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OTTAWA June 1st, 1942.

R E P O R T

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1226.

Investigation of Metallurgical Characteristics of 12 mm. Homogeneous Type Armour Plate.

(Copy No. 23.)

BUREAU OF MINES
DIVISION OF METALLIC MINERALS

ORE DRESSING AND
METALLURGICAL LABORATORIES

CANADA
DEPARTMENT
OF
MINES AND RESOURCES
MINES AND GEOLOGY BRANCH

O T T A W A June 1st, 1942.

REPORT

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ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1226.

Investigation of Metallurgical Characteristics of 12 mm. Homogeneous Type Armour Plate.

Origin of Material and Object of Investigation:

On March 27th, 1942, Mr. W. L. Auchincloss, of the Inspection Board of the United Kingdom and Canada, 58 Lyon Street, Ottawa, Ontario, submitted for examination a piece of 12 mm. armour plate reported to have failed to meet ballistic specifications as set out in Specification No. I.T. 1000. It was requested that any characteristic or property that could explain the poor ballistic behaviour be determined, if possible.

(Origin of Material and Object of Investigation, cont'd) -

After a preliminary examination of the plate, these laboratories requested and received, for purposes of comparison, one good piece of similar armour made from recent production and one good piece of similar armour from past production.

On April 16th the following letter, reporting developments, was written:

"552 Booth Street,
Ottawa, Ontario,
April 16, 1942.

Mr. W. L. Auchincloss,
Inspector of Tanks,
For Inspector General,
Inspection Board of United Kingdom and Canada,
58 Lyon Street,
Ottawa, Ontario.

Re: 12 mm. Armour Plate.

Dear Mr. Auchincloss:

This morning I reported progress on our current armour plate investigation to your Mr. A. S. MacLaren whom I contacted in your absence.

To date this work has consisted mainly of eliminating certain factors that might have affected the performance. The conclusions arrived at so far are;

1. There is an equal amount of decarburization on both good and bad armour plate. Therefore this factor probably can be eliminated.

2. The McQuaid-Ehn grain size of the bad plate is 3. This means good hardenability. One of the good plates also had a McQuaid-Ehn size of 3 and the other a McQuaid-Ehn size of 8, which indicates poor hardenability. Therefore it would appear that the factor of relative hardenability can be eliminated.

It is the opinion of this staff that the cause of the poor quality might be found in the heat treating practice. Armour plate practice to date would indicate that for this particular plate it is better to have transformation on hardening take place at a temperature of from 500° F. to 300° F. and that this temperature is fairly critical. This is controlled by removing from the quench after a certain definite time interval that should be determined for each different set of conditions. The control of this time interval apparently is the critical point.

This problem is being very thoroughly investigated, as we feel that the information to be gained thereby is of fundamental value. We will keep you informed of any significant developments from time to time.

Yours very truly,
H. V. Kinsey,
For C. S. Parsons,
Chief of Division."

HVK:JG.

(Origin of Material and Object of Investigation, cont'd) -

All preliminary work has been completed and the following data can be presented.

To simplify the presentation of these data the three armour plates are designated as follows;

Type of Plate

Plate A:	Failed to meet ballistic specifications.
Plate B:	Plate of recent production that met ballistic specifications.
Plate C:	Plate of previous production that met ballistic specifications.

Chemical Analysis:

Table I is a summary of the results of chemical analysis;

Table I. - Chemical Analysis.
- Per cent -

		Specified	Plate A	Plate B	Plate C
Carbon	-	0.25 - 0.35	0.25	0.29	0.25
Manganese	-	0.40 - 0.70	0.55	0.51	0.54
Silicon	-	0.20 min.	0.32	0.29	0.34
Sulphur	-	0.05 max.	0.013	0.021	0.019
Phosphorus	-	0.04 max.	0.013	0.019	0.014
Nickel	-	0.40 - 1.0	0.70	0.75	0.75
Chromium	-	0.50 - 1.0	0.84	0.79	0.88
Molybdenum	-	0.40 - 0.60	0.52	0.48	0.53
Aluminium®	-		Nil	Trace	Nil
Vanadium®	-		Faint trace	Trace	Faint trace
Titanium®	-		Faint trace	Trace	Trace
Zirconium®	-		Nil	Nil	Nil
Boron®	-		Nil	Nil	Nil

® Spectrographic analysis.

