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X4791

ARMOR

A Preliminary Study of the Effects of the Conchoidal Fracture Upon the Physical and Metallurgical Characteristics of Cast Armor.

by

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5 October 1943

WATERTOWN ARSENAL
WATERTOWN, MASS.

Watertown Arsenal Laboratory
Report Number WAL 710/413
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OBJECT

To determine if the conchoidal fracture indicates poor physical and metallurgical properties and to properly evaluate the conchoidal fracture in accordance with the Fibre Fracture Test.

CONCLUSIONS

1. On the basis of the fibre fracture test, it is advisable to consider steel as rejectable when it exhibits appreciable amounts of conchoidal areas on the fractured surfaces.

2. The conchoidal fracture is accompanied by very poor impact strength and by low elongation and low reduction of area of tensile test specimens.

3. Of four samples of 1½" thick cast armor submitted for examination, the two having the greatest amount of conchoidal areas contained ten and four times the normal amount of aluminum observed in cast armor, possessing aluminum contents of 0.17% and 0.06% respectively. No conchoidal areas developed on fractures of a steel containing 0.03% aluminum.

4. No definite grain boundary segregates were observed upon examination at both high and low magnifications of unetched, polished surfaces of steels exhibiting appreciably conchoidal fractures, although a hot acid macro-etch produces a strong attack at the primary austenite grain boundaries.

5. The relatively few heat treatments performed at this Arsenal indicate that although the conchoidal fracture cannot be completely eliminated by high temperature homogenization, some improvement in the impact strength can be produced.

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APPROVED:

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INTRODUCTION

Captain W. B. Reed of the Inspection Division, Tank-Automotive Center, submitted four samples of 1½" thick cast armor manufactured by the Ford Motor Company to this Arsenal. Some of the specimens exhibited a peculiar fracture, called "conchoidal", which consists of distinctive large facets and smooth, bright, silvery colored, curved surfaces dispersed in varying amounts throughout an otherwise normal-appearing fracture matrix.

It is believed that certain ballistic failures have occurred which are traceable to the conchoidal fracture. It was accordingly requested that this Arsenal conduct a metallurgical examination of the submitted specimens to determine if the conchoidal fracture is accompanied by deleterious changes in the physical and metallurgical characteristics of the steel with the view that, if this were true, such material be considered subject to rejection.

The phenomenon of the conchoidal fracture is being studied by the staff of the Battelle Memorial Institute, who have to date released some preliminary reports upon their investigation.[1,2] They conclude that the pecular intergranular fracture is probably caused by a precipitation at the primary austenite grain boundaries of aluminum nitride and that the gas content and deoxidation treatment are probably the most important factors contributing to the formation of the intergranular fracture.

An extensive study of the properties of steel breaking with fractures remarkably similar in appearance to those displayed by the submitted samples was made by Austin.[3] He was able to produce the intergranular fracture by heating steel samples to 1350-1400°C (2450-2550°F). The theory advanced for the production of the distinctive fracture was the melting and flowing around grain boundaries of certain complex nonmetallic inclusions, giving rise to the cellular network observed upon etching in acid. Austin found that the intergranular fracture was accompanied by low Izod impact values and very low elongation and reduction of area values in tensile tests. The condition studied by Austin was found responsible for the rupture of high pressure vessels.

1. "Progress Report on Effects of Hydrogen, Nitrogen, and Oxygen in Armor Plate" (OD-38-2) OSRD No. 1233. C. H. Lorig, A. R. Elsea, Battelle Memorial Institute, February 16, 1943.

2. "Progress Report on Effects of Hydrogen, Nitrogen, and Oxygen in Armor Plate" (OD-38-2) OSRD. No. 1395. C. H. Lorig, A. R. Elsea, Battelle Memorial Institute, May 5, 1943.

3. "Burnt Alloy Steels" G. W. Austin. The Iron and Steel Institute, First Report of the Alloy Steels Research Committee, 1936. Pages 189-211.

MATERIALS AND TEST PROCEDURE

Armor Samples

The four armor samples submitted for examination were approximately 8"x12"x1½" in size and had stamped upon them their heat numbers, some ballistic data, and their fracture ratings as determined either at the Ford Motor Company or the Tank-Automotive Center. This information and the numbers assigned the plates at this Arsenal are as follows:

W.A. No.	Ford Motor Co. Heat No	Ballistic Data	Fracture Rating
A	3594	Failed	Conchoidal
C	3135	Bal. excess - 205 ft/sec.	Conchoidal
E	3261	Bal. excess - 198 ft/sec.	Crystalline
G	3267	Bal. excess - 152 ft/sec.	Fibrous

More complete information regarding the ballistic properties of the above plates was obtained from the Aberdeen Proving Ground Firing Records and is contained in Appendix A.

The four sections were notched by flame cutting for a depth of approximately 1" in from the middle of the two-layer sides, and each fractured with an impact blow under a 1000-pound forge hammer. The fractures were examined and rated. A .505" tensile test bar and four standard V-notch Charpy impact bars were machined from one of the fractured halves of each of the four sections in the as-received condition. Specimens for hot acid macro-etching and microscopic examination were cut from the same portions of the samples as the test specimens. The chemical analyses of the steels were determined at this Arsenal.

Sections of the remaining halves of the original samples were subjected to various heat treatments to produce microstructures of tempered martensite free from high temperature transformation products. Sections cut from steel A, which showed the most pronouncedly conchoidal fracture, were tempered at 600°F to determine if hydrogen, which would diffuse out of the steel upon tempering, is a factor responsible for the conchoidal fracture. Other sections from steel A were quenched in water after heating at 2300°F, then requenched from the normal hardening temperature in an effort to improve the fracture.

V-notch Charpy bars and specimens for macro-etching and microscopic examination were secured from the reheat treated samples after they were notched and fractured.

DATA AND DISCUSSION

1. Chemical Analysis

The chemical analyses of the four armor sections as reported by the manufacturer and as determined at this Arsenal are included in Table I.

TABLE I

Chemical Analyses

Reported by Ford Motor Company

Steel W.A. No.	Ford Heat	C	Mn	Si	S	P	Cr	Mo	Cu
A	3594	.29	1.09	.57	.021	.014	.64	.38	.23
C	3135	.27	1.21	.60	.032	.028	.55	.24	-
E	3261	.29	1.20	.47	.011	.036	.59	.19	-
G	3267	.35	1.06	.39	.015	.024	.56	.23	-

Watertown Arsenal Analysis

Steel	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al	Sn
A	.29	1.13	.56	.026	.014	trace	.69	.39	.21	.17	.01
C	.31	1.31	.59	.025	.020	.35	.61	.21	.15	.06	.01
E	.28	1.21	.54	.025	.040	.11	.53	.20	.15	.03	.01
G	.26	1.18	.52	.027	.026	trace	.57	.21	.15	.05	.01

Many samples of cast armor made by numerous manufacturers have been analyzed for aluminum at this Arsenal. Excluding the present steels, thirty-one recently made determinations show an average aluminum content of 0.017% in cast armor, with the value rarely exceeding 0.025%. The subject steels thus have an aluminum content of from two to ten times the average amount.

