DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 156

METALLOGRAPHIC FEATURES REVEALED BY THE DEEP ETCHING OF STEEL

BY

H. S. RAWDON, Physicist
SAMUEL EPSTEIN, Laboratory Assistant
Bureau of Standards

ISSUED MARCH 19, 1920

PRICE, 10 CENTS
Sold only by the Superintendent of Documents, Government Printing Office
Washington, D. C.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1920

METALLOGRAPHIC FEATURES REVEALED BY THE DEEP ETHCING OF STEEL

By Henry S. Rawdon and Samuel Epstein

CONTENTS

I. INTRODUCTION

The term "deep etching," as used here, refers to the use of acids of relatively high concentration for the roughening of the surface of metallographic specimens. Samples etched in this manner are intended primarily for a study of the macroscopic structure rather than for microscopic examination. In general, a very mild etching reagent is required for the latter purpose. The deep etching of steel is one of the earliest metallographic methods used for the study of iron and steel, particularly for a quick shop test. The method has, however, been given prominence recently by its application to the study of rails containing the defects known as transverse fissures and of steel forgings containing similar defects.[1]

Various views have been put forth as to the nature of the features revealed by this method of etching. The interpretations of the features revealed in transverse fissured rails by this method of etching may be cited as typical of the difference of opinion existing. That a variation in solubility of the steel in different directions is responsible for the transverse "cracks" revealed by the etching is one extreme view held. The other extreme is that

[1] F. M. Waring and K. E. Hofammann, The Deep Etching of Rails and Forgings, A. S. T. M. Proceedings, 19, 1919; also discussion on the same. H. M. Wickhorst, Transverse Fissure Rails on Atchison, Topeka & Santa Fe R. R., heat 41177, report No. 80 to rail committee, Am. Ry. Eng. Assn., April, 1919. P. H. Dudley, Report on Transverse Fissures, report No. 77 to rail committee, Am. Ry. Eng. Assn., January, 1919. H. Baucke, Action of Electrolytes upon Metals under Stress, Int. Zeit. für Metallographie, 4, p. 129; also Proc. Int. Assn. Test. Materials. VIth Congress, 1912.

cracks exist throughout the interior previously to the etching and that the etching merely renders them visible. According to still another view, the existence of internal stresses of a rather high magnitude may be responsible for the results produced. In order to show clearly the various conditions which this method of etching will reveal, together with the description of suitable methods for distinguishing between the different features, the series of examinations described below was undertaken.

II. METHOD

Various acids have been used for the deep etching of steels. The different mixtures vary considerably from alcoholic hydrochloric acid (1 volume alcohol to 1 volume hydrochloric acid, specific gravity 1.19) used by Baucke [2] to a rather complex mixture of hydrochloric and sulphuric acids (9 volumes hydrochloric acid, 3 volumes sulphuric acid, 1 volume water) used by Waring and Hofammann.[3] In the work described below hydrochloric acid (specific gravity, 1.19) was used; this was heated nearly to 100° C before the specimens which had been previously ground smooth were immersed. This is the usual practice with all solutions other than the alcoholic ones. Heating, however, should not be regarded as a necessity—it merely hastens the action. Several other acids were tried to show their action upon materials known to be defective; these included nitric acid (1 volume of acid to 1 of water) and sulphuric acid similarly diluted. Both of these reagents revealed the defects, although the action was not so rapid as in the case of hydrochloric acid. The conclusion appears to be warranted that, provided the acid is concentrated enough to give a vigorous reaction, the choice of the acid to be used is a matter of minor importance.

III. FEATURES REVEALED BY DEEP ETCHING

The different features which may be revealed by the deep etching of steel may be considered under the following headings: Chemical inhomogeneity, mechanical nonuniformity, and the presence of physical discontinuities within the steel.

1. CHEMICAL INHOMOGENEITY

The use of acid etching for the purpose of revealing variations in the distribution of the various chemical constituents which may occur in steel is so well known as to require only a brief

[2] Loc. cit. [3] Loc. cit.

discussion. The variations in the chemical composition are usually the direct result of the segregation accompanying solidification, although occasionally other factors may be responsible; for example, lack of complete solution and diffusion of the special additions in alloy steels, composition changes which may occur in such processes as welding, carburization, etc.

