SECOND INFORMAL QUARTERLY REPORT
October 15, 1942

to

NATIONAL DEFENSE
RESEARCH COMMITTEE
of
OFFICE OF SCIENTIFIC
RESEARCH AND DEVELOPMENT

on

N.D.R.C. Research Project NRC 14,
Contract No. OEMsr-450

The Improvement of Low-Alloy Armor Steels

S-633

BATTELLE
MEMORIAL INSTITUTE
505 King Avenue
COLUMBUS, OHIO

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INTRODUCTION

The current research program on this project can be conveniently divided into three major problems:

1) A study of the effects of addition agents and changes in composition on the hardenability and mechanical properties of low-alloy armor steels. The addition agent given most consideration so far is boron, added either as ferroboron or in the form of two proprietary alloys. Changes in composition have been mainly in the direction of lower molybdenum contents with simultaneous additions of boron. The possibility of using silicon and aluminum to improve the properties of armor steels was also examined. Considerable data on the effects of boron were presented in the last

quarterly report; these have been supplemented by the information contained in this report. The first or exploratory phase of the boron program has now been completed, and a more comprehensive survey of the problem, which is outlined in the discussion of the boron-treated steels, has been started.

2) A program of heat treatment and tests on cast armor steels to determine the effects of homogenizing time and temperature on the hardenability and mechanical properties of cast plate from five different producers.

3) To produce ballistically acceptable face-hardened armor plate having a lower alloy content than used heretofore.

EXPERIMENTAL WORK

Effect of Addition Agents and Changes in Composition on Low-Alloy Steels

All melting was done in magnesia-lined induction furnaces. The melting practice was standardized as closely as possible to avoid the introduction of variables from this source. Hardenability specimens for the wrought material were machined from 1-1/8-inch square forgings while the impact specimens were cut from 9/16-inch stock that had been rolled down from the forged bars. When tensile specimens were made, they were machined from 3/4 inch rounds.

Cast steels were homogenized at 1900° F. and wrought steels were normalized at 1700° F. for 2½ hours. Water quenching was from 1575 or 1600° F. depending on the composition of the steel. The cast specimens were then tempered to a hardness within the range of 270 to 290 Brinell, while the hot worked steels were tempered to 350 to 370 Brinell.

Jominy end-quench test results are given by reporting four values:

1) The Rockwell "C" hardness at 1/16 inch from the quenched end.

2) The distance from the quenched end at which the hardness is 5 Rockwell "C" below the hardness at 1/16 inch from the end.

3) The distance from the quenched end at which the hardness is 10 Rockwell "C" below the hardness at 1/16 inch from the end.

4) The Rockwell "C" hardness at $2\frac{1}{2}$ inches from the quenched end. It is believed that these values give a good picture of the hardenability characteristics of the steels and afford a ready means for comparison that is not so easily obtained by examining each hardenability curve.

Wrought Steels Treated with Ferroboron - Table 17

The previous quarterly report contained data on steels treated with ferroboron in which the boron contents exceeded 0.005 per cent. Since this quantity is larger than that considered necessary for obtaining increased hardenability from a boron addition, the present series of steels have been prepared with boron additions amounting to 0.003 and 0.005 per cent.

The results given in Table 17 indicate that there is little difference in the degree of hardenability conferred by either the 0.003 or 0.005 per cent addition. The hardenability of boron-free steels of comparable analysis is decidedly lower as shown by the data for Heats 8374 and 8376, taken from the July 15 quarterly report.

Cast Steels Treated with Ferroboron - Table 18

The keel blocks for the boron-treated steels listed in this group were poured from the same heats listed in Table 17 for wrought steels. The boron addition has produced a similar increase in hardenability in the castings, although high hardenability values obtained with the boron-free steels.

TABLE 17. CHEMISTRY AND PROPERTIES OF WROUGHT BORON-TREATED NICKEL-CHROMIUM MOLYBDENUM AND MANGANESE-MOLYBDENUM STEELS

Boron Range: 0.003 - 0.005 Per Cent. (Added)

Heat No.	Chemistry, Per Cent(1)							Jominy End Quench Hardenability				Mechanical Properties	
								Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to Obtain a Drop of		Hardness at $2\frac{1}{2}$-In. from End, Rc	Brinell Hardness Number	Izod (4) Impact, Ft.Lbs.
	C	Mn	Si	Ni	Cr	Mo	B		5 Rc	10 Rc			
Nickel-Chromium-Molybdenum Steels.													
8374	0.17	0.86	0.44	0.53	0.53	0.34	.000	48.5	5.0	6.5	25.0	362	44.0(5)
8446	0.25	0.79	0.41	0.54	0.53	0.35	.001(2)	49.5	10.0	16.0	32.5	362	36.8
8447	0.24	0.77	0.39	0.54	0.52	0.35	.003(3)	49.5	11.0	15.0	33.0	363	40.1
Manganese-Molybdenum Steels													
8376	0.27	1.46	0.46	----	----	0.35	.000	51.0	5.0	7.0	24.0	361	41.0(5)
8448	0.25	1.33	0.41	----	----	0.33	.001(2)	49.5	10.5	15.5	28.0	365	35.2
8449	0.25	1.31	0.39	----	----	0.35	.002(3)	49.5	13.5	18.5	31.5	363	36.0

(1) 0.10 per cent Al added to all heats except 8374 and 8376 which were deoxidized with 0.20 per cent Al.