No facilities exist at this Arsenal for the analysis of the gas content of steel so it was impossible to determine the nitrogen content of the submitted samples.

Steels A and C, which are the two described as having conchoidal fractures, have the highest aluminum contents of the four steels, namely 0.17% and 0.06% respectively.

Experimental heats of steel made at the Battelle Memorial Institute[2] using varying amounts of aluminum in the deoxidation practice (from 0 to 28 lbs. Al/Ton) and varying amounts of nitrogen through

2. See footnote 2 on page 2.

the addition of high nitrogen ferrochromium and calcium cyanamide ($CaCN_2$) tend to show that the conchoidal fracture is associated with both the aluminum and nitrogen content of the steel.

2. Fracture Tests

The photographs of the fractures of steels A, C, E and G in the as-received condition produced at this Arsenal by impact blows of the forge hammer are shown in Figures 1 and 2. The fracture of steel A is conchoidal and dendritic, the dendrites being very long and prominent and largely confined to the lower half of the cross-section shown in Figure 1. Steel A has the most decidedly conchoidal fracture and has by far the highest aluminum content.

The fracture of steel C contains some conchoidal patches in an otherwise normal fibrous matrix. The fracture of steel E is crystalline, and that of steel G contains crystalline streaks in a fibrous matrix. No conchoidal patches were observed in the fractures of steels E and G.

3. Hardness Surveys

Hardness traverses made across the thickness of sections cut from the four specimens in the as-received condition are included in Table II.

TABLE II

Brinell Hardnesses of Cast Armor Sections

Steel	Outer Third of Cross-section	Middle	Outer Third of Cross-section
A	241	235	235
C	255	255	262
E	248	241	241
G	223	212	223

With the exception of steel C, the hardnesses of the armor sections are low for 1½" thick plate. Excellent ballistic properties have been obtained with 1½" cast armor in the range of 260-280 Brinell, so that the sacrifice in penetration resistance resulting from lower hardnesses is not generally warranted. It appears that the subject armor has been tempered to lower hardnesses in an effort to improve the ductility and the shock resisting properties of the material, yet the ballistic test plates from which sections A and G were taken failed the shock test; plate 3594 (steel A) back spalling, and plate 3267 (steel G) cracking excessively under impact of the 75 MM T21 proof projectile.

4. Tensile Tests

A .505" tensile test bar was machined from each of the four samples in the as-received condition The tensile data are listed in Table III.

TABLE III

Tensile Properties of Cast Armor Sections

Steel	Brinell Hardness	Yield Strength (Divider Method) p.s.i.	Tensile Strength p.s.i.	% Elong.	% R.A.	Fracture
A	235-241	79,750	103,250	2.5	8.8	Conchoidal and dendritic.
C	255-262	73,000	107,500	7.0	14.8	Dendritic with shrinkageporosity.
E	241-248	90,500	117,500	9.0	24.0	45° shear.
G	212-223	69,250	106,250	11.0	24.0	45° shear.

The low reduction of area and low elongation of materials breaking with conchoidal fractures check the results obtained by the Battelle Memorial Institute[1] and by Austin.[3] The elongation and reduction of area of steels E and G are also considerably lower than obtained with good quality steel at the same hardness levels.

5. Reheat Treatments

After fracturing the four armor sections, the remaining half section of steel A was cut into four pieces, which together with half sections of steels C, E, and G were reheat treated in attempts to improve the fractures and physical properties. The four samples cut from steel A were numbered B, B1, B2, and B3; the half section of steel C was numbered D; that of E was numbered F; and that of G, H.

Specimens B, B1, B2, B3 and D were first tempered at 600° F. for 6½ hours for the purpose of eliminating any hydrogen possibly present in the steel, after which samples B1, B2, and B3 were reheat treated. Sample B1 was requenched and tempered to produce a tempered martensitic microstructure. Samples B2 and B3 were heated at 2300° F. in an effort to dissolve the aluminum nitrides and/or other intergranular material responsible for the conchoidal fracture. The high temperature treatments were followed by the normal quench and draw to produce tempered martensite. Samples F and H were heat treated to tempered martensite.

The heat treatments and the hardnesses developed upon quenching and tempering are listed in Table IV.

1, 3. See footnotes 1 and 3 on page 2.

TABLE IV

Reheat Treatments and Brinell Hardness

Steel No.	Ford Motor Co. Heat No.	Heat Treatment	BHN after Quench	BHN after Temper
B	3594	600° F. - 6½ hrs. - air	-	235-255
B1	3594	600° F. - 6½ hrs. - air 1650° F. - 2 hrs. - water 1125° F. - 1½ hrs. - air 1175° F. - 1 hr. - air	495	277
B2	3594	600° F. - 6½ hrs. - air 2300° F. - 1 hr. - air 1650° F. - 2 hrs. - water 1175° F. - 2 hrs. - air	444	255
B3	3594	600° F. - 6½ hrs. - air 2300° F. - 2 hrs. - water 1650° F. - 2 hrs. - water 1175° F. - 2 hrs. - air	460	248
D	3135	600° F. - 6½ hrs. - air	-	269-277
F	3261	1600° F. - 1½ hrs. - water 1125° F. - 1½ hrs. - air 1175° F. - 1 hr. - air	514	277
H	3267	1600° F. - 1½ hrs. - water 1125° F. - 1½ hrs. - air 1175° F. - 1 hr. - air	495	277

The requenched specimens were tempered back to 260-280 Brinell rather than to the hardness levels of the original armor sections because it is felt that the higher hardness is preferable for 1½" thick cast armor.

After reheat treatment the sections were notched and fractured as before. Photographs of the fractured surfaces of specimens B, D, F, and H are shown in Figures 1 and 2 for comparison with the fractures of the steels as-received. The hydrogen relief heat treatment produced no change in the steels having conchoidal fractures. The fracture of steel F (Heat 3261) is now completely fibrous, whereas in the as-received condition, the steel had a crystalline fracture. The fracture of steel H (Heat 3267) has small scattered crystalline patches distributed throughout a fibrous matrix in addition to containing scattered conchoidal areas. The fracture of the steel as-received contained no conchoidal patches, consequently it is assumed that the steel contains scattered conchoidal regions and that the original fracture did not occur through any of those regions, since none of the other heat treatments changed the conchoidal condition.

