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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/664

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APR 23 1985

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Study of "Woody" Fractures in Rolled Armor Plate

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WAR DEPARTMENT
ORDNANCE OFFICE
JUL 28 1944

BY

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Research Metallurgist

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6 April 1954

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DATE 19 June 1944

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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT NO. WAL 710/664

Partial Report on Problem B-2.2

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19 June 1944

Study of "Woody" Fractures in Rolled Armor Plate

This 1944 report investigates a

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17. IN. ABSTRACT steel

A series of 3/4", 1", and 1 1/2" thick plates submitted by the Republic Steel Corporation which showed a marked tendency toward "woody" fractures were investigated. The "woody" fracture usually has a fine striated appearance and shows occasionally evidence of ruptured fibres. The "woody" condition develops when the fracture plane is parallel to the major rolling direction and is caused by the presence of fine nonmetallic inclusions in the planes of rupture which have a "stepped" appearance. The types of inclusions generally found in the steels investigated which exhibit "woody" fractures are silicates or complex oxide-sulphide-silicates. Occasionally, streaks of titanium nitride or complex oxides associated with zirconium nitrides are found which also result in the same effect. The nonmetallic inclusions are occasionally associated with metallic banding. The degree of "woody" appearance increases with the quantity of nonmetallic inclusions as well as the inequality-in-reduction in the two rolling directions. Therefore, steels showing "woody" fractures possess directional properties.

Due to the small number of samples examined and also to the inadequacy of the ballistic tests applied, no conclusions can be drawn on the relation between the "woody" fracture and ballistic properties of the plates.

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1. This investigation was conducted as part of the program on the fracture test as a measure of steel soundness now in progress at this arsenal. "Woody" fractures usually have a fine striated appearance with the shelving in some cases so minute as to be indistinguishable as such with the naked eye. The striations in these types of fractures are either fairly continuous or may show evidence of fragmented fibres which are similar to the ruptured grain in certain types of wood, see Figure 1. The "woody" condition may be confined to the central portion of the section

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or may occur uniformly throughout. Personnel at the Ordnance Research Center have expressed concern over this condition and indicated the desirability of ascertaining the factors responsible.

2. This type of fracture, which has been observed in certain electric and open hearth steels when the fracture plane is parallel to the major rolling direction, was known to be caused by elongated or intermittent types of nonmetallic inclusions. Preliminary studies were made on several 3/4" and 1 1/2" thick fracture test bars submitted on 19 January 1944 by the Republic Steel Corporation. These samples showed the "woody" condition. In order to determine the metallurgical characteristics of this type of material more thoroughly, samples of production plate 12x12x3/4" and 12x12x1 1/2" were requested and obtained from the Republic Steel Corporation. One sample of 1 inch thick thoroughly cross rolled plate manufactured by the Great Lakes Steel Corporation was also investigated. The Republic Steel Corporation later submitted large V-notch Charpy impact bars for test in the laboratory and this material was also examined as a part of this investigation. These bars were 3/4 and 1" square and are referred to below along with the other samples involved. Ballistic behaviors under the projectile-through-plate tests are recorded on the plates involved when this information was available.

<u>Sample No.</u>	<u>Approximate size inches</u>	<u>Behavior under Projectile-Through-Plate Test</u>	
		<u>Exit Dia. Inches</u>	<u>Spec. AXS-495 Rev. 2 Spec. AXS-488 Rev. 1</u>
<u>Republic Steel Corp.</u>			
1	4x1 1/4x3/4	2x3/4	Failed
6	4x1 1/4x3/4	1-3/4x2 1/4	Acceptable
5	4x1 1/4x1 1/2	3x3-3/4	Failed
9	4x1 1/4x1 1/2	2 1/4x2-5/8	Acceptable
RH 11761	12x12x3/4	2-3/4x3	Failed
RH 53715	12x12x3/4	2 1/4x3	Failed
RH 11761	12x12x1 1/2	2-5/8x3 1/4	Failed
RH 11792	12x12x1 1/2	2-3/8x3 1/4	Acceptable
A-1	1x1x6	2 1/4x2 1/2	Acceptable
B-2	1x1x6	2 1/4x2-3/8	Acceptable
C-4	3/4x3/4x6	2 1/4x2-3/8	Acceptable
D-2	3/4x3/4x6	2x2-3/4	Acceptable
<u>Great Lakes Steel Corp.</u>			
10	3x1x6	2x2-3/4	Acceptable

3. Metallurgical examination consisted of the following tests.

- a. Chemical Analyses.
- b. Fracture Test for Steel Soundness.
- c. Fracture Test for Fibre.
- d. Macroscopic Examination.
- e. Microscopic Examination.
- f. V-notch Charpy Impact Tests.
- g. Tensile Tests.
- h. Hardness Tests.

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

- a. Chemical Analyses.

The chemical analyses of the series of samples are given in

Table I.

Table I
Chemical Analyses

Sample No.	Thick- ness Inches	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	B	Al	Ti	Zr
<u>Republic</u>															
1	3/4	.26	.86	.25	.017	.011	1.58	.75	.26	Trace	.09	.0019	.01		
6	3/4	.25	1.17	.28	.023	.020	.84	.77	.29	Trace	.07	.0015	.025		
5	1 1/2	.28	1.06	.26	.021	.016	.90	.77	.28	Trace	.10	.0016	.015		
9	1 1/2	.28	1.10	.25	.026	.013	.87	.74	.28	Trace	.09	.0014	.015		
RH 11761	3/4	.28	.94	.22	.015	.011	1.88	1.00	.30	.085	.10	Trace	.015		
RH 53715	3/4	.29	1.28	.35	.017	.014	1.02	.78	.33	Trace	.10	.0025	.02		
RH 11761	1 1/2	.28	.87	.20	.023	.011	1.63	.96	.29	.08	.08	Trace	.01		
RH 11792	1 1/2	.28	1.22	.30	.011	.015	.95	.72	.35	Trace	.09	.003	.015		
A-1	1	.27	1.19	.25	.025	.013	.85	.78	.29	Trace	.09	.0014	.02		
B-2	1	.29	1.16	.27	.017	.018	.79	.76	.29	Trace	.07	.0016	.02		
C-4	3/4	.25	1.20	.28	.020	.014	.85	.77	.28	Trace	.07	.0014	.025		
D-2	3/4	.28	1.16	.30	.017	.017	.81	.77	.26	Trace	.09	.0011	.01		
<u>Great Lakes</u>															
10	1	.30	1.02	.81	.021	.022	Trace	.54	.23	N11	.07	Trace	.013	.06	.08

With the exception of the Republic heat No. RH 11761 and the Great Lakes plate No. 10 the balance of the heats were treated with special addition agents containing boren. Only a trace of this element, namely 0.0009%, was detected in the 3/4" and 1 1/2" thick plates rolled from heat No. RH 11761 and the Great Lakes plate No. 10.

b. Fracture Tests for Steel Soundness.

Figures 2-4 inclusive illustrate fractures of the "woody" type and those exhibiting shelving. The results of these tests are summarized in Table II.

TABLE II

Summary of Fracture Tests for Steel Soundness

Sample No.	Approximate Size of Notched Bar Broken Slowly under Press	Fracture Rating		Description of Fracture	*Behavior under Projectile Through Plate Test
		**Long	Trans		
<u>Republic</u>					
1	4x1-1/4x3/4"	B	-	Woody	Failed 2x3-1/4" ex. dia.
6	4x1-1/4x3/4"	B	-	Traces of Woodiness	Acceptable 1-3/4x2-1/4" ex. dia.
5	4x1-1/4x1 1/2"	B	-	Woody	Failed 3x3-3/4" ex. dia.
9	4x1-1/4x1 1/2"	B	-	Traces of Woodiness	Acceptable 2-1/4x2-5/8" ex. dia.
RH 11761	6x4x3/4"	B	B	No woodiness in Long and Trans fractures	Failed 2-3/4x3" ex. dia.
RH 53715	6x4x3/4"	D	D	Shelving in Long and Trans directions. Traces of Woodiness only in Long. fracture.	Failed 2-1/4x3" ex. dia.
RH 11761	6x4x1 1/2"	O	-	Woodiness only in Long fracture.	Failed 2-5/8x3-1/4" ex. dia.
RH 11792	6x4x1 1/2"	O	B	Woodiness only in Long. fracture.	Acceptable 2-3/8x2-3/8" ex. dia.
<u>Great Lakes</u>					
10	3x6x1"	B	B	No woodiness in Long and Trans fractures.	-----

*Specification AISI-495, Revision 2. Specification AISI-488, Revision 1.

