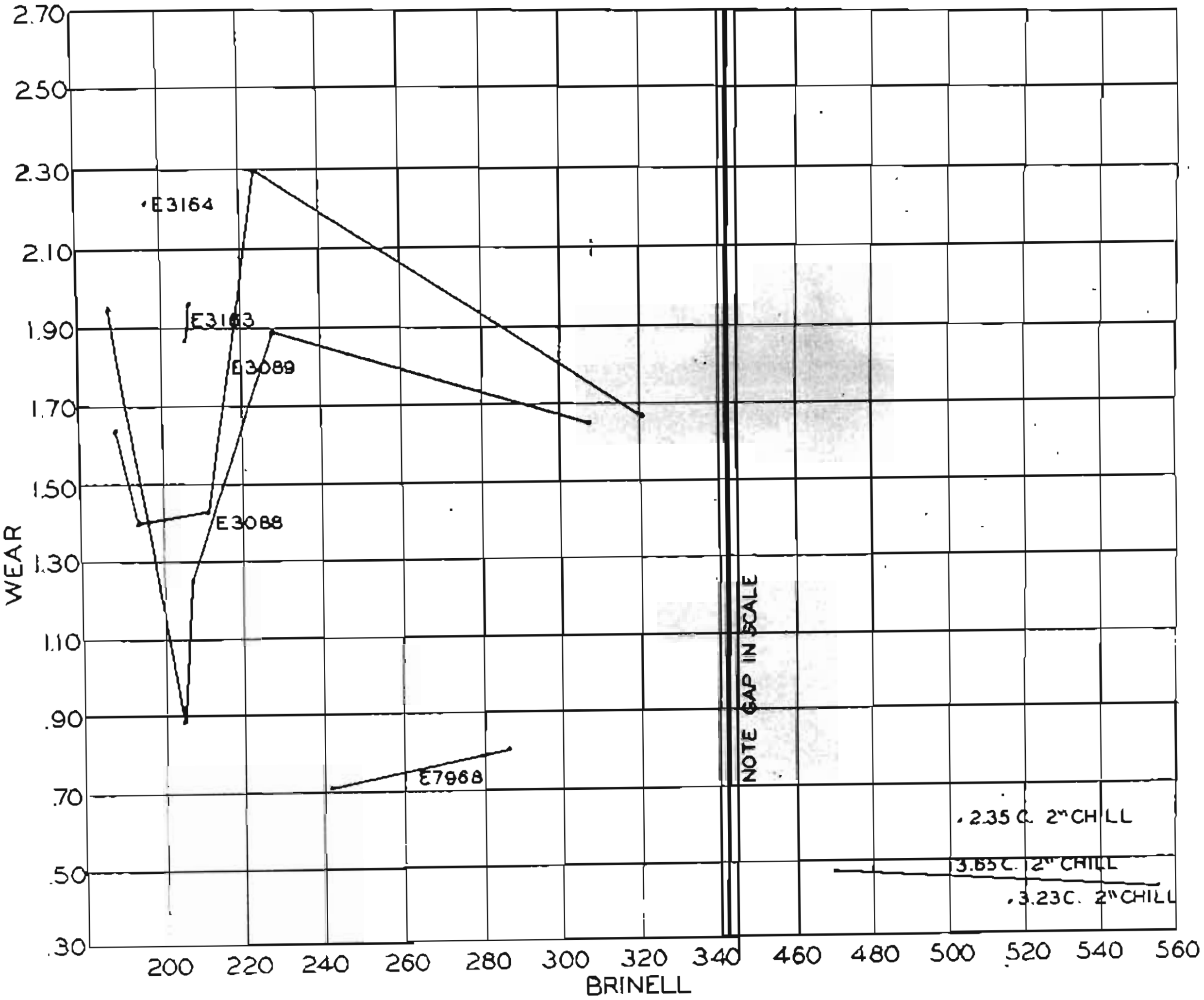

Fig. 9 - Wear Vs. Brinell Hardness for Carbon Molybdenum Castings.

composition. The physical properties of this composition were not obtainable, but it is thought that they are not sufficient to allow its use.

WHAT CAUSES GOOD WEAR?

It will be noticed that the carbon content in all of the composition studied, with the exception of the carbon-manganese materials, had a greater influence on wear resistance than Brinell hardness. The carbon-manganese material appears to act in the opposite direction, e.i. higher hardness gives better wear resistance, more or less, regardless of carbon content. Why? The answer appears to be found in the micro structures.