(2) 0.003 per cent boron added as ferroboron.

(3) 0.005 per cent boron added as ferroboron.

(4) Average of three trip-notch specimens, except where noted otherwise.

(5) Average of two triple-notch specimens.

TABLE 18. CHEMISTRY AND PROPERTIES OF CAST BORON-TREATED NICKEL-CHROMIUM MOLYBDENUM AND MANGANESE-MOLYBDENUM STEELS

Boron Range: 0.003 - 0.005 Per Cent. (Added)

Heat No.	Chemistry, Per Cent[1]							Jominy End Quench Hardenability				Mechanical Properties	
	C	Mn	Si	Ni	Cr	Mo	B	Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to Obtain a Drop of 5 Rc	No. of 16ths of an Inch to Obtain a Drop of 10 Rc	Hardness at 2½-In. from End, Rc	Brinell Hardness Number	Izod (4) Impact, Ft.Lbs.
Nickel-Chromium-Molybdenum Steels.													
8302-1	0.23	0.87	0.43	.40/.60	.40/.60	.30/.40	.000	50.0	9.5	15.0	32.5	283	42.0[5]
8446	0.25	0.79	0.41	0.54	0.53	0.35	0.001[2]	49.5	12.0	20.0	33.0	273	35.0
8447	0.24	0.77	0.39	0.54	0.52	0.35	0.003[3]	48.0	11.0	15.5	30.0	280	36.0
Manganese-Molybdenum Steels.													
8304-1	0.26	1.43	0.40	----	----	.30/.40	.000	50.5	10.0	14.5	31.5	280	41.0[5]
8448	0.25	1.33	0.41	----	----	0.33	0.001[2]	48.0	17.0	24.5	31.0	285	39.0
8449	0.25	0.31	0.39	----	----	0.35	.002[3]	48.0	12.0	15.0	27.0	285	34.5

(1) 0.10 per cent Al added to all heats.

(2) 0.003 per cent boron added as ferroboron.

(3) 0.005 per cent boron added as ferroboron.

(4) Average of three triple-notch specimens except where noted otherwise.

(5) Average of two triple-notch specimens.

Wrought Boron-Treated Steels Covering a Range of Molybdenum Contents - Tables 19 and 20.

From the results of some earlier tests on boron-treated alloy steels made with and without molybdenum (See pp. 16 and 17, July 15 quarterly report), it appears that whenever boron and molybdenum occurred together there was a noticeable drop in notched-bar impact resistance. If this condition should be general, the addition of boron to molybdenum-containing steels might lead to difficulties which would outweigh the advantage of increased hardenability. The possible interrelation between boron and molybdenum has been investigated further by melting a 300-pound induction furnace heat of two base analyses and treating them in the following manner:

1) The first ingot was poured without a molybdenum or boron addition.

2) A boron addition of 0.003 per cent was made to the metal remaining in the furnace and a second ingot poured.

3) Approximately 0.10 per cent molybdenum was added to the furnace and a third ingot poured.

4) The molybdenum content of the metal in the furnace was raised to about 0.15 per cent and another ingot poured, and finally,

5) A last addition brought the molybdenum content to about 0.25 per cent and a fifth and last ingot poured.

The results, given in Table 19, show that the maximum hardenability is reached at a molybdenum content between 0.10 and 0.15 per cent. The lack of a further increase in hardenability when the molybdenum was increased beyond this range conceivably could have been caused by a loss of boron as the five ingots were successively poured. The possibility of "fading" in the effect of boron was not investigated, however.

TABLE 19. CHEMISTRY AND PROPERTIES OF WROUGHT BORON-TREATED ALLOY STEELS COVERING A RANGE OF MOLYBDENUM CONTENTS

Heat No.	Chemistry, Per Cent(1)							Jominy End Quench Hardenability				Shephard(3) Grain Size	Mechanical Properties	
	C	Mn	Si	Ni	Cr	Mo	B(2)	Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to Obtain a Drop of 5 Rc	No. of 16ths of an Inch to Obtain a Drop of 10 Rc	Hardness at $2\frac{1}{2}$-In. from End, Rc		Brinell Hardness Number	Izod Impact, Ft.Lbs.
Nickel-Chromium-Molybdenum Steels.														
8585-1	0.30	0.86	0.43	0.56	0.51	---	----	52.0	4.0	5.0	11.5	6-7	370	29.5(4)
8585-2						---	.001	51.0	8.0	10.0	19.0	7	361	38.5(4)
8585-3						.09	.002	51.0	8.5	11.5	25.5	7	363	37.5(4)
8585-4						.14	.002	50.5	11.0	13.5	28.0	7-8	366	33.0(4)
8585-5						.20	.002	50.0	11.5	16.0	28.5	7	366	33.0(4)
Manganese-Molybdenum Steels.														
8586-1	0.30	1.59	0.42	----	----	---	----	51.5	4.0	5.0	14.5	7	353	46.0(5)
8586-2						---	.001	51.5	10.5	12.5	17.5	7	345	34.0(5)
8586-3						.08	.001	50.0	12.0	16.0	23.5	7	354	29.3(5)
8586-4						.14	.001	52.0	14.5	18.5	29.0	7	374	19.0(5)
8586-5						.24	.001	51.0	11.0	15.0	26.0	7	360	28.0(5)

(1) 0.10 per cent Al added to all heats.