The fractures of samples heated to 2300° F. and requenched and tempered show a slight change from the fracture of the steel in the as-received condition, being more fibrous in areas.

6. Macro-etched Structures

Ground sections of the four steels in the as-received condition were macro-etched in a hot 50% hydrochloric acid solution. The acid selectively attacked the dendrite boundaries (primary austenite grain boundaries) of steel A, see Figure 3. No such attack was developed in any of the other three steels, although the fracture of steel C contains some conchoidal patches. This indicates a scattered distribution in steel C of the factors responsible for the conchoidal fracture.

Steel G possesses an unusual macrostructure in that one half of the cross-section consists of columnar dendrites while the other half consists of fine equiaxed dendrites with a sharp line of demarcation between the two.

A small piece of sample B was polished through No. 000 paper and etched in hot 50% hydrochloric acid. The structure revealed by etching is shown in Figure 4. It is apparent that some material segregated along the boundaries of the primary austenite grains has been dissolved by the acid. The network is frequently discontinuous and at times extends around groups of primary austenite grains rather than around individual grains.

7. Impact Tests

Four standard V-notch Charpy impact bars were machined from each of the steels in the as-received condition and from reheat treated samples F and H. Two impact bars were machined from each of samples B1, B2, and B3. In all cases, the V-notch was cut in the surface of the Charpy bar closest to the original cast surface of the plate section.

The two impact bars from samples B1, B2, B3 and two from sections A, C, E, F, G, and H were tested at +20°C. (+68°F.). The remaining two bars of each steel were tested at -40°C. (-40°F.). The results of the impact tests and descriptions of the resultant fractures are presented in Appendix B.

None of the fractures of the four steels in the as-received condition (A, C, E, and G) was fibrous, indicating that the steels had been incompletely quench hardened. Because the steels had not been quenched out to a fully martensitic structure, the room temperature impact strength was not equal to that usually obtained with properly heat treated material at the same hardness levels, while the impact strength at -40°C. (-40°F.) was considerably lower than that of tempered martensitic steels.

The impact strength of sample B1, which was reheat treated to tempered martensite, was not improved over that of sample A, and the fracture remained conchoidal. The high temperature treatment prior to the quench and draw raised the impact strength of three out of four Charpy impact bars but did not result in the elimination of the conchoidal fracture. The pretreatment at 2300°F. followed by air cooling raised the average room temperature impact strength from 10.7 ft.lbs. to 26.4 ft.lbs., and the fractures changed from conchoidal to conchoidal and fibrous. The pretreatment at 2300°F. followed by water quenching raised the impact strength of one specimen to 40.1 ft.lbs., but the other showed only 16.0 ft.lbs.; the fracture of the former being fibrous with a few conchoidal patches and that of the latter entirely conchoidal, see Figure 5. Whenever the fracture is predominately conchoidal, the impact strength is always low.

The results obtained with steel C indicate that a small amount of conchoidal patches dispersed in an otherwise fibrous matrix apparently does not impair the impact properties of the material; compare the impact values of steel C with those of reheat treated sample F, Appendix B.

Reheat treatment to tempered martensitic microstructures improved the impact properties of heats 3261 and 3267. It is noteworthy that sample F (heat 3261), which was completely quench hardened, has better impact properties at a hardness of 277 BHN than sample E (heat 3261 as-received) at a hardness of 241-248 BHN. Sample H (heat 3267) reheat treated to 277 BHN has approximately the same room temperature impact strength as sample G (heat 3267 as-received) at a hardness of 212-223 BHN, and has superior impact strength at a temperature of -40°C. (-40°F.).

It cannot be over-emphasized that properly quench hardened and tempered steels may have as good or better impact ductility at 260-280 Brinell than poorly heat treated material at a hardness of 220-240 Brinell. Tempering armor to a low hardness level for the purpose of improving the low impact strength resulting from inadequate quench hardening is contrary to good practice since the resistance to penetration is sacrificed to meet the requirements of the shock test. It is true that such poorly heat treated armor frequently does meet the specification requirements of 1½" thick cast armor, but this is due only to the fact that the requirement for ballistic limit in this thickness of armor is extremely lenient.

Because of the unusual macrostructure of heat 3267 (samples G and H) it was noted in each case whether the Charpy bar was machined from the portion of the steel containing the equiaxed dendrites or the columnar dendrites in an effort to determine the effect, if any, of the solidification pattern upon the impact properties. Charpy bars G-1, G-4, H-2, and H-4 contained columnar dendrites perpendicular to the notched surfaces, and G-2, G-3, H-1, and H-3 contained the equiaxed dendrites. Examination of the data in Appendix B reveals that, in this case, the dendritic pattern has no particular effect upon the impact strength of the material. The slightly reduced impact strength of specimen H-1 is believed due to shrinkage porosity visible on the fractured surfaces.

8. Microscopic Examination

Specimens for microscopic examination were taken from the four as-received sections and from the reheat treated samples. All microspecimens from the two heats (3594 and 3135) exhibiting the conchoidal fracture to the greatest degree were examined thoroughly at both high and low magnifications for segregates of non-metallic material or porosity at grain boundaries, both in the unetched condition and after etching in various reagents, including picral, nital, Vilella's reagent, and electrolytic chromic acid. Except for very occasional disconnected grain boundary segregates of inclusions, such as shown in Figure 6a, found in heat 3594, no trace of any definite grain boundary segregate was observed. The distribution of non-metallic inclusions typified by Figure 6a occurs normally in steels of average physical properties and possibly bears no relation to the conchoidal fracture.

Section A, heat 3594 as-received, has a microstructure consisting of high temperature transformation products resulting from incomplete quench hardening. Dendritic segregation, with greater amounts of ferrite rejected in the dendritic axes occurs throughout the cross-section, see Figures 6b and c. Reheat treatments of sections cut from sample A, namely specimens B1, B2, and B3, produced tempered martensitic microstructures, Figures 6d, e, and f.

The microstructure of steel C (heat 3135 as-received) contains some ferrite and pearlite in a matrix of tempered martensite, see Figures 6g and h. The microstructure of steel C does indicate, however, more satisfactory quench hardening than detected in steel A.