For example, let us take the Chromium Molybdenum castings. EE1322 (C 1.29, Cr. 2.10, Mo. .25) with Brinell of 190 gives a wear of 2.96 (Fig.10), at 218 Brinell, wear is 3.08 (Fig.11), at 224 the wear falls back to 2.95, (Fig.12), a higher Brinell gives 2.81 (Fig.13). Fig. 10 and Fig. 12 have the carbides about the same shape and size, well spherodized and the wear of these two specimens is the same. On the other hand, Fig. 11 showing the structure giving the poorest wear has much smaller carbides, although well spherodized. As we get to the higher Brinell Fig. 13, there is slightly less carbide present, but yet well spherodized. The wear of this composition is not very good in comparison to the higher carbon material. However, EE1318, having a carbon content of .76 hypoeutectoid steel with approximately the same Chromium and Molybdenum acts decidedly different. Fig. 14 shows the microstructure giving the lowest Brinell and lowest wear. This is a completely spherodized structure with very fine carbides. Figures 15, 16, and 17 respectively, show the structures of succeeding higher Brinells and corresponding higher wear resistance. The spherodized carbides in each case get smaller and smaller until in Fig. 17 we have a pearlite which has the best wear resistance and greatest hardness.

On the other extreme, EE1421 (C 2.20, Cr. 2.53, Mo. .39) gives the best wear for this type composition. Figures 18, 19, and 20 show the structure obtained at succeedingly higher Brinells and lower wear figures respectively. Note the size of the carbide particles. By increasing the Brinell from 257 to 345, a difference of 88 points, wear is decreased only .20, whereas in the case of EE1318 increasing the Brinell 64 points, decreases the wear .72. The high carbon material does not react readily to hardness in giving good wear resistance, whereas the lower carbon does.

In the case of the Chrome Molybdenum forgings Fig. 21 to Fig. 28 inclusive, photomicrographs of the EE1332 and EE1333 may be studied, EE1333 having the highest carbon gives a better average wear than EE1332 a lower carbon material. Again it will be noticed that carbon content controls the wear resistance. The size and distribution of the carbides again appears as an important factor. It will be noted that the carbides are uniform in size and distribution.

The carbon manganese forgings are peculiar in that wear resistance appears to depend on the Brinell hardness alone and not to any extent on carbon content. Fig.29 to Fig.32 shows the micro structure encountered in EE1396 (C. .93, Mn. 1.67) Fig. 29 has a Brinell of 184 and a wear of 3.03; Fig.30, Brinell of 195 and wear of 3.22; Fig.31, Brinell 213, wear 2.65; Fig. 32, a Brinell of 321 and a wear of 1.26. Succeeding higher Brinells give succeeding better wear. Fig. 29 is a partially spherodized structure, Fig. 30 is pearlitic as is Fig. 31, and Fig. 32 is a mixture of pearlite and sorbite. The carbides are not prominent in any case. The structures shown are typical for all forgings of this composition. The one carbon manganese casting studied had atypical chilled structure with the pearlite well spherodized, and with considerable excess of carbide in large masses.

Fig. 33 and Fig. 34 show the typical structure encountered the high carbon Manganese Molybdenum castings. The massive size and amount of the carbides should be noted. Wear resistance of this composition is very good.

The micro-structures of all compositions were studied but are not included in this report. The ones used are typical of the structures encountered.

To summarize all of the above, it is only necessary to note that the carbon steels, C-Mn. steels, the hypoeutectoid Cr. Mo. forgings and castings have a pearlitic or sorbitic structure with no excess of carbides. However, when spherodized, these structures have the carbides in very small globules. The types having the above structures have wear that depends on the Brinell hardness. On the other hand, those compositions which have considerable excess of carbide, hypoeutectoid steels, some of which is in large masses and the matrix spherodized in large spheroids, have excellent wear resistance. This resistance is not altogether dependent on the hardness.

The compositions containing appreciable amounts of Chromium and Molybdenum give the best wear resistance. It is well known that these two elements, together with Tungsten, and Vanadium have a tendency to take up the carbon of the steel and precipitate it as complex carbide eutectics, the amount being a function of relative amounts of carbon, chromium, molybdenum, tungsten and vanadium present. With high carbon content, iron and Manganese, in the presence of low silicon will also form Iron and Manganese carbides in the form of Ledeburite. These are chill cast structures which also give good wear resistance.

These carbides are exceedingly hard and brittle. If they are embedded in a soft matrix, which is strong enough to hold them in place, they will offer considerable resistance to abrasive wear. Especially is this so if the carbides are large enough and close enough together to keep the grit from attacking the soft matrix or to get under them and pry them out. Consequently a well spherodized matrix, having large carbide particles, gives excellent wear. Breaking up the large carbides by forging gives smaller spheroids which, if plentiful enough, give good wear resistance.

On the other hand, the compositions, which are such that little or no carbides can be formed, such as the lower carbon, and lower carbon-manganese steels must offer a matrix which is hard enough to withstand the cutting action of the grit. For this reason Brinell hardness plays such an important part in the wear of such meterial.

In the beginning of this discussion, two types of hardness; intrinsic and conferred hardness, were mentioned. It can now easily be seen that the intrinsic hardness, especially in the resistance to wear, is a function of the amount, size, and hardness of the carbides present. Conferred hardness, on the other hand, will improve wear by offering a hard matrix to be worn. Intrinsic hardness, because of its ability to offer a much harder surface to be subject to wear, appears to be the best way to get good wear resistant steels. Throughout this discussion, forgings and castings have been treated more or less separately. The idea being kept in mind during the investigation to determine, if possible, the best way to fabricate the material. The evidence collected points to the fact that carbon content, together with the alloying elements, is the one thing that controls wear resistance. Whether the material is forged or cast is not of any great importance, except that too high a carbon content cannot be readily forged.