Figure 1 illustrates the case of chemical inhomogeneity due to segregation. The bar evidently has been rolled from an ingot having a decidedly segregated center; the difference in composition between center and outer portions has persisted throughout the process of rolling. The steel has the composition shown in Table 1.

Fig. 1.—*Chemical inhomogeneity of rolled steel revealed by deep etching*

The highly segregated center of the ingot has persisted throughout the rolling of the material to the one-half-inch square shown. ×1

The greater solubility of the abundant sulphide streaks in the central portion as compared to the purer metal is responsible for the roughened appearance of the center. Each dark spot (Fig. 1) represents a pit which was previously occupied by sulphide or some other inclusion. These pits are later deepened and enlarged by the action of the acid after the inclosed impurity has been removed.

TABLE 1.—Composition of Segregated Steels

Specimen	Carbon	Manganese	Phosphorus	Sulphur	Silicon
Segregated bar (Fig. 1):	Per cent	Per cent	Per cent	Per cent	Per cent
Outside layer	0.08	0.45	0.076	0.029	0.002
Segregated center	.09	.45	.138	.064	.002
Steel casting (Fig. 2)	.31	.75	.039	.053	.263

Fig. 2 illustrates a condition which has resulted from what may be termed "secondary segregation." The photograph shows a section of a large steel casting which, although it met the prescribed specifications as to mechanical properties and heat treatment, fractured as a result of the handling received during transportation. The composition is given in Table 1. The macroscopic examination of the material after deep etching, together with the subsequent study of the microstructure, showed that although a sufficient grain refinement had been brought about by the annealing which the material had received (72 hours at 900° C (1650° F), cooled in furnace) the material still

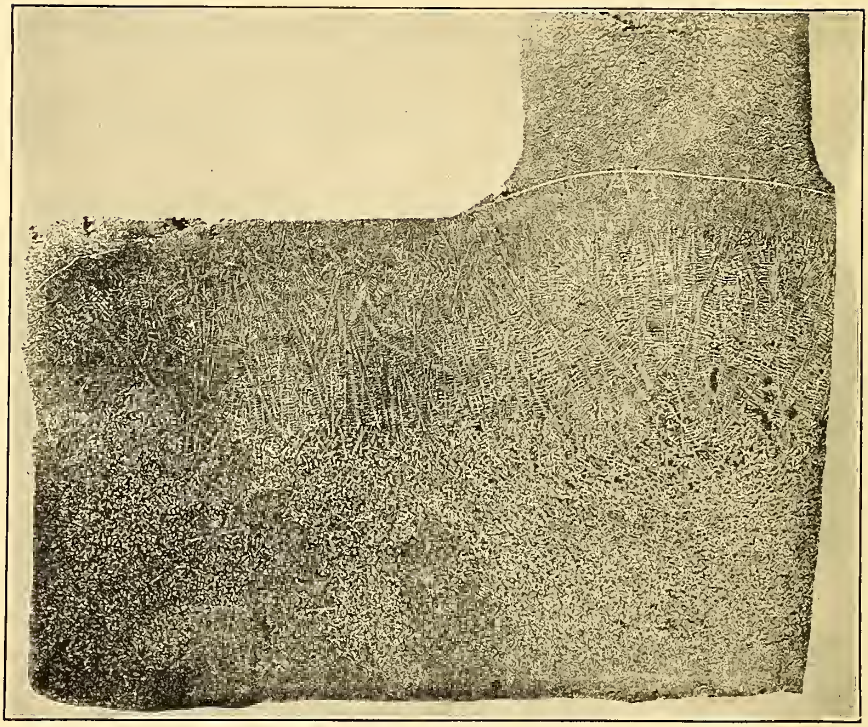


FIG. 2.—*Chemical inhomogeneity of cast steel revealed by deep etching*

The specimen was photographed after being moistened with glycerin. Although the steel casting was annealed for 72 hours at 900° C, the original dendritic pattern persists. The distribution of the impurities, originally located in the angles between the dendrites, has not been changed by the treatment. ×½

