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REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1588.

Examination of Two Pieces of 7-mm.
Bullet-Proof Plate.

(Copy No. 10.)

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Introduction:

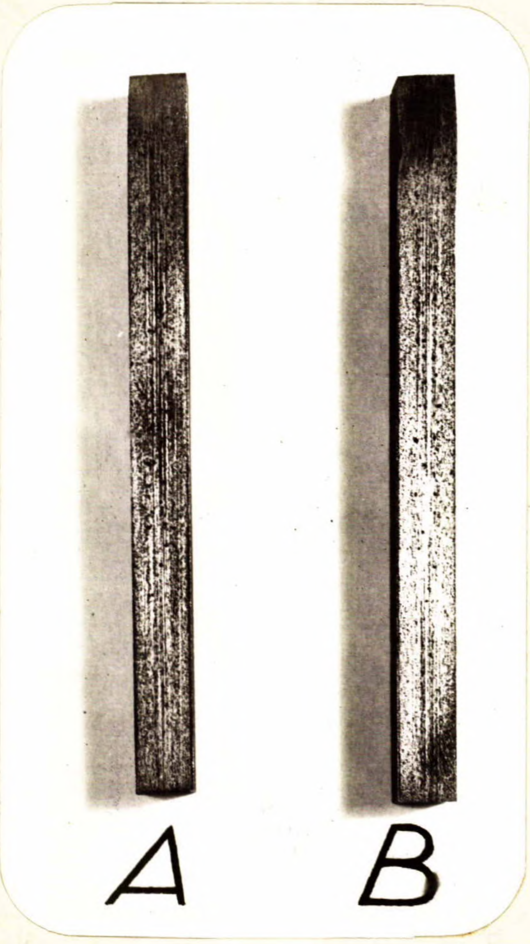
On December 3rd, 1943, two pieces of 7-mm. bullet-proof plate, approximately 2 x 6 inches in size, were received from the Shurly-Dietrich-Atkins Company Limited, Galt, Ontario. In a covering letter, received on the same date, it was reported that the pieces had been sheared from locations about twelve inches apart in a larger plate which had been fired at in the ballistic test. One of the pieces, identified as A, contained the point where a bullet had struck and failed to penetrate; the other piece, identified as B, contained the spot where a bullet had penetrated the plate. The velocity of the bullet striking A was reported as 2,158 feet per second, and that of the one striking B as 2,130 feet per second.

In the letter a metallurgical examination was requested to determine, if possible, the cause for the failure of the plate to withstand the bullet penetration.

Macro-Examination:

On examining the two pieces it was seen that in one piece, A, the bullet had failed to penetrate, while in the other, the bullet has passed completely through the plate. A longitudinal section was cut from each piece and macro-etched for thirty minutes in 50 per cent hydrochloric acid. Figure 1 is a photograph of these two pieces after etching.

Figure 1.



MACRO-ETCHED LONGITUDINAL SECTIONS FROM 7-mm. BULLET-PROOF PLATE.

Hardness:

A number of hardness readings were taken on a longitudinal section from each piece of plate, using the Vickers testing machine with the 50-kilogram load. The readings were analysed mathematically and it was seen that a significant difference existed between the two sets of readings. Table I

(Hardness, cont'd) -

lists the results (the mathematical calculations are shown in the Appendix, Page 11).

TABLE I.