In considering the advisability or using forgings or castings, the fact that the forgings give much better physical properties must be borne in mind. The use of a lower carbon content with slightly poorer wear resistance may at times be necessary, in order to meet the physical requirements to which the material is to be subjected. The high carbon castings may be used only where they can be properly supported and are not liable to be subjected to any great amount of impact.

CORRELATION OF THE TYPE OF WEAR TO SERVICE CONDITIONS

A number of roll shells and crusher parts, made from various compositions discussed in this thesis, have been put into actual service. Up to the present time, no results have been obtained. It has, however, been determined that a .70/.80 carbon, Chrome-Molybdenum roll shell shows an actual saving of about .06 cents per ton of ore crushed when compared with a .70/.80 carbon shell, without the alloying elements. Our test shows a wear of 2.54 for the Chrome-Molybdenum material and 2.61 for the straight carbon. A small difference in wear yet enough to make it economical for the concentrator to buy the Chrome-Molybdenum material.

A number of these compositions that show good wear resistance with good tensile properties are not applicable to any but abrasive resistance. Under impact they batter up very easily and will not equal the service that can be given by Hatfield's Manganese Steel.

SUMMARY

1. A machine for testing the wearing qualities of metals against abrasives, with reasonable ability to duplicate results, is described.

2. Tests were run on specimens of carbon, carbon-manganese, manganese molybdenum, carbon-chrome-molybdenum, carbon-molybdenum, and carbon chromium steels of varying carbon content, and Brinell hardness.

3. Wear appears to depend on hardness, both intrinsic and conferred; Intrinsic, which is controlled by the carbon content, being the most influential.

4. The addition of alloying elements, which have the ability to precipitate out of solution as carbides, improves wear resistance. Chromium and molybdenum are two such elements.

5. The size, hardness and distribution of the carbides influences wear. The maximum amount of carbides imbedded in a soft matrix, such as ferrite, being the best.