In an effort to establish some definite data on decarburization, samples for chemical analysis were obtained from the skin of each plate, as follows:

Sample No. 1 represented the skin to a depth of 0.015 in., Sample No. 2 represented the metal between 0.015 in. and 0.030 in. below the surface, Sample No. 3 represented the metal between 0.030 in. and 0.045 in. below the surface, and Sample No. 4 represented the metal between 0.045 in. and 0.060 in. below the surface. The average depth below the surface for each sample

(Chemical Analysis, cont'd) -

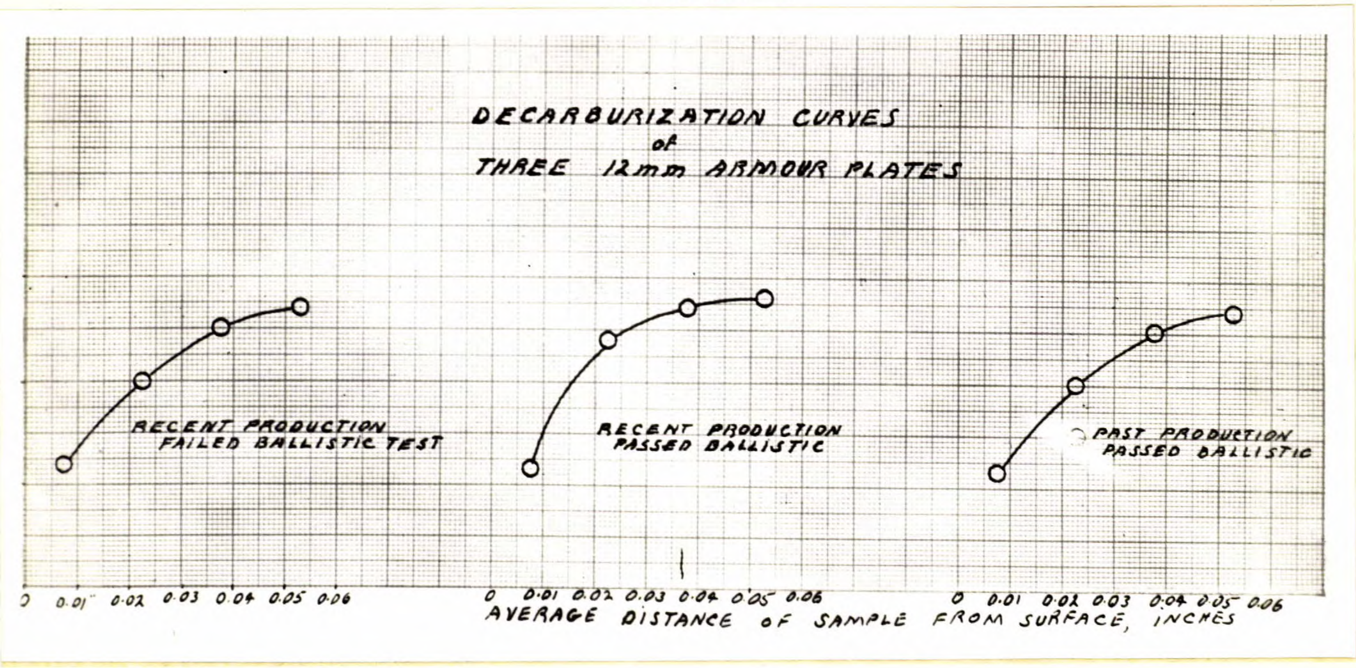
and the carbon analysis of each sample will be found in Table II.

Table II. - Summary of Decarburization Analysis.

Sample No.	Average depth of sample below surface, in inches	Carbon, per cent		
		Plate A	Plate B	Plate C
1	0.0075	0.12	0.115	0.115
2	0.0225	0.20	0.24	0.20
3	0.0375	0.25	0.27	0.25
4	0.0525	0.27	0.28	0.27

These results are plotted below in Figure 19.

Figure 19.



Physical Tests:

Values for the ultimate tensile strength, yield strength, elongation, and reduction in area were obtained both parallel to the direction of rolling (longitudinal) and across the direction of rolling (transverse). These results are given in Table III.

(Continued on next page)

(Physical Tests, cont'd) -

Table III.

	Plate A		Plate B		Plate C	
	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse
Ultimate tensile strength, p.s.i.	175,000	172,000	176,500	174,000	172,500	165,000
Yield strength, p.s.i.	162,500	160,000	165,000	163,000	157,500	152,500
Elongation, per cent	18	16	20	14	20	17
Reduction in area, per cent	57	40	57	43	57	45

Such tensile tests are given "merit values" in the automobile industry by the following formula:

$$\text{Merit Value} = \left(6X \text{ Reduction in area} + \frac{\text{Tensile strength}}{1000}\right).5.$$

It is interesting to determine these "merit values" and to compare the ratio of the transverse merit value to the longitudinal merit value as an indication of the quality of the plate. This is done in Table IV.