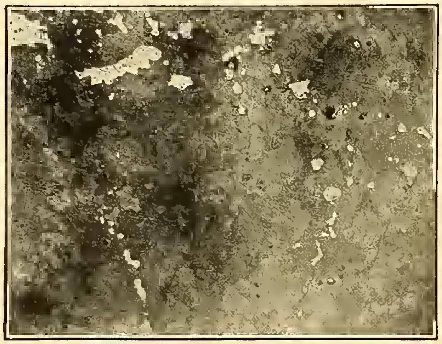


FIG. 3.—*Porous condition of cast steel*

Same material as Fig. 2, heat tinted. The white spots which are due to the exudation of alcohol and water used for washing from within the metal have prevented the uniform coloring of the surface. Each spot marks a spongy area. ×25 possessed essentially the same dendritic structure that resulted upon casting. This was due to secondary segregation or the occurrence of numerous inclusions between the treelike crystals. Such impurities are not materially changed by heat treatment either in location or chemical composition and hence the original appearance, and many of the accompanying mechanical properties, are maintained in spite of the annealing. The microscopic examination showed also that in addition to the inclosures trapped between the fingers of the dendrites, the metal was also porous and spongy at such points. This is shown in Fig. 3. The specimen was polished and cleaned as for microscopic examination but was heat tinted to reveal the structure instead of being etched. The water and alcohol used for washing and drying the surface were absorbed at each porous spot and oozed out upon heating, thus preventing a uniform oxide tint from forming at such spots. The action of the deep etching upon the material shown in Fig. 2 has consisted essentially, then, in the relatively more rapid dissolving of the impurities and in the enlarging of the pores of the spongy areas. In addition to these features, Fig. 2 also illustrates what may be found in welded materials etched in this manner. The projection or boss in the upper portion of the figure was added after the main casting had been made. The white (deeply etched) line marks the junction surface between the two.

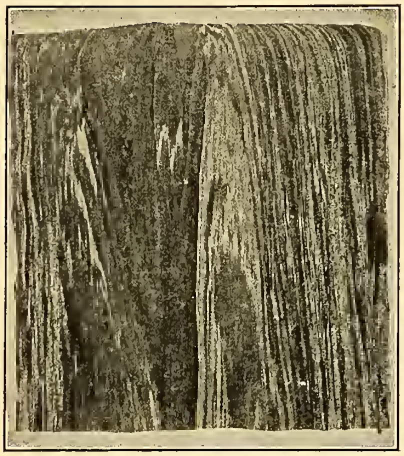
A special application of the use of deep etching in the inspection of wrought iron is illustrated by Figs. 4 and 5. Wrought iron, when ground smooth or filed and then etched with concentrated acid,[4] shows the presence of steel streaks by the white glistening appearance of such streaks; the body of the wrought iron remains dark. Fig. 4, *a*, shows the appearance of a large commercial wrought-iron shackle which was examined to determine its purity. The white streaks are of steel and have the structure shown by Fig. 4, *b*.

Fig. 5 shows the results of a similar examination of a bar of high-grade Swedish iron. The light streaks are of steel of a composition approaching that of eutectoid steel.

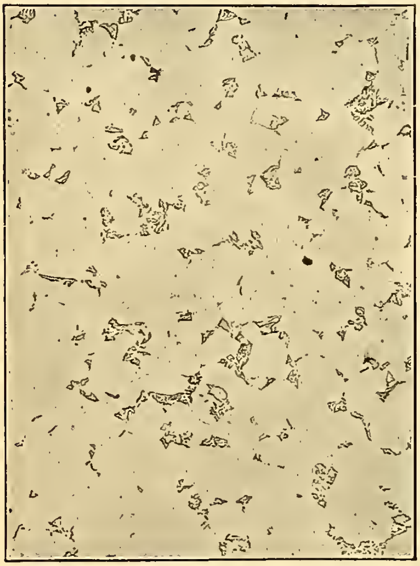
2. MECHANICAL NONUNIFORMITY

It is quite often the case that metals, even when subjected to no service load or stress, are far from being in a state of mechanical uniformity. Internal initial stresses of considerable magnitude

[4] Steel in Wrought Iron Pipe, Iron Age, 97; p. 1132; 1916.