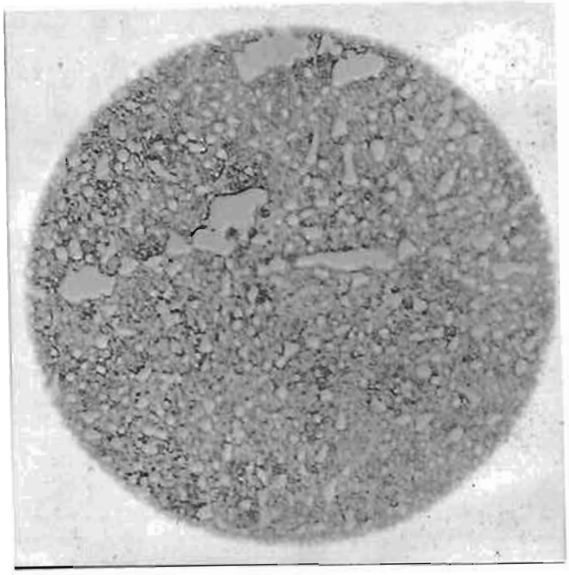

Fig.10.EE1322(C1.29,Cr.2.10,Mo. .25)
Brinell-190,Wear-2.96. X500

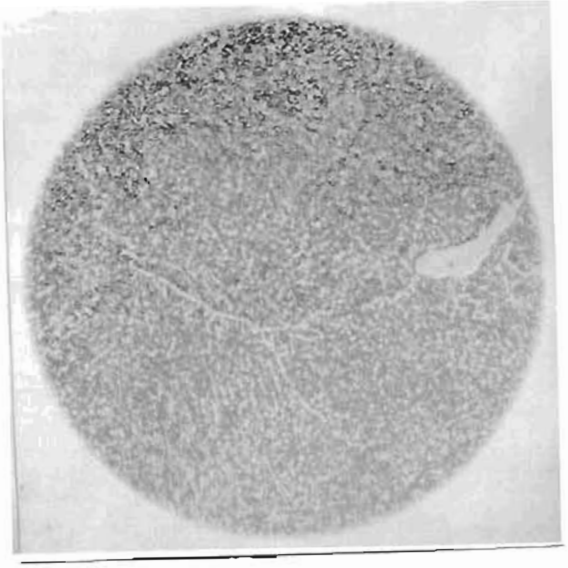

Fig.11.EE1322-Brinell 218
Wear-3.08 X500

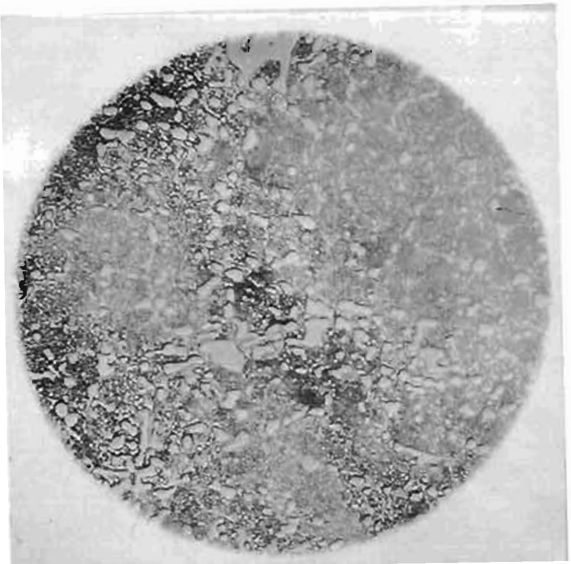

Fig.12-EE1322-Brinell 224
Wear-2.95 X500

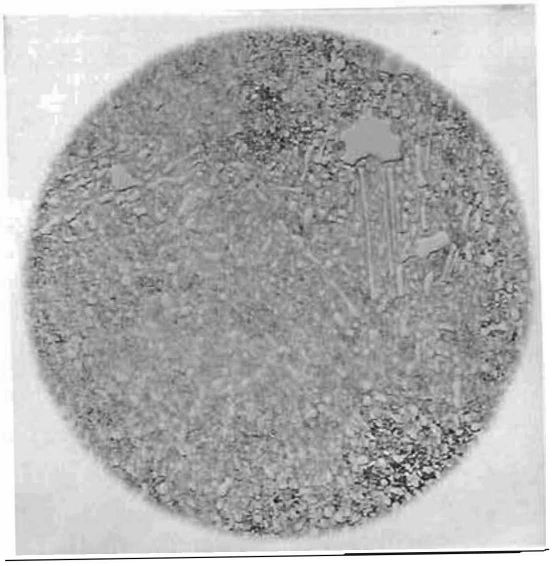

Fig.13-EE1322-Brinell 312
Wear-2.81 X500

All specimens etched with 10% Nital

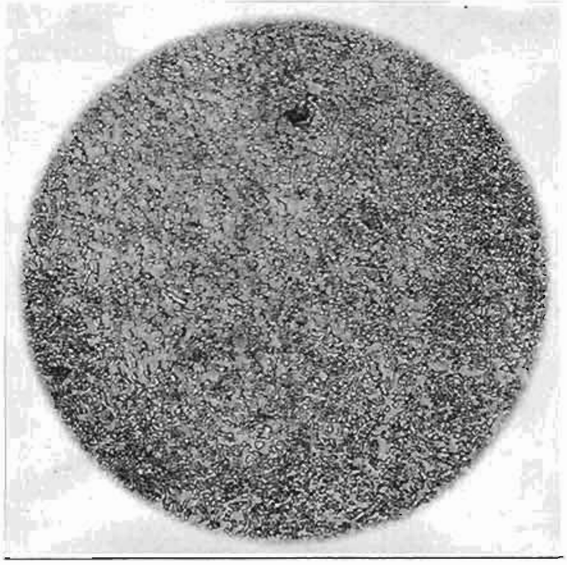

Fig.14-EE1318(C.76,Cr.1.92,Mo..34)
Brinell-192, Wear 3.06 X500

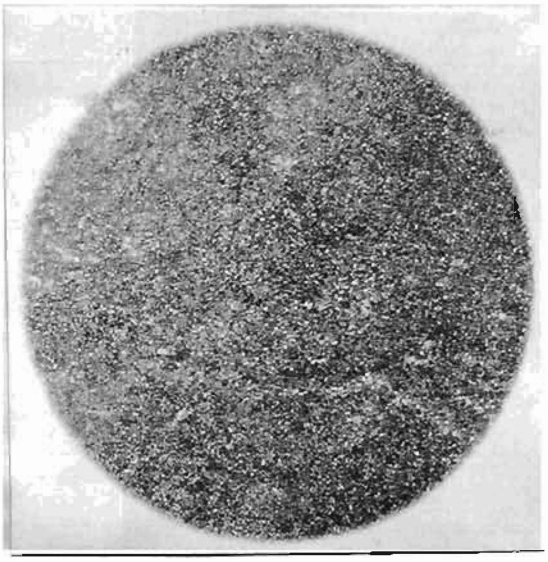