Table IV.

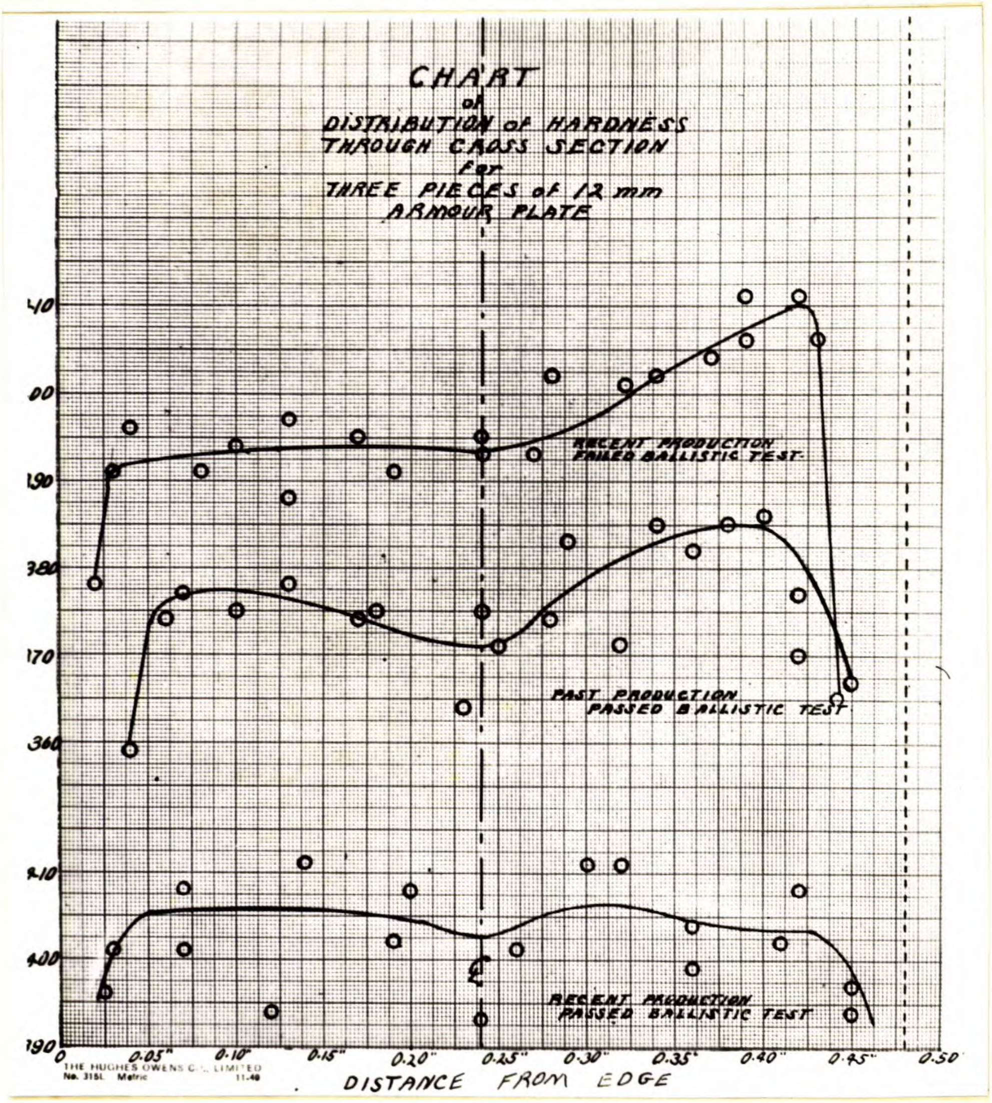
	Plate A		Plate B		Plate C	
	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse
Merit value	103.4	82.4	103.7	90.4	102.9	89
Ratio, M.V. (Trans.)/ M.V. (Long.)	0.796		0.872		0.865	
Ratio, R.A. (Trans.)/ R.A. (Long.)	0.70		0.76		0.79	

A survey of the hardness through the cross-section of these plates was very carefully made. The results of this survey are given in Figure 20.

(Continued on next page)

(Physical Tests, cont'd) -

Figure 20.



The ability of metal to resist cold working can be measured by making impressions with a Brinell ball, at at least three different loads, for example 1,000 kilograms, 2,000 kilograms, and 3,000 kilograms, plotting the diameter of the impressions thus obtained against the load on a logarithmic scale and determining the slope of the resulting straight line. This value is termed the "n" value.