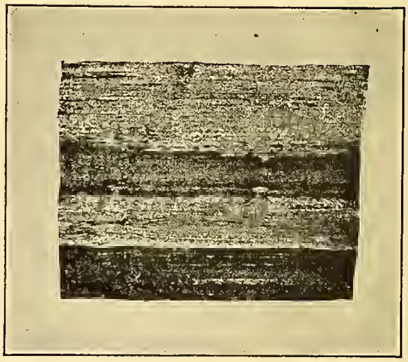


(a) Polished specimen of commercial wrought iron, deeply etched in concentrated hydrochloric acid. ×1

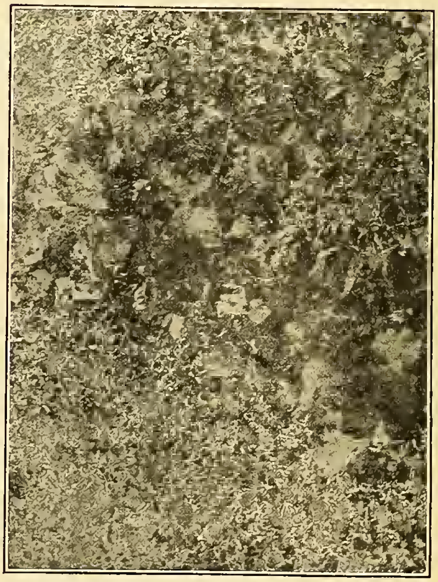


(b) Microstructure of one of the white bands of (a) above. The material of the bands has the structure of low-carbon steel. Etching, 2 per cent alcoholic nitric acid. ×100

FIG. 4.—*Chemical inhomogeneity of commercial wrought iron revealed by deep etching*



(a) Polished specimen of Swedish wrought iron deeply etched in concentrated hydrochloric acid. ×1



(b) Microstructure of one of the white bands of (a). The material here has the structure of a steel of nearly eutectoid composition. Etching, 2 per cent alcoholic nitric acid. ×100

FIG. 5.—*Chemical inhomogeneity of high-grade Swedish wrought iron revealed by deep etching*

often exist, particularly if the material has been cold worked Very sudden or unequal cooling of different parts of the same piece may give rise to a similar condition. Considerable work has been done on this subject as related to brass and bronzes, and materials of this kind highly internally stressed may be made to crack spontaneously by the use of proper etching reagents.[5] As yet, but little attention[6] has been paid to the behavior of steels in this respect.

As suitable material for demonstrating the effect of deep etching by concentrated acid upon steels initially stressed internally, commercial balls for ball bearings of different sizes and grades were used. The chemical composition of the specimens used is given in Table 2.

TABLE 2.—Chemical Composition of Balls Used

Diameter of ball	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1 inch	1.05	0.32	0.013	0.030	0.15	1.28
½ inch	.94	.38	.018	.022	.18	(*a*)
⅜ inch	1.25	.25	.011	.016	.21	.007

[a] Not detected.

As shown in the above table, balls of three different sizes and compositions were used. The appearance of the balls after etching gave rather definite indications as to the method of manufacture. Some of the smallest balls had been turned out by lathe tools, as was clearly shown by the ends of the fibers on the opposite faces of the balls after etching. All of the others showed the two poles and work lines which are evidence of forging and pressing. The 1-inch balls most probably were forged individually; the others by the string method.

Previous to etching, the balls were examined for the presence of cracks or other surface defects by the magnetic method to be described later. None of the specimens was found to be defective. The behavior of the balls when etched with hot concentrated hydrochloric acid was determined for the material in the commercial state; that is, as received and also after different heat treatments. Some of the specimens were also sectioned in half, some perpendicular, and others parallel to the direction of the fibers. The results of the deep etching tests are summa-

[5] B. S. Tech. Papers, Nos. 82, 83, and 84. The technical literature of the subject is summarized in No. 82.

[6] Baucke, loc. cit.

TABLE 3.—Action of Deep Etching Upon Balls for Ball Bearings

A. COMMERCIAL BALLS

Diameter	Weight (grams)		Results
	Before etching	After etching	
1 inch	66.95	13.43	Did not split.
	66.93	24.75	Do.
	66.95	29.86	Do.
½ inch	11.85	9.50	Split through poles.
	11.86	2.84	Did not split.
	11.86	7.15	Split through poles.
	11.86	9.17	Do.
	11.85	6.55	Did not split.
	11.86	9.34	Split through poles.
	11.87	2.97	Did not split.
⅜ inch	3.51	2.51	Split through poles.
	3.51	1.78	Do.
	3.51	2.02	Do.
	3.47	.92	Did not split.
	3.48	1.32	Do.
	3.46	1.75	Do.
	3.49	1.83	Do.
	3.51	1.23	Do.