Fig.15-EE1318- Brinell 206
Wear 2.97 X500

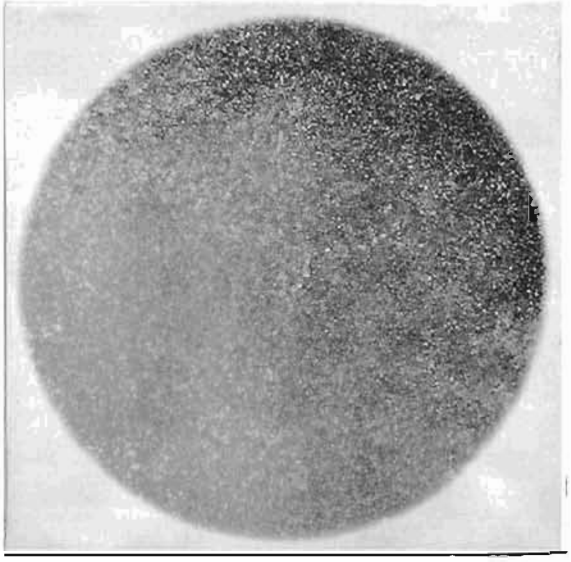

Fig.16-EE1318- Brinell 218
Wear 2.83 X500

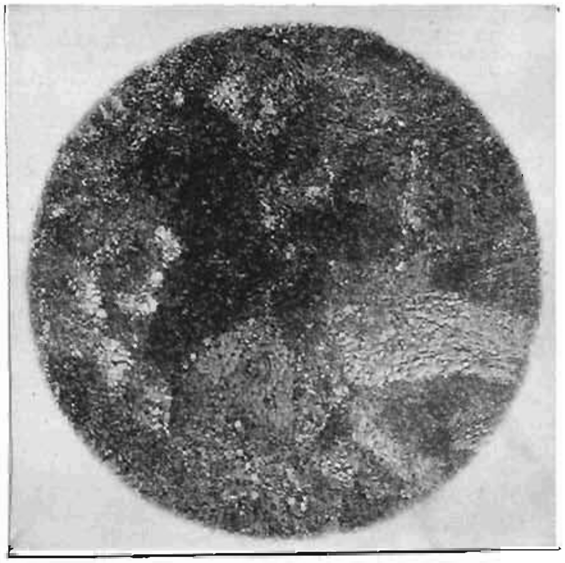

Fig.17-EE1318 - Brinell 256
Wear 2.34 X500

All specimens etched with 10% Nital.

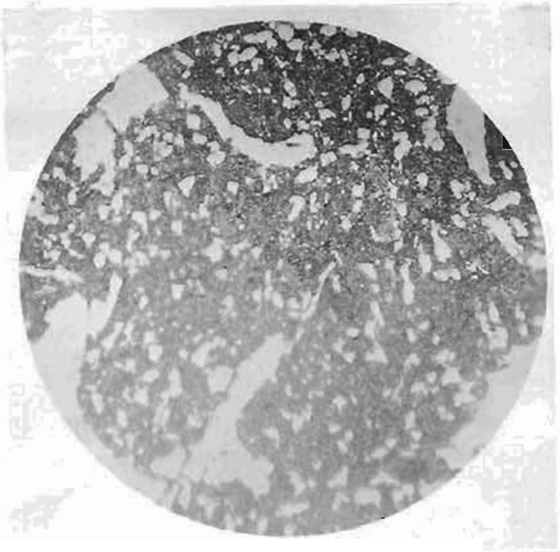

Fig.18–EE1421(C.2.20,Cr.2.53,Mo..39)
Brinell 254, Wear 1.24   X500

Fig.19,EE1421–Brinell 257
Wear 1.21   X500

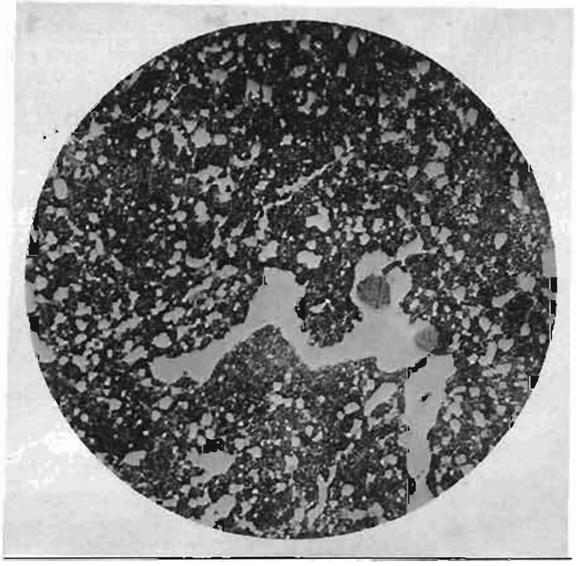

Fig.20–EE1421–Brinell 345
Wear 1.04   X500

All specimens etched with 10% Nital.