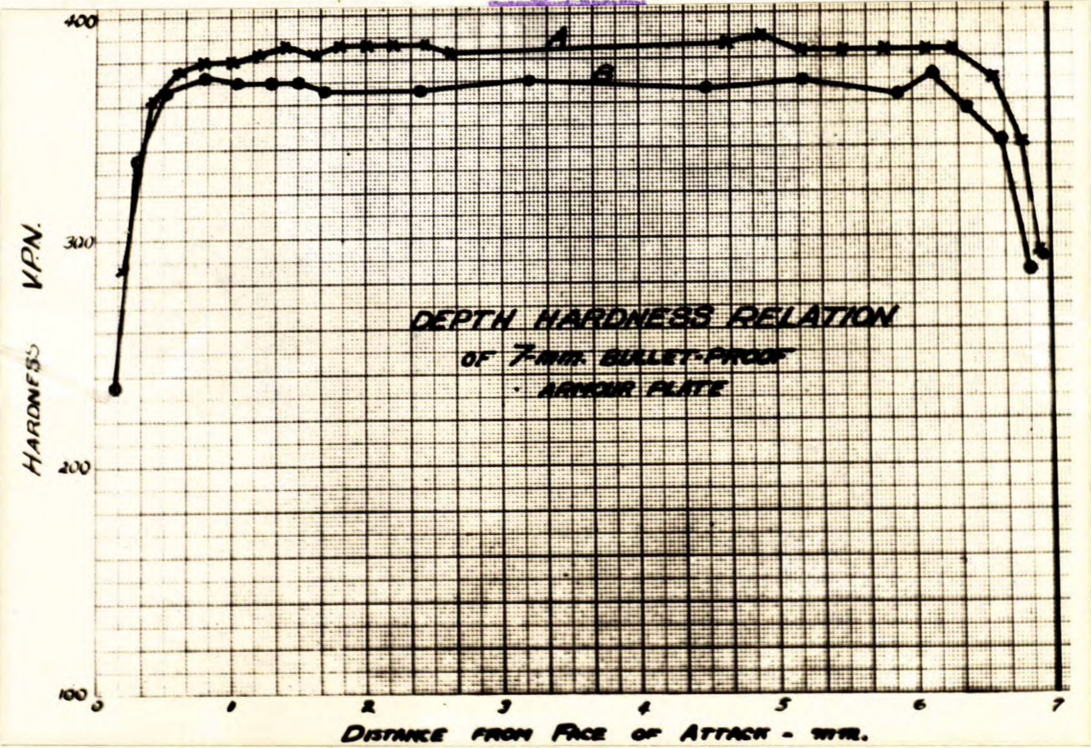
Plate No.	No. of readings	HARDNESS VALUES: Maximum V.P.N.	Maximum Brinell®	Minimum V.P.N.	Minimum Brinell®	Average V.P.N.	Average Brinell®	Standard deviation σ	Range of hardness, V.P.N.
A	21	395	379	385	372	389.8	376	3.44	389.8 ± 10.3
B	20	375	363	362	351	371.4	359	4.06	371.4 ± 12.2

® NOTE. - The Brinell hardness numbers listed were converted from the Vickers hardness numbers by means of the Scott-Gray conversion chart.

Depth-Hardness Survey:

Hardness readings were taken across the face of a longitudinal section, from edge to edge, using the Vickers machine with the 10-kilogram load. The results are shown graphically in Figure 2. The face of attack is the face of the plate which the bullet struck.

Figure 2.



DEPTH-HARDNESS RELATIONSHIP OF 7-mm. BULLET-PROOF PLATE.
Note lowering of hardness at surface, indicating partial surface decarburization.

Physical Properties:

Table II lists the physical properties of the plate material in the longitudinal and transverse directions, as determined by tensile tests on micro-tensile test bars 0.160 inch in diameter.

TABLE II.

Plate No.	Direction of test bar	Ultimate strength, p.s.i.	Elongation in 1 inch, per cent	Reduction of area, per cent
A	Longitudinal	163,750	19	50
A	Transverse	173,120	12	34
A	Transverse	171,900	14	35
B	Longitudinal	175,000	18	48
B	Longitudinal	168,750	18	52
B	Transverse	163,750	11	35
B	Transverse	161,900	14	34

Inclusions:

A microspecimen was cut from each piece of plate at the point where the bullet had struck the plate. Before preparing the specimens for metallographic examination they were heated to 1600° F. and water-quenched so that any non-metallic inclusions would be retained in the steel during polishing.

