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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/560

Metallurgical Examination of 4"-6" Thick Cast Armor

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WATERTOWN ARSENAL
WATERTOWN, MASS.

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Final Report on Problem B-4.46

2 December 1944

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ABSTRACT

Twelve (12) samples of 4" thick and one sample of 6" thick cast armor, tested as part of the Ordnance Research Center Project 3780(328-AM3-304) for the development of specifications for 4", 5", and 6" thick cast armor were subjected to a metallurgical examination including fracture tests, hardness surveys, macroscopic and microscopic examinations, V-notch Charpy tests, hardenability tests and chemical analysis. In general, crystallinity detected in the sections was due to slack quenching and also to temper embrittlement(too slow cooling from the tempering temperature). Samples were free from pronounced casting defects. Correlations were established between fibre fracture tests and V-notch impact values. The acid open hearth steels when heat treated properly had satisfactory ballistic and metallurgical properties at 200-220 Brinell hardness. The basic open hearth steels investigated possess poor metallurgical properties since they were not made according to the best steelmaking practice and also due to the fact that these steels were, in most cases, improperly heat treated.

1. As requested by the Ordnance Research Center, Aberdeen[1], metallurgical examination has been completed on one sample of 6" thick cast armor and twelve (12) samples of 4" thick cast armor representing the product of three manufacturers. These tests were conducted in connection with a part of the Ordnance Research Center Project 3780(328-AM3-304) for the development of specifications for 4", 5", and 6" thick cast armor. A description of the samples is given as follows:

1. Wtn 470.5/22 - APG 470.5/194, 15 July 1944.

Plate No.	Heat No.	Thickness	Manufacturer
12	1232B	4"	Union Steel Castings
13	886A	4"	"
14	886A	4"	"
17	1247B	4"	"
29	1325B	4"	"
31	1344B	4"	"
32	984a	6"	"
41A	1093	4"	Pittsburgh Steel Foundry
45	10135	4"	"
47	9335	4"	"
740-1	--	4"	Continental Foundry & Machine Co.
811-5	--	4"	"
918-1	--	4"	"

The purpose of this investigation was to d termine the metallurgical quality of the material.

2. Metallurgical examination consisted of the following tests:

a. Chemical analysis of representative samples of cast armor.

b. Fibre fracture test.

c. Brinell hardness survey.

d. Macroscopic examination.

e. Microscopic examination.

f. V-notch Charpy impact tests at +70°F. and -40°F.

g. End quench hardenability tests.

3. The results of the above tests are presented in detail below.

a. Chemical analyses. Chemical analyses of representative samples are given in Table I. (See page .) The steels listed in Table I are essentially of two types, namely, chromium-molybdenum (2.31-3.33% Cr, .48-.60% Mo) with

manganese varying from .76-1.12% and the manganese-nickel-chromium-molybdenum classification (1.14-1.44% Mn, 1.46-1.56% Ni, .82-1.31% Cr). All steels contained from a trace to .001% boron; traces of titanium, .01-.02% aluminum, and small residuals of copper. Vanadium was apparently added to sample No. 740-1 while only a trace of this element was found in sample No. 918-1. Sample No. 740-1 contains a higher phosphorus content (.040) than the other acid open hearth steels produced by Continental Foundry and Machine Co.

b. Fibre Fracture Test. Fibre fracture tests were made upon deeply notched sections and the steels rated with respect to their heat treated condition, the results of which are given in Table II. Varying amounts of crystallinity were detected in the fractures of the castings submitted by the three manufacturers. The samples exhibiting a large percentage of fibre are enumerated as follows:

Nos. 17, 29, 31 - Union Steel Castings
No. 45 - Pittsburgh Steel Foundry
Nos. 811-5, 918-1 - Continental Foundry & Machine Co.

A survey of the summary of the results of the fibre fracture tests and ballistic properties of the plates investigated shows that in most cases crystallinity is associated with backspalling conditions. The fact that plate No. 811-5, which exhibited a high percentage of fibre, failed by a large exit diameter may be due to its low hardness. The specified striking velocity of the crystalline plate No. 13 was 1400 f/s and, as a result of a change in specification requirements, the specified striking velocity of plate No. 12 of the same thickness was 1450 f/s. Since plate No. 13 showed tendencies for a large back exit diameter under the conditions under which it was tested, it is believed that this type of a plate would have failed if this plate had been subjected to an impact of a higher striking velocity.

In order to determine if crystallinity observed in the fibre fracture test was associated with temper brittleness, several typical samples measuring about 6" x 3" x 1" were retempered at 1175°F. for three hours, followed by water quenching (1175°F.-1200°F., just below or at the same tempering temperature used by the manufacturers). The results of these tests which are presented in Table II indicate that sample Nos. 12, 32, and 47 were susceptible to temper brittleness, since a quench from the retempering temperature resulted in an essentially fibrous fracture. Traces of crystallinity observed in these retempered samples may have been due to improper quenching practice. Since sample No. 13 was crystalline after this retempering treatment, it is inferred that it was improperly quenched. The results of further studies on the susceptibility of this and other samples to temper brittleness are presented in Table V.

c. Cross-Sectional Brinell Hardness Surveys. The results of the cross-sectional Brinell hardness surveys are given in Table III. The hardness

values determined on each cross section were fairly uniform. All castings were heat treated to an average Brinell hardness range of 207-245. Most of the samples investigated were heat treated to a relatively low hardness level. It is believed, however, that cast armor would possess satisfactory impact properties when heat treated to an entirely fibrous fracture at a Brinell hardness range of 210-250.

a. Macroscopic Examination. The results of the macroscopic examination are given in Table IV. Sample No. 17 exhibited pronounced segregation throughout the section while sample Nos. 12, 13, 29, and 32 are quite free from segregations. The balance of the steels contain varying amounts of impurities.

e. Microscopic Examination. Typical nonmetallic inclusions and representative microstructures are presented in Figures 1-5 inclusive. A series of interdendritic nonmetallic inclusions of various types including eutectic sulphides and groups of sulphides were present in the samples examined, see Figure 1. Cast armor sample Nos. 41A and 47, manufactured by the Pittsburgh Steel Foundry Corporation, contained segregations of eutectic sulphides while sample No. 45 made by the same company was relatively free from this type of nonmetallic inclusion. Cast armor sample Nos. 740-1, 811-5, and 918-1, manufactured by the Continental Foundry and Machine Co., contained occasional segregations of eutectic sulphides associated with groups of sulphides. The cast armor manufactured by the Union Steel Castings, Nos. 12, 13, 14, 17, 29, 31, and 32, contained scattered groups of sulphides. The microstructure of the cast armor sample Nos. 41A, 45, and 47, manufactured by the Pittsburgh Steel Foundry Corp., is shown in Figure 2. A fairly uniform distribution of carbides was evident near the surface and at the center of sample No. 41A. Some grain boundary carbides associated with ferrite were present in the center of sample No. 45 while a more uniform microstructure was evident at the surface of this sample. Grain boundary carbides were present throughout the section of sample No. 47, some ferrite being evident near the surface. The microstructure of sample Nos. 12, 13, 14, 31, and 32, manufactured by the Union Steel Castings, is shown in Figures 3 and 4. In general, carbide segregations were evident in these sections, in most cases at the surface and also at the center of the sample. This condition is most noticeable in sample No. 13. The 6" thick sample No. 32 shows evidence of carbide segregations associated with ferrite in the center of the section. The microstructure of sample Nos. 740-1, 811-5, and 918-1, manufactured by the Continental Foundry and Machine Co., is shown in Figure 5. It is apparent that the austenitizing temperature used in the heat treatment of sample No. 740-1 failed to properly dissolve the carbides in the austenite. The microstructure of the central portion of sample No. 811-5 is similar to tempered intermediate transformation products.