(2) 0.003 per cent boron added as ferroboron.

(3) Grain size measured on fractured hardenability specimen.

(4) Average of one triple-notch specimen.

(5) Average of three triple-notch specimens.

TABLE 20. LOW-TEMPERATURE IMPACT PROPERTIES OF WROUGHT BORON-TREATED ALLOY STEELS COVERING A RANGE OF MOLYBDENUM CONTENTS

Heat No.	Chemistry, Per Cent(1)							Mechanical Properties			
	C	Mn	Si	Ni	Cr	Mo	B(2)	Brinell Hardness Number	Izod Impact, Ft.-Lbs. (3) Room Temp.	Izod Impact, Ft.-Lbs. (3) -40° F.	Difference, Ft.-Lbs.
Nickel-Chromium-Molybdenum Steels.											
8221-1	0.26	0.86	0.29	.40/.60	.40/.60	.30/.40	.000	363	58.0	37.5	20.5
8222-1	0.25	0.88	0.29	.40/.60	.40/.60	.30/.40	.000	359	41.0	27.5	13.5
8585-1	0.30	0.86	0.43	0.56	0.51	.00	.000	373	27.5	17.5	10.0
8585-2						.00	.001	354	44.0	24.0	20.0
8585-3						.09	.002	359	41.0	25.0	16.0
8585-4						.14	.002	361	38.0	28.0	10.0
8585-5						.20	.002	363	39.0	25.5	13.5
Manganese-Molybdenum Steels.											
8224-1	0.31	1.54	0.28	----	----	.30/.40	.000	363	36.5	25.5	11.0
8225-1	.30	1.54	0.31	----	----	.30/.40	.000	363	50.0	25.5	24.5
8586-1	0.30	1.59	0.42	----	---	.00	.000	345	49.5	30.0	19.0
8586-2						.00	.001	341	43.0	21.5	21.5
8586-3						.08	.001	347	38.0	23.0	15.0
8586-4						.14	.001	383	35.0	14.5	20.5
8586-5						.24	.001	361	35.0	24.0	11.0

(1) 0.10 per cent Al added to all heats except those marked with an asterisk.

(2) 0.003 per cent boron added as ferroboron to those steels containing boron. Results given in this column determined by analysis.

(3) Average of two specimens.

There is no evidence of a drop in toughness as the molybdenum content is increased in the nickel-chromium base steel, but a drop does occur in the other steel, although some toughness is recovered when the molybdenum reaches 0.24 per cent. Since this information regarding the toughness of boron-treated alloy steels containing molybdenum is still inconclusive, a further check on this point was obtained by making some low-temperature impact tests on these steels using a Charpy-type specimen with a V-notch. It is known that steels which tend toward brittleness lose their impact resistance rather suddenly at subnormal temperatures. In this instance, the tests were carried out at -40° F. (-40° C.), a temperature low enough to reveal severe cases of embrittlement. All of the steels were lower in impact resistance at -40° F. than at room temperature, and some more so than others, but there is no basis for considering the steels containing both molybdenum and boron to be more brittle than those with molybdenum or boron alone. In general, those steels having the lowest impact values at -40° F. were also inferior at room temperature. Data on the low-temperature impact properties of the wrought boron-containing steels are contained in Table 20.

Most of the original Izod impact specimens from Heat 8585 were found to contain quenching cracks after the impact tests were made. New impact specimens were, therefore, machined from the various steels from this heat and water quenched as before, except that a 300° F. draw was used immediately after the quench. This treatment eliminated the difficulty, and has become standard practice for all the specimens prepared since.

Cast Boron-Treated Steels Covering a Range of Molybdenum Content - Tables 21 and 22.

The cast steels were poured in the same sequence outlined for the wrought steels, and the compositions of the wrought steels were duplicated as closely as possible.

Maximum hardenability, as shown in Table 21, is again reached at a molybdenum content between 0.10 and 0.15 per cent. There is no loss of toughness as the molybdenum content is increased in either of the two base analyses.

Impact tests at -40° F. reveal the interesting fact that the cast steels lost very little of their resistance at this temperature as compared to the wrought steels (Table 20). In the manganese-molybdenum series, the steels with low percentages of molybdenum have a larger drop in impact values than the others. Sufficient specimens were available from the castings poured from Heat 8583 to carry out impact tests at -60° F. (-51° C.). Even at this temperature the toughness remained quite high.

At the present time a series of steels are being prepared which, when complete, will comprehensively cover a fairly large range of molybdenum and boron contents. It is believed that the data obtained from the tests on these steels will provide a reliable index as to the utility of boron as a depth-hardening agent and to its possible influence on other properties, particularly when molybdenum is present in normal or subnormal amounts. The investigation will again feature Jominy hardenability data, and impact properties at room and at sub-zero temperatures. In addition some work will be done on the susceptibility of the steels to temper brittleness and the possible influence of boron on temper brittleness. The observed fluctuations in impact resistance of the steels which have already been studied indicate