B. HEAT-TREATED BALLS (HEATED TO 900° C, COOLED IN AIR; HEATED TO 850° C QUENCHED IN COLD WATER (20° C))

1 inch	65.86	43.68	Did not split.
½ inch	11.73	7.65	Split through poles.
	11.45	11.35	Do.
	11.74	2.70	Did not split.
⅜ inch	3.39	1.70	Do.
	3.45	3.43	Split through poles.

C. HEAT TREATED (HEATED TO 900° C, COOLED IN AIR; HEATED TO 850° C, QUENCHED IN OIL)

1 inch	65.75	49.5	Did not split.
½ inch	11.74	4.45	Do.
	11.73	7.73	Do.
	11.73	3.3	Do.
⅜ inch	3.45	1.5	Do.
	3.42	3.25	Do.
	3.43	1.6	Do.

D. COMMERCIAL BALLS SECTIONED IN HALF

1 inch	32.85	17.50	Did not split.
	47.72	35.50	Do.
½ inch	7.45	3.85	Do.
	5.42	4.85	Split through pole.
⅜ inch	1.75	.93	Did not split.
	2.33	1.35	Do.
	1.95	.95	Do.
	1.93	.80	Do.

rized in Table 3. Since it was necessary to remove the specimens from the acid at stated intervals for examination, the loss of weight rather than the length of the etching period has been given as being more indicative than the time of etching of the amount of etching necessary to demonstrate which balls are defective.

It will be noticed from the above table that none of the large (1-inch diameter) balls showed any tendency to split upon deep etching, as did over 50 per cent of the medium-sized (one-half-inch diameter) balls and about 30 per cent of the small (three-eighths inch diameter) ones. The small ones which split were limited entirely to those which, as shown by the appearance of the etched surface, had been forged (or pressed) rather than turned out.

Fig. 6, *a*, *b*, and *c*, shows the appearance of some of the balls after etching. The specimens were removed from the acid as soon as the cracks appeared, hence before the openings had been widened appreciably by the acid. In all cases the cracks are very definite ones, resembling knife cuts extending through the poles and often reaching in as far as the center of the ball. They follow somewhat the direction of the fibers of the material. Without doubt the splitting of the balls under the corrosive action of the concentrated acid is to be attributed to the presence of initial stresses of relatively high magnitude in the material. It was not possible, on account of the nature of the material, however, to attempt any measurement of the approximate value or distribution of such stresses. The sudden appearance of the cracks, the immediate widening of the fissure with an appreciable accompanying increase in the diameter of the ball, the occurrence of such cracks only in the forged or pressed material and in the smaller balls which had been hardened entirely throughout, the failure of all the materials to split when hardened less severely than the commercial material, and the definite orientation of the cracks with respect to the poles of the balls all are lines of evidence indicating the presence of internal stresses as the cause of the behavior of the balls upon deep etching. Baucke [7] in his discussion of experiments along this line states that it is necessary to section the balls before etching, and that whole balls etched intact will not split. In order to demonstrate whether the tendency of sectioned balls to split upon etching is greater than that of whole balls, a series of specimens were sectioned. The results

[7] Loc. cit.

(*a*) Fragments of three balls, respectively 1, one-half, and three-eighths inch in diameter, after prolonged etching in concentrated hydrochloric acid. These balls did not split. ×2

(*b*) Appearance of balls, one-half and three-eighths inch in diameter, which split when deeply etching, as a consequence of the initial stresses in the material. All of these balls were made by forging or pressing, as indicated by the definite poles. The cracks originate at the poles. ×2

(*c*) Appearance of balls, three-eighths inch in diameter, after etching. The two balls at the right were turned out, the other two were forged or pressed. None of the balls which were turned out could be cracked by deep etching. ×2

FIG. 6.—*Presence of initial stresses in hardened steel revealed by deep etching*

obtained upon etching are tabulated under D, Table 3. In general, the tendency to split upon etching appears to be less for the sectioned balls than for the whole ones. It is very probable that the stresses within the material are materially relieved by cutting the ball in two, and hence they would be expected to show less tendency to split in the acid.