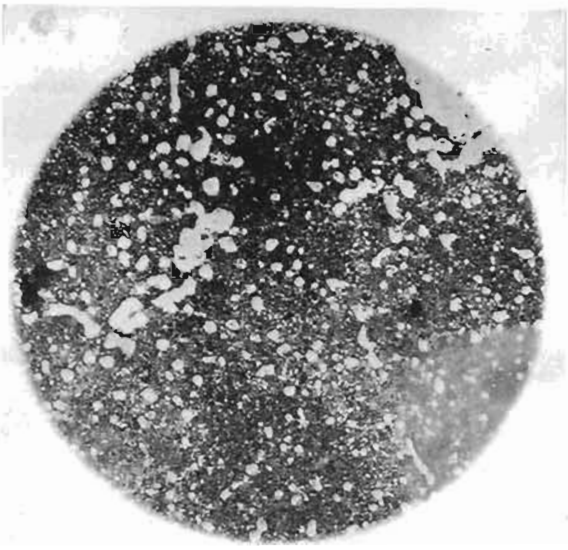

Fig.21-EE1332(C.1.81,Cr.2.37,Mo..30)
Brinell 224, Wear 1.77 X500

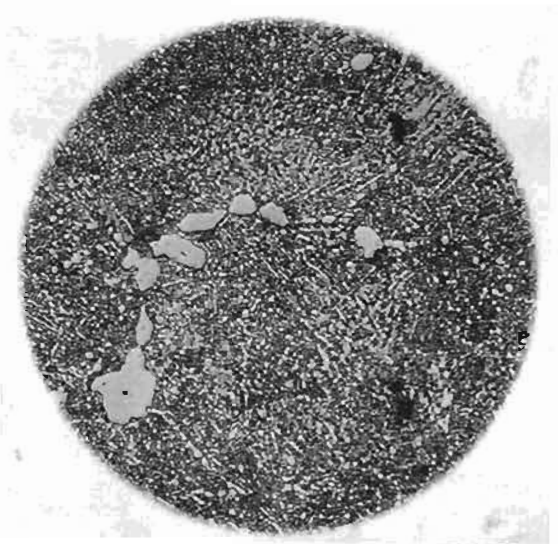

Fig.22,-EE1332-Brinell 248
Wear 2.17 X500

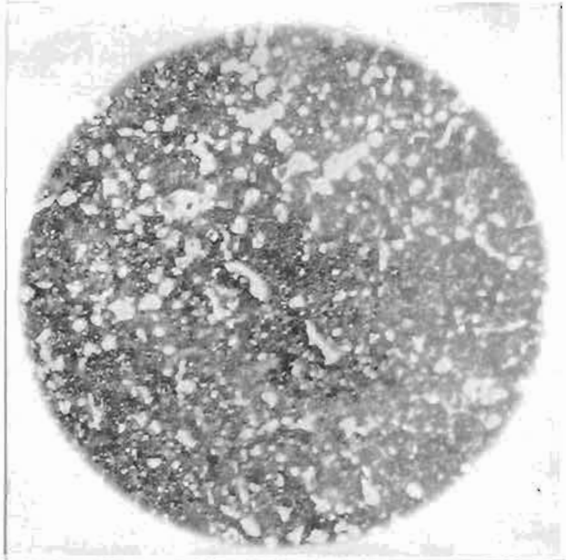

Fig.23-EE1332-Brinell 279
Wear 1.72 X500

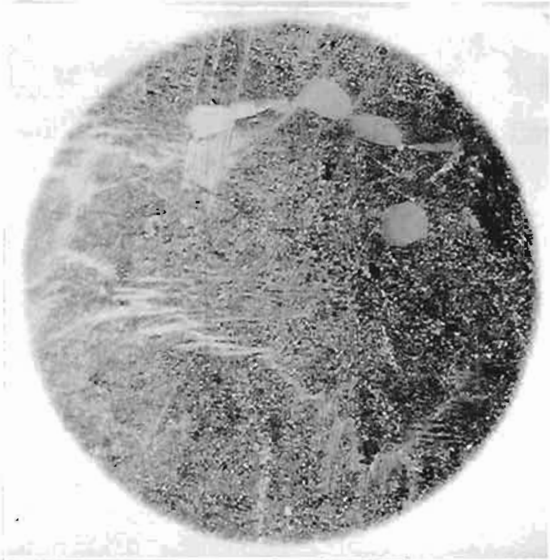

Fig.24-EE1332 - Brinell 311
Wear 2.08 X500

All specimens etched with 10% Nital.