Steel E (heat 3261 as-received) contains large amounts of rejected ferrite and coarse pearlite resulting from high temperature transformation, see Figures 7a and b. Reheat treatment of a portion of the same steel produced a tempered martensitic microstructure, Figures 7c and d. Steel G (heat 3267 as-received) has an unsatisfactory microstructure consisting of large amounts of rejected ferrite and grain boundary carbides, see Figures 7e and f. After reheat treatment, small amounts of ferrite and pearlite occur in a tempered martensitic matrix, indicating a slight degree of transformation occurring at elevated temperatures, Figure 7g and h.

SUMMARY

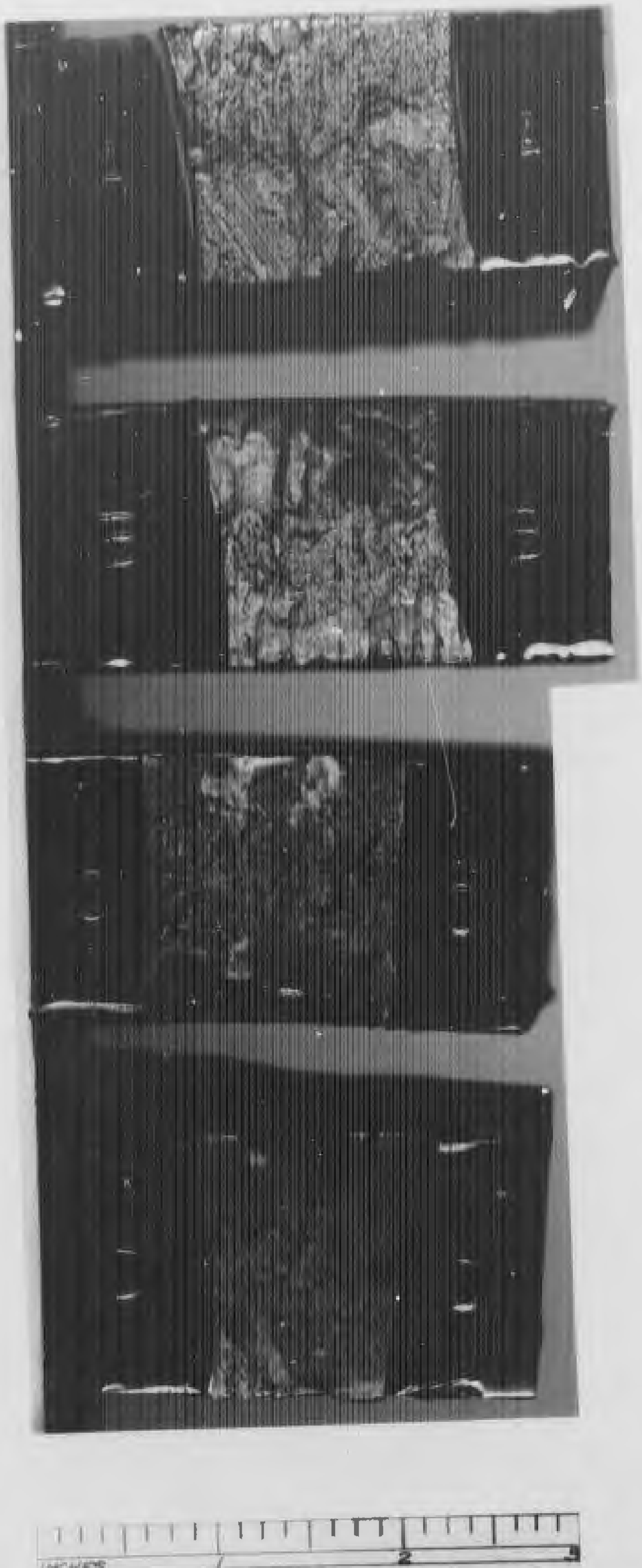
Although the exact cause of the formation of the conchoidal fracture observed in certain cast armor steels is in all cases, not certain, its effects upon the physical properties of the metal are known. This report, as well as the data recorded by other observers,[1,3] reveals that the conchoidal fracture is accompanied by low impact strength and low ductility as measured by the tensile test. The heat treatments conducted at this Arsenal have not been successful in entirely eliminating the conchoidal fracture, although it is indicated that some improvement in impact strength can be produced by heat treatment.

In view of the deleterious effects of the conchoidal fracture upon the properties which are deemed of great importance in armor, it is advisable for the Ordnance Department to consider steels exhibiting appreciable amounts of conchoidal areas in the fracture rejectable on the basis of the fibre fracture test.

The submitted steels in which the conchoidal fractures occur have unusually high residual aluminum contents, believed resulting from poorly controlled melting practice. The solution of the problem of conchoidal fractures lies within the province of the manufacturers of the cast armor. Careful control of the deoxidation practice is indicated.

The unsatisfactory microstructures of the submitted steels reveal poor heat treating practice leading to incomplete quench hardening.

1,3. See footnotes on page 2.



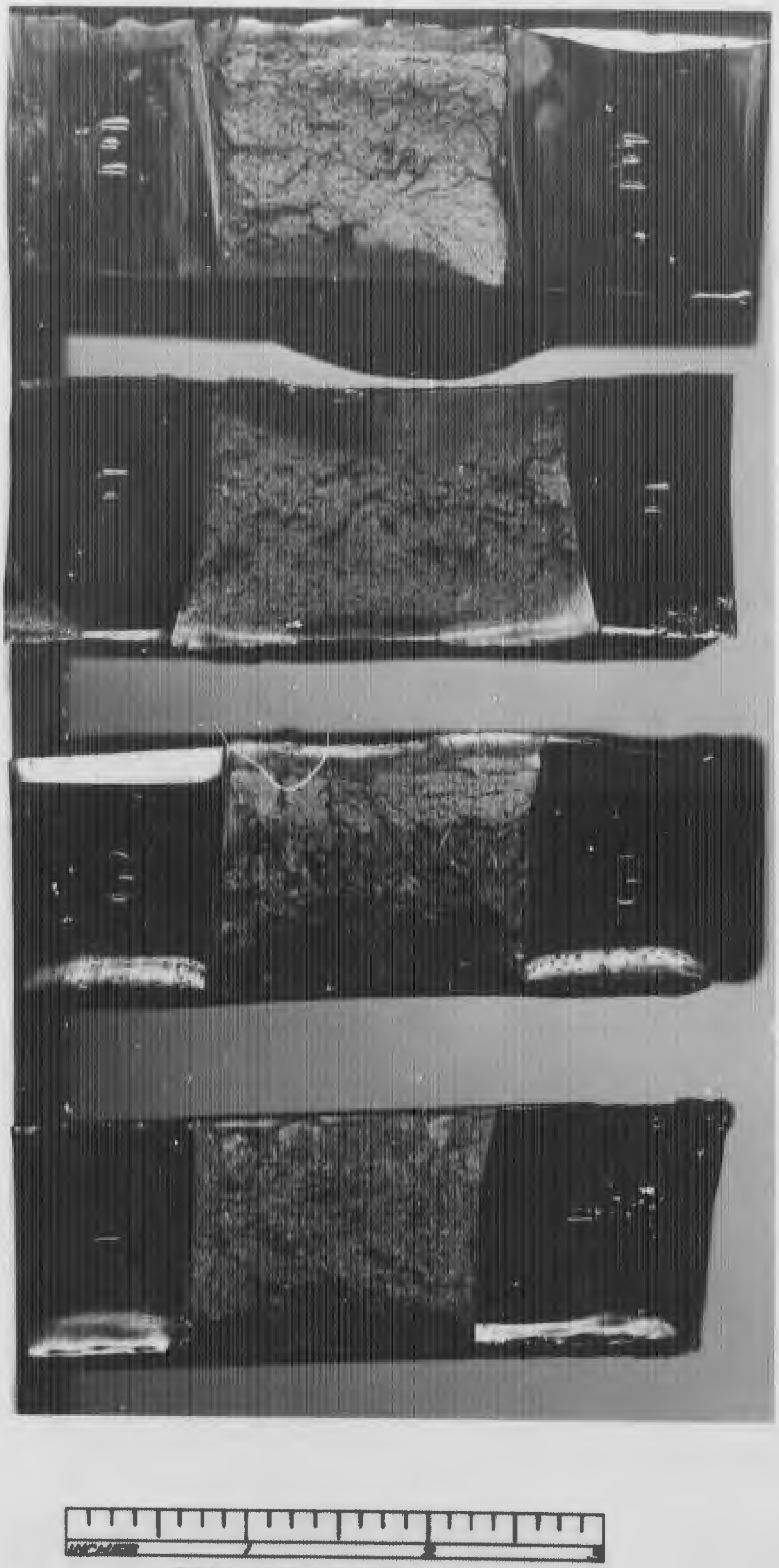
ORDNANCE DEPT. U.S.A.

WATERTOWN ARSENAL

1½" CAST ARMOR MFD BY FORD MOTOR CO.
CONCHOIDAL FRACTURES

A. HEAT NO. 3594. FAILED. AS REC'C.
B. HEAT NO. 3594. HEATED 6½ HRS AT 600°F.
C. HEAT NO. 3135. PASSED. AS REC'D.
D. HEAT NO. 3135. HEATED 6½ HRS AT 600°F.
WTN.71C-2120

FIGURE 1



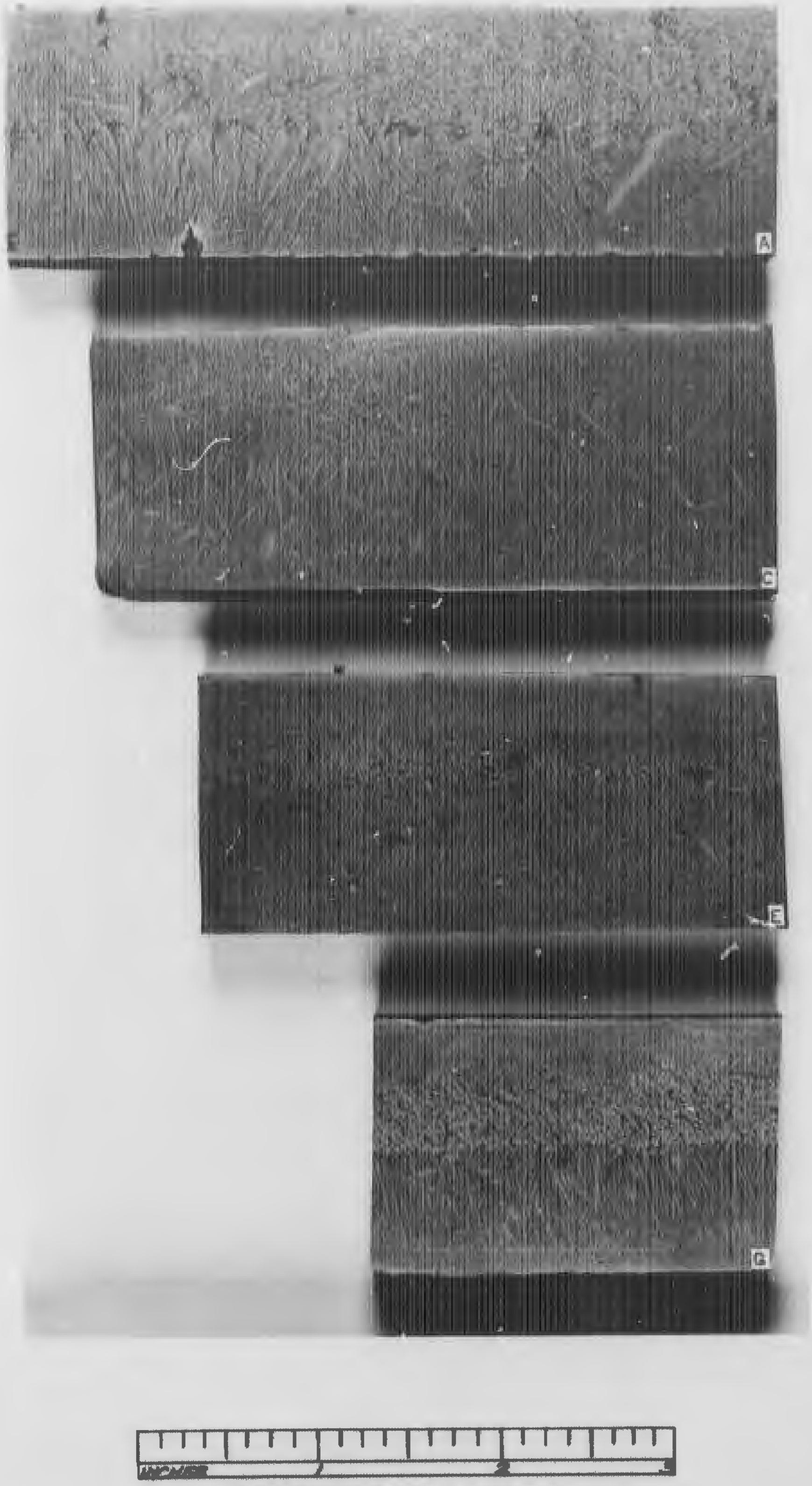
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

1½" CAST ARMOR MFG. BY FORD MOTOR CO.

E. HEAT NO. 3261. PASSES. CRYSTALLINE FRACTURE.
F. HEAT NO. 3261. REHEAT TREATED. FIBROUS FRACTURE.
G. HEAT NO. 3267. PASSED. MIXED FRACTURE.
H. HEAT NO. 3267. REHEAT TREATED. MIXED AND CONCHOIDAL FRACTURE.

WTN.710-2119

FIGURE 2

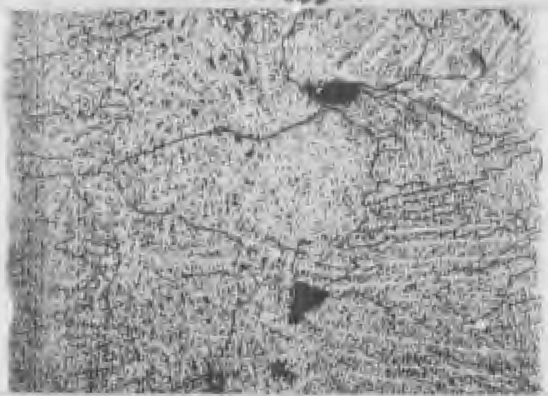


MACROETCHED SECTIONS OF $1\frac{1}{2}$" CAST ARMOR MFG BY FORD MOTOR COMPANY
A. HEAT NO. 3594 C. HEAT NO. 3135 E. HEAT NO. 3261 G. HEAT NO. 3267
WTN.710-2129

FIGURE 3

FORD MOTOR COMPANY

HEAT #3504

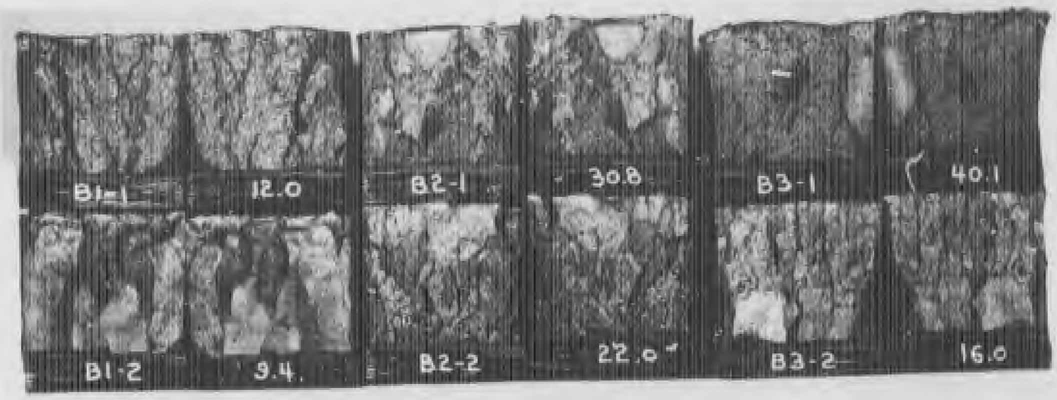


Hot Acid Etch. Sample B X2
Hair-line boundary attack in steel having conchoidal fracture.

Hot Acid Etch. Lower right hand corner of above photo. X6
Heavy etching attack at dendrite boundaries.

FIGURE 4

FORD MOTOR COMPANY HEAT #3504



Fractured V-Notch Charpy Impact Bars. Mag. X2

B1

Heat Treatment:

600°F - 8 hrs. - air cool.	
1650°F - 2 hrs. - water quench.	- 405 BHN
1125°F - 1½ hrs. - air cool.	- 302 BHN
1175°F - 1 hr. - air cool.	- 277 BHN

Fracture:

	Charpy
B1-1 - Conchoidal and Dendritic	12.0
B1-2 - Conchoidal	9.4

B2

Heat Treatment:

600°F - 8 hrs. - air cool.	
2300°F - 1 hr. - air cool.	
1650°F - 2 hrs. - water quench.	- 444 BHN
1175°F - 2 hrs. - air cool.	- 255 BHN

Fracture:

	Charpy
B2-1 - Conchoidal and Fibrous	30.8
B2-2 - Conchoidal and Fibrous	22.0

B3

Heat Treatment:

600°F - 8 hrs. - air cool.	
2300°F - 2 hrs. - water quench.	
1650°F - 2 hrs. - water quench.	- 460 BHN
1175°F - 2 hrs. - air cool.	- 248 BHN

Fracture:

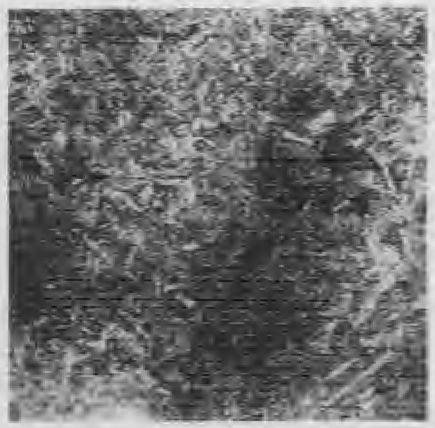
	Charpy
B3-1 - Fibrous and Conchoidal	40.1
B3-2 - Conchoidal	16.0

Size of Heat Treated Sections - ½ x 1½ x 3" FIGURE 5

FORD MOTOR COMPANY HEAT #3594 Etched in Nital-Picral

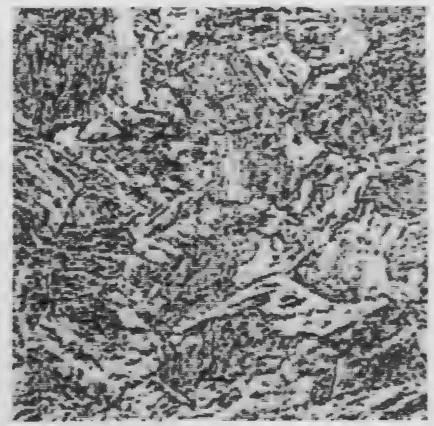
Unetched -A- X1000

Small disconnected inclusions occasionally found at grain boundaries.



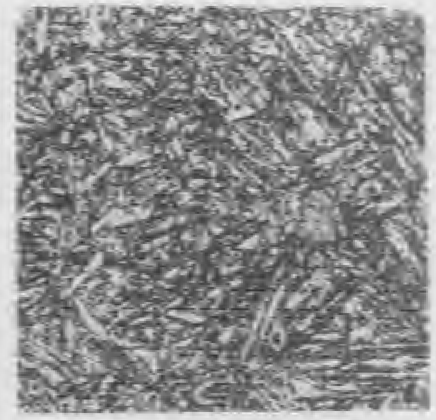
#A -B- X200

As received.
Dendritic segregation.