Photomicrographic work was conducted by B. Phelps.

f. V-Notch Charpy Impact Tests at +70°F. and -40°F. The results of the V-notch Charpy impact tests made on samples taken near the surface and at the center of representative samples are given in Table V. Sample Nos. 31 and 32, which were made by Union Steel Castings, had fairly high V-notch Charpy values for acid open hearth steels, namely, 58.6-78.1 ft./lbs. at room temperature and 49.2-69.4 ft./lbs. at -40°F. The balance of the acid open hearth steels made by Union Steel Castings and Continental Foundry and Machine Co. had impact values varying from about 29-46 ft./lbs. at room temperature to 12-49 ft./lbs. at -40°F. The impact values of the basic open hearth steels manufactured by the Pittsburgh Steel Foundry were not typical of good quality basic open hearth steels. The low impact values of sample Nos. 45 and 47 are probably associated with the eutectic sulphides detected in these steels, see Figure 1. Generally speaking the results of the fibre fracture tests correlate fairly well with the V-notch Charpy tests determined at +70°F. and -40°F. Sample No. 31 which exhibited nearly all fibre throughout the section had good impact values at the surface and at the center of the section at +70°F. and -40°F. To some degree, this relationship existed in sample Nos. S11-5 and 918-1. The low impact values obtained at -40°F. at the center of sample Nos. 12, 13, 14, 41, 45, 47, and 740-1 are, undoubtedly, due to a combination of factors, namely, improper quenching and temper brittleness. In this connection, it was determined that the low impact values found in the central areas of sample Nos. 13, 41A, 47, and 740-1 were partly due to temper brittleness (see retempering experiments in Table V). It is shown that the impact value is raised to some degree by retempering small sections from the center of the castings at a temperature just below or at the temperature used by the manufacturers and quenching in water. It was also determined that all steels investigated in this program were susceptible to temper brittleness after slow cooling from the tempering temperature. (See Table V.)

g. End Quench Hardenability Data. End quench hardenability tests were made on sample Nos. 13, 31, 32, 41A, 45, 740-1, and S11-5. The results of these tests are tabulated in Table VI. The samples were austenitized at 1725°F. for 6½ hours previous to end quenching. Each Jominy bar was ground to a depth of .050" previous to making Rockwell C hardness determinations and microscopic examination. An abrupt drop in hardness was evident in Jominy bars, Nos. 41A and 45, while in the other samples investigated a gradual decrease in hardness was observed. Figure 6 illustrates the Jominy curves of several typical samples. Microscopic examination of the Jominy bars indicated that the distances from the quenched end at which the structure was 90% martensite (balance intermediate temperature transformation products) were 16/16 on sample Nos. 41A and 45, and 38/16 on sample No. 31. Martensite was evident at 40/16 on sample Nos. 13, 32, 740-1, and S11-5. With the exception of sample Nos. 41A and 45A, the remainder of samples tested had sufficient hardenability for 4" thick armor.

4. The results of this investigation indicate -

a. 4"-6" thick cast armor of the type investigated can be made essentially fibrous by proper heat treatment at a Brinell hardness range of 200-220. Some of the high Cr-Mo acid open hearth steels had exceptionally high V-notch Charpy impact values.

b. Crystallinity in the sections examined was chiefly due to improper quenching practice and to temper embrittlement (inadequate quenching from the tempering temperature).

c. Susceptibility to temper brittleness may be reduced considerably by a rapid quench from the tempering temperature.

d. The basic open hearth Cr-Mo steels produced by Pittsburgh Steel Foundry were not made according to the best steelmaking practice. Two of these steels examined have insufficient hardenability for 4" thick armor. The acid open hearth Mn-Cr steels manufactured by Union Steel Castings appear to be satisfactory for the thicknesses involved when heat treated properly at a Brinell hardness of 200 or greater. This is true when the manganese and chromium are on the low side. The acid open hearth Mn-Ni-Mo steel produced by Continental Foundry and Machine Co. had only a moderately high V-notch Charpy impact value although essentially fibrous at the hardness of about 200 Brinell. The Mn-Ni-Cr-Mo analysis produced by the same company was unsatisfactory. As a result of Jominy hardenability tests it is indicated that the two types of acid open hearth steels produced by the Continental Foundry & Machine Company have sufficient hardenability for 4" thick sections.

e. A satisfactory correlation was established between fibre and V-notch Charpy impact tests.

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TABLE I

Chemical Analyses

Sample No.	Thickness	Manufacturer	Analyzed by	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	Ti	B	Al
12	4"	Union Steel Castings	W.A.	.28	1.07	.44	.033	.028	trace	3.00	.57	trace	.045	trace	trace	.025
13	4"	Union Steel Castings	W.A.	.29	1.10	.48	.029	.029	trace	3.27	.58	trace	.045	trace	.001	.025
14	4"	Union Steel Castings	W.A.	.28	1.12	.47	.026	.028	trace	3.33	.60	trace	.04	trace	.0011	.025
17	4"	Union Steel Castings	Mfr.	.29	1.05	.33	.014	.030	-	2.89	.51					
29	4"	Union Steel Castings	Mfr.	.26	.83	.34	.017	.030	-	2.98	.55					
31	4"	Union Steel Castings	W.A.	.29	.95	.28	.026	.032	trace	2.61	.58	nil	.085	trace	.001	.025
32	6"	Union Steel Castings	W.A.	.30	1.06	.43	.030	.039	trace	3.01	.53	nil	.025	trace	trace	.025
41A	4"	Pittsburgh Steel Fdry.	W.A.	.29	.76	.47	.024	.025	trace	2.31	.48	nil	.085	trace	trace	.02
45	4"	Pittsburgh Steel Fdry.	Mfr.	.26	.72	.42	.015	.019	-	2.10	.52					
47	4"	Pittsburgh Steel Fdry.	W.A.	.33	.92	.49	.023	.022	trace	3.26	.55	nil	.12	trace	.001	.01
740-1	4"	Continental Fdry&Mach. Co.	W.A.	.27	1.44	.39	.028	.040	1.58	1.31	.46	.13	.035	trace	trace	.01
811-5	4"	Continental Fdry&Mach. Co.	Mfr.	.33	1.64	.41	.032	.035	1.45	.12	.59					
918-1	4"	Continental Fdry&Mach. Co.	W.A.	.32	1.14	.36	.020	.022	1.46	.82	.49	.065	.045	trace	trace	.01