**Longitudinal fracture parallel to major direction of rolling.

Transverse fracture at right angles to major direction of rolling.

The fracture test reveals the directional properties in samples Nos. 1, 5, RH 53715 (3/4" thick), RH 11761 (1 1/2" thick) and RH 11792 (1 1/2" thick) whereas samples Nos. 6 and 9 were more thoroughly cross rolled. Sample Nos. RH 11761 (3/4" thick) and GLS 10 were relatively free from nonmetallic segregations and were thoroughly cross rolled, no "woodiness" being evident in either of these samples.

No conclusions could be drawn on the relation between "woody" fractures and spalling characteristics due to the insufficient number of samples examined and also to the apparent inadequacy of the ballistic test applied.

c. Fracture Test for Fibre.

Fracture tests for fibre were made on samples of the 3/4" and 1 1/2" thick plates which were requested for metallurgical study and the results are reported below:

<u>Sample Number</u>	<u>Fracture Rating</u>	<u>Brinell Hardness</u>
RH 11761 - 3/4"	Fibrous	293
RH 53715 - 3/4"	Fibrous	269
RH 11761 - 1 1/2"	Fibrous	262
RH 11792 - 1 1/2"	Fibrous	269

d. Macroscopic Examination.

Figures 5-7 inclusive illustrate the macrostructure of samples etched in hot acid which had a "woody" fracture and also those which showed no evidence of a "woody" fracture. These results are summarized in Table III.

Table III
Macrostructure

Sample No.	Projectile Through Plate Test	Fracture	Macrostructure	
			Longitudinal	Transverse
<u>Republic</u>				
1 3/4"	*F	Woody	Slight evidence of centerline segregation	Evidence of centerline segregation more deeply etched.
6 3/4"	*P	Traces of Woodiness	Centerline segregation	Centerline segregation more deeply etched.
5 1 1/2"	F	Woody	center segregation	Center segregation more deeply etched.
9 1 1/2"	P	Traces of Woodiness	Fairly uniform banding	Pronounced center segregation more deeply etched.
RH 11761 3/4"	F	No Woodiness	Satisfactory	Satisfactory
RH 53715 3/4"	F	Shelving Traces of Woodiness	Satisfactory	Centerline segregation more deeply etched.
RH 11761 1 1/2"	F	Woody	Center segregation	Center segregation more deeply etched.
RH 11792 1 1/2"	P	Woody	Center segregation	Center segregation more deeply etched.
A-1 1"	P	Woodiness Evident	Center segregation	Center segregation more deeply etched.
B-2 1"	P	Traces of Woodiness	Slight banding	Some center segregation more deeply etched.
C-4 3/4"	P	Traces of Woodiness	Satisfactory	Some center segregation more deeply etched.
D-2 3/4"	P	Traces of Woodiness	Occasional banding	Fairly uniform more deeply etched.

Great Lakes

10 1"	-	No Woodiness	Satisfactory	Satisfactory
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*F=Failed

*P=Passed

The samples which showed evidence of directional properties, by virtue of the fact that these etched more deeply in the transverse direction, also revealed the presence of "woodiness" in the fractures to various degrees. In other words, a fairly good correlation between "woody" fractures and the macrostructure was established. If extreme differences in etching characteristics exist in the two directions (indicating directional properties), the "woody" type fracture may be expected to be observed in the longitudinal fracture.

e. Microscopic Examination

Typical nonmetallic inclusions and representative microstructures found in samples showing various degrees of "woody" fractures are presented in Figures 8 to 14 inclusive. The results are tabulated in Table IV.

The results of the microscopic examination indicate that fine nonmetallic inclusions in the plane of rupture result in the "woody" type of fracture. Figure 1, illustrates a "woody" fracture, broken in the longitudinal direction of the $1\frac{1}{2}$ " thick plate No. RH 11761. This fracture was nickel plated in order to preserve the contour of the fracture during the metallographic polishing operation and subsequently cut transversely and examined for the presence of nonmetallic inclusions in planes of rupture. As noted in Figure 8, the cross section of a "woody" fracture has a "stepped" appearance. Microscopic examination revealed the presence of fine nonmetallic inclusions on the "shelves" of the stepped fracture, indicating that rupture has occurred along these planes. These nonmetallic inclusions were identified as silicates, complex oxide-sulphide-silicates and in one case zirconium nitride was present on a plane of rupture, see Figure 8. The distribution of nonmetallic inclusions in the cross section of these materials is also shown in Figure 8.

In the longitudinal section of the $1\frac{1}{2}$ " thick plate No. RH 11761, and in other samples examined, elongated nonmetallic inclusions of the same type, namely complex oxide-sulphide-silicates were detected, see Figures 9 and 10. Occasionally other types of nonmetallic inclusions such as alumina and titanium nitride stringers were found in samples showing the "woody" type of fracture, see Figures 9 and 10.

It was observed that the degree of "woodiness" of fracture was more intense with the increase in the amount of nonmetallic inclusions, note the absence of elongated nonmetallic inclusions in plate No. RH 11761 ($3/4$ " thick) which did not exhibit a "woody" fracture and the presence of the nonmetallic inclusions in plates Nos. RH 11761 ($1\frac{1}{2}$ " thick) and RH 11792 ($1\frac{1}{2}$ " thick), Figure 10. Also, microscopic examination of some of the broken large size Charpy bars to which reference is made in Figure 13 and in Table VI, indicated that with a greater amount of "woodiness" in the fractures an increase in the amount of nonmetallic inclusions was clearly demonstrated.

Table IV
Microstructure

Sample No.		Projectile Through Plate Test	Fracture	Unetched Typical Inclusions	Picral Etch Typical Structure	Oberhoffer's Etch Metallic Segregation
Republic						
1		EF	Woody	Fine oxide sulphide silicates well distributed.	Ferrite and tempered martensite.	Pronounced banding
3/4"						
6		EF	Traces of woodiness	Scattered fine oxide sulphide silicates.	Ferrite and tempered martensite.	Occasional banding
3/4"						
5"		F	Woody	Alumina streaks well distributed.	Ferrite and tempered martensite, upper temperature transformation products.	Pronounced banding
1 1/2"						
9		P	Traces of woodiness	Scattered fine oxide sulphide silicates.	Tempered martensite	Pronounced banding
1 1/2"						
HH 11761		F	No woodiness	Few scattered aluminum oxides	Tempered martensite	Pronounced banding
3/4"						
HH 53715		F	Shelving Traces of woodiness	Fine oxide sulphide silicates well distributed.	Tempered martensite	Pronounced banding
3/4"						
**HH 11761		P	Woody	Fine oxide sulphide silicates well distributed.	Tempered martensite, upper temperature transformation products.	Pronounced banding
1 1/2"						
HH 11792		P	Woody	Fine oxide sulphide silicates well distributed.	Ferrite and tempered martensite, upper temperature transformation products.	Pronounced banding
1 1/2"						

Table IV (Cont'd)

Sample No.	Projectile Through Plate Test	Fracture	Microstructure		Oberhoffer's Etch Metallic Segregation
			Unetched Typical Inclusions	Pieral Etch Typical Structure	
<u>Republic</u>					
A-1 1"	P	Woodiness evident	Alumina streaks near surface	Tempered martensite	Pronounced banding
B-2 1"	P	Traces of woodiness	Occasional streaks of Titanium nitride.	Tempered martensite	Pronounced banding
C-4 3/4"	P	Traces of woodiness	Occasional fine streaks of alumina inclusions.	Tempered martensite	Pronounced banding
D-2 3/4"	P	Traces of woodiness	Occasional streaks of oxide sulphide silicates associated with titanium nitride.	Tempered martensite	Pronounced banding
<u>Great Lakes</u>					
10 1"		No woodiness	Uniform distribution of fine oxides.	Tempered martensite	Pronounced banding

*Failed *Passed

**A study on the relation of nonmetallic inclusions to the path of rupture in "woody" fractures is shown in Figure 8.

In the case of sample No. 10, which showed no evidence of a "woody" fracture, see Figure 4, no elongated nonmetallic inclusions were evident. A uniform distribution of small nonmetallic inclusions was scattered throughout the matrix, see Figure 10.