On examining the unetched polished specimens under the microscope, the inclusions were found to be long stringers. Figure 7, at X250, shows some typical inclusions. The inclusion rating of both pieces of plate was found to be 2.5 by comparison with A.S.T.M. standard inclusion rating charts.

Micro-Examination:

Microspecimens cut from each piece of plate at the points where the bullet had struck the plate were prepared for metallographic examination. They were etched in 4 per cent picral and examined under the microscope. Figures 3 and 4, both at X1500, show the structures of pieces A and B respectively near the points

(Micro-Examination, cont'd) -

of impact of the bullets. Figures 5 and 6, both at X250, show the structures at the surfaces of pieces A and B respectively after a 2 per cent nital etch.

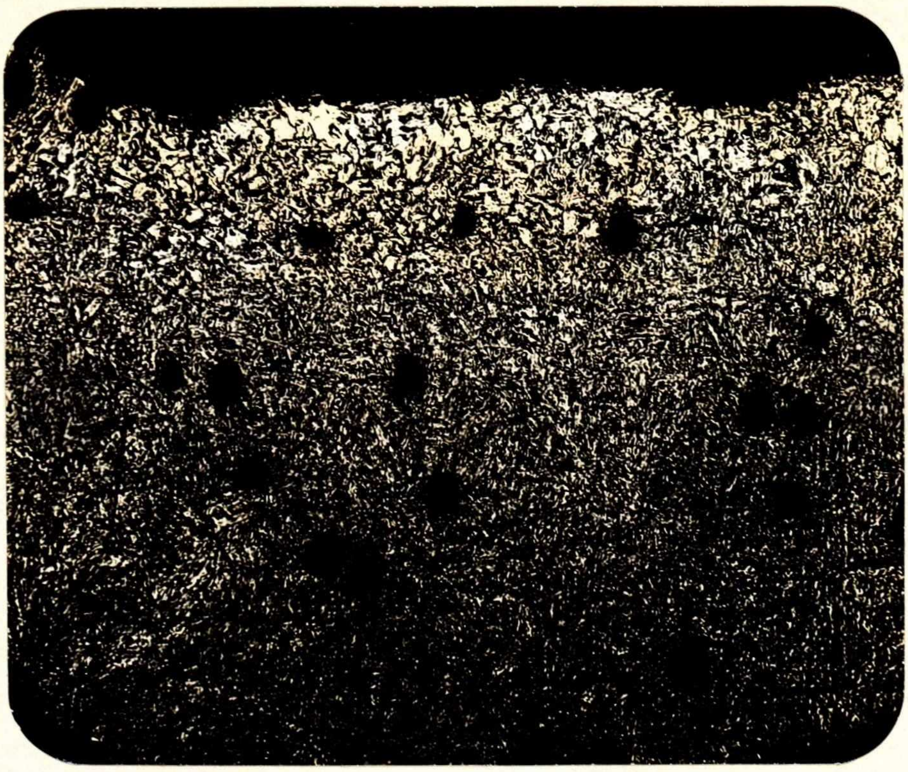
Figure 3.

X1500, picral etch.
STRUCTURE OF PLATE A (LONGITUDINAL).
Tempered martensite.

Figure 4.

X1500, picral etch.
STRUCTURE OF PLATE B (LONGITUDINAL).
Tempered martensite.

Figure 5.



X250, nital etch.

SURFACE OF PLATE A.

Note decarburization at surface.

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X250, nital etch.

SURFACE OF PLATE B.

Note decarburization at surface.