TABLE II

Results of Fibre Fracture Test and Ballisti

Plate No.	Thickness Inches	Heat No.	Manufacturer	Ave. BHN	Results of Fibre Fracture Test on Samples "as-Received"	Results on Sam at 11 an
12	4.00	1232B	Union Steel Castings	217	Fibre in 1" from each face with 40% crystallinity (dendritic) in cetral 2" of section.	Appreci crystal
13	4.00	886A	"	219	Practically completely crystalline.	Nearly
14	4.00	886A	"	222	Fibre in 3/4-1" from each face. Central third about 30% crystalline (dendritic).	About throug
17	4.02	1247B	"	215	Essentially fibrous with 10-20% crystallinity in central 1" of section.	
29	3.99 4.00	1325B	"	218	Essentially fibrous with 10% crystallinity in central 1" of section.	
31	4.00	1341B	"	216	Fibrous, trace of crystallinity.	
32	6.00	984A	"	207	Fibrous in 1" from each face - central section 40% crystalline, (dendritic).	Essen crysta sectio
41A	4.20 4.24	1093	Pittsburgh Steel Foundry	215	Fibre in 1" from one face, balance crystalline.	Fibre essen ter o
45	3.98 4.00	10135	"	245	Dull gray fine mixed fracture. Essentially fibrous (dendritic).	
47	4.00	9335	"	238	Mixed fracture - 40-50% crystalline.	Essen of cr
740-1	4.16	—	Continental Foundry & Machine Co.	221	Fibre in 1" from each face, balance of section 50% crystalline.	
811-5	4.18 4.13	—	"	213	Essentially fibrous with 5% crystallinity in central 1" of thickness.	
918-1	4.02 3.98	—	"	229	Essentially fibrous with 5% crystallinity in central 1" of thickness.	

TABLE II

...s of Fibre Fracture Test and Ballistic Tests

...lts of Fibre Fracture Test on Samples "As-Received"	Results of Fibre Fracture Test on Samples after Retempering at 1175°F-1200°F. for 3 Hrs. and Quenching in Water	Ballistic Properties as Reported by APG, Spec. AXS-1015 Shock Test 4" Plate, 155mm AP112, 30° Obl. 6" Plate, 6" AP MK27, 15° Obl.
...re in 1" from each face with crystallinity (dendritic) ...ctral 2" of section.	Essentially fibrous, traces of crystallinity.	Satisfactory Shock Test - PP(N), exit dia. 2-3/4x3-3/4", cracks 7"-7½". 1444f/s HP, Spec. 1450f/s.
...tically completely ...stalline.	Nearly completely crystalline.	Satisfactory Shock Test - PP(N), hole 5-7/8x 6-1/4", back exit 9-1/2x9-3/4". 1404f/s HP, Spec. 1400f/s.
...re in 3/4-1" from each face. ...tral third about 30% crystal- ...e (dendritic).	about 50% crystallinity throughout section.	Failed Shock Test CP(N), exit dia. 9-1/4x9-1/2" with backspalling. 1446f/s LC, Spec. 1450f/s. Failed resistance to penetration, CP(N).
...entially fibrous with 10-20% ...stallinity in central 1" of ...tion.	—	SATISFACTORY Shock Test - PP(N), hole 2x5", cracks 6" and 15". 1408f/s HP, Spec. 1406f/s.
...entially fibrous with 10% ...ystallinity in central 1" ...section.	—	SATISFACTORY Shock Test - PP(N), hole 2-3/8x 3-7/8", cracks on bulge 5-1/2x 5-3/4", 1380f/s HP, Spec. 1397f/s.
...rous, trace of crystallinity.	—	SATISFACTORY Shock Test - PP(N), small opening. 1407f/s HP, Spec. 1400f/s.
...rous in 1" from each face - ...tral section 40% crystalline, ...endritic).	Essentially fibrous, about 10% crystallinity throughout section. section.	SATISFACTORY Shock Test - PP(N), opening 5/8x 5/8". 1602f/s HP, Spec. 1600f/s.
...bre in 1" from one face, ...lance crystalline.	Fibre in 1" from one face, essentially crystalline in center of fracture.	Failed Shock Test CP(N), hole 6x6-1/16", exit dia. 9-11/16x10-1/4". 1536f/s LC, Spec. 1530f/s.
...ll grey fine mixed frac- ...re. Essentially fibrous ...endritic).	—	SATISFACTORY Shock Test - PP(N), face open- ing 3-1/2x3-7/8". 1393f/s HP, Spec. 1394f/s.
...xed fracture - 40-50% crys- ...lline.	Essentially fibrous, traces of crystallinity.	SATISFACTORY Shock Test - PP(N), face open- ing 1/8x3/4". 1402f/s HP, Spec. 1400f/s.
...bre in ½" from each face, ...lance of section 50% crys- ...lline.	—	Failed Shock Test CP(N), exit dia. with back spall- ing 7-1/4x10". 1504f/s LC, Spec. 1514f/s.
...ssentially fibrous with 5% ...rystallinity in central 1" ...f thickness.	—	Failed Shock Test CP(N), exit dia. 9x9½". 1519f/s LC, Spec. 1522f/s.
...ssentially fibrous with 5% ...rystallinity in central 1" ...f thickness.	—	SATISFACTORY Shock Test - PP(N), opening 1/8x 1/8". 1402f/s HP, Spec. 1406f/s.

TABLE III

Cross-Sectional Brinell Hardness Survey

Plate No.	Thickness	Heat No.	Manufacturer	Cross-Sectional Brinell Hardness Survey Range	Average
12	4"	1232 B	Union Steel Castings	212-217	217
13	4"	886 A	" " "	217-223	219
14	4"	886 A	" " "	217-223	222
17	4"	1247 B	" " "	212-217	215
29	4"	1325 B	" " "	217-223	218
31	4"	1344 B	" " "	207-229	216
32	6"	984 A	" " "	201-217	207
41A	4"	1093	Pittsburgh Steel Foundry	212-217	215
45	4"	10135	" " "	235-255	245
47	4"	9335	" " "	229-241	238
740-1	4"	--	Continental Foundry & Machine Company	217-229	221
811-5	4"	--	" " " "	212-217	213
918-1	4"	--	" " " "	229-229	229

The hardnesses were uniform across the sections in all cases.