(Continued on next page)

(Physical Tests, cont'd) -

This determination is based on the relationship:

$$L = ad^n$$

Where L = load applied
a = a constant
d = diameter of impression
n = a constant.

During the ball test we pass continuously, as "d" increases, through increasing angles of indentation (and therefore degrees of deformation) and thus obtain from the value of the exponent "n" a measure of the rate of change of the resistance of the metal.

A complete explanation of this relationship can be found, commencing on Page 49, in "The Hardness of Metals and Its Measurement,"[@] by Hugh O'Neill, D.Sc., M. Met., now Director of the research laboratories of the L. M. S. Railway, Derby, England. Under the heading "The Researches of E. Meyer," the author discusses the work done by Mr. Meyer.

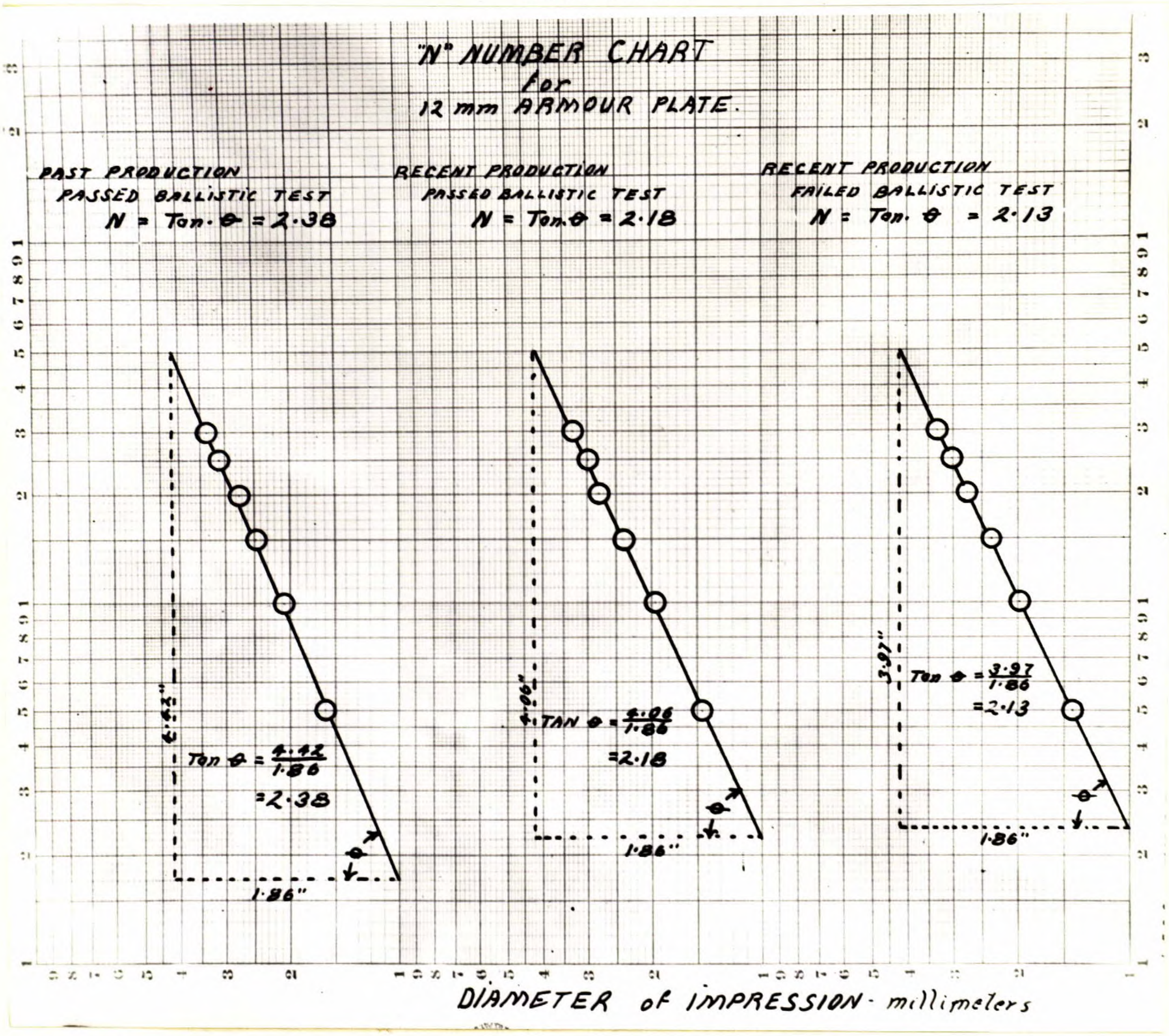
Figure 21 is a chart showing the "n" value determinations for the three pieces of armour being examined.