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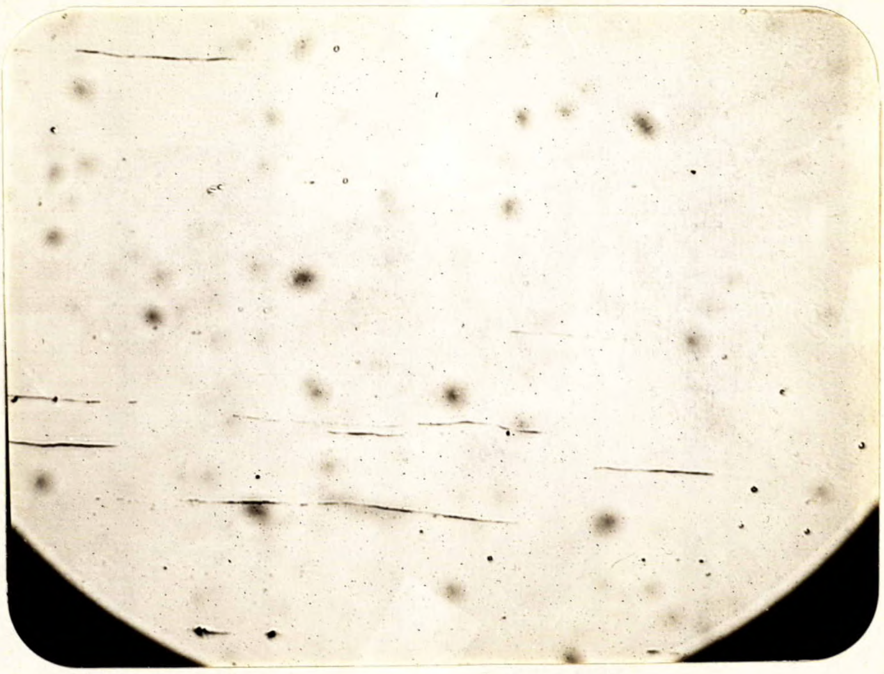
Figure 7.



X250, unetched.

TYPICAL GROUP OF INCLUSIONS.

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Discussion:

The only difference between the two pieces of plate as determined by the laboratory tests lies in the hardness. Plate A has an average hardness of 390 V.P.N. (376 Brinell equivalent) while plate B, which had failed ballistically, has an average hardness of 371 V.P.N. (359 Brinell equivalent). This difference was probably caused by local variations in the cooling rate during quenching. However, this difference alone is not considered to be sufficient to explain the difference in ballistic properties of the two plates.

It was reported that the velocity of the bullet striking plate A was 2,158 feet per second, while that of the one striking B was 2,130 feet per second. Since these velocities can only be determined with an accuracy of ± 35 feet per second, little can be said for the difference between them.

The macro-etching in hydrochloric acid indicates the

(Discussion, cont'd) -

rolling direction of the plate. The laminations revealed (see Figure 1) are normal for rolled plate and do not appear to be excessive.

Both the depth hardness surveys (see Figure 2) and microscopic examination (see Figures 5 and 6) show that the two pieces of plate are partially decarburized at the surface to a depth of about 0.020 inch (0.5 mm.), on both surfaces. One surface of each piece, the face which the bullet struck in each case, shows lower hardness readings than the other surface, indicating that one surface of the large plate from which the pieces were cut was decarburized more than the other surface. This decarburization probably occurred during the heating of the plate at the hardening temperature, and the greater decarburization probably occurred on the surface which was uppermost in the furnace (i.e., not in contact with the hearth).

The physical properties of the plate material in the longitudinal and transverse directions, as determined by tensile tests on micro-tensile test bars, appear to be normal. The per cent elongation and the reduction of area are greater on a test bar taken in the longitudinal direction than on one taken in the transverse direction. This is due to the long stringers of non-metallic inclusions which are longitudinal in direction and hence do not affect the properties of the plate as much in that direction as in the transverse direction. It is surprising that difference in hardness between the two pieces does not show up in the tensile strengths. The two specimens taken in the transverse direction from piece B gave lower ultimate strengths than did the two specimens taken in the longitudinal direction. On the other hand, the two transverse specimens from

(Discussion, cont'd) -

piece A gave higher ultimate strengths than the one longitudinal specimen. It is felt that the result from this one longitudinal specimen may be low. Unfortunately, insufficient material remains to check this. However, it is felt that the hardness readings are sufficiently accurate to be taken as an indication that the tensile strength of piece A is higher than that of B. So it may be said that the ultimate tensile strength, as well as the elongation and reduction of area, is higher in the longitudinal direction than in the transverse direction.

Microscopic examination showed the inclusions to be long grey stringers, probably of manganese sulphide. They were squeezed out into this form by the hot rolling of the plate. This type of inclusion is known to lower the ballistic properties of armour plate. It may be that the bullet striking B, by chance struck a group of inclusions with the result that the plate failed at that point.

The microstructure of the plate material appears to be normal for the heat treatment the plate received. This consisted of a quench from above the critical, either in water-cooled platens or in water (probably the former), followed by a draw at 1000-1100° F. To the casual observer, no difference in microstructure existed between the two pieces, A and B. There is some indication, on comparing Figures 3 and 4, that piece B may tend to have a feathery structure commonly associated with high-temperature transformation products, while piece A has a tempered martensitic structure. However, there is insufficient evidence to say definitely that a difference in structure exists between the two pieces.

Summing up the results of the tests described herein, it is felt that insufficient difference exists between the two

(Discussion, cont'd) -

pieces of plate to explain the difference in ballistic properties metallurgically. Rather, it is felt that the failure occurred due to a difference in the velocities of the two bullets which was not detected.

CONCLUSIONS:

1. The two pieces of plate differ slightly in hardness, A being slightly harder than B which had failed ballistically. It is not felt that this explains the difference in ballistic properties.

2. Both pieces are partially decarburized at the surface to a depth of about 0.020 inch.

3. The physical properties of the plate material appear to be normal. They are greater in the longitudinal direction than in the transverse direction, due to the presence of non-metallic inclusions.

4. The inclusions are in the form of long grey stringers and have a rating, in each piece of plate, of 2.5.

5. The microstructures of both pieces of plate are practically similar.

6. No difference in properties of the two pieces of plate was brought to light by the tests carried out, which would explain the ballistic failure of one of the pieces.

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APPENDIX.

The following method of presenting data may be found in the A.S.T.M. Manual on Presentation of Data (1943):

Piece A	Piece B
$\Sigma A = 8185$	$\Sigma B = 7427$
$\bar{A} = \frac{\Sigma A}{N_a} = \frac{8185}{21} = 389.8$	$\bar{B} = \frac{\Sigma B}{N_b} = \frac{7427}{20} = 371.4$
$\Sigma A^2 = 3190421$	$\Sigma B^2 = 2758337$
$(\bar{A})^2 = 151913$	$(\bar{B})^2 = 137900$
$\sigma_a = \sqrt{\frac{A^2}{N_a} - (\bar{A})^2}$	$\sigma_b = \sqrt{\frac{B^2}{N_b} - (\bar{B})^2}$
$= \sqrt{\frac{319042}{21} - 151913}$	$= \sqrt{\frac{2758337}{20} - 137900}$
$= 3.44$	$= 4.06$

$$\text{Standard error of difference:} \sqrt{\left(\frac{\sigma_a}{\sqrt{N_a}}\right)^2 + \left(\frac{\sigma_b}{\sqrt{N_b}}\right)^2}$$

$$= \sqrt{\left(\frac{3.44}{\sqrt{21}}\right)^2 + \left(\frac{4.06}{\sqrt{20}}\right)^2}$$

$$= 1.32$$

$$\frac{\bar{A} - \bar{B}}{\text{Standard error of difference.}} = \frac{389.8 - 371.4}{1.32} = 13.9$$

Since this is greater than 3, there is a significant difference between the readings on A and B.

Definition of Symbols:

$\Sigma A, \Sigma B$ = Sum of the readings on piece A, B.

$\bar{A}, \bar{B}$ = Average of the readings on A, B.

N_a, N_b = Number of readings taken on A, B.

$\Sigma A^2, \Sigma B^2$ = Sum of the squares of the readings on A, B.

σ_a, σ_b = Standard deviation of the readings on A, B.

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