TABLE 21. CHEMISTRY AND PROPERTIES OF CAST BORON-TREATED ALLOY STEELS COVERING A RANGE OF MOLYBDENUM CONTENTS

Heat No.	Chemistry, Per Cent(1)							Jominy End Quench Hardenability				Shephard(3) Grain Size	Mechanical Properties	
	C	Mn	Si	Ni	Cr	Mo	B(2)	Hardness 1/16-Inch from End, Rc	No. of 16ths of an Inch to Obtain a Drop of 5 Rc	No. of 16ths of an Inch to Obtain a Drop of 10 Rc	Hardness at $2\frac{1}{2}$-In. from End, Rc		Brinell Hardness Number	Izod Impact, Ft-Lbs.
Nickel-Chromium-Molybdenum Steels.														
8583-1	0.31	0.84	0.43	0.57	0.53	----	----	51.0	3.5	4.5	12.0	6-7	277	36.0(4)
8583-2						Trace	.002	50.5	7.5	9.5	15.0	7-8	282	38.0(4)
8583-3						.08	.001	50.0	9.0	12.0	26.5	6-7	288	34.0(4)
8583-4						.16	.001	50.0	10.0	13.5	30.5	6-7	284	39.5(4)
8583-5						.23	.001	48.0	7.5	10.0	29.5	7	285	37.0(4)
Manganese-Molybdenum Steels.														
8584-1	0.32	1.60	0.43	----	----	----	----	50.0	3.5	4.5	15.0	7	272	36.0(5)
8584-2						----	.001	51.5	9.0	11.0	19.5	6-7	269	37.0(5)
8584-3						.08	.001	51.0	12.0	15.0	24.5	7	280	38.5(5)
8584-4						.14	.001	51.0	14.5	18.0	32.0	7	288	35.5(5)
8584-5						.25	.001	50.0	11.0	17.0	30.5	6-7	275	38.5(5)

(1) 0.10 per cent Al added to all heats.

(2) 0.003 per cent boron added to all heats as ferroboron. Values given determined by analysis.

(3) Grain size measured on fractured hardenability specimen.

(4) Average of one triple-notch specimen.

(5) Average of three triple-notch specimens.

TABLE 22. LOW-TEMPERATURE IMPACT PROPERTIES OF CAST BORON-TREATED ALLOY STEELS COVERING A RANGE OF MOLYBDENUM CONTENTS

Heat No.	Chemistry, Per Cent(1)							Mechanical Properties				
								Brinell Hardness Number	Izod Impact, Ft.-Lbs.(3)			
	C	Mn	Si	Ni	Cr	Mo	B(2)		Room Temp.	-40°F.	Difference	-60°F.
Nickel-Chromium-Molybdenum Steels.												
8301-1*	0.24	0.80	0.37	.40/.60	.40/.60	.30/.40	.000	285	63.0	63.5	-0.5	----
8302-1	0.23	0.87	0.43	.40/.60	.40/.60	.30/.40	.000	302	40.5	41.0	-0.5	----
8583-1	0.31	0.84	0.43	0.57	0.53	.00	.000	277	33.0	28.5	4.5	22.5
8583-2						Trace	.002	269	34.0	32.5	1.5	23.0
8583-3						.08	.001	290	32.5	29.5	3.0	35.5
8583-4						.16	.001	283	38.5	36.0	2.5	31.5
8583-5						.23	.001	285	35.0	34.0	1.0	31.5
Manganese-Molybdenum Steels.												
8303-1*	0.27	1.44	0.41	----	----	.30/.40	.000	281	59.5	55.5	4.0	----
8304-1	0.26	1.43	0.40	----	----	.30/.40	.000	297	39.0	37.0	2.0	----
8584-1	0.32	1.60	0.43	----	----	.00	.000	256	34.5	27.5	7.0	----
8584-2						.00	.001	259	36.0	26.5	10.0	----
8584-3						.08	.001	271	35.0	23.0	12.0	----
8584-4						.14	.001	290	34.0	25.0	9.0	----
8584-5						.25	.001	272	39.0	37.0	2.0	----

(1) 0.10 per cent Al added to all heats except those marked with an asterisk.

(2) 0.003 per cent boron added as ferroboron to those steels containing boron.

(3) Average of two specimens.

the existence of temper embrittling effects even in the presence of molybdenum. Should the work show that boron or the reduction in molybdenum content has an important effect in either suppressing or accentuating temper brittleness, a more comprehensive study will be started on the problem of rendering steels immune to this form of brittleness.

Wrought Alloy Steels Treated with Special Deoxidizers - Table 23.

Silcaz No. 3 and Grainal X-79 are two types of commercial deoxidizers which contain some boron, as shown by their analyses in Table 23. If used in large enough quantities to add a few thousandths per cent boron to the steel, they should act to increase the hardenability from the boron addition alone, disregarding the possible beneficial influences of the other metals in these alloys. The recommended addition of 7.5 pounds per ton (0.375 per cent) will add roughly 0.002 per cent boron to the steel.

The results of experimental trials with these deoxidizers on wrought steels, as listed in Table 23, show that the effect of the two alloys on hardenability is practically the same. The Grainal-treated steels are somewhat higher in impact strength than those treated with Silcaz, but it is questionable whether the difference is significant.