Generally speaking, metallic banding was associated with the nonmetallic inclusions, see Figure 11. It was indicated that metallic banding alone as revealed by Oberhoffer's etch, is not always responsible for "woody" fractures as noted in the case of sample No. RH 11761 ($3/4$ " thick) in which metallic banding is present and is not associated with elongated nonmetallic inclusions, see Figure 11. Also sample No. 10, which contained no elongated nonmetallic inclusions, showed the presence of metallic banding but did not have a "woody" fracture, see Figure 4.

Most of the samples investigated had a tempered martensitic structure but in some cases small amounts of pro-eutectoid ferrite were present, see Figure 12. In the case of the failed $1\frac{1}{2}$ " thick plate No. 5, and the satisfactory $1\frac{1}{2}$ " thick plate No. RH 11792, the presence of some upper transformation products was evident. The amount of this constituent in each plate was less than 15% and therefore was not considered objectionable.

Note: A. Hurlich conducted the metallographic work on the occurrence of nonmetallic inclusions in the planes of rupture of "woody" fractures, see Figure 8. The balance of the photomicrographic work was conducted by M. Yoffa.

f. V-notch Charpy Impact Tests

The results of the V-notch Charpy Impact tests made on longitudinal and transverse sections of $3/4$ ", 1", and $1\frac{1}{2}$ " thick plates at $+70^{\circ}\text{F}$ and at -40°F are given in Table V. With the exception of plates Nos. RH 11761, $3/4$ " thick, and 10, 1" thick, the noticeable difference between the longitudinal and transverse Charpy values of the various plates indicate definite directional properties. The two plates referred to above had fairly uniform impact values in the longitudinal and transverse directions.

It has been observed that good quality $1\frac{1}{2}$ " thick plate, free from directional properties, when heat treated to the same hardness as some of the material tested in this investigation (250-260 Brinell hardness), has a V-notch Charpy value in the transverse direction of approximately 80 ft./lbs. as noted in Table V. The transverse Charpy values of material of the same hardness level which possessed directional properties varied from 20-48 ft./lbs. This would indicate that the ratio of V-notch Charpy values of satisfactory cross rolled plate to that of improperly cross rolled plate would be approximately 2:1.

The results of the impact tests described in Table V correlated with the fracture studies for steel quality.

There was no marked variation in the impact values obtained on bars cut in the same direction of rolling at -40°F and at $+70^{\circ}\text{F}$. Apparently this material was satisfactorily heat treated, the fractures of the impact bars in all cases being fibrous.

Another series of V-notch Charpy tests were made on large size Charpy bars, $3/4 \times 3/4 \times 6$ " and $1 \times 1 \times 6$ " which constituted the full gauge of the plates tested. Also comparative tests were made on the standard $.394 \times .394$ " V-notch Charpy bar and are included in the summary of results shown in Table VI.

This particular material which showed only traces of woodiness as fractured, see Figure 13 was heat treated to several hardness levels, namely from about 320 to 388 Brinell and had impact values not too inferior to cross rolled material heat treated to the same hardness levels. These steels all exhibited fibrous fractures at the several hardness levels.

In general, the Charpy values of this series of samples showing evidence of woodiness were somewhat lower than those determined on other types of cross rolled armor plate at the same hardness levels.

g. Tensile Tests

Tensile tests made in the longitudinal and transverse directions on samples from $3/4$ ", 1" and $1\frac{1}{2}$ " thick plates are given in Table VII.

Directional properties are evident in plates which exhibited "woody" fractures revealed by the fracture test for steel soundness and other metallurgical tests.

Plates Nos. RH 11761, $3/4$ " thick and No. 10 were apparently cross rolled to a greater extent than the rest of the series as noted by the small differences in the ductility of the longitudinal and transverse tests.

The results of the physical tests correlated closely with the metallurgical tests reported herein.

h. Hardness Tests

The Brinell hardness tests were made on the cross sections of the plates and the values are reported in Tables V, VI, VII. In all cases the plates were heat treated to a uniform hardness along the cross section.

5. The "woody" type of fracture has been observed in many electric and open hearth steels, both domestic and foreign. It is apparent that this condition results from an improper refining and deoxidation practice at the steel source. In an improperly refined and deoxidized heat, these

Table V
V-notch Charpy Impact Values Determined on
3/4", 1" and 1 1/2" Thick Plate

<u>Sample No.</u>	<u>Thick-ness</u>	<u>Specimen Direction</u>	<u>Temp. of Test</u>	<u>Foot Pounds</u>	<u>Description of Fracture</u>
<u>Republic</u>					
RH 53715	3/4"	Long.	269 +70°F	54.6	*F - Pronounced continuous laminations
RH 53715	3/4"	Long.	269 -40°F	52.8	F - Pronounced continuous laminations
RH 53715	3/4"	Trans.	269 +70°F	20.8	F - "woody" fracture, fine fragmented and continuous striations.
RH 53715	3/4"	Trans.	269 -40°F	17.4	F - "Woody" fracture, fine fragmented and continuous striations.
RH 11761	3/4"	Long.	293 +70°F	40.5	F - No "woodiness"
RH 11761	3/4"	Long.	293 -40°F	35.8	F - No "woodiness"
RH 11761	3/4"	Trans.	293 +70°F	36.3	F - No "woodiness"
RH 11761	3/4"	Trans.	293 -40°F	33.3	F - No "woodiness"
RH 11792	1 1/2"	Long.	269 +70°F	90.5	F - Broken ends of striations
RH 11792	1 1/2"	Long.	269 -40°F	83.0	F - Broken ends of striations
RH 11792	1 1/2"	Trans.	269 +70°F	52.6	F - "Woody" fracture, fine continuous striations
RH 11792	1 1/2"	Trans.	269 -40°F	47.5	F - "Woody" fracture, fine continuous striations
RH 11761	1 1/2"	Long.	262 +70°F	95.1	F - Broken ends of striations
RH 11761	1 1/2"	Long.	262 -40°F	93.0	F - Broken ends of striations
RH 11761	1 1/2"	Trans.	262 +70°F	32.9	F - "Woody" fracture, fine continuous striations
RH 11761	1 1/2"	Trans.	262 -40°F	30.4	F - "Woody" fracture, fine continuous striations
<u>Great Lakes</u>					
10		Long.	320 +70°F	32.8	F - No "woodiness"
10		Trans.	320 +70°F	26.4	F - No "woodiness"
10S		Long.	320 +70°F	35.5	F - No "woodiness"
10S		Trans.	320 +70°F	25.3	F - No "woodiness"

*F=Fibrous

Note: With the exception of sample 10S, V-notch was cut in bars perpendicular to surface of plate.

On sample 10S, V-notch was cut parallel to surface of plate.