(Continued on next page)

@ Published by Chapman & Hall Limited, London, 1934.

(Physical Tests, cont'd) -

Figure 21.



Hardenability;

From an examination of the curves in Figure 20, it is evident that all three plates hardened uniformly throughout their cross-section.

McQuaid-Ehn grain sizes were determined by carburizing samples of each plate at 1700° F. for 7 hours and cooling in the furnace. The results of these tests are given in Figures 1, 2, and 3.

(Figures 1, 2, and 3 appear on next page)

Figure 1.

McQuaid-Ehn grain size, at 1700° F., of 12 mm. armour plate, recent production, which failed to pass the ballistic tests.
Photomicrograph at X100, picral etch.
Grain size No. 3.

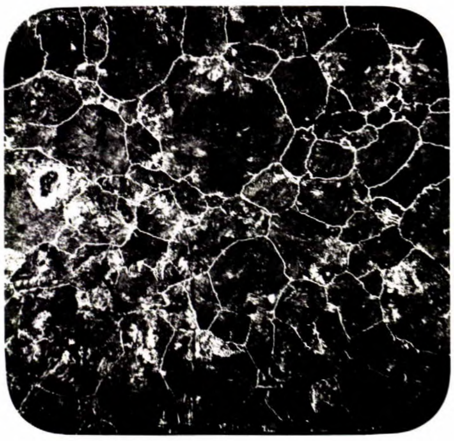
—

Figure 2.

McQuaid-Ehn grain size, at 1700° F., of 12 mm. armour plate, recent production, which passed ballistic tests.
Photomicrograph at X100, picral etch.
Grain size No. 8.

—

Figure 3.



McQuaid-Ehn grain size, at 1700° F., of 12 mm. armour plate, past production, which passed ballistic tests.
Photomicrograph at X100, picral etch.
Grain size No. 3.

—

Microscopic Examination:

Photomicrographs of the structure of the metal as received are given in Figures 4 to 9 inclusive. To establish the type of structure characteristic of transformation at constant temperatures, samples were transformed at 500° F. and 900° F. These structures are shown in Figures 10 to 15.

Figures 16 to 18 show the extent of decarburization.

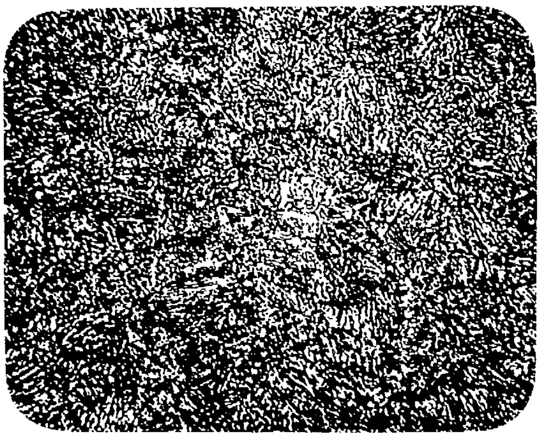
(SEE FIGURES 4 TO 18)
(ON FOLLOWING PAGES)

Figure 4.

Photomicrograph (X1000, picral etch) of 12 mm. armour plate, recent production, which failed to pass ballistic tests.

Note mixed structure of bainite and tempered martensite.

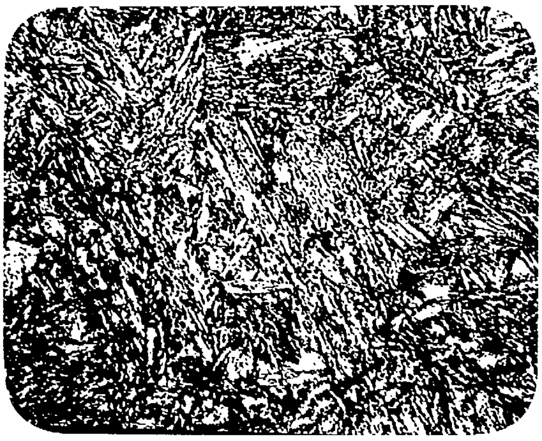
Figure 5.



Photomicrograph (X1000, picral etch) of 12 mm. armour plate, recent production, which passed ballistic tests.

Note uniform structure of tempered martensite.

Figure 6.



Photomicrograph (X1000, picral etch) of 12 mm. armour plate, past production, which passed ballistic tests.