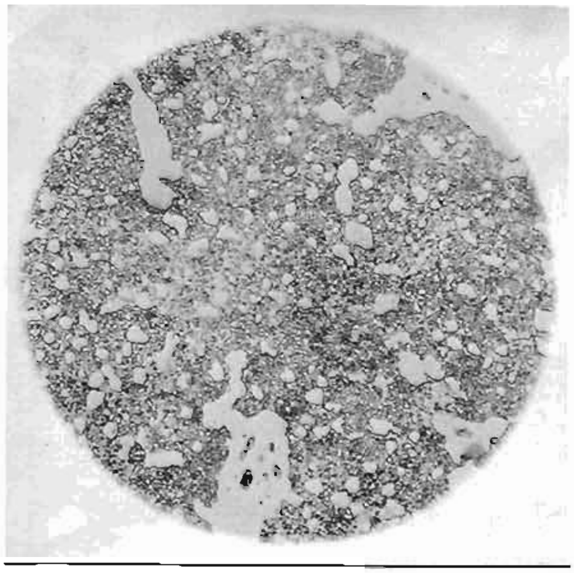

Fig.25-EE1333(C.2.02,Cr.2.14,Mo..28
Brinell 236 Wear 1.45 X500

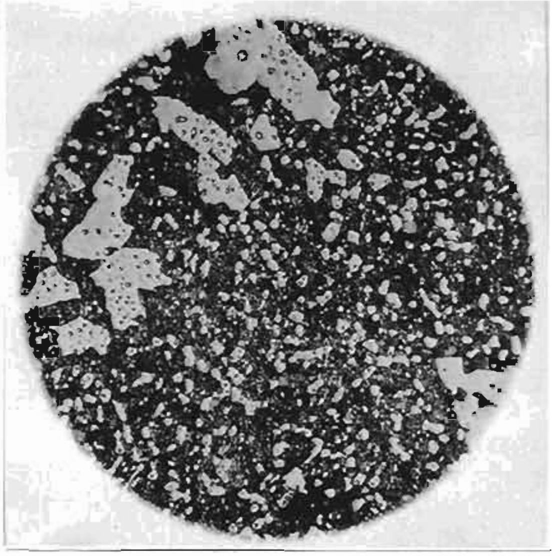

Fig.26, EE1333 - Brinell 255
Wear 1.52 X500

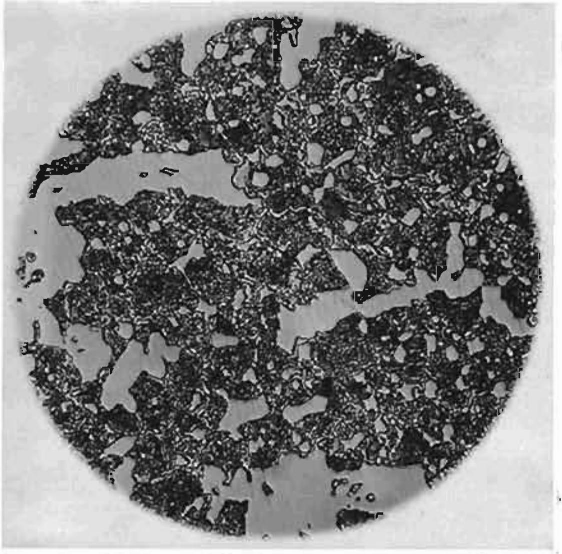

Fig. 27, EE13333 - Brinell 291
Wear 1.39 X500

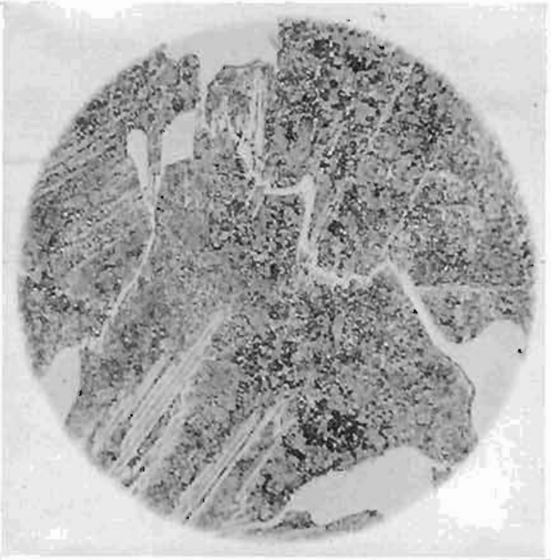

Fig.28, EE1333 - Brinell 346
Wear 1.26 X500

All specimens etched with 10% Nital.