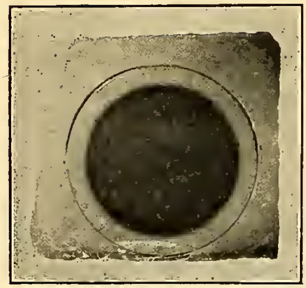
The method used for sectioning the hardened balls is of interest. A cylindrical hole very slightly smaller across than the diameter of the ball was drilled into a block of soft steel to a depth slightly greater than the radius. The ball was pressed into the hole by squeezing in a vise and the portion projecting beyond the face of the steel block was ground off on a wet grinding wheel. No evidence of tempering of the hardened balls during grinding could be observed in the polished specimen.

Fig. 7, *a*, *b*, *c*, and *d*, shows the structure of the large (1-inch diameter) balls. The outer metal has been rendered martensitic to the depth shown in Fig. 7, *a*. The central portion is largely troostitic. In Fig. 8 the structure typical of the small and the medium sized balls is shown.

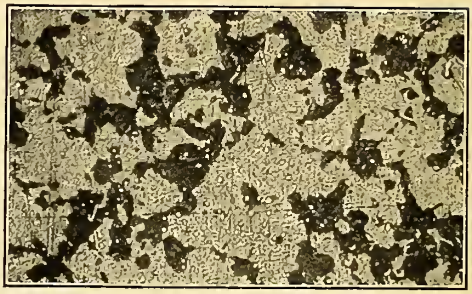
These specimens were martensitic throughout. This difference in microstructure is in accordance with the results of the etching tests—only the severely hardened specimens showed any tendency to split upon deep etching. It will be noted in Table 2 that the balls of one-half inch diameter are of a steel containing no alloying element and of a carbon content considerably lower than that of either of the other two. In order to render this steel relatively as hard as the other two types, a much more severe treatment must be resorted to, and this fact probably accounts largely for the greater tendency of this series to split than the other two. That the mechanical work which the material received (i. e., the magnitude of the internal stresses) also contributes to the tendency to split is evident in view of the fact that balls of similar size and hardness (i. e., as indicated by the structure) turned out in the lathe rather than forged or pressed showed no tendency to split upon etching.

3. PHYSICAL DISCONTINUITIES.

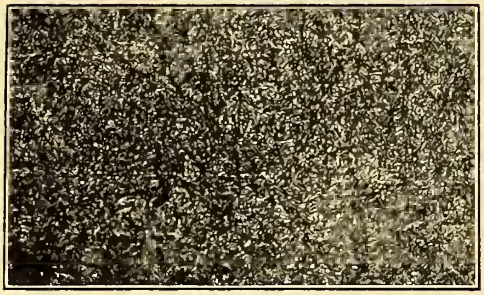
A third condition which may be revealed by deep etching is the presence of discontinuities within the steel. These may be in the form of pores or tiny cavities whereby the metal is rendered spongy, as previously described, or as separations or fissures, the two faces of which are often in such intimate contact that the



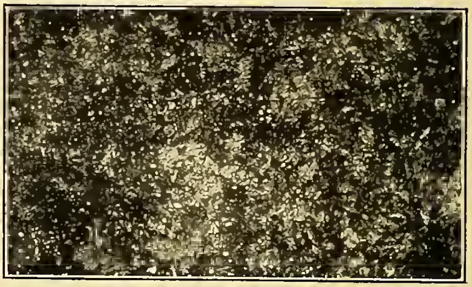
(*a*) Hardened ball, 1 inch in diameter, cut through the center and polished. ×1



(*c*) Microstructure of the intermediate thin zone between the outer light-colored layer and the dark-colored central sphere of (*a*). This transition zone consists of martensite and troostite with some specks of carbide. ×500

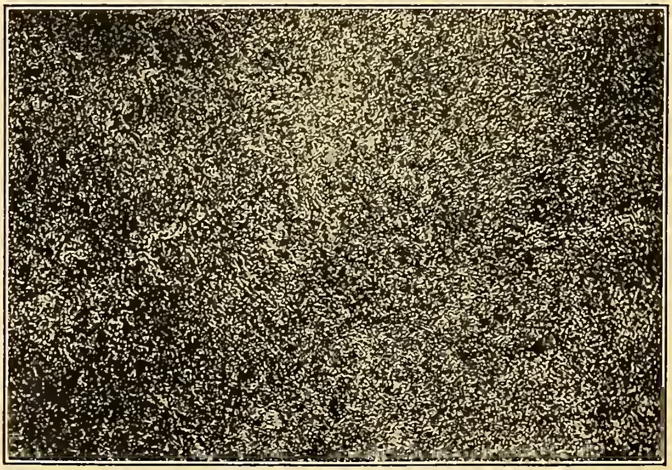


(*b*) Microstructure of the outer spherical layer (light-colored) of (*a*). This layer is martensitic throughout with tiny globules of cementite. ×500