Table VI

V-notch Charpy Impact Values Determined on
3/4" and 1" Thick Plate Heat Treated at Several Hardness Levels

Sample No.	Thickness	Direction	BHN	Foot Pounds 4700F		Fracture	Fracture
				3/4" and 1" Thick Charpy Bars	Standard Charpy Bar		
A-1	1"	Trans.	331	202	25.3	*F - Evidence of woodiness	*F - Trace fine woodiness
A-2	1"	Trans.	341	158	21.3	F - Evidence of woodiness	F - Trace fine woodiness
A-3	1"	Trans.	363	146	18.1	F - 50% woody	F - Trace fine woodiness
A-4	1"	Trans.	375	123	16.9	F - Trace woody	F - Trace fine woodiness
B-1	1"	Trans.	341	158	19.4	F - Trace woody	F - Trace fine woodiness
B-2	1"	Trans.	363	140	17.3	F - Trace woody	F - Trace fine woodiness
B-3	1"	Trans.	375	134	13.6	F - Trace woody	F - Trace fine woodiness
B-4	1"	Trans.	388	123	15.5	F - Trace woody	F - Trace fine woodiness
C-1	3/4"	Trans.	321	100	25.5	F - Trace woody	F - Trace fine woodiness
C-2	3/4"	Trans.	341	79	18.3	F - Trace woody	F - Trace fine woodiness
C-3	3/4"	Trans.	352	79	16.4	F - Trace woody	F - Trace fine woodiness
C-4	3/4"	Trans.	375	79	16.5	F - Trace woody	F - Trace fine woodiness
D-1	3/4"	Trans.	341	79	18.1	F - Trace woody	F - Trace fine woodiness
D-2	3/4"	Trans.	363	60	12.4	F - Trace woody	F - Trace fine woodiness
D-3	3/4"	Trans.	375	60	13.8	F - Trace woody	F - Trace fine woodiness
D-4	3/4"	Trans.	388	60	12.4	F - Trace woody	F - Trace fine woodiness

*F=Fibrous fracture

Note: V-notch milled parallel to surface of plate and parallel to direction of rolling.
 Depth of notch on 3/4" thick plate - 1/8".
 Depth of notch on 1" thick plate - 1/4".

Table VII

Results of Tensile Tests Made on 3/4", 1" and 1 1/2" Thick Plate

Sample No.	Thick-ness	Direction	Y.S.		T.S. Lb./Sq. In.	% El	% RA	BHN	Remarks
			Lb./Sq. In.	.1% Set					
RH 53715	3/4"	Long.	119,700		136,000	19.7	60.8	269	Shelving in Long. and Trans. directions. Traces of woodiness only in Long. directions.
RH 53715	3/4"	Trans.	119,700		136,000	15.0	42.4		
RH 11761	3/4"	Long.	134,100		146,000	16.8	56.7	293	No evidence of woody fracture in Long. and Trans. directions. No directional properties.
RH 11761	3/4"	Trans.	133,500		146,000	16.8	54.8		
RH 11792	1 1/2"	Long.	116,300		134,800	19.7	64.9	269	Woody fracture only in Long. direction. Directional properties.
RH 11792	1 1/2"	Trans.	116,900		135,300	17.9	55.6		
RH 11761	1 1/2"	Long.	118,000		129,250	20.7	65.5	262	Woody fracture only in Long. direction. Directional properties.
RH 11761	1 1/2"	Trans.	117,900		129,250	16.8	49.8		
10	1"	Long.	156,250		170,000	14.3	50.6	320	No evidence of woody fracture in Long. and Trans. directions. Directional properties not marked.
10	1"	Trans.	152,500		169,000	14.3	47.0		

*Fracture descriptions are those recorded in the Fracture Test for Steel Soundness.

nonmetallic inclusions are present in the metal during teeming and subsequently segregate during the solidification of the ingot and are elongated in the major direction of hot rolling. It has been demonstrated that "woody" fractures are formed when the fracture plane is parallel to the major direction of rolling and that the path of rupture proceeds in a "stepped" fashion along planes of weakness caused by embedded nonmetallic inclusions, chiefly of the silicate type.

A "woody" condition in rolled armor is indicative of poor metallurgical properties and, therefore, is not desirable in good quality steel, the production of which is essential to meet the new ballistic requirements for rolled homogeneous armor. The "woody" fracture condition, being associated with considerable directional characteristics in the steel, may be expected to influence shock failures because of excessive directional cracking. It is probable that "woodiness" to varying degrees will always be observed in the longitudinal fracture of a fully heat treated steel (breaking in a fibrous manner) which is straight-away or essentially straight-away rolled. The "woody" fracture can apparently be avoided by equality in percentage reduction in the two directions. The larger and more numerous the inclusions become the greater is the degree of "woodiness" developed in a steel with directional characteristics when fractured longitudinally.

E. L. Reed

E. L. REED
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APPROVED:

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Major, Ordnance Dept.
Chief, Armor Section



WATERTOWN ARSENAL

1 1/2" THICK ROLLED ARMOR EXHIBITING WOODY FRACTURE
17 MAY 1944 MAG. X 2 WTN.710-2307

FIGURE 1



SAMPLE # 1
FAILED



SAMPLE # 6
SATISFACTORY



SAMPLE # 5
FAILED



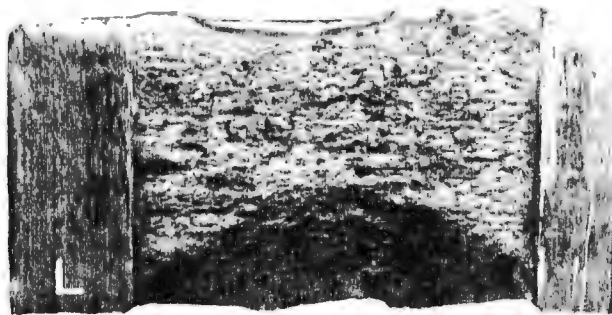
SAMPLE # 9
SATISFACTORY



ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

FRACTURES OF SAMPLES OF ROLLED PLATE SUBMITTED BY
REPUBLIC STEEL CORP. 24 JAN 1944 WTN.710-2267

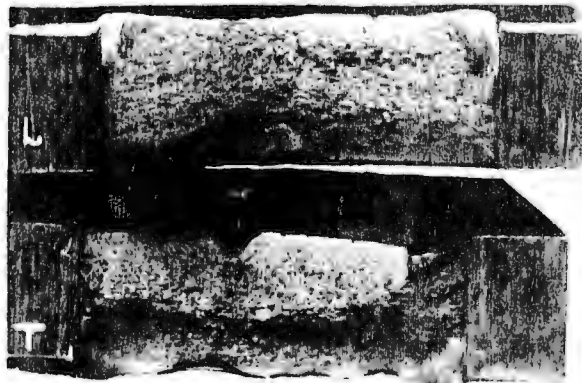
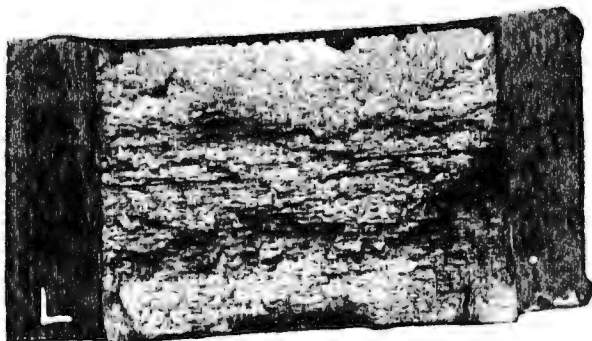
FIGURE 2



1 1/2" PLATE RH 11792
PTP TEST 2 3/8" X 2 3/8" EXIT DIA.



3/4" PLATE RH 53715
PTP TEST 2 1/4" X 3" EXIT DIA.



3/4" PLATE RH 11761
PTP TEST 2 3/4" X 3" EXIT DIA.



1 1/2" PLATE RH 11761
PTP TEST 2 5/8" X 3 1/4" EXIT DIA.