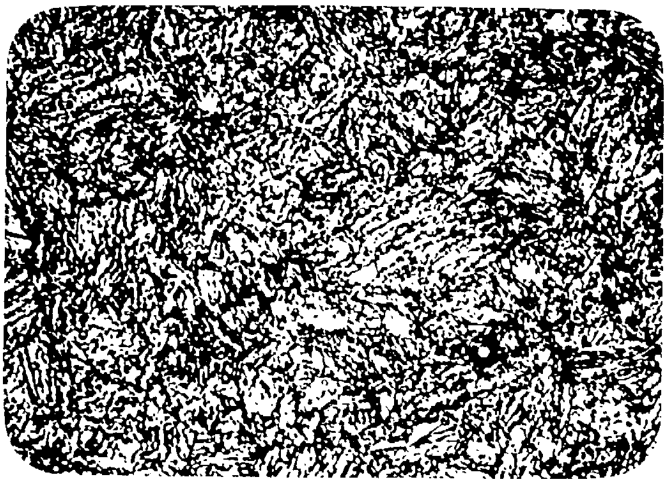
Note mixed structure of bainite and tempered martensite.

Figure 7.

Photomicrograph (X2000, picral etch) of 12 mm. armour plate, recent production, which failed to pass ballistic tests.

Note mixed structure of bainite and tempered martensite.

Figure 8.



Photomicrograph (X2000, picral etch) of 12 mm. armour plate, recent production, which passed ballistic tests.

Note uniform structure of tempered martensite.

Figure 9.

Photomicrograph (X2000, picral etch) of 12 mm. armour plate, past production, which passed ballistic tests.

Note mixed structure of bainite and tempered martensite.

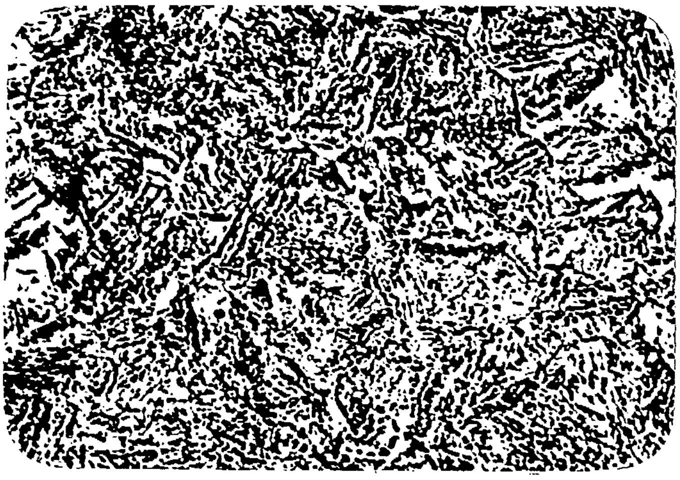
Figure 10.

Photomicrograph (X2000, picral etch) of 12 mm. armour plate, recent production, which failed to pass ballistic tests.

Quenched from 1600° F. into salt bath at 500° F.; held for ½ hour; air-cooled.

Note characteristic bainite.

Figure 11.



Photomicrograph (X2000, picral etch) of 12 mm. armour plate, recent production, which passed ballistic tests.

Quenched from 1600° F. into salt bath at 500° F.; held for ½ hour; air-cooled.

Compare with Figures 10 and 12.

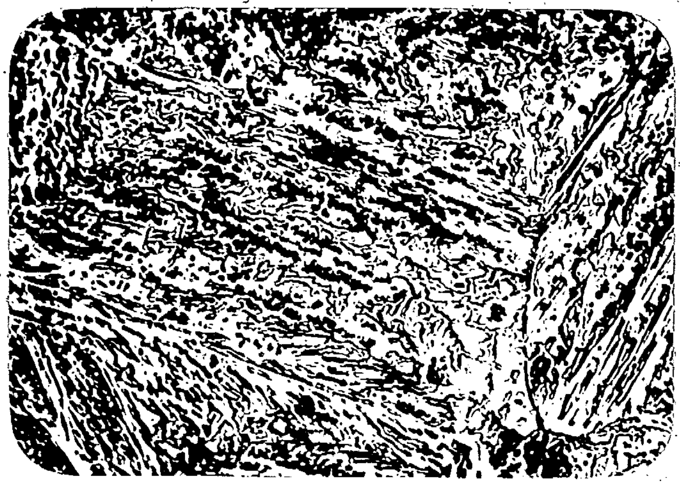
Figure 12.

Photomicrograph (X2000, picral etch) of 12 mm. armour plate, old production, which passed ballistic tests.

Quenched from 1600° F. into salt bath at 500° F.; held for ½ hour; air-cooled.

Note characteristic bainite.

Figure 13.