It is apparent from the hardenability data that the deepest hardening steels are those containing their full share of molybdenum, that is, about 0.35 per cent. Not enough tests were made with steels containing 0.20 per cent molybdenum to state definitely whether or not they are inferior in hardenability to those with 0.35 per cent molybdenum is corroborated by the results in Tables 19 for steels containing about 0.20 per cent molybdenum that were treated with ferroboron. Except for Steel 8453 in Table 23, however, the difference in hardenability of the boron-treated

TABLE 23. CHEMISTRY AND PROPERTIES OF WROUGHT NICKEL-CHROMIUM-MOLYBDENUM AND MANGANESE-MOLYBDENUM STEELS TREATED WITH SPECIAL DEOXIDIZERS

Heat No.	Chemistry, Per Cent							Jominy End Quench Hardenability				Shephard(4) Grain Size	Mechanical Properties	
	C	Mn	Si	Ni	Cr	Mo	Deoxidizer Added(1)	Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to obtain a Drop of 5 Rc	No. of 16ths of an Inch to obtain a Drop of 10 Rc	Hardness at 2½-In. from End, Rc		Brinell Hardness Number	Izod(2) Impact, Ft.-Lbs.
Nickel-Chromium-Molybdenum Steels.														
8450	0.24	0.81	0.46	0.53	0.58	0.36	Silcaz	47.5	15.5	24.0	34.5	7	370	31.2
8451	0.21	0.85	0.45	0.54	0.52	0.20	Silcaz	47.5	12.0	17.5	30.0	6-7	360	36.6
8523	0.29	0.80	0.41	0.54	0.53	----	Grainal	51.0	9.0	11.0	13.5	7	367	39.5(3)
8524	0.30	0.81	0.42	0.54	0.52	0.33	Grainal	51.5	17.5	28.5	40.0	7	362	38.5(3)
8525	0.32	0.82	0.41	0.55	0.53	----	Silcaz	51.5	8.5	10.5	19.0	7	358	32.0(3)
8591	0.30	0.80	0.40	0.54	0.54	0.35	Silcaz	51.5	15.0	21.5	35.5	6-7	356	31.1(3)
Manganese-Molybdenum Steels.														
8452	0.29	1.40	0.44	----	----	0.33	Silcaz	51.0	13.0	19.0	32.0	7-8	368	27.5
8453	0.30	1.44	0.44	----	----	0.21	Silcaz	51.5	4.5	5.5	21.0	7-8	369	28.8
8592	0.30	1.51	0.39	----	----	----	Grainal	50.5	9.0	11.0	15.0	7	363	34.0
8593	0.29	1.52	0.40	----	----	0.34	Grainal	51.0	18.0	26.0	36.0	7	358	38.0
8594	0.31	1.58	0.40	----	----	----	Silcaz	49.0	8.5	10.5	16.5	6-7	363	33.0(3)
8595	0.31	1.52	0.39	----	----	0.35	Silcaz	51.5	16.5	24.0	35.0	7	359	33.0

(1) Seven and a half pounds per ton added to each steel (0.375%)

	Silcaz No. 3	Grainal X-79
Ti	10.35	19.6
Si	39.18	3.4
Zr	4.24	3.6
Mn	---	7.5
Al	5.85	13.0
B	0.50	0.54
Ca	8.60	---
C	---	0.05
Cu	---	1.7
	Balance Fe	Balance Fe

(2) Average of three triple-notch Izod specimens except where noted otherwise.

(3) Average of one triple-Notch specimen.

(4) Grain size from fractured hardenability specimen.

steels containing 0.20 per cent molybdenum and those containing 0.35 per cent is not very great. The rapid drop in hardness on the end-quench specimen for Steel 8453 is unusual, considering its analysis and its hardness of 21 Rockwell "C" at 2½ inches from the quenched end, which is higher than for steels having a more gradual loss in hardness at the quenched end.

It appears from the data in Table 23 that both Silcaz No. 3 and Grainal X-79 can be substituted for ferroboron to obtain the same degree of hardenability. If there is a difference, it is in favor of the complex deoxidizers, as the majority of the steels treated with these materials harden to a slightly greater depth than those treated with 0.10 per cent aluminum and ferroboron.

Cast Alloy Steels Treated with Special Deoxidizers - Table 24.

The cast steels listed in Table 24 were poured from the same heats prepared for the wrought steels listed in Table 23. The comments made in the discussion of the wrought steels apply equally well to the cast steels.

Two discrepancies in the hardenability results for the cast steels as compared to the results obtained with the wrought steels are apparent. The depth of hardening of cast Steels 8452 and 8594 are, respectively, about 100 and 20 per cent greater than in the comparison wrought steels. Since, ordinarily, differences of these magnitudes would not be expected, the hardenability tests are being repeated.

A peculiar situation with regard to the impact properties becomes evident if the Izod values in Table 23 are compared with those in Table 24. In Table 23, it is seen that Steels 8450, 8451, 8452, and 8453, which were melted and processed as one series, have, on the average, slightly inferior impact resistance as compared to the other steels listed in the table, which

TABLE 24. CHEMISTRY AND PROPEI OF CAST NICKEL-CHRCMIUM-MOLYBDENUM AND MANGANESE-MOLYBDENU 'LS TREATED WITH SPECIAL DEOXIDIZERS