WATERTOWN ARSENAL

REPRODUCED AT GOVERNMENT EXPENSE
4461 B. O. 16 6880000 OFFICE OF THE ASSISTANT SECRETARY FOR ARMS AND AMMUNITION
MAR 23 1944 WTN.751-2286

FIGURE 3

LONGITUDINAL

TRANSVERSE



FRACTURES FOR STEEL SOUNDNESS "B" RATING



MACROSTRUCTURE

WATERTOWN ARSENAL

FRACTURES FOR STEEL SOUNDNESS AND MACROSTRUCTURE OF 3/4" THICK ARMOR PLATE NO. 10 CONTAINING:

C	MN	SI	S	P	CR	MO	ZR
.30	1.02	.81	.021	.022	.54	.23	.08

16 MAY 1944

MIC X 8

MPN 710-2306

FIGURE 4

LONGITUDINAL



SAMPLE # 1

TRANSVERSE



SAMPLE NO 1



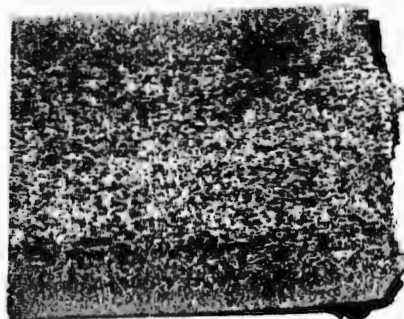
SAMPLE # 6



SAMPLE # 6



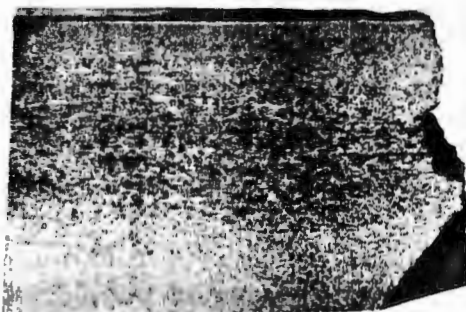
SAMPLE # 5



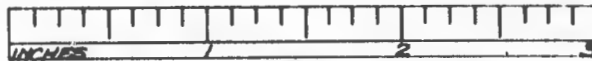
SAMPLE # 5



SAMPLE # 9



SAMPLE # 9

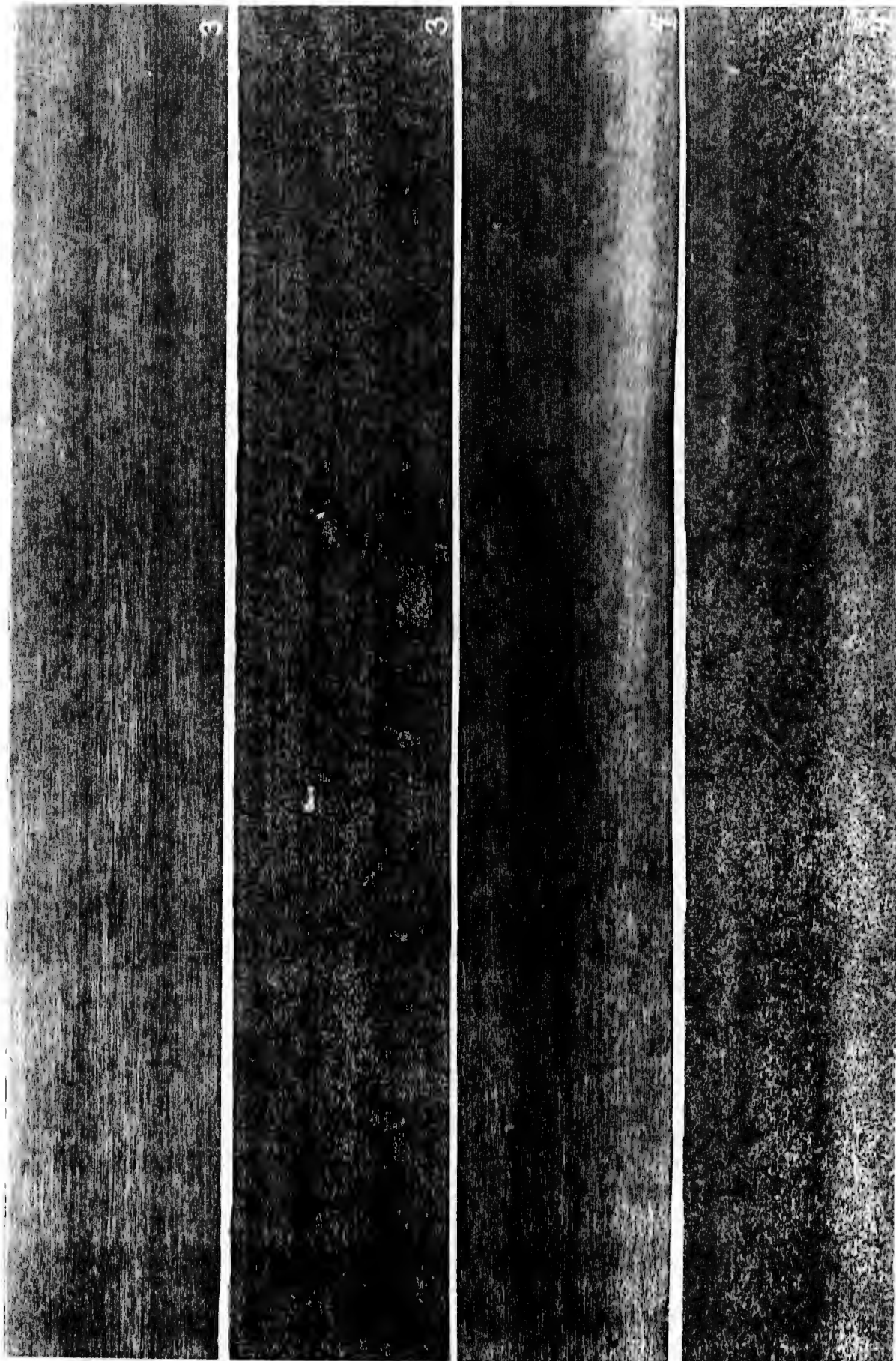


ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

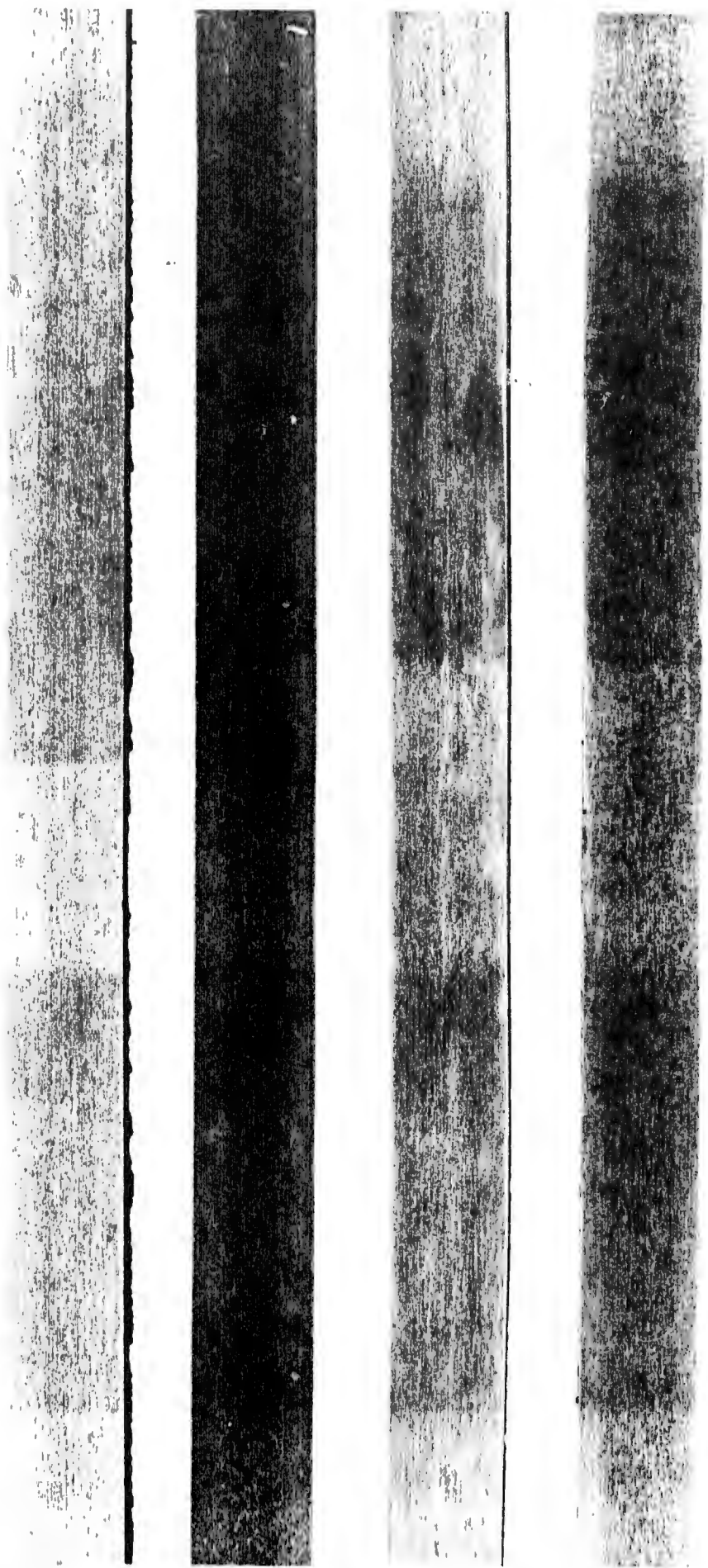
SAMPLES NOS 1 AND 5 - POOR BALLISTIC PROPERTIES
SAMPLES NOS 6 AND 9 - SATISFACTORY BALLISTIC PROPERTIES