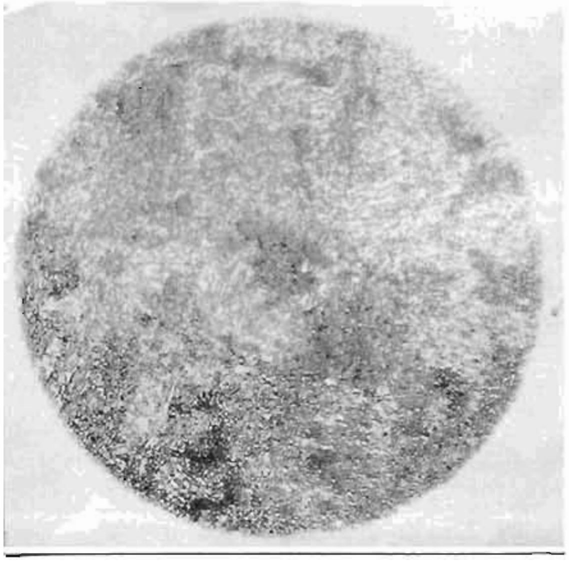

Fig.29-EE1396(C..93,Mn.1.67)Brinell 184
Wear 3.03 X500

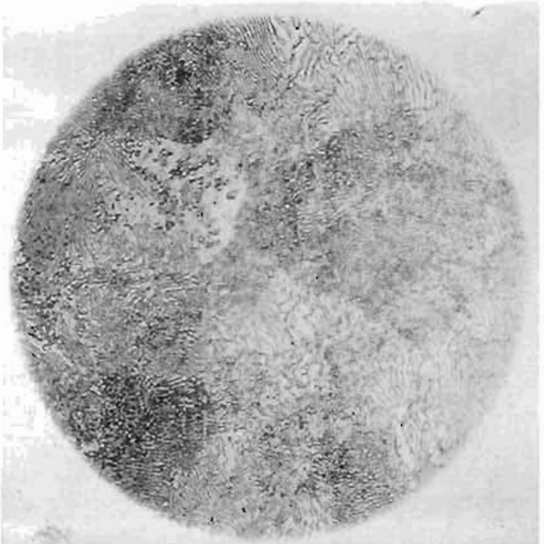

Fig.30, EE1346 - Brinell 195
Wear 3.22 X500

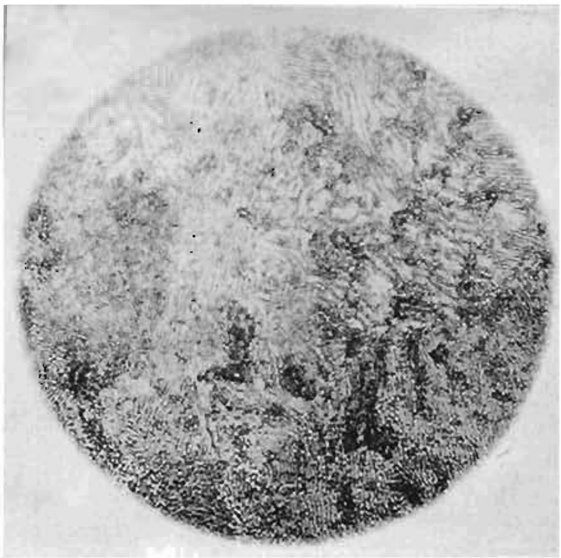

Fig.31-EE1396- Brinell 213
Wear 2.65 X500

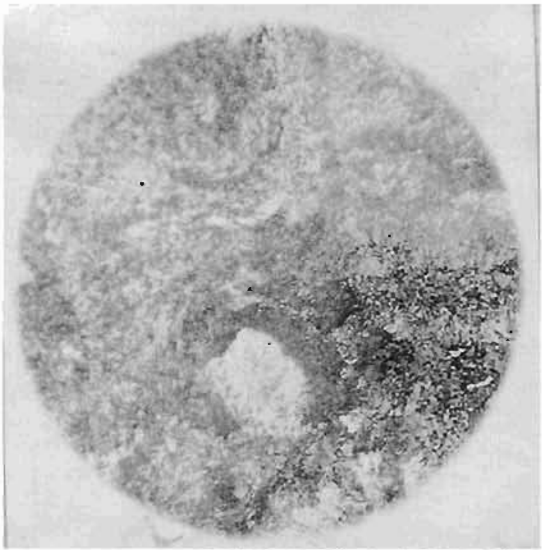

Fig.32, EE1396 - Brinell 321
Wear 1.26 - X500

All specimens etched with 10% Nital.

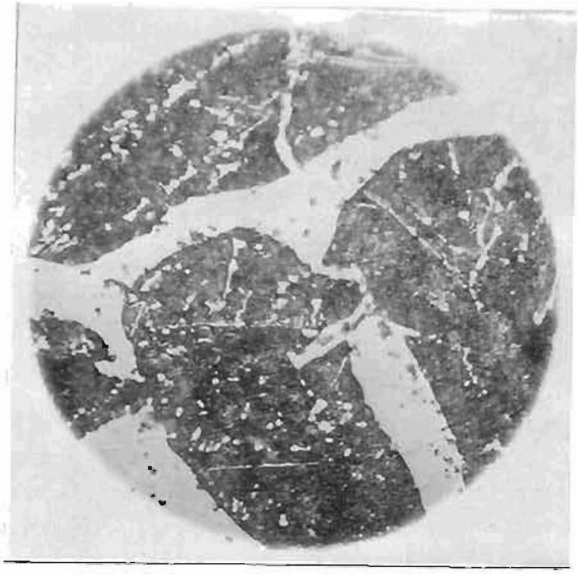

Fig. 38 - EE1461 (C. 2.20, Mn. 2.33, Mo. .41)
Brinell 252 - Wear .597 - X500

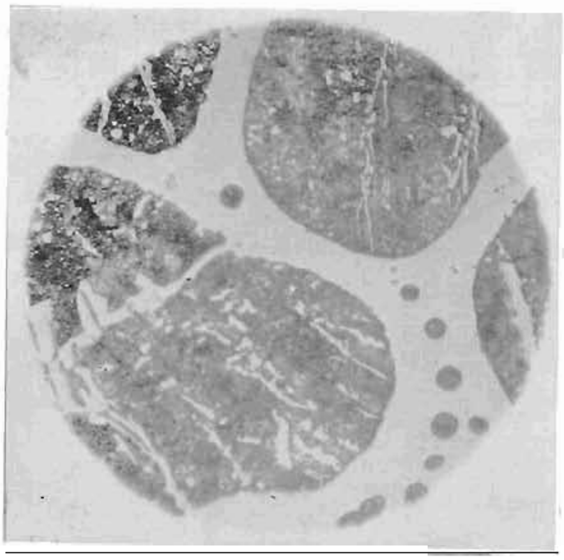

Fig. 39 - EE1461 - Brinell 331 - Wear .553
X500

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