Photomicrograph (X2000, picral etch) of 12 mm. armour plate, new production, which failed in ballistic tests.

Quenched from 1600° F. into salt bath at 900° F.; held for ½ hour; air-cooled.

Note presence of two types of transformation products.

Figure 14.

Photomicrograph (X2000, picral etch) of 12 mm. armour plate, new production, which passed ballistic tests.

Quenched from 1600° F. into salt bath at 900° F.; held for ½ hour; air cooled.

Note presence of only one type of transformation product.

Figure 15.

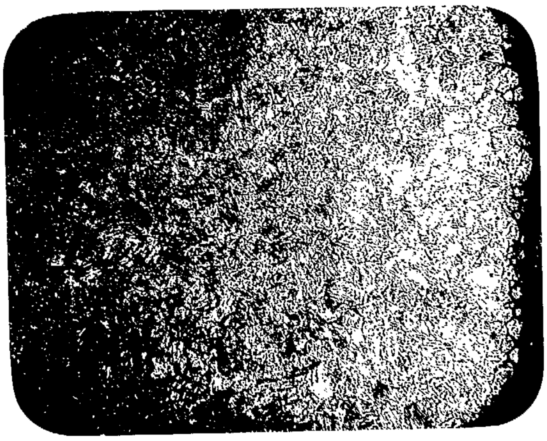
Photomicrograph (X2000, picral etch) of 12 mm. armour plate, old production, which passed ballistic tests.

Quenched from 1600° F. into salt bath at 900° F.; held for ½ hour; air-cooled.

Note presence of two types of transformation products.

(Page____)

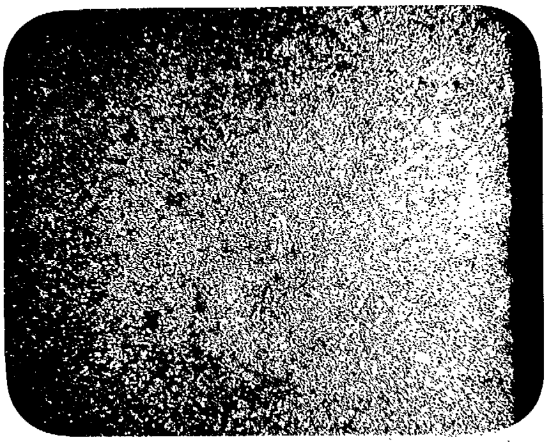
Figure 16.



Photomicrograph (X100, picral etch) of 12 mm. armour plate, new production, which failed to pass ballistic tests.

Note decarburized zone at surface.

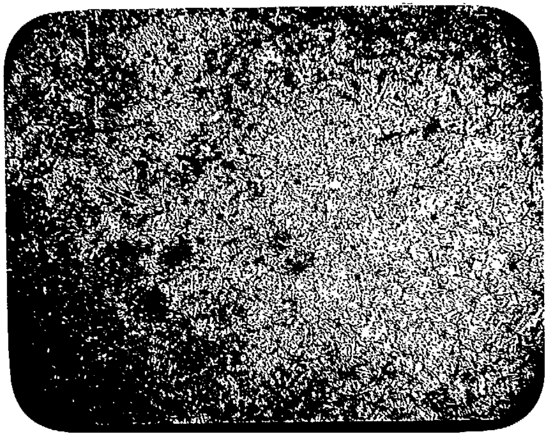
Figure 17.



Photomicrograph (X100, picral etch) of 12 mm. armour plate, recent production, which passed ballistic tests.

Note decarburized zone at surface.

Figure 18.



Photomicrograph (X100, picral etch) of 12 mm. armour plate, old production, which passed ballistic tests.

Note decarburized zone at surface.

Summary of Results:

Table V. - Summary of Results.

	Plate A	Plate B	Plate C
Chemical analysis	Significant differences in Al, Ti and V.		
Decarburization	All the same degree.		
Uniformity of hardness	Equal uniformity in hardness.		
McQuaid-Ehn Grain No.	3	8	3
Merit value ratio, transverse: longitudinal	0.796	0.872	0.865
"n" values	2.13	2.18	2.38
Microstructure	Mixed bainite and martensite	Martensite	Mixed bainite and martensite
Vickers hardness value	390 - 410	400 - 410	370 - 385
Ballistic comparison	Poor	Good	Good

Discussion of Results:

It is interesting to note particularly the presence of aluminium in Steel B and its absence in Steels A and C. This could explain the differences in McQuaid-Ehn grain size. The larger traces of vanadium and titanium in Steel B, combined with the change in deoxidation practice, could explain the apparent shift in the "S" curve which will be discussed later.