(*d*) Microstructure of the central sphere of (*a*). The metal is largely troostite with specks of carbide. None of the balls of this size split when deeply etched with concentrated acid. Etching, throughout, 2 per cent alcoholic nitric acid.

FIG. 7.—*Structure of hardened steel balls*



Microstructure of the balls one-half and three-eighths inch in diameter. These balls were martensitic throughout. This structure is typical of the specimens which split when deeply etched with acid. Etching, 2 per cent alcoholic nitric acid. ×500

FIG. 8.—*Microstructure of hardened steel balls*

defects can be definitely located only by special methods and with great care. Two types of materials characteristic of the second condition are flaky gun steel and rails containing transverse fissures.

In Fig. 9 is shown the appearance of a specimen of a defective gun forging (composition: Carbon 0.38 per cent, chromium 0.20 per cent, nickel 2.92 per cent) in which the defects are quite readily detected after polishing. Deep etching accentuates these by widening and deepening the fissures.

Fig. 9, *c*, shows the appearance of a section of a 1-inch round trepanned out of a large bloom of gun steel similar to that of the forging of Fig. 9, *a*, suspected of being defective. Subsequent deep etching revealed the cracks shown in Fig. 9, *c*. Presumably the cracks here revealed are identical with the defects found in the finished forging (Fig. 9, *a* and *b*). It will be noted that the crack is intercrystalline for the greater part of its course.

Defects similar in appearance to those just described have been found in abundance in rails containing transverse fissures, by means of deep etching.[8] In this case, however, the presence of the defects, gashes or cracks, in the material previous to etching has never been demonstrated. Hence there have resulted considerable differences of opinion as to the significance of the results obtained by the deep etching of transversely fissured rails. As materials typical of this type of defect, specimens were taken from three different rails which had developed transverse fissures in service. The compositions of the three, which differed widely in this respect, are listed in Table 4.

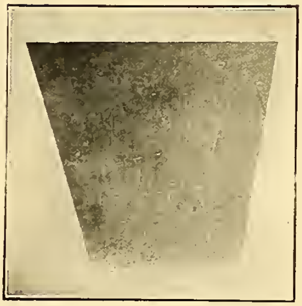
TABLE 4.—Composition of Rails Containing Transverse Fissures

Rail No.	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium	Nickel
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1	0.63	0.71	0.014	0.022	0.09	0.50	1.89
2	.62	.91	.020	.036	.01	(a)	(a)
3	.90	1.22	.094	.022	.14	(a)	(a)

[a] Not detected.

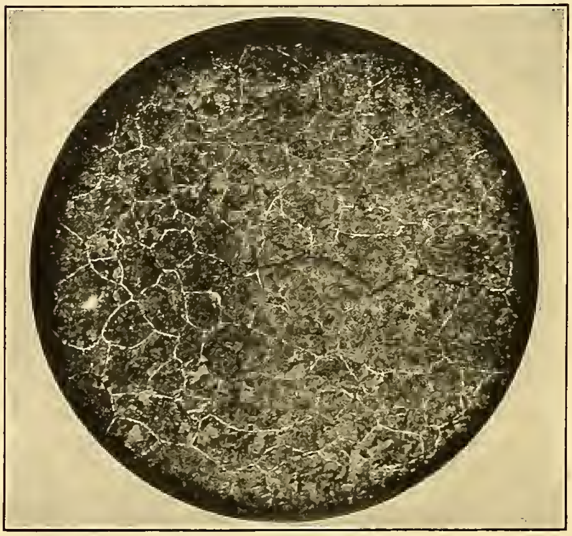
Portions of the head of each of the three rails were cut parallel to the tread into a series of slices. Each of the slices, after grinding, was etched to demonstrate the presence of gashes of transverse cracks. In each case these were found in abundance in the central

[8] Waring and Hofammann, loc. cit. Wickhorst, loc. cit.