MACROSTRUCTURE OF ROLLED PLATE SUBMITTED BY REPUBLIC STEEL CORP
31 JANUARY 1944 WTN.710-2269

FIGURE 5



WATERTOWN ARSENAL
 (3) 1 1/2" PLATE RH 11792 - LONGITUDINAL (3) 1 1/2" PLATE RH 11792 - TRANSVERSE (4) 1 1/2" PLATE RH 11761 - LONGITUDINAL
 (4) 1 1/2" PLATE RH 11761 - TRANSVERSE MAG. XI 10 MARCH 1944
 WTN.71C-2288



Figure

WATERTOWN ARSENAL

{ 1 } 3/4" PLATE RH 53715 - LONGITUDINAL (1) 3/4" PLATE RH 11761 - TRANSVERSE (2) 3/4" PLATE RH 11761 - LONGITUDINAL
{ 2 } 3/4" PLATE RH 11761 - TRANSVERSE MAG XI 10 MARCH 1944 WTN.710-2287
MACROSTRUCTURE OF ARMOR PLATE SUBMITTED BY REPUBLIC STEEL CORP.

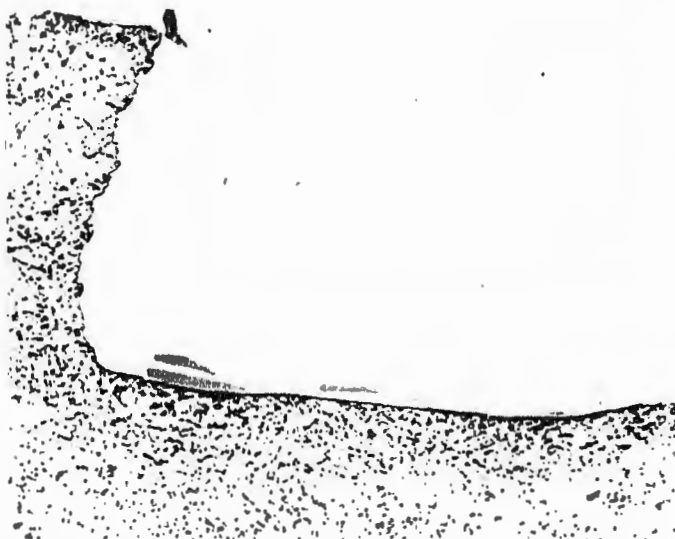
Nonmetallic Inclusions on "Steps" of "Woody" Fracture



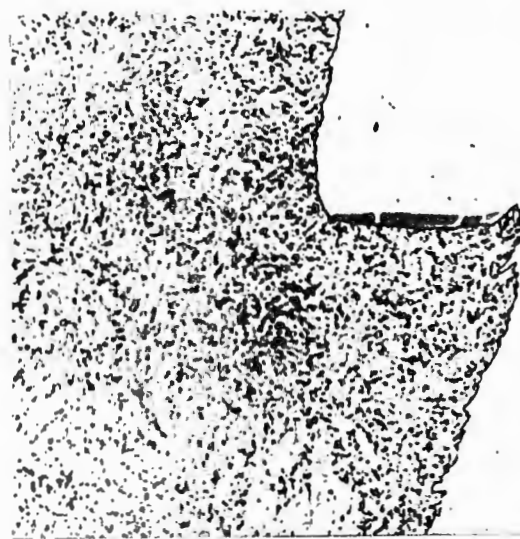
Sample No. RH 11761 - $1\frac{1}{8}$ " thick. Typical contour of "woody" fracture. Stepped appearance. Sulphide-silicate inclusions in steel base. Failed PTP test. Macy. X100



Sample No. RH 11761 - $1\frac{1}{8}$ " thick. Series of fine nonmetallic inclusions on stepped rupture. Fragment of zirconium nitride (yellow under white light) at tip of middle step, see arrow. Gray inclusions are oxide-silicate inclusions.



Sample No. RH 11761 - $1\frac{1}{8}$ " thick. Sulphide-silicate inclusion on stepped plane of rupture of "woody" fracture.



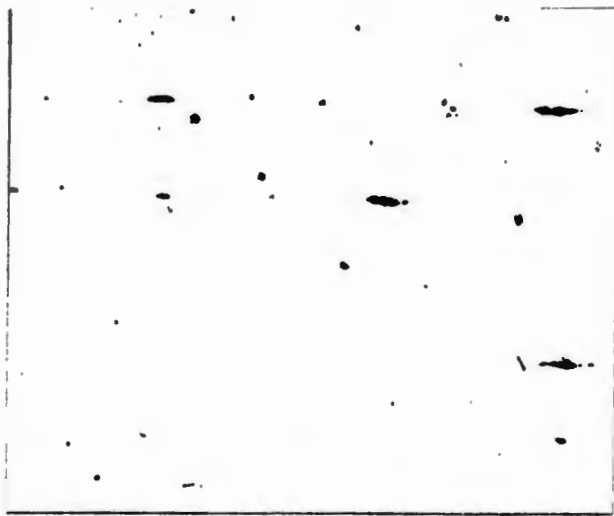
Sample No. H 11761 - $1\frac{1}{8}$ " thick. Broken silicate inclusion on stepped plane of rupture of "woody" fracture.

Transverse Section Picral Etch Magnification X1000

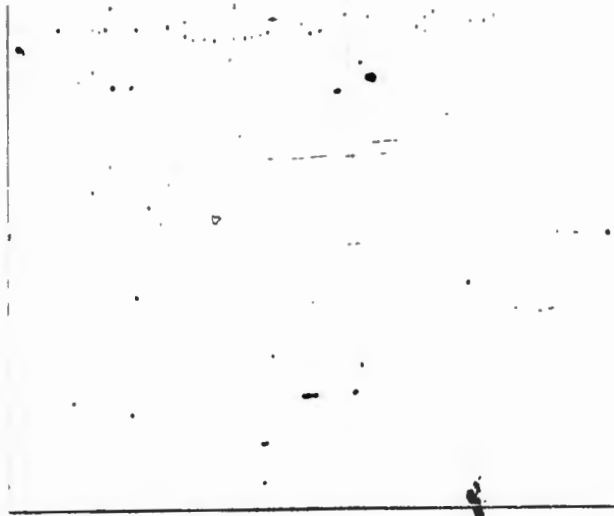
REPRODUCED AT GOVERNMENT EXPENSE

FIGURE 1

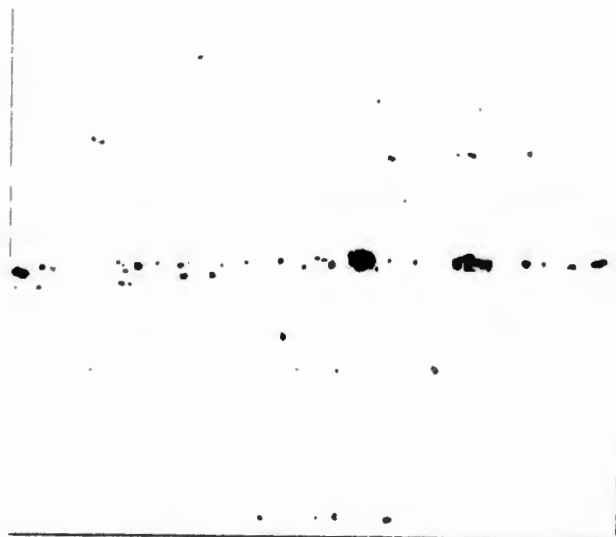
Typical Nonmetallic Inclusions in 3/4" and 1 1/2" Thick Fracture Test Bars