It is also interesting to note that Steel B, in spite of its finer grain size, showed no more tendency toward a soft core than did Steels C and A. This would indicate that, for a plate of this thickness, it is possible to obtain a sufficiently high degree of hardenability with a steel of this analysis to produce satisfactory armour.

The degree of decarburization apparently does not vary enough to seriously impair the ballistic properties and may be considered normal.

The ratio of the merit value of the transverse tensile

(Discussion of Results, cont'd) -

strength to the merit value of the longitudinal tensile strength gives promise of a method of predicting the ballistic behaviour of rolled armour plate as do also the "n" values. A high ratio indicates good homogeneity. A high "n" value also indicates greater capacity for work hardening.

Two phenomena determine the resultant structure after quenching and drawing:

(a) Rate of cooling on quenching.
(b) Time - temperature transformation ("S" curve) characteristics.

It is very easy to vary the quenching rate due to the difference in the method of handling the plate from the furnace to the quenching tank. Hardness after quenching may show the variations in this operation and enable closer control to be attempted.

The "S" curve can also change from heat to heat. This can be due to the variations in melting or deoxidation practice which are reflected in the grain size and/or the variations in residual alloying elements (Ni, Cr, Mo, etc.) from the scrap used or titanium, vanadium, boron, etc., from complex deoxidizers such as those now available.

In this respect, it will be noted that Plate B, which shows a grain size of 8, is the only plate containing aluminium and also that it contains traces of vanadium and titanium to a greater degree than do Plates A and C. Note now Figures 13, 14 and 15. These photomicrographs show the structure obtained in the steel from each of the three plates when allowed to transform at 900° F. for ½ hour followed by air cooling. Transformation was completed in Plate B at the end of half an hour while it was not completed in Plates A and C. This would indicate that the "S" curve, in its upper ranges, anyway, had been moved to

(Discussion of Results, cont'd) -

the left in Plate B.

For some other reason the shape of the "S" curve has also been changed in the lower regions. This is indicated from the structures obtained by transforming at 500° F. Note that Figures 10 and 12 show a completely bainitic structure while the structure in Figure 11 indicates that transformation could have taken place either at a higher temperature or at a relatively higher position on the "S" curve. Since all three pieces transformed in the same salt bath at 500° F., the latter case only could be true, and this means that the lower portion of the "S" curve for Steel B must have been depressed.

The "as received" structures can mean only one thing: Plate B has received a much more violent quench than Plates C or A.

By the use of a standard hardenability test, such as the Jominy test, it is possible to detect shifts in the relative position of the "S" curve for steels of the same analysis from heat to heat. Naturally, if identical hardness and microstructure are to be maintained, cognizance of this must be taken and quenching methods adjusted to suit.

If quenching methods are maintained constant and the "S" curve does not change, results similar to A and B should not occur.

CONCLUSIONS:

The following tentative conclusions may be drawn, subject to modification when further data become available. It must be realized that when all metallurgical and ballistical properties are fluctuating, as they normally do, concrete proof of any relationship between ballistic and other properties can

(Conclusions, cont'd) -

only be obtained from a large number of tests.

1. Under existing conditions, such variations as might occur in decarburization or homogeneity of hardness do not apparently exert any appreciable effect on the ballistic properties of the plates examined.

2. From the McQuaid-Ehn grain number and from spectrographic analysis, it would appear that the deoxidation practice is probably not always the same.

3. From the structures existing in the plates as received, it is evident that quenching practice is not always the same.

4. Both "n" value tests and the tensile merit value ratio would appear to be worthy of further investigation in an effort to coordinate ballistic properties with physical properties and microstructure.

5. In steel of this analysis, it is evidently possible to meet present ballistic specifications with a mixed structure.

6. Physical tests would indicate that Plate A is not as homogeneous as Plates B and C. This could explain poor ballistic performance.

7. It is probable that variations in the conditions of the ballistic test are responsible for the apparent discrepancies in these results. It is reported that a variation of 0.005 inch in the thickness of the plate may either pass or fail the plate ballistically. It is also possible that the ballistic requirements of this thickness of plate are unreasonably high.

Recommendations:

1. Routine hardenability tests of a standard nature, such as the Jominy test, could be conducted on every heat to check the structural characteristics of the steel.

2. Routine hardness tests after quenching and before tempering, and also an occasional microscopic examination, would be useful precautions.

3. Such data as relate to deoxidation, melting, rolling and heat treatment practice could be tabulated for each heat of armour steel and correlated, if possible, with hardenability tests and with ballistic and physical properties.

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HVK:GHB.