(*a*) Transverse radial section from a forging for a gun tube polished to show interior defects. ×1

(*b*) Specimen (*a*) after deep etching in concentrated hydrochloric acid. The defects readily visible in (*a*) have been greatly widened and deepened by the etching. ×1



(*c*) Cross section of a 1-inch "round" trepanned out of a large bloom intended for a gun tube, etched with 2 per cent alcoholic nitric acid. The crack, which undoubtedly is of the same origin as the defects in (*a*) and (*b*), probably originated at a rather high temperature. It is largely intercrystalline in its course. ×3

FIG. 9.—*Defects in gun forgings revealed by deep etching*

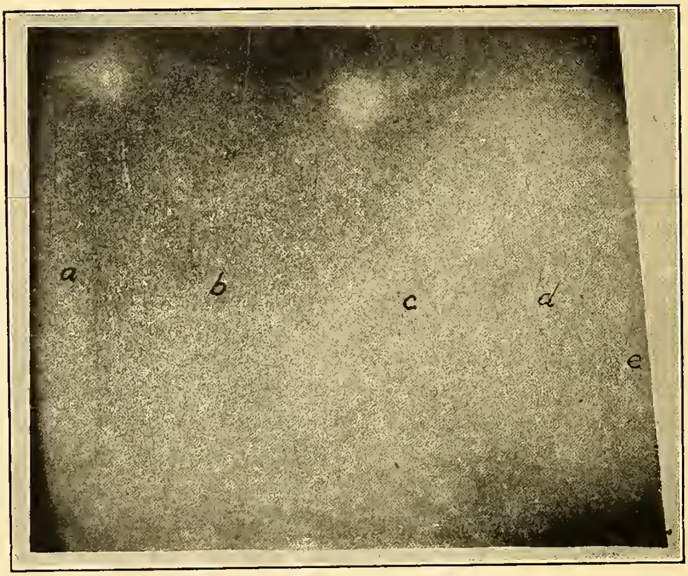
and lower portions of the head, as has been shown by previous investigators.

It is extremely difficult, however, to demonstrate by ordinary metallographic methods the presence of these defects within the material before the deep etching. Radiographic examination of thin slices (one-quarter inch thick) proved to be ineffective as a means for locating them. The only method by which the cracks could be located, without etching the specimen, was a magnetic one. This method was finally adopted for the preliminary examination of all the specimens suspected of containing cracks of any kind. The sample, which must be well polished, as for microscopic examination, is magnetized and then immersed in kerosene, or a similar liquid, containing *very* fine iron dust in suspension. "Cast-iron mud" from disks used for lapping was used for the purpose. The particles of iron dust collect upon the face of the specimen, and at the points where, because of a discontinuity in the metal, a change in the density of the magnetic flux occurs, orient themselves to correspond to the shape of the discontinuity. The specimens are then washed in clean kerosene to remove as much as possible of the excess iron dust which clings to the surface.[9]

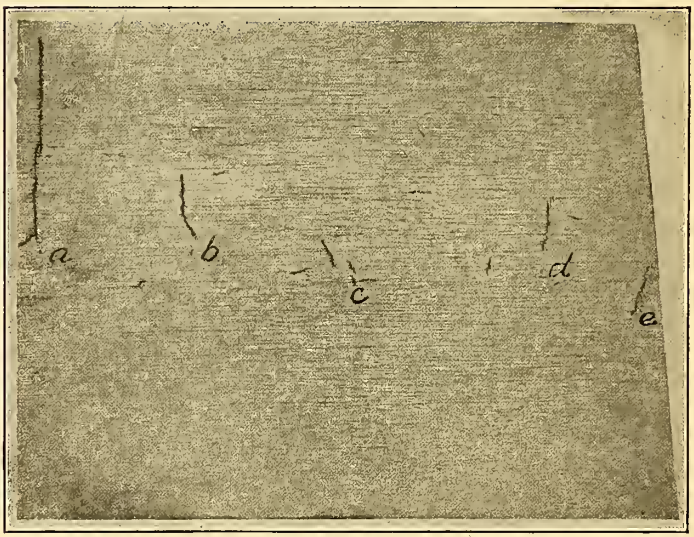
In Fig. 10 is shown the appearance of a slