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# R E P O R T

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 2032.

## Metallurgical Examination of Flame-Hardened Street Car Rails.

(Copy No. 8.)

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## Introduction:

On February 18, 1946, Mr. J. Ross, engineer of the Dominion Oxygen Company Limited, 159 Bay Street, Toronto, Ontario, requested verbally the assistance of these Laboratories, with regard to flame-hardened street car rails. At the same time the following information was supplied:

> The Toronto Transportation Commission had approached the Dominion Oxygen Company with the object of flame-hardening street car rails to prevent wear. Older street cars with conventional wheel braking had given rail service in the order of 20 years. Newer types of street cars, with magnetic rail braking, had reduced rail service to approximately 5 years at stop locations. Since all rails are imported and their replacement costs are high, it was desired to extend the service life of the rails where continual braking is causing rapid wear.

The Dominion Oxygen Company in their experimental work had developed three techniques of flame hardening. Three samples were submitted for examination, representative of these techniques, with the request that they be given a metallurgical

(Introduction, cont'd) -

examination with a view to determining the most suitable to increase service life.

No information was received as to the techniques used to produce the samples.

Object of Investigation:

To examine flame-hardened street car rail samples representative of three different hardening techniques, with a view to selecting the most suitable for the service conditions.

PROCEDURE:

(1) Transverse sections ¼-inch thick were machined from each of the three samples. These sections were polished and etched. Figure 1 shows the sections in this condition.

(2) Chemical analysis samples were machined from each sample. Table I lists the results of the analysis.

TABLE I. - Chemical Analysis.

| | Sample No. 1 | Sample No. 2 | Sample No. 3 |
|---|---|---|---|
| | - Per Cent - | | |
| Carbon | 0.79 | 0.72 | 0.80 |
| Phosphorus | 0.014 | 0.004 | 0.020 |
| Sulphur | 0.031 | 0.022 | 0.031 |
| Manganese | 0.82 | 0.76 | 0.82 |
| Silicon | 0.23 | 0.17 | 0.23 |
| Chromium | Nil. | Nil. | Nil. |
| Nickel | Nil. | Nil. | Nil. |
| Molybdenum | Nil. | Nil. | Nil. |

(3) Small specimens were machined from two areas of each of the three ¼-in.-thick transverse sections. Sketch No. 1 (on Page 9 ) shows the location of the specimens within the sections. All specimens were mounted, polished, etched, and examined under the microscope. The following table lists the photomicrographs shown at the end of this report.

(Continued on next page)

(Procedure, cont'd) -

TABLE II.

| | | |
|---|---|---|
| Figure | 2 | - Normal structure typical of all three samples. |
| " | 3 | - Transition zone structure typical of all three samples. |
| " | 4 | - Structure at centre of hardened zones, typical of all three samples. |
| " | 5 | - Structure close to hardened surface of Sample No. 1. |
| " | 6 | - Structure close to hardened surface of Sample No. 2. |
| " | 7 | - Structure close to hardened surface of Sample No. 3. |
| " | 8 | - Grain size at hardened surface of Sample No. 1. |
| " | 9 | - " " Sample No. 2. |
| " | 10 | - " " Sample No. 3. |

The structures shown in Figures 8 to 10 were produced by means of a new etchant recently reported(1). It was stated that this new etchant (0.5 grams picric acid in 100 c.c. of water, used at 165° F.) gave contrast between martensite and ferrite. It was found that with etching times of the order of 2 minutes the austenitic grain size of the hardened case was revealed. This makes the etchant particularly valuable for revealing grain sizes imparted to hardenable steels by different heat treatments.

(4) After the microscopic examination, the same samples were used for hardness traverses. Figure 1 shows the direction of the traverse relative to the rail cross-section. A Tukon hardness tester with a 500-gram load was used and the resulting Knoop numbers were converted to Rockwell "C" figures, which are more familiar to industrial personnel. Hardness readings were taken at a spacing of 0.02 in. from the hardened surface to unaffected metal. The following table lists the results secured:

(Continued on next page)

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(1) "Effects of Cooling Transformation upon Subsequent Isothermal Reactions" - C. A. Leedholm and W. C. Coons, METAL PROGRESS, Jan. 1946, pp. 104-107.

(Procedure, cont'd) -

TABLE III. - Hardness Readings.

| Distance, inches | SAMPLE NO. 1 | | | | SAMPLE NO. 2 | | | | SAMPLE NO. 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | | B | | A | | B | | A | | B | |
| | Kn. | R 'C' | Kn. | R 'C' | Kn. | R 'C' | Kn. | R 'C' | Kn. | R 'C' | Kn. | R 'C' |
| 0.00 | 518 | 49 | 376 | 37.5 | 508 | 48.5 | 363 | 35 | 490 | 46.75 | 396 | 39 |
| 0.02 | 549 | 52 | 563 | 52.5 | 542 | 51.75 | 482 | 47 | 567 | 52.5 | 511 | 49 |
| 0.04 | 591 | 53.5 | 570 | 52.75 | 567 | 53 | 448 | 44.5 | 567 | 52.5 | 518 | 49.25 |
| 0.06 | 628 | 55.5 | 591 | 54 | 530 | 50 | 490 | 47.25 | 567 | 52.5 | 490 | 47.25 |
| 0.08 | 577 | 53 | 533 | 50.75 | 524 | 49.75 | 465 | 45.5 | 511 | 49 | 508 | 48.5 |
| 0.10 | 533 | 50.75 | 542 | 51 | 554 | 52 | 490 | 47.25 | 598 | 54.5 | 550 | 50 |
| 0.12 | 436 | 42.5 | 551 | 51.5 | 527 | 50 | 452 | 44.75 | 611 | 55 | 504 | 48 |
| 0.14 | 394 | 38 | 514 | 49 | 496 | 48 | 527 | 50.25 | 585 | 54 | 448 | 44.5 |
| 0.16 | 272 | 21.5 | 471 | 46.5 | 368 | 35.5 | 533 | 50.5 | 573 | 53.25 | 502 | 48 |
| 0.18 | 272 | 21.5 | 421 | 41.25 | 357 | 33.5 | 499 | 48 | 514 | 48.5 | 461 | 45 |
| 0.20 | 310 | 27.5 | 327 | 29 | 273 | 22.5 | 347 | 32.5 | 542 | 51.5 | 518 | 49.5 |
| 0.22 | | | 314 | 27.25 | 296 | 24.9 | 376 | 36 | 372 | 36.25 | 405 | 39.75 |
| 0.24 | | | 295 | 25 | 258 | 18.5 | 363 | 35.75 | 355 | 33.5 | 396 | 39 |
| 0.26 | | | 287 | 23 | | | 267 | 20 | 312 | 27.25 | 363 | 35 |
| 0.28 | | | 288 | 23.1 | | | 294 | 24.5 | 296 | 25 | 316 | 28.25 |
| 0.30 | | | | | | | 291 | 24.75 | 285 | 22.5 | 327 | 29.75 |
| 0.32 | | | | | | | | | | | 267 | 20 |
| 0.34 | | | | | | | | | | | 254 | 18.5 |

The data in the above tables are shown in graph form at the end of this report (see Pages 9 and 10), Rockwell 'C' figures rather than the Knoop hardness numbers.

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DISCUSSION:

The etched transverse sections of the rail show a uniform heat penetration and very good uniformity around the changing rail contour. This indicates the use of a contoured flame head. There is obviously a considerable difference in heat input between the three samples, judging by the variation in heat penetration. These differences may be secured by variations in gas pressures and speeds of travel, by use of preheating heads, etc. No evidence was found of any cracking in any of the samples.

The chemical analyses are quite normal with regard to all elements with the exception of carbon. The carbon contents of Samples Nos. 1 and 3 are somewhat higher than usually encountered with rail steels. Unfortunately, chemical specifica-

(Discussion, cont'd) -

tions are not available to check this point more closely.

The microscopic examination reveals no cracking of the hardened case. The structures reveal a normal response of the metal to the thermal cycle of flame hardening. There are, however, considerable differences in the structure of the samples at the hardened surface. The major difference is in the grain size, Sample No. 1 being fine-grained and Sample No. 3 being coarse-grained. Sample No. 2 is intermediate between the two extremes. A minor difference is the wholly martensitic structure of Sample No. 1 and the mixture of martensite and bainite of Sample No. 3. This would indicate that the critical cooling rate for complete hardening had been exceeded in No. 1 but that the cooling rate at the surface of No. 3 was slightly less than the critical rate. In this application and to this extent the structure at the surface of Sample No. 3 is of no great importance since martensite and bainite are of equivalent hardness, but that bainite has been detected indicates an upper limit of heat input. If this is exceeded other structures may be formed which would be much less resistant to wear. Too high a heat input, in an attempt to secure great depth of full hardness, also brings attendant difficulties in securing a sufficiently rapid cooling rate to bring about complete hardening.

The differences in grain size in the samples is of major importance in an application of this type. Coarse-grained, plain carbon steels are low in impact resistance(2) and fatigue strength and also have a lower elastic limit. In this case flaking and surface cracking might result and lead to rapid failure due to propagation of fatigue cracks. The fine-grained steels present the reverse side of this picture and therefore might be expected to give better service life. For this reason, the technique used to produce Sample No. 1 would appear to be

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(2) "The Alloys of Iron and Carbon" - Samuel Epstein, p. 376. (McGraw-Hill Book Co., Inc., 1936.)

(Discussion, cont'd) -

the most desirable in spite of the relatively thin hardened case produced. In flame-hardening operations, the grain size of the hardened surface is an indication of the maximum temperature attained in this area. Since Sample No. 1 is fine-grained, the upper critical temperature has either been only just exceeded or the time above the austenitizing temperature has been very short. On the other hand, the coarse-grained Sample No. 3 has been either well above the upper critical or above the austenitizing temperature for considerable periods. All other conditions being held constant, this effect can be produced by variations in speed of travel alone.

Others(3) investigating rail wear have found high rates of wear at deceleration areas where magnetic braking was in use. Acceleration areas at the same stops showed higher-than-normal wear also, due to the rapid acceleration possible with more modern equipment on which magnetic braking is used. Rapid wear areas may have their rail service life extended by the use of medium manganese or alloy steel rails or, alternatively, by flame hardening of new rails when replacement is made, or "in situ" hardening on partly worn rails. Flame hardening(4) has not been entirely satisfactory in some cases, due to "flaking off" of the hardened surface. Unfortunately, no details are given concerning the flame-hardening technique used, nor as to the structures and hardness patterns produced. However, Australian experience with flame hardening to a depth of 3/16 inch (approximately that of Sample No. 2) indicates that this almost exactly doubles service life for the same total depth of wear (3/16 inch) as compared with unflame-hardened

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(3) "Prolonging the Life of the Tramway Rail" - A.H. Blanch, A.M.I.E., The Journal of the Institution of Engineers, Australia, Vol. 15, No. 11-12, Nov.-Dec. 1943, pp. 239-246.

(4) "Sandburg Sorbitic Steel Rails in Canada" - Iron and Steel of Canada, Nov.-Dec. 1933, pp. 115-119.

(Discussion, cont'd) -

rails at the same area. After the original hardened case had worn off completely, a second flame hardening "in situ" extended the service life to a total of 60 per cent longer than unflame hardened rails.

Where a second treatment is applied the rail should be carefully examined for unsoundness, corrugations, and defective joints. Corrugations should be ground off and all repairs made before the second treatment is carried out.

It will be noted, from the data in Table III and the hardness penetration graphs, that the initial surface readings are lower than those farther from the surface. This is believed to be due to surface decarburization which cannot be detected in martensitic structures. It would also appear that the full potential hardness of the steels in all three samples has not been developed. Each sample is capable of producing hardnesses in the neighbourhood of 67 Rockwell "C". Since the microscopic examination reveals that the surface layers have been fully 'quenched out' and no free carbides were detected, the samples were either tempered or sufficient heat remained in the sample after the passage of the quenching head to allow a self-tempering action. This is highly desirable in that fully hardened material is brittle and would require tempering to eliminate freedom from danger of cracking.

To summarize, it is believed that the techniques used to produce Samples No. 1 or No. 2 would be superior with regard to service life than that used to produce Sample No. 3. The advantages of finer grain size, uniformity of structural constituents, etc., pointed out above, tend to eliminate No. 3 from consideration. It is further believed that a technique intermediate between 2 and 3 would be best of all, provided it gave a finer grain size than that of No. 2 and almost an equivalent depth of maximum hardness.

Conclusions:

1. All techniques used to produce the samples examined gave good uniformity of penetration of heat across the complete cross-section.

2. Chemical analyses show nothing abnormal, except slightly higher carbon contents in Samples Nos. 1 and 3 than is usual for this type of steel.

3. All samples show normal response to the thermal cycle of flame hardening.

4. The high heat input with Sample No. 3 has resulted in the critical cooling rate not being completely achieved. This has resulted in a mixed bainitic and martensitic structure in contrast to the fully martensitic structures of the other two samples.

5. Sample No. 1 has a fine-grained hardened case, while the reverse is true of Sample No. 3. The grain size of the hardened case of Sample No. 2 is intermediate between those of the other two.

6. A desirable depth of maximum hardness of 3/16 inch, together with a fine-grained hardened case, might be produced by a technique intermediate between those used to produce Samples Nos. 1 and 2. Best all-around service might be expected from the technique used to produce Sample No. 1, but the depth of maximum hardness does not exceed approximately 0.140 inch.

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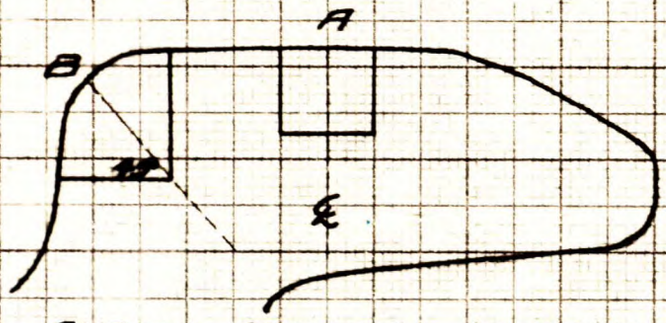
(Sketch No. 1 and three small charts appear on Pages 9 and 10. Figures 1 to 10 follow, on Pages 11 to 16.)

# T.T.C. FLAME HARDENED STREETCAR RAIL.

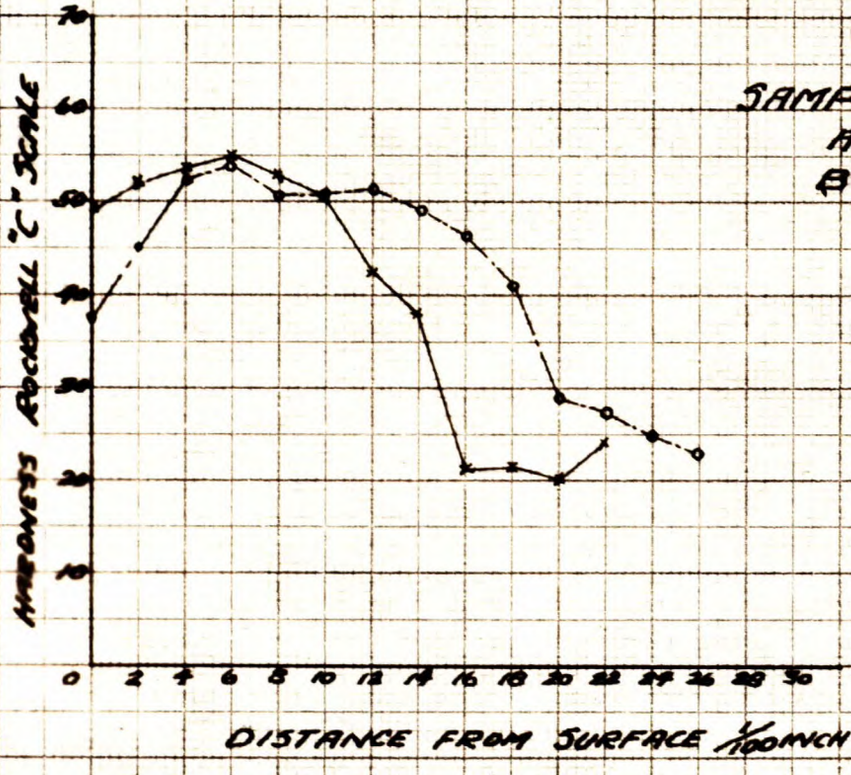
## GRAPHS OF HARDNESS VS. DISTANCE FROM SURFACE.

SKETCH No. 1




SKETCH SHOWING LOCATION OF READINGS

TUKON HARDNESS TESTER
500GM. LOAD 8MM. OBJECTIVE
TRAVERSE SPACING .02 INCH
KNOOP NUMBERS CONVERTED TO ROCKWELL "C" SCALE.




SAMPLE No. 1

A ——×——×——

B ——◇——◇——

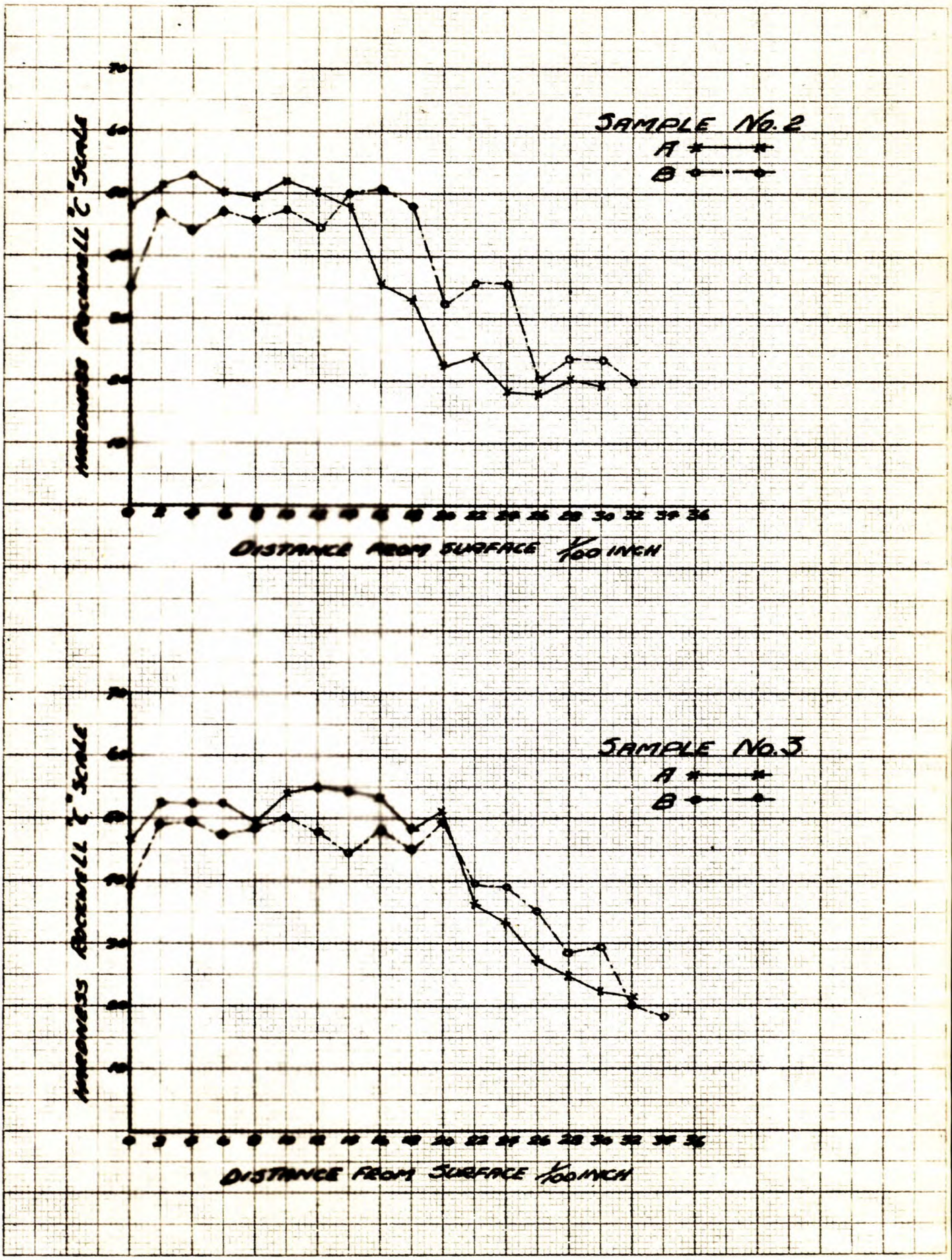


Figure 1.


TRANSVERSE SECTIONS OF EACH SAMPLE, ETCHED IN HCl.

Note variation in depth of penetration. All samples show uniformity of hardening over entire cross-section.

Figure 2.

X500, etched in
4 per cent picral.

STRUCTURE OF FINE AND COARSE PEARLITE TYPICAL OF NORMAL METAL OF ALL SAMPLES.

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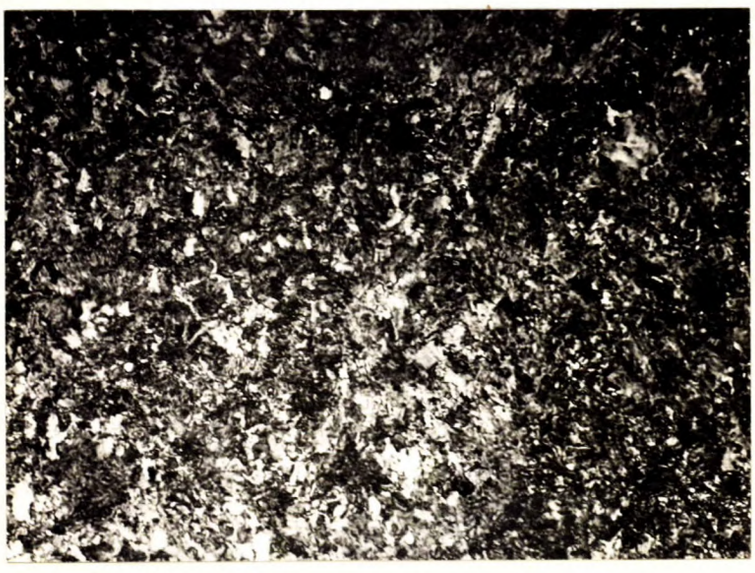
Figure 3.



X500, etched in
4 per cent picral.

TRANSITION ZONE STRUCTURE TYPICAL OF ALL SAMPLES.

Very fine pearlite.

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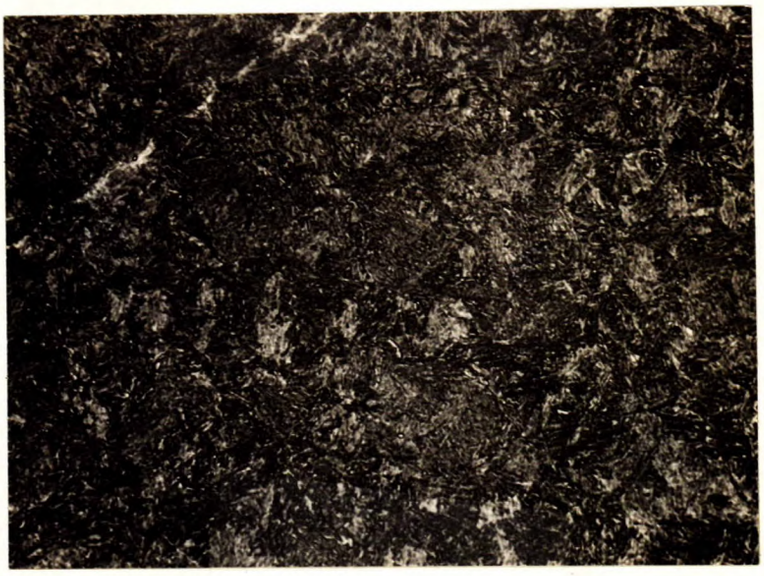
Figure 4.



X500, etched in
4 per cent picral.

TYPICAL MARTENSITIC STRUCTURE AT CENTRE
OF ALL HARDENED ZONES.

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Figure 5.

X500, etched in
4 per cent picral.

MARTENSITIC STRUCTURE AT HARDENED SURFACE
OF SAMPLE NO. 1.

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Figure 6.

X500, etched in
4 per cent picral.

MARTENSITIC STRUCTURE AT HARDENED SURFACE
OF SAMPLE NO. 2.

—

Figure 7.

X500, etched in
4 per cent picral.

BAINITE AND MARTENSITE IN STRUCTURE AT
HARDENED SURFACE OF SAMPLE NO. 3.

Compare with Figure 5.

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Figure 8.

X100, etched in 0.5 per cent picric acid in water at 165° F.

GRAIN SIZE (6-5) AT HARDENED SURFACE OF SAMPLE NO. 1.

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Figure 9.

X100, etched in 0.5 per cent picric acid in water at 165° F.

GRAIN SIZE (2-4) AT HARDENED SURFACE OF SAMPLE NO. 2.

—

Figure 10.

X100, etched in 0.5 per cent picric acid in water at 165° F.

GRAIN SIZE (AVERAGE 1) AT HARDENED SURFACE OF SAMPLE NO. 3.

Compare with Figures 8 and 9.

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