#A -C- X1000

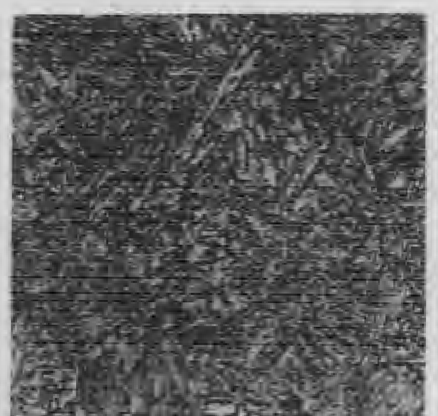
Incompletely quench hardened. Rejected ferrite and grain boundary carbides.



#B1 -D- X1000

Reheat-treated.
Tempered martensite.

HEAT #3594



#B2 -E- X1000

Reheat-treated.
Tempered martensite.

#B3 -F- X1000

Reheat-treated.
Tempered martensite.

HEAT #3135

#C -G- X200

As received.

#C -H- X1000

Incompletely quench hardened. Rejected ferrite and pearlite in matrix of tempered martensite.

FIGURE 6

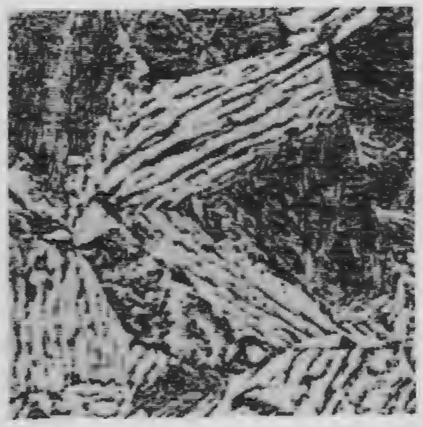
FORD MOTOR COMPANY

HEAT # 3261

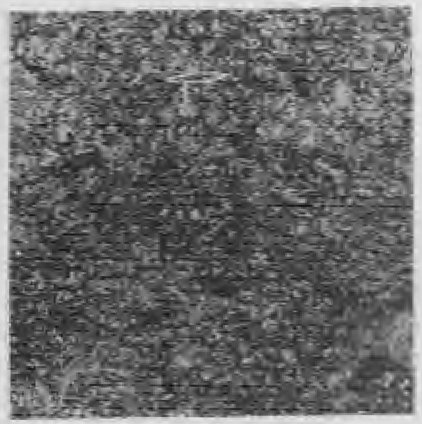
Etched in Nital-Picral

WTN.639-5000

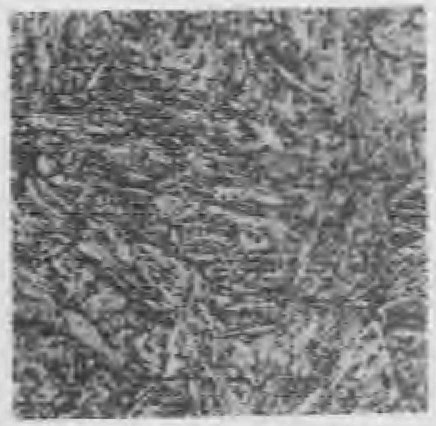
#E -a- X200
As received. Coarse, segregated structure.



#E -b- X1000
Incompletely quench hardened. Rejected ferrite and pearlite.

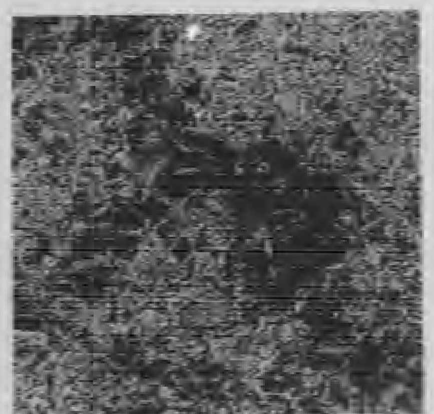


#F -c- X200
Reheat-treated. Homogeneous structure.

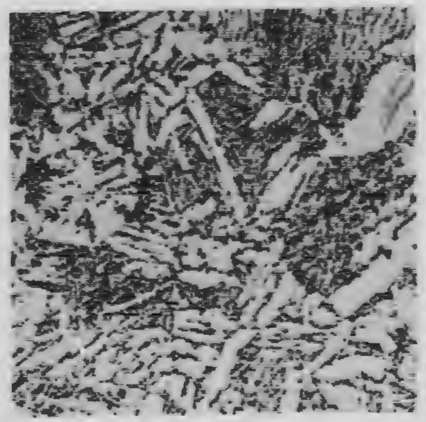


#F -d- X1000
Reheat-treated. Tempered martensite.

HEAT #3267

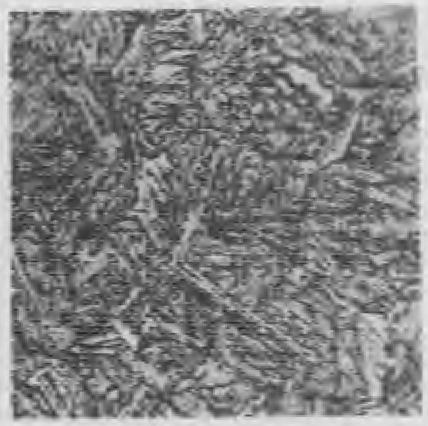


#G -e- X200
As received. Dendritic segregation.



#G -f- X1000
Incompletely quench hardened. Rejected ferrite and carbides.

#H -g- X200
Reheat-treated. Relatively homogeneous structure.



#H -h- X1000
Reheat-treated. Small amount of rejected ferrite and pearlite in tempered martensite.

FIGURE 7

APPENDIX A

Ballistic Test Data Abstracted from

Aberdeen Proving Ground Firing Records

Watertown Arsenal No. - A
Ford Motor Co. Heat No. - 3594
Plate Thickness - 1.43"

A.P.G. Firing Record No. 94404
Date - April 24, 1943

Projectile	Obliquity	Lowest Velocity Complete Penetration	Highest Velocity Partial Penetration	Ballistic Limit Ft/sec.	Specified Limit Ft/sec.	Remarks
37 MM M74 AP	0°	1114	1080	1097	1008	Passed.
75 MM T21 Proof Projectile	0°	1057			1058	Failed - 10-27/32"x10-5/16" back spall.

Plate failed on shock test.

Heat Treatment:	Temp.	Hrs. Rise	Hrs. Soak	Coolant
	1850	1	5	Air
BHN reported by mfr. 229	1650	1½	3	Water
	1125	3	10	Air

Physical Properties:	Yield Point p.s.i.	Tensile Strength p.s.i.	% Elong.	% R.A.	Izod Ft.lbs.
	93,000	112,000	12	23	30

Watertown Arsenal No. - C
Ford Motor Co. Heat No. - 3135
Plate Thickness - 1.49"

A.P.G. Firing Record No. 78699
Date - March 4, 1943

Projectile	Obliquity	Lowest Velocity Complete Penetration	Highest Velocity Partial Penetration	Ballistic Limit Ft/sec.	Specified Limit Ft/sec.	Remarks
37 MM M74 AP	0°	1267	1231	1249	1044	Passed
75 MM T21 Proof Projectile	0°		1036		1018	Passed

Plate passed.

Heat Treatment:	Temp.	Hrs. Rise	Hrs. Soak	Coolant
	1800	3	5	Air
BHN reported by mfr. 277	1700	2	3	Water
	1100	3	8	Water

Physical Properties:	Yield Point p.s.i.	Tensile Strength p.s.i.	% Elong.	% R.A.	Izod Ft.lbs.
	111,000	127,500	15	34	45

Watertown Arsenal No. - E
Ford Motor Co. Heat No. - 3261
Plate Thickness - 1.43"

A.P.G. Firing Record No. 81854
Date - March 16, 1943

Projectile	Obliquity	Lowest Velocity Complete Penetration	Highest Velocity Partial Penetration	Ballistic Limit Ft/sec.	Specified Limit Ft/sec.	Remarks
37 MM M74 AP	0°	1221	1192	1206	1008	Passed - small surface cracking.
75 MM T21 Proof Projectile	0°		980		976	Passed.

Plate passed.

Heat Treatment:	Temp.	Hrs. Rise	Hrs. Soak	Coolant
	1800	1	5	Air
BHN reported by mfr. 255	1700	1½	3	Water
	1100	3	10	Water

Physical Properties:	Yield Point p.s.i.	Tensile Strength p.s.i.	% Elong.	% R.A.	Izod Ft.lbs.
	107,000	124,500	16	39	42

Watertown Arsenal No. - G
Ford Motor Co. Heat No. - 3267
Plate Thickness - 1.38"

A.P.G. Firing Record No. 83893
Date - March 23, 1943

Projectile	Obliquity	Lowest Velocity Complete Penetration	Highest Velocity Partial Penetration	Ballistic Limit Ft/sec.	Specified Limit Ft/sec.	Remarks
37 MM M74 AP	0°	1154	1106	1130	978	Passed.
75 MM T21 Proof Projectile	0°	933			941	Failed, 9-1/4", 6-1/4", 7-1/4" cracks.

Plate failed on shock test.

Heat Treatment:	Temp.	Hrs. Rise	Hrs. Soak	Coolant
	1800	1	5	Air
BHN reported by mfr. 229	1700	1½	3	Water
	1100	3	10	Water

Physical Properties:	Yield Point p.s.i.	Tensile Strength p.s.i.	% Elong.	% R.A.	Izod Ft.lbs.
	96,000	113,000	18	41	50

APPENDIX B

V-Notch Charpy Impact Data

Heat Treatment	Steel Designation Ford Heat	W.A.	BHN	Temperature °C	°F	Charpy Impact Ft.Lbs.	Fracture*
As-Received	3594	A-1	235-255	+20	+68	15.5	Kd
		A-2	"	+20	+68	16.6	Kd
		A-3	"	-40	-40	18.1	Kd
		A-4	"	-40	-40	18.2	Kd
Reheat-treated 600°F. - 6½hrs. - air 1650°F. - 2hrs. - water 1125°F. - 1½hrs. - air 1175°F. - 1hr. - air	"	B1-1	277	+20	+68	12.0	Kd
		B1-2	"	+20	+68	9.4	K
Reheat-treated 600°F. - 6½hrs. - air 2300°F. - 1hr. - air 1650°F. - 2hrs. - water 1175°F. - 2hrs. - air	"	B2-1	255	+20	+68	30.8	Kf
		B2-2	"	+20	+68	22.0	Kf
Reheat-treated 600°F. - 6½hrs. - air 2300°F. - 2hrs. - water 1650°F. - 2hrs. - water 1175°F. - 2hrs. - air	"	B3-1	248	+20	+68	40.1	Fk
		B3-2	"	+20	+68	16.0	K

* F - Fibrous

C - Crystalline

K - Conchoidal

Kd - Conchoidal and dendritic

FC - Fibrous and crystalline

Fc - Mostly F and slightly C

Cf - Mostly C and slightly F

Cfe - C with Fibrous edge

Kf - Mostly K and slightly F

Fk - Mostly F and slightly K

Fck - Mostly Fc and slightly K

Heat Treatment	Steel Designation Ford Heat	W.A.	BHN	Temperature °C	°F	Charpy Impact Ft.Lbs.	Fracture
As-Received	3135	C-1	255-262	+20	+68	41.9	Fck
	"	C-2	"	+20	+68	42.5	Fck
	"	C-3	"	-40	-40	32.3	FC
	"	C-4	"	-40	-40	29.5	FC
As-Received	3261	E-1	241-248	+20	+68	35.5	Cf
	"	E-2	"	+20	+68	28.0	Cf
	"	E-3	"	-40	-40	14.1	C
	"	E-4	"	-40	-40	15.6	C
Reheat-treated 1600°F. - 1½hrs. - water 1125°F. - 1½hrs. - air	3261	F-1	277	+20	+68	44.1	F
	"	F-2	"	+20	+68	45.6	F
	"	F-3	"	-40	-40	24.7	Cfe
	"	F-4	"	-40	-40	26.4	Cfe
As-Received	3267	G-1	212-223	+20	+68	47.3	FC
	"	G-2	"	+20	+68	45.9	FC
	"	G-3	"	-40	-40	22.2	Cfe
	"	G-4	"	-40	-40	21.3	Cfe
Reheat-treated 1600°F. - 1½hrs. - water 1125°F. - 1½hrs. - air	3267	H-1	277	+20	+68	37.4	Fc
	"	H-2	"	+20	+68	44.9	Fc
	"	H-3	"	-40	-40	28.8	Cf
	"	H-4	"	-40	-40	30.8	Cf