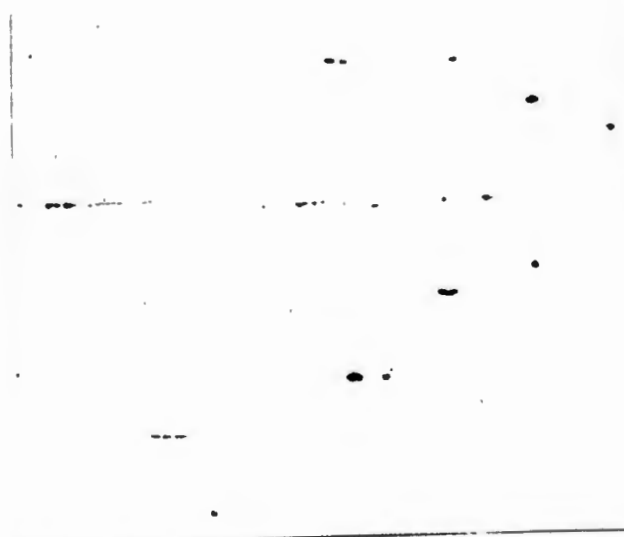
Sample No. 1 - 3/4" thick. Fine oxide-sulphide-silicate inclusions well distributed. "Woody" fracture - Failed PTP test.



Sample No. 6 - 3/4" thick. Scattered fine oxide-sulphide-silicate inclusions. Traces of "woodiness" in fracture - Passed PTP test.




Sample No. 5 - 1 1/2" thick. Typical alumina inclusion streak in center of plate. Silicates were also present. "Woody" fracture - Failed PTP test.




Sample No. 9 - 1 1/2" thick. Scattered fine oxide-sulphide-silicate inclusions. Traces of "woodiness" in fracture - Passed PTP test.

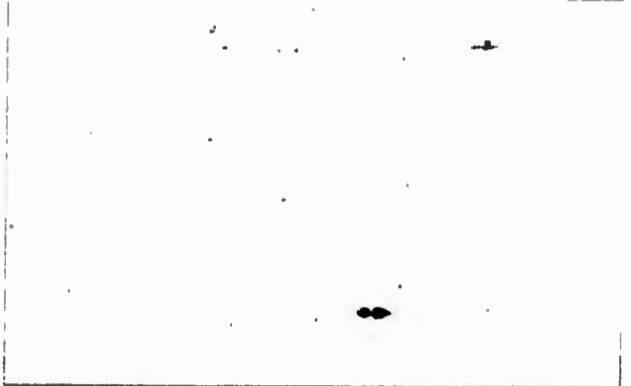
Typical Nonmetallic Inclusions in 3/4" and 1 1/2" Thick Plates



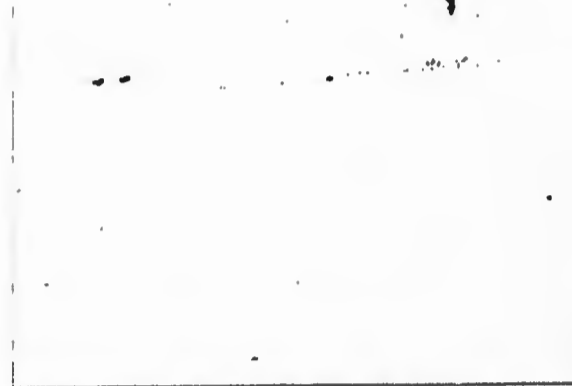
Sample No. RH 53715 - 3/4" thick.
Fine oxide sulphide silicate inclusions well distributed. Some "woodiness" and pronounced shelving in fracture.
Failed PTP test.



Sample No. RH 11761 - 3/4" thick.
Few scattered oxide of alumina inclusions. No evidence of "woody" fracture. Failed PTP test.



Sample No. RH 11761 - 1 1/2" thick.
Fine oxide sulphide silicate inclusions well distributed. "Woody" Fracture.
Failed PTP test.



Sample No. RH 11792 - 1 1/2" thick.
Fine oxide sulphide silicate inclusions well distributed.
"Woody" fracture. Passed PTP test.

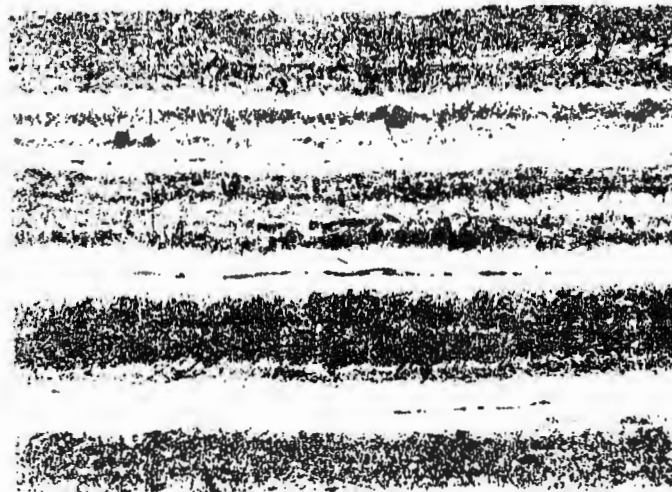
Sample No. B-2. 1x1" V-notch Charpy bar. An occasional streak of titanium nitride inclusions. Traces of "woody" fracture.

Sample No. 10. Uniform distribution of fine oxides. No "woodiness" in fracture.

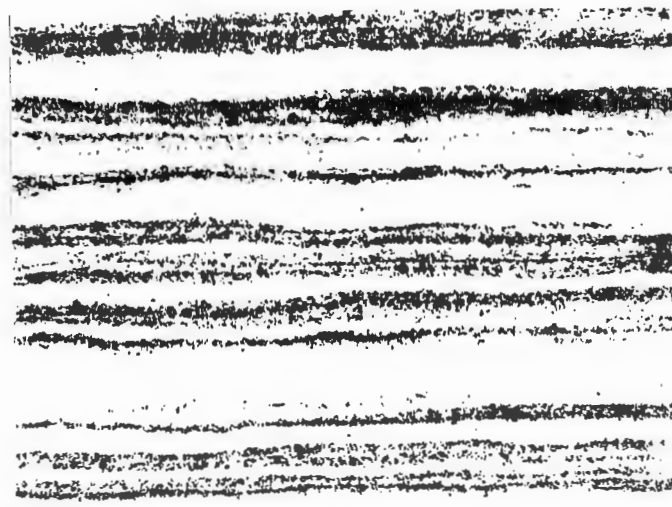
Metallic Banding Associated With Nonmetallics in 3/4" and 1 1/2" Thick Plate



Sample No. RH 53715 - 3/4" thick.
Pronounced banding associated with occasional sulphide silicate inclusions. Some "woodiness" and marked shelving in fracture. Failed PTP test.



Sample No. 5 - 1 1/2" thick. Pronounced banding associated with fine oxide-sulphide-silicate inclusions. "Woody" fracture. Failed PTP test.



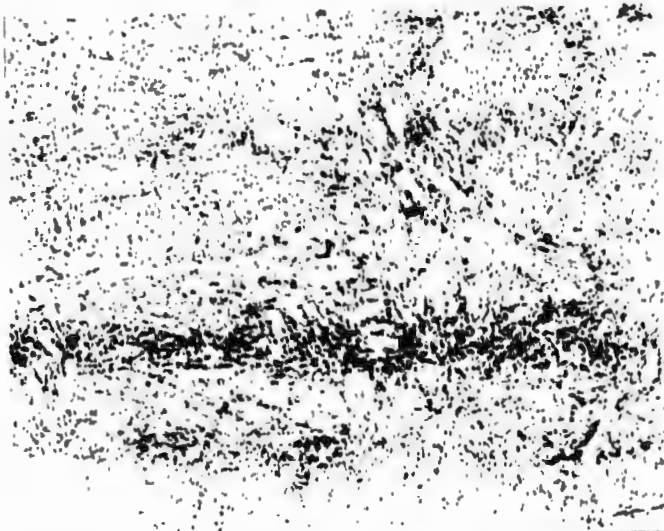
Sample No. RH 11761 - 3/4" thick.
Pronounced banding associated with a few small inclusions. No evidence of "woody" fracture. Failed PTP test.



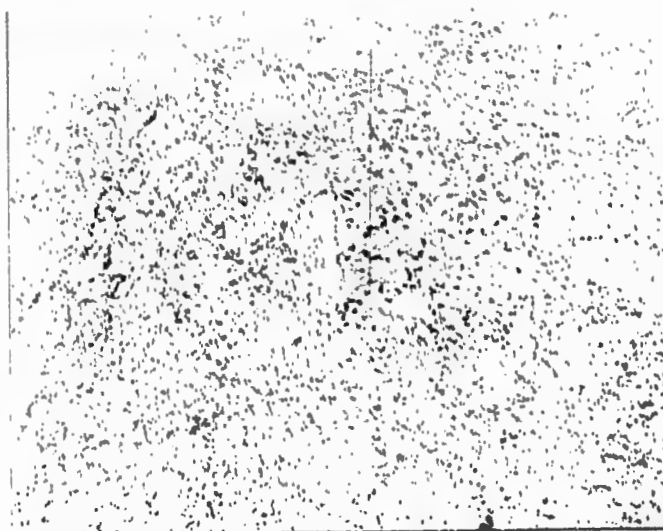
Sample No. RH 11792 - 1 1/2" thick.
Pronounced banding associated with sulphide-oxide-silicate inclusions. "Woody" fracture. Failed PTP test.

Longitudinal Sections Oberhoffer Etch Magnification X100

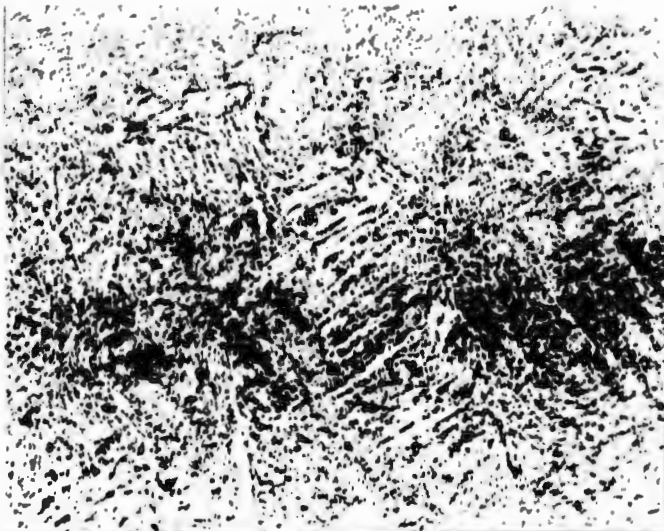
Microstructure of 3/4" and 1 1/2" Thick Fracture Test Bars



Sample No. 1 - 3/4" thick. Ferrite, tempered martensite, banded structure. "Woody" fracture - Failed PTP test.



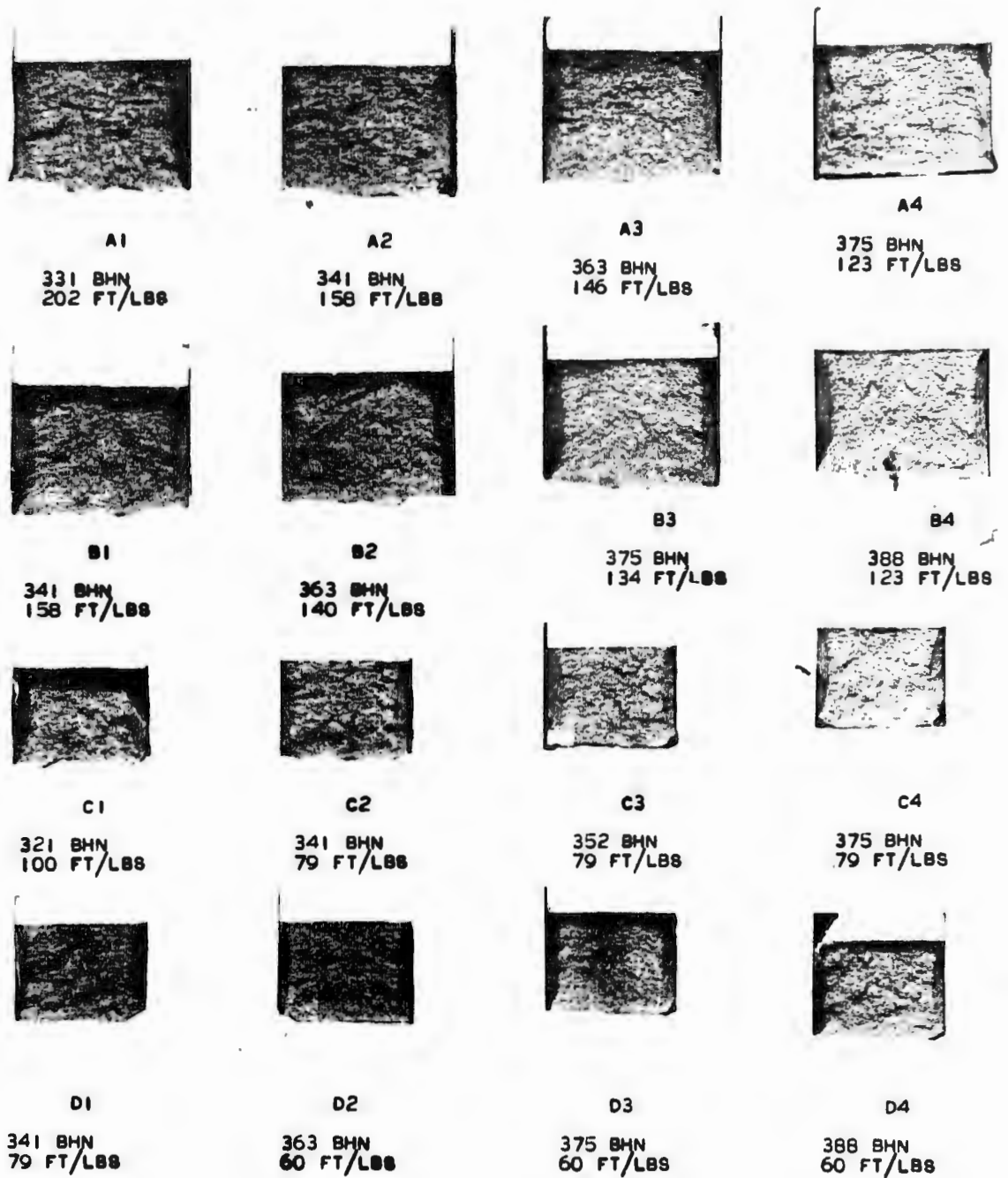
Sample No. RH 11761 - 1 1/2" thick. Tempered martensite and trace of upper temperature transformation products. "Woody" fracture - Failed PTP test.



Sample No. RH 11792 - 1 1/2" thick. Ferrite, upper temperature transformation products and tempered martensite. "Woody" fracture. Passed PTP test.



Sample No. 9 - 1" thick. Tempered martensite, banded structure. Traces of "woody" fracture - Passed PTP test.



WATERTOWN ARSENAL

FRACTURES OF 1" AND 3/4" SQUARE V-NOTCH CHARPY BARS MACHINED FROM
 REPUBLIC STEEL CORP. ARMOR HEAT TREATED TO SEVERAL HARDNESS LEVELS
 24 MARCH 1944 MAG. XI WTN.710-2292

FIGURE