TABLE IV

Results of Macroscopic Examination

Plate No.	Heat No.	Mfgr.	Macroscopic Examination
12	1232 B	Union	Clean metal
13	886 A	"	Clean metal
14	886 A	"	Equiaxed dendrites Slag inclusion near one surface
17	1247 B	"	Pronounced segregation
29	1325 B	"	Clean metal
31	1344 B	"	Equiaxed dendrites Occasional pronounced segregation near center of section
32	984 A	"	Clean metal
41A	1093	Pittsburgh	Scattered segregation cavities extending in 1" from one surface
45	10135	"	Continuous chain-like impurities in center of section
47	9335	"	Equiaxed dendrites
740-1	—	Continental	Interdendritic segregation noted in center of segregation
811-5	—	"	Columnar dendrites throughout section, some segregation at center
918-1	—	"	Clean metal in 1½" from one surface, segregation scattered over balance of section

Sample No.	Manufacturer	Thickness	Result of Fibre Fracture test on Sections cut from test plate	Location of V-Notch Charpy bar	Temp. of Te
12-1	Union Steel Castings	4"	Fibre in 1" from each face with 40% crystallinity in central 2" of section.	3/4" from surface	+7
12-3		4"		Center	+
12-2		4"		3/4" from surface	-
12-4		4"		Center	-
13-1	"	4"	Practically completely crystalline.	3/4" from surface	
13-3		4"		Center	
13-2		4"		3/4" from surface	
13-4		4"		Center	
14-1	"	4"	Fibre in 3/4" from each face. Central third about 30% crystalline (dendritic).	3/4" from surface	
14-3		4"		Center	
14-2		4"		3/4" from surface	
14-4		4"		Center	
31-1	"	4"	Fibrous, trace of crystallinity.	3/4" from surface	
31-3		4"		Center	
31-2		4"		3/4" from surface	
31-4		4"		Center	
32-1	"	6"	Fibrous in 1" from each face, central section 40% crystalline (dendritic).	3/4" from surface	
32-3		6"		Center	
32-2		6"		3/4" from surface	
32-4		6"		Center	
41-A-1	Pittsburg Steel Foundry	4"	Fibre in 1" from one face, balance crystalline.	3/4" from surface	
41-A-3		4"		Center	
41-A-2		4"		3/4" from surface	
41-A-4		4"		Center	
45-1	"	4"	Dull gray fine mixed fracture, essentially fibrous (dendritic).	3/4" from surface	+7
45-3		4"		Center	+
45-2		4"		3/4" from surface	-
45-4		4"		Center	-
47-1	"	4"	Mixed fracture, 40-50% crystalline.	3/4" from surface	+7
47-3		4"		Center	+7
47-2		4"		3/4" from surface	-4
47-4		4"		Center	-4
740-1-1	Continental Foundry & Machine Co.	4"	Fibre in 1/2" from each face, balance of section 50% crystalline.	3/4" from surface	+7
740-1-3		4"		Center	+7
740-1-2		4"		3/4" from surface	-4
740-1-4		4"		Center	-4
811-5-1	"	4"	Essentially fibrous with 5% crystallinity in central 1" of thickness.	3/4" from surface	+7
811-5-3		4"		Center	+7
811-5-2		4"		3/4" from surface	-4
				Center	-4

+70°F.	217	49.8	Fc 40%	--	--	--	--	--	--
+70°F.		44.5	Fc 40%	--	--	--	--	--	--
-40°F.		23.6	Fc 90%	--	--	--	--	--	--
-40°F.		35.9	Fc 70%	--	--	--	--	--	--
+70°F.	219	47.1	Fc 25%	1200°F.	3 hrs.	water	+70°F.	44.2	Fc 45%
+70°F.		30.7	Fc 70%	1200°F.	3 hrs.	water	-40°F.	30.8	Cb 85%
-40°F.		22.2	Cb	1200°F.	3 hrs.	furnace*	+70°F.	10.5	Cb 90%
-40°F.		16.4	Cb	1200°F.	3 hrs.	furnace	-40°F.	5.6	Cb
+70°F.	222	50.6	Fc 15%	--	--	--	--	--	--
+70°F.		38.2	Fc 40%	--	--	--	--	--	--
-40°F.		28.0	Fc 80%	--	--	--	--	--	--
-40°F.		36.2	Fc 50%	--	--	--	--	--	--
+70°F.	216	67.5	Fc trace	1200°F.	3 hrs.	water	+70°F.	61.5	Fc 10%
+70°F.		78.1	Fc trace	1200°F.	3 hrs.	water	-40°F.	47.8	Fc 40%
-40°F.		63.7	Fc trace	1200°F.	3 hrs.	furnace	+70°F.	42.0	Fc 60%
-40°F.		69.4	Fc trace	1200°F.	3 hrs.	furnace	-40°F.	18.2	Cb
+70°F.	207	63.7	Fc trace	1200°F.	3 hrs.	water	+70°F.	60.3	Fc 35%
+70°F.		58.6	Fc 20%	1200°F.	3 hrs.	water	-40°F.	38.8	Fc 70%
-40°F.		40.2	Fc 35%		--	--	--	--	--
-40°F.		52.8	Fc 25%		--	--	--	--	--
+70°F.	215	73.2	Fc trace	1175°F.	3 hrs.	water	+70°F.	60.5	Fc 30%
+70°F.		63.7	Fc trace	1175°F.	3 hrs.	water	-40°F.	49.9	Fc 40%
-40°F.		54.6	Fc 40%	1175°F.	3 hrs.	furnace	+70°F.	62.2	Fc 40%
-40°F.		23.2	Fc 90%	1175°F.	3 hrs.	furnace	-40°F.	19.6	Cb
+70°F.	245	41.5	Fc 30%	--	--	--	--	--	--
+70°F.		29.5	Fc 70%	--	--	--	--	--	--
-40°F.		29.9	Fc 70%	--	--	--	--	--	--
-40°F.		20.5	Cb	--	--	--	--	--	--
+70°F.	238	37.4	Fc trace	1175°F.	3 hrs.	water	+70°F.	60.3	Fc 35%
+70°F.		44.1	Fc trace	1175°F.	3 hrs.	water	-40°F.	50.5	Fc 45%
-40°F.		22.2	Cb	--	--	--	--	--	--
-40°F.		16.8	Fc 80%	--	--	--	--	--	--
+70°F.	221	34.2	Fc 70%	1200°F.	3 hrs.	water	+70°F.	36.6	Fc 70%
+70°F.		29.5	Fc 80%	1200°F.	3 hrs.	water	-40°F.	21.3	Cb
-40°F.		17.4	Cb	1200°F.	3 hrs.	furnace	+70°F.	7.3	Cb 80%
-40°F.		12.1	Cb	1200°F.	3 hrs.	furnace	-40°F.	3.2	Cb
+70°F.	213	46.6	F	--	--	--	--	--	--
+70°F.		42.0	F	--	--	--	--	--	--
-40°F.		46.6	Fc 15%	--	--	--	--	--	--
-40°F.		35.4	Fc 25%	--	--	--	--	--	--
+70°F.	229	54.1	F	--	--	--	--	--	--
+70°F.		36.6	Fc 20%	--	--	--	--	--	--
-40°F.		49.2	Fc 5%	--	--	--	--	--	--
-40°F.		41.5	Fc 15%	--	--	--	--	--	--

llowing fracture symbol refers to estimated surface area which is crystalline.