Heat No.	Chemistry, Per Cent						Deoxidizer Added(1)	Jominy End Quench Hardenability				Shephard(4) Grain Size	Mechanical Properties	
	C	Mn	Si	Ni	Cr	Mo		Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to Obtain a Drop of 5 Rc	No. of 16ths of an Inch to Obtain a Drop of 10 Rc	Hardness at $2\frac{1}{2}$-In. from End, Rc		Brinell Hardness Number	Izod(2) Impact, Ft.-Lbs.
Nickel-Chromium-Molybdenum Steels.														
8450	0.24	0.81	0.46	0.53	0.58	0.36	Silcaz	49.5	15.0	22.0	35.5	6-7	286	46.0
8451	0.21	0.85	0.45	0.54	0.52	0.20	Silcaz	47.5	11.0	17.0	31.0	7	286	44.0
8523	0.29	0.80	0.41	0.54	0.53	----	Grainal	51.0	10.0	11.5	13.5	6-7	287	26.5(3)
8524	0.30	0.81	0.42	0.54	0.52	0.33	Grainal	51.0	14.0	20.0	36.0	7	293	31.5(3)
8525	0.32	0.82	0.41	0.55	0.53	----	Silcaz	51.0	8.5	11.0	17.5	7	285	26.5(3)
8591	0.30	0.80	0.40	0.54	0.54	0.35	Silcaz	52.0	14.5	23.0	36.0	7	288	31.5(3)
Manganese-Molybdenum Steels.														
8452	0.29	1.40	0.44	----	----	0.33	Silcaz	51.5	25.5	41.0+	43.0	7	287	43.6
8453	0.30	1.44	0.44	----	----	0.21	Silcaz	52.5	4.0	5.5	23.0	7-8	280	41.4
8592	0.30	1.51	0.39	----	----	----	Grainal	51.5	8.5	10.5	16.5	7	285	32.5
8593	0.29	1.52	0.40	----	----	0.34	Grainal	51.5	19.5	32.0	38.5	-	285	33.5
8594	0.31	1.58	0.40	----	----	----	Silcaz	51.5	9.0	10.5	16.5	-	286	20.5
8595	0.31	1.52	0.39	----	----	0.35	Silcaz	52.0	14.5	22.0	35.5	-	282	27.5

(1) Seven and a half poundx per ton added to each steel (0.375%)

	Silcaz No. 3	Grainal X-79
Ti	10.35	19.6
Si	39.18	3.4
Zr	4.25	3.6
Mn	---	7.5
Al	5.85	13.0
B	0.50	0.54
Ca	8.60	---
C	---	0.05
Cu	---	1.7
	Balance Fe	Balance Fe

(2) Average of three triple-notch specimens except where noted otherwise.

(3) Average of one triple-notch specimen.

(4) Grain size from fractured hardenability specimen.

were processed as another series. On the other hand, in Table 24, this relationship is reversed and cast Steels 8450, 8451, 8452, and 8453 are superior in impact strength to the other comparable steels listed in the table. Since the cast steels have been tempered to a lower hardness range than the wrought steels, it would appear that the change in the relative position of the two series as regards impact strength may be tied up with the heat treatment. Tests are now underway to ascertain whether the effect may be owing to temper brittleness, which ordinarily would not be expected to appear in steels containing molybdenum.

Plain Carbon Cast Steels Covering a Range of Silicon and Aluminum Contents - Table 25.

Data were presented in the last quarterly report on the hardenability and mechanical properties of alloy steels containing about 0.45 per cent silicon and treated with 0.20 per cent aluminum. The object at that time was to investigate the effects of silicon and aluminum when present in percentages above those normally used, and also to evaluate the effect of boron when added to these steels. Whenever boron was used, the hardenability was increased but it could not be ascertained from the data whether or not any especial benefit was realized from the excess silicon and aluminum. According to Grossmann ("Hardenability Calculated from Chemical Composition" A.I.M.E. Tech. Publ. No. 1437, 1942) both silicon and aluminum increase hardenability. It would be interesting to know how intense their action is in this direction, and whether or not there is a possibility for their use in improving the depth-hardening properties of armor steels.

Two plain carbon cast steel heats were melted and each cast into three keel blocks, with additions being made before each cast to accomplish

TABLE 25. CHEMISTRY AND PROPERTIES OF CAST PLAIN CARBON STEEL
COVERING A RANGE OF SILICON AND ALUMINUM CONTENTS

Heat No.	Chemistry, Per Cent C	Mn	Si	Al Added	Jominy End Quench Hardenability: Hardness 1/16-In. from End, Rc	No. of 16ths of an Inch to Obtain a Drop of 5 Rc	10 Rc	Hardness at 2½-In. from End, Rc	Shephard[5] Grain Size	Izod Brinell Hardness Number	Izod Impac Ft.-L
8652-1	0.29	0.79	0.26	0.10	46.5	2.5	3.0	-0.5	6-7	214	41.0
8652-2	0.28	0.80	0.58	0.10	48.0	2.5	3.0	3.5	6-7	266	42.0
8652-3			(0.60)[1]	0.30	49.0	3.0	4.0	4.5	5-6	282	20.0
8653-1	0.26	0.68	0.53	0.10	46.5	2.5	3.5	1.5	6-7	245	46.5
8653-2				0.20	45.0	2.5	3.0	1.0	6-7	247	43.5
8653-3				0.40	43.0	2.5	3.0	1.5	6	241	15.5

(1) Desired value.
(2) Izod values were obtained after quenching from 1650° F. and draw
(3) Tensile values were obtained after quenching from 1600° F. and d
(4) One triple-notch specimen.
(5) Grain size from fractured hardenability specimen.

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Mechanical Properties(2)					
Izod(4) Impact, Ft.-Lbs.	Tensile Brinell Hardness Number	Yield(3) Strength, Lb./sq.in.	Tensile(3) Strength, Lb./sq.in.	Per Cent(3) Reduction of Area	Per Cent(3) Elongation in 2 Inches
41.0	234	120,000	130,800	40.4	10.0
42.0	250	116,800	135,000	40.4	14.7
20.0	260	118,800	137,250	10.7	6.7
46.5	252	116,200	129,800	36.0	13.0
43.5	243	104,500	125,500	45.8	15.0
15.5	235	108,700	124,000	8.5	6.2

drawing to indicated hardness.
and drawing to indicated hardness.

the changes in silicon and aluminum contents indicated in Table 25. It is obvious that in these two heats neither silicon or aluminum increases have been effective in increasing the hardenability.

Erratic hardness tests on the tensile specimens led to the conclusion that the quenching temperature was not high enough above the critical, consequently the impact specimens, which had not then been tested, were quenched from a higher temperature and redrawn. Good ductility and impact values are achieved with aluminum contents up to 0.30 per cent (and 0.60 per cent silicon), but beyond this percentage of aluminum, these properties are adversely affected.

DISCUSSION

The information obtained to date has indicated that boron will increase the hardenability of rolled and cast alloy steels when the boron is added to the steel either as ferroboron or in the form of a complex deoxidizer alloy.

One series of heats reported in the previous quarterly report indicated a loss of toughness when boron was added to steels containing 0.35 per cent molybdenum, however, no added evidence that boron and molybdenum combinations reduce toughness was obtained from the results given in this report. It appears that boron can at least be safely added to steels containing up to 0.25 per cent molybdenum. When boron is added as Silcaz No. 3 or Grainal X-79, the depth of hardening seems to be somewhat greater than when it is added as ferroboron. A 0.003 per cent boron addition is as effective in promoting hardenability as one of 0.005 per cent.

Since this preliminary work was split up into a number of more or less unrelated series which represent an incomplete coverage of the field, work on a new series of heats has been inaugurated which will, it is believed, definitely establish the efficacy of boron. Both wrought and cast steels of two base compositions are being made with molybdenum contents of 0, 0.10, 0.20, 0.30, and 0.40 per cent. These five compositions (in each of the two base alloy steels) are then being repeated with the addition of 0.0015 per cent boron as ferroboron. Similar series will be made with boron additions of 0.003 and 0.006 per cent, respectively. Another series of these five compositions are to be treated with Grainal in sufficient quantity to add about 0.002 per cent boron, and finally, the series will be repeated with the addition of the same quantity of Silcaz No. 3. Instead of pouring each heat into both ingots and keel blocks, duplicate heats of each composition will be made and cast separately into either an ingot or a keel block. Hardenability, impact tests, and tests for temper brittleness are planned and other tests will follow if they seem warranted.

The Effect of Homogenizing Time and Temperature on the Properties of Cast Armor Plate

The analyses and producers of the five 36 x 36 x 2-inch plate used for this study are listed in Table 26. Each of the plates was marked out and cut into at least 18 coupons, measuring 5-3/4 x 7 inches. Thin sections for macro-examination of the cross section were also removed from the full dimensions of the plate. These were as centrally located in the plate as possible. A numbering system identifies the position of each coupon and their subdivisions with respect to their positions in the original plate.

The macro specimens have been etched and photographed. Coupons from each plate have been homogenized at 1650, 1750, 1850, 1950, and 2050°F. for 2, 6, and 12 hours. A portion of each coupon was then removed for

TABLE 26. MANUFACTURER AND ANALYSES OF CAST ARMOR PLATES USED IN THE HOMOGENIZING HEAT TREATMENT STUDY

Manufacturer	Plate No.	% C	% Mn	% Si	% P	% S	% Cr	% Ni	% Mo
American Steel Foundries	1	.27	1.50	.44	.022	.022	.32	---	.14
Symington Gould Corporation	2	.24	1.23	.32	-.04	-.04	.43	---	.45
Sivyer Steel Castings Company	3	.26	.97	.54	.031	.049	.49	.44	.40
General Steel Castings Corporation	4	.31	1.68	.47	.014	.020	.11	---	.46
Continental Roll and Steel Foundries	5	.30	.78	.37	.045	.046	.50	.46	.37

machining a Jominy bar, macro and micro sections, and two fracture grain size comparison sections, one for heat treating with the Jominy bar and the other to be carried along with the quenching operation on the rest of the coupon. A similar group of specimens were obtained from a coupon representing the as-received plates.

The remainder of each coupon was heated to 1600° F., held for 4 hours and quenched in water. Again a portion of each coupon, large enough to provide for 12 Charpy impact bars and a micro and macro section, was cut off. Both sections of each coupon were then tempered to a hardness range of 240 to 230 Brinell. The cut-off section was air cooled after the draw; while the coupon proper, which will provide 16 Charpy impact bars, two triple-notch Izod specimens, three tensile bars, and a block for checking the cross sectional Brinell hardness, was water quenched after the draw. Impact tests on specimens having this difference in the method of cooling after the draw may disclose any susceptibility toward temper brittleness.

None of the mechanical test specimens will be machined from the mid-sections of the plates. It is hoped that by using only the metal close to the surface for the mechanical tests, the effects of unsoundness in the castings may be minimized. Tests will be made on as-received plate as well as on the coupons receiving the various homogenizing heat treatments.

Jominy bars have been quenched and hardness readings are now being recorded. The grain size specimens have been fractured and compared with a set of Shephard grain size standards. Work is proceeding on the microscopical examinations of the homogenized plate. The coupon sections are now being machined into the required test specimens. At present, it is planned to test V-notch Charpy bars at room temperature, 0, -20, -40, and -60° F., and the Izod specimens at room temperature.

Face-Hardened Armor Plate Investigations

The initial phase of the study of face-hardened armor steels was to investigate the possibilities of lowering the alloy content of the plate without too greatly reducing the ballistic properties. The low-alloy steels listed in Table 27 were, therefore, melted, rolled into $\frac{1}{2}$-inch plate, and rough machined into impact specimens which were pseudo-carburized in cast iron borings at 1700° F. for 32 hours. These specimens were then quenched in oil from 1500° F. and tempered for 4 hours at 300° F. The hardness and impact test results are given in the table. It was found that the steels were higher in hardness and lower in impact than a commercial steel having an analysis used for face-hardened armor.

A second group of fourteen low alloy armor steels has been prepared and rolled into half-inch plate. The carbon contents of these steels vary from 0.10 to 0.22 per cent in order to determine the effects of this variation on core properties. The alloy contents were adjusted to combinations that held promise of producing the desired properties. Carburizing and final heat treatment of these steels will be carried out as soon as the necessary laboratory tests to determine the character and depth of case have been completed. Hardenability characteristics of these steels will also be determined by the Jominy end-quench method.

Experiments are now being conducted on the alteration of the case structure through a modification of the carburizing treatment. This work was suggested by a paper by Mahin and Spencer ("Depth and Character of Case Induced by Mixtures of Ferro-Alloys with Carburizing Compound" Trans., American Society for Steel Treating, Vol. 15, 1929, pp. 117-144), in which they described the use of ferrosilicon-carburizing compound mixtures for

TABLE 27. PROPERTIES AND CHEMICAL COMPOSITION OF PSEUDO-CARBURIZED STEEL

Heat No.	Chemical Composition							Rockwell "C" Hardness	Izod Impact, Ft.-Lbs.
	% C	% Mn	% Si	% Ni	% Cr	% Mo	% B		
8438	.21	1.06	.23	1.03	.32	.34	----	53.0	20.0
8439	.22	1.57	.23	1.03	.32	.34	----	54.0	23.5
8440	.20	2.01	.24	1.03	.31	.35	----	55.3	24.0
8441	.22	1.63	.87	1.03	.30	.35	----	54.0	25.0
8442	.21	1.55	.30	1.03	1.04	.33	----	57.3	18.5
8443	.21	1.65	.85	1.03	1.05	.35	----	55.0	22.5
8444	.22	1.64	.85	1.03	1.04	.20	----	54.0	23.5
8445	.23	1.64	.85	1.03	1.03	.20	.002	56.3	16.4
8479	.18	.47	.22	3.60	----	.32	----	52.0	21.5
8542*	.24	.47	---	3.4	.17	.29	----	45.3	27.4

* Commercial plate.

NOTE; All steels quenched in oil from 1550° F. and tempered for 4 hours at 300° F.

obtaining a decrease in the amount of hyper-eutectoid material and an increase in the relative proportion of eutectoid and hypoeutectoid case. Because the elimination of the hyper-eutectoid zone in case-hardened armor plate should prove desirable from the standpoint of increased ductility and toughness in the outer zone of the case with little or no sacrifice in hardness. It is believed that this process is worthy of investigation. Regardless of alloy content, maximum hardness of about 65 Rockwell "C" is obtained in a quenched steel having a carbon content of about 0.60 per cent; beyond this carbon content the hardness does not increase but remains practically constant. In the case of a carburized steel, therefore, the extra carbon in the zones having a carbon content above 0.60 per cent contributes nothing to the hardness of the case and may induce brittleness and spalling. While higher carbon may be desirable for certain applications such as in parts subject to wear, where resistance to abrasion is of most importance and brittleness is secondary, its presence in a part where hardness and toughness are of primary concern is of doubtful value.

Single preliminary test results obtained with the ferrosilicon-carburizing compound mixture are quite encouraging; however, no attempt to summarize the data can be made because of the lack of sufficient information on which to base conclusions. A general survey of the process is planned. If this shows promise, a more detailed research program will be initiated.

A correlative study which is being dovetailed with the investigation of the carburizing process is the use of such alloys like Grainel X-79 and Silcaz No. 3 to enhance the properties of face-hardened armor. Present information indicates that the contribution of alloys of this type may be three fold: 0) Their boron contents will increase the hardenability of the steels, which may allow for a reduction in alloy content. 2) Their grain-refining properties should be of benefit to the core of the surface-hardened steels--another factor which may allow for a reduction in alloy content without a loss in toughness. 3) It has been shown that the toughness of hardened steel is considerably improved when this type of deoxidizer is used, a property that should be of particular benefit in toughening the case of face-hardened armor steels.

The data from which this report was written are recorded in B.M.I. Notebooks No. 1041, pp. 4 to 31; No. 1043, pp. 9 to 24; No. 1017, pp. 71 to 97; No. 1089, pp. 3 to 12; and No. 1036, pp. 4 to 23. Additional data are on file at Battelle.

P. C. Rosenthal

John Kura

Murray Udy

George Krumlauf

Research Engineers

Approved:

C. H. Lorig
Supervising Metallurgist

CHL:gl
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