+70°F.	217	49.8	Fe 40%	—	—	—	—	—	—
+70°F.		44.5	Fe 40%	—	—	—	—	—	—
-40°F.		23.6	Fe 90%	—	—	—	—	—	—
-40°F.		35.0	Fe 70%	—	—	—	—	—	—
+70°F.	219	47.1	Fe 25%	1200°F.	3 hrs.	water	+70°F.	44.2	Fe 45%
+70°F.		30.7	Fe 70%	1200°F.	3 hrs.	water	-40°F.	30.8	Cb 85%
-40°F.		22.2	Cb	1200°F.	3 hrs.	furnace*	+70°F.	10.6	Cb 90%
-40°F.		18.4	Cb	1200°F.	3 hrs.	furnace	-40°F.	5.6	Cb
+70°F.	222	50.6	Fe 15%	—	—	—	—	—	—
+70°F.		38.2	Fe 40%	—	—	—	—	—	—
-40°F.		28.0	Fe 80%	—	—	—	—	—	—
-40°F.		36.2	Fe 50%	—	—	—	—	—	—
+70°F.	216	67.5	Fe trace	1200°F.	3 hrs.	water	+70°F.	61.5	Fe 10%
+70°F.		58.1	Fe trace	1200°F.	3 hrs.	water	-40°F.	47.8	Fe 40%
-40°F.		63.7	Fe trace	1200°F.	3 hrs.	furnace	+70°F.	42.0	Fe 65%
-40°F.		69.4	Fe trace	1200°F.	3 hrs.	furnace	-40°F.	18.2	Cb
+70°F.	207	63.7	Fe trace	1200°F.	3 hrs.	water	+70°F.	60.3	Fe 35%
+70°F.		58.6	Fe 20%	1200°F.	3 hrs.	water	-40°F.	38.8	Fe 70%
-40°F.		49.2	Fe 35%		—	—	—	—	—
-40°F.		52.8	Fe 25%		—	—	—	—	—
+70°F.	215	73.2	Fe trace	1175°F.	3 hrs.	water	+70°F.	60.5	Fe 30%
+70°F.		63.7	Fe trace	1175°F.	3 hrs.	water	-40°F.	49.9	Fe 40%
-40°F.		54.6	Fe 40%	1175°F.	3 hrs.	furnace	+70°F.	62.2	Fe 40%
-40°F.		23.2	Fe 90%	1175°F.	3 hrs.	furnace	-40°F.	19.6	Cb
+70°F.	245	41.5	Fe 30%	—	—	—	—	—	—
+70°F.		29.5	Fe 70%	—	—	—	—	—	—
-40°F.		29.9	Fe 70%	—	—	—	—	—	—
-40°F.		22.5	Cb	—	—	—	—	—	—
+70°F.	238	37.4	Fe trace	1175°F.	3 hrs.	water	+70°F.	60.3	Fe 35%
+70°F.		44.1	Fe trace	1175°F.	3 hrs.	water	-40°F.	50.5	Fe 45%
-40°F.		22.2	Cb	—	—	—	—	—	—
-40°F.		16.8	Fe 80%	—	—	—	—	—	—
+70°F.	221	34.2	Fe 70%	1200°F.	3 hrs.	water	+70°F.	36.6	Fe 70%
+70°F.		29.5	Fe 80%	1200°F.	3 hrs.	water	-40°F.	21.3	Cb
-40°F.		17.4	Cb	1200°F.	3 hrs.	furnace	+70°F.	7.3	Cb 85%
-40°F.		12.1	Cb	1200°F.	3 hrs.	furnace	-40°F.	3.3	Cb
+70°F.	213	46.8	F	—	—	—	—	—	—
+70°F.		42.0	F	—	—	—	—	—	—
-40°F.		36.6	Fe 15%	—	—	—	—	—	—
-40°F.		33.4	Fe 25%	—	—	—	—	—	—
+70°F.	229	54.1	F	—	—	—	—	—	—
+70°F.		36.6	Fe 20%	—	—	—	—	—	—
-40°F.		49.2	Fe 5%	—	—	—	—	—	—
-40°F.		41.5	Fe 15%	—	—	—	—	—	—

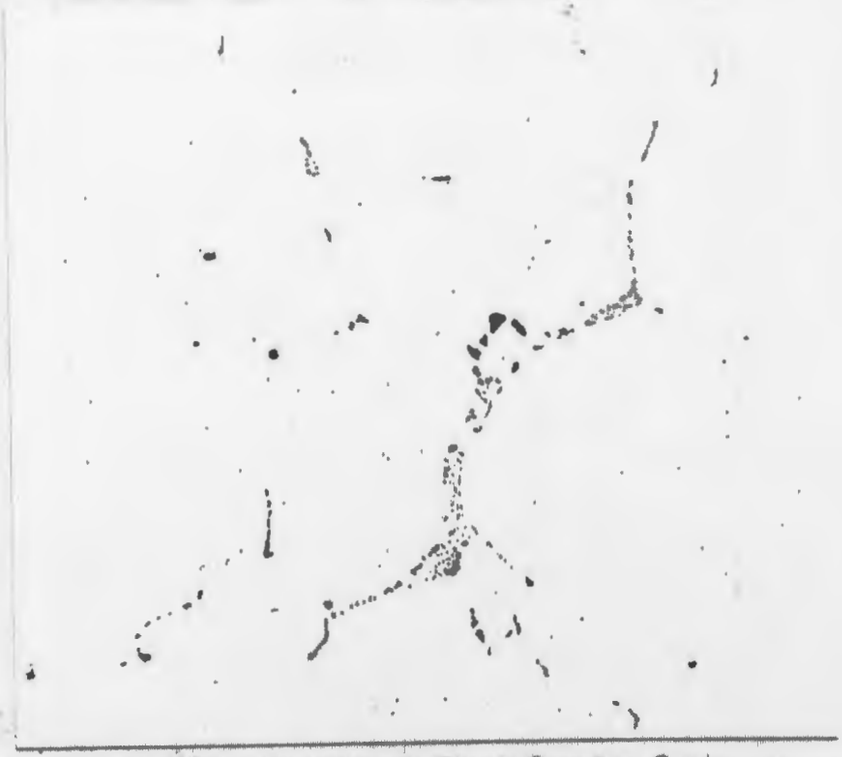
following fracture symbol refers to estimated surface area which is crystalline.

TABLE VI

End Quench Hardenability Tests

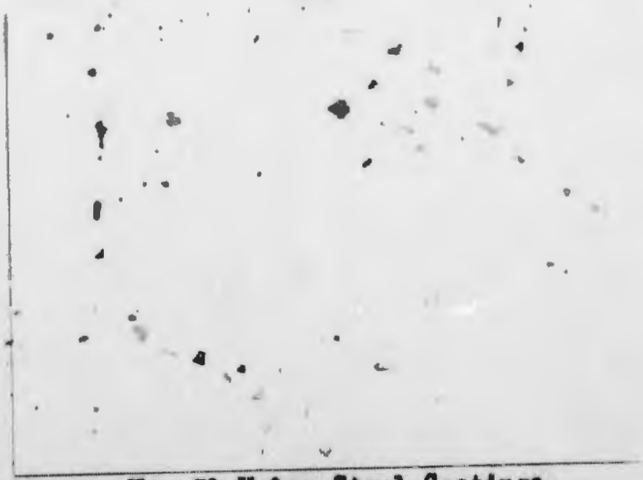
Sample No.	Manufacturer	Jominy Hardenability Data: 1/16" from Quenched End Rc	Jominy Hardenability Data: 2½" from Quenched End Rc	Jominy Hardenability Data: No. of 1/16" from Quenched End at Which Abrupt Hardness Drop Occurs	Hardenability Criterion: No. of 1/16" from Quenched End at Which Structure Is 90% Martensite
13	Union	50.5	49.5	—	40
31	Union	47.5	45.5	—	38
32	Union	50.5	48.5	—	40
41A	Pittsburgh	48.5	40.5	32	16
45	Pittsburgh	47.5	38.5	39	16
740-1	Continental	50.5	49.0	—	40
811-5	Continental	50.5	49.0	—	40

Nonmetallic Inclusions



No. 45 - Pittsburgh Steel Foundry Corp.
Typical eutectic sulphides. This type of nonmetallics was occasionally found in sample Nos. 41A and 47.

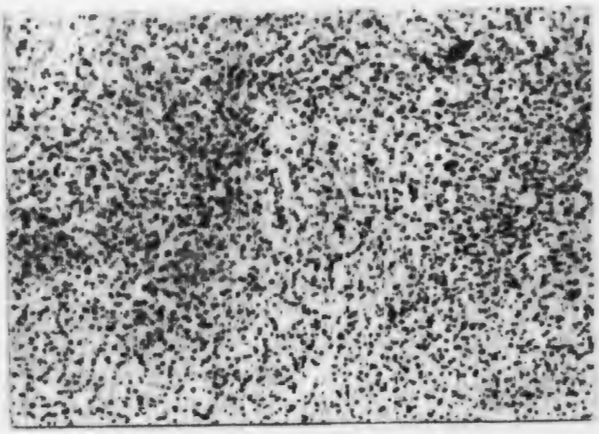
No. 740-1 Continental Foundry & Machine Co.
Occasional grain boundary eutectic sulphides associated with scattered sulphides. Typical of Continental Castings.



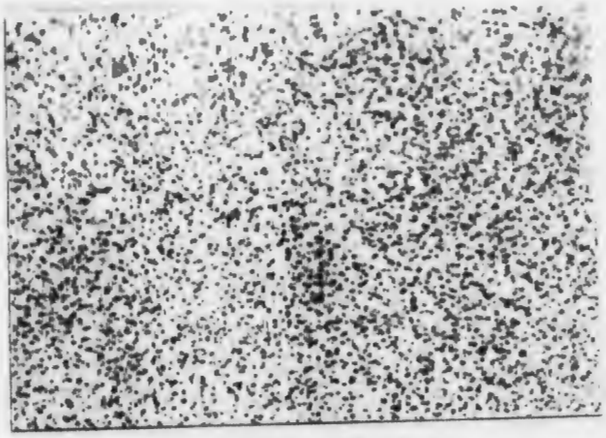
No. 31 Union Steel Castings
Occasional pronounced segregation of sulphides. Typical of Union Castings.

FIGURE 1

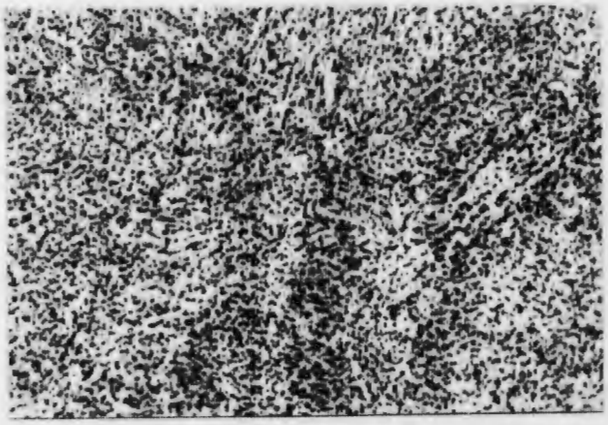
Microstructures of 4" Thick Cast Armor
Manufactured by Pittsburgh Steel Foundry Corp.



No. 41a - Near Surface
Fairly uniform distribution of carbides.

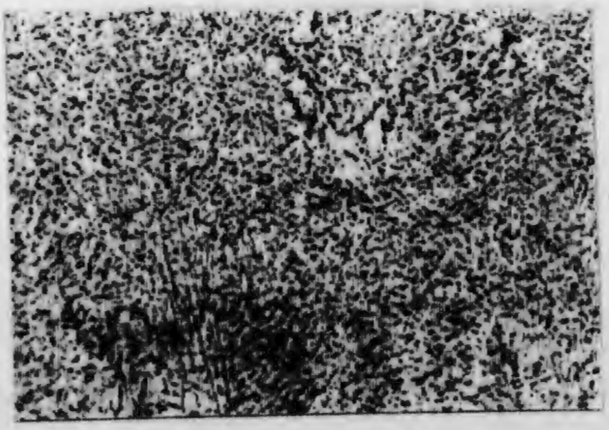


No. 41a - Center
Uniform distribution of carbides.

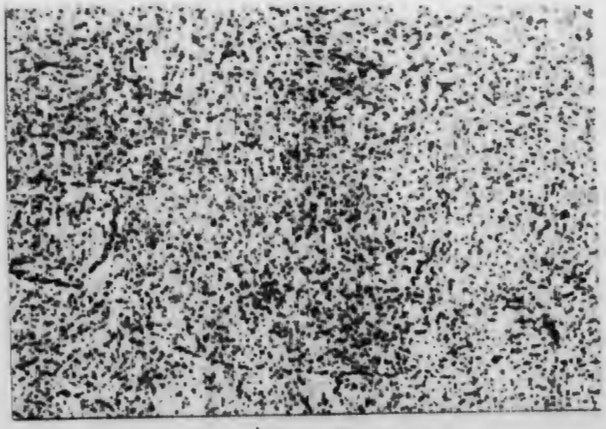


No. 45 - Near Surface
Fairly uniform distribution of fine carbides.

No. 45 - Center
Grain boundary carbides associated with ferrite.



No. 47 - Near Surface
Ferrite and carbide segregations.



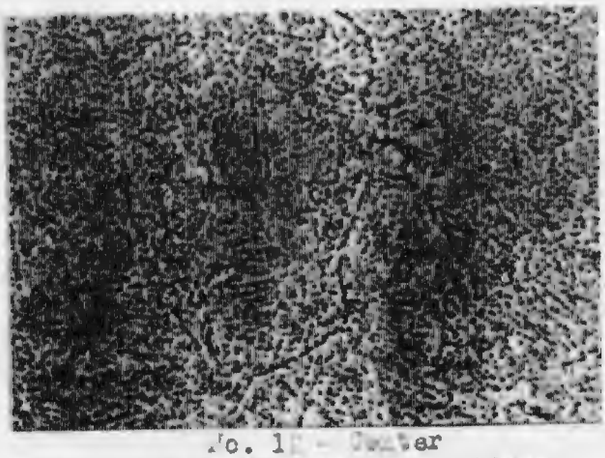
No. 47 - Center
Evidence of some grain boundary carbides.

Photomicrographs Taken at X1000 - Etched in Picral

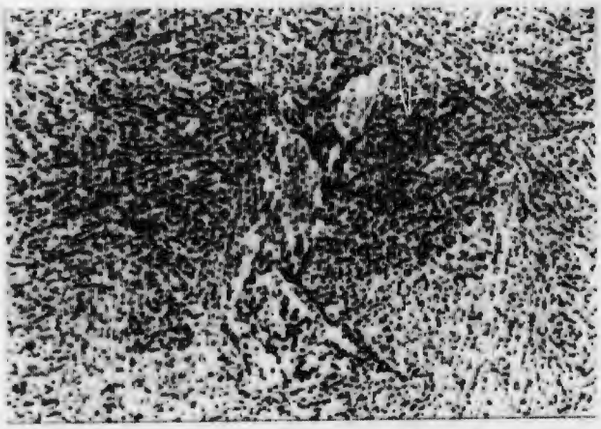
FIGURE 2

Microstructure of 4" Thick Cast Armor
Manufactured by Union Steel Castings

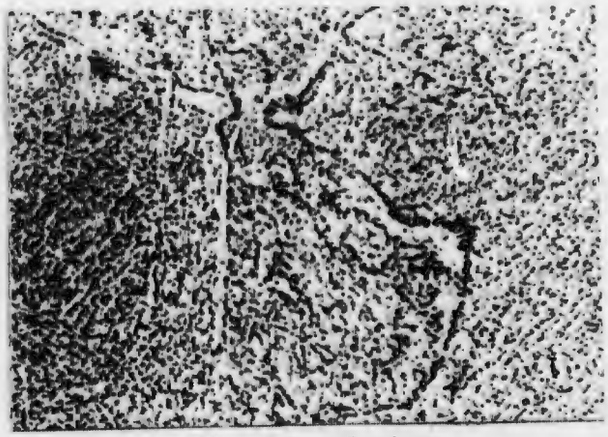
No. 14 - Near Surface
Trace of grain boundary carbides.



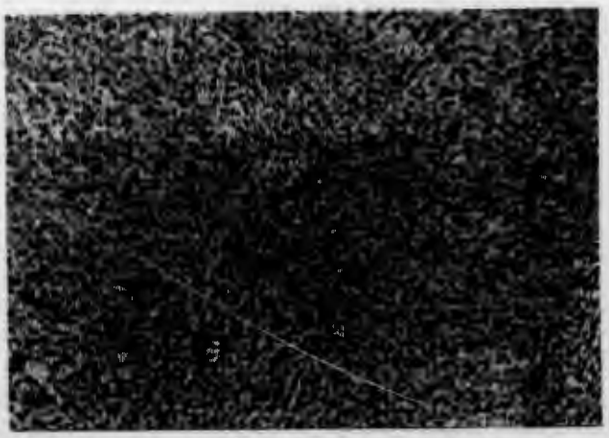
No. 14 - Center
Evidence of grain boundary carbides.



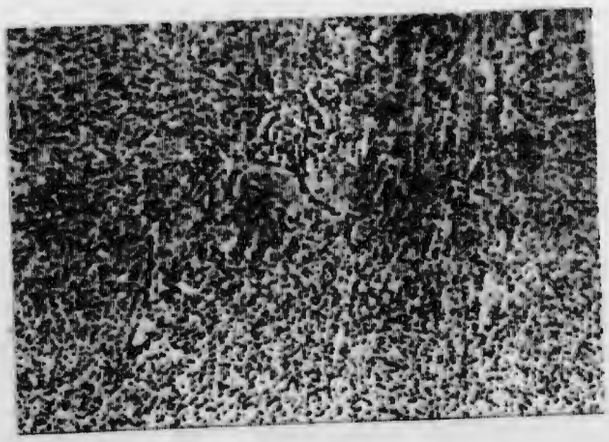
No. 13 - Near Surface
Ferrite, grain boundary carbides.



No. 13 - Center
Ferrite, heavy grain boundary carbides.



No. 14 - Near Surface
Uniform distribution of fine carbides.

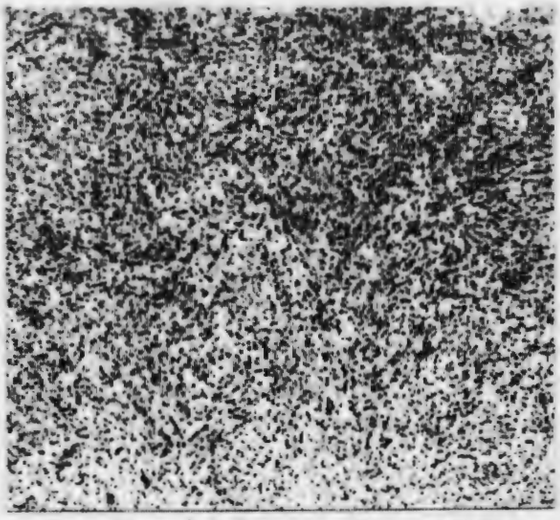


No. 14 - Center
Evidence of some grain boundary carbides

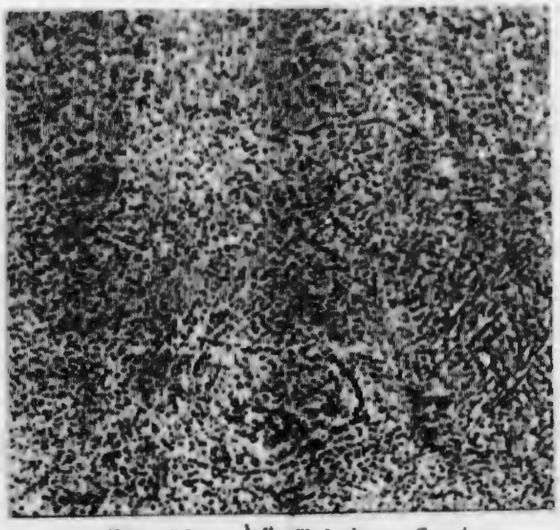
Photomicrographs Taken at X1000 - Etched in Picral.

FIGURE 3

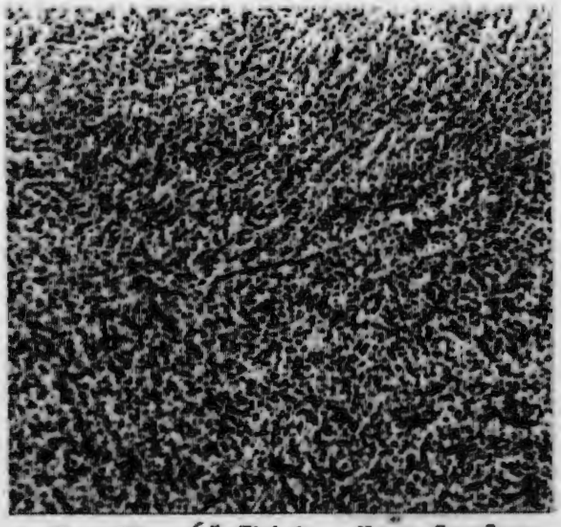
Microstructure of 4"-6" Thick Cast Armor
Manufactured by Union Steel Castings



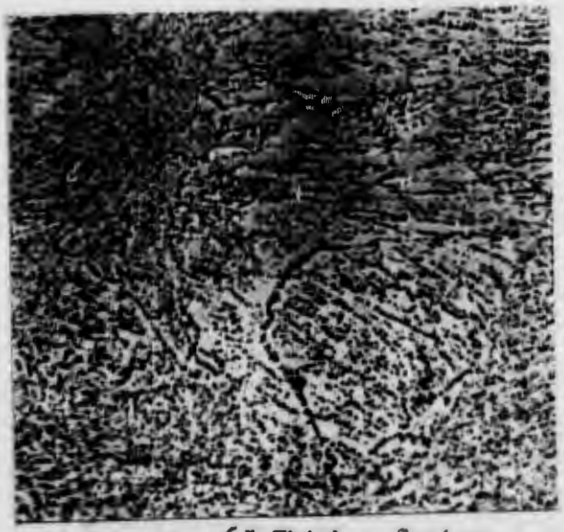
No. 31 - 4" Thick - Near Surface
Fairly uniform distribution of carbides.



No. 31 - 4" Thick - Center
Grain boundary carbides.



No. 32 - 6" Thick - Near Surface
Trace of grain boundary carbides.

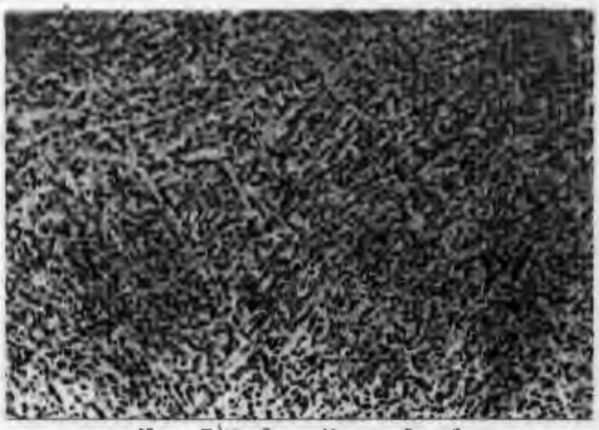


No. 32 - 6" Thick - Center
Ferrite and pronounced grain boundary carbides.

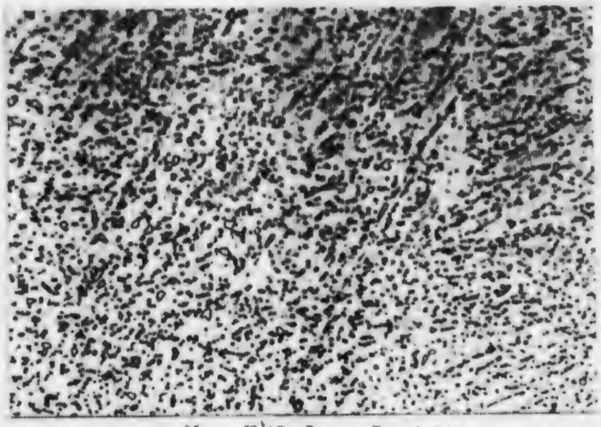
Photomicrographs Taken at X1000 - Etched in Picral

FIGURE 4

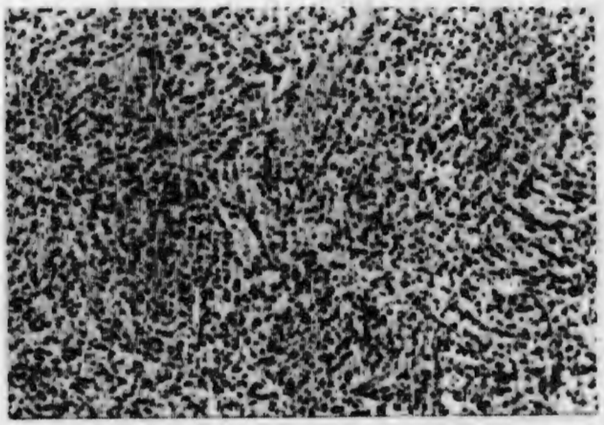
Microstructure of 4" Thick Cast Armor
Manufactured by Continental Foundry & Machine Co.



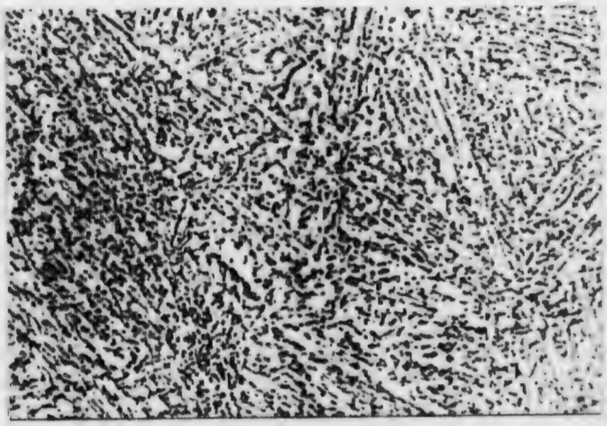
No. 740-1 - Near Surface
Mixture of course and fine carbides.



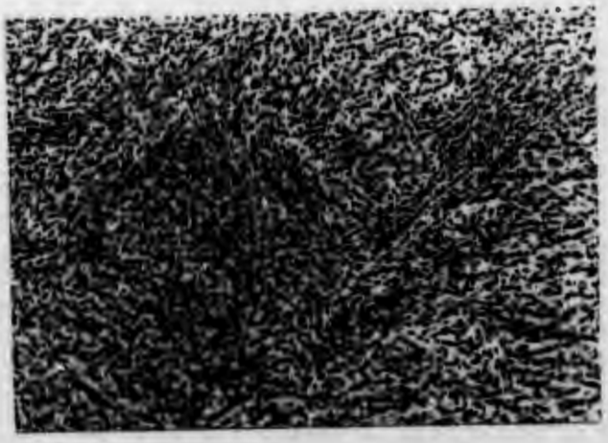
No. 740-1 - Center
Fairly uniform distribution of course and fine carbides.



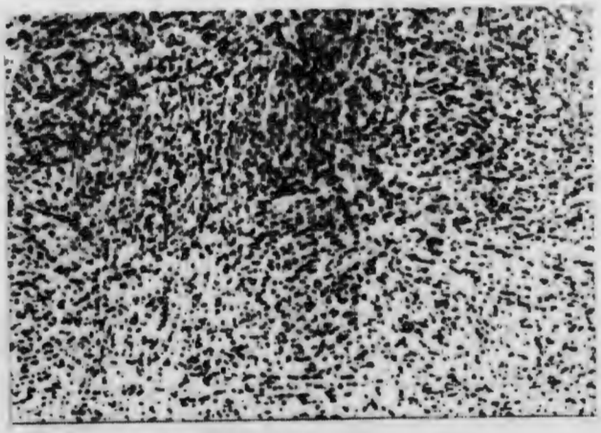
No. 811-5 - Near Surface
Fairly uniform distribution of carbides.



No. 811-5 - Center
Carbides in acicular pattern.



No. 918-1 - Near Surface
Evidence of grain boundary carbides.



No. 918-1 - Center
Uniform distribution of carbides.

Photomicrographs Taken at X1000 - Etched in Picral

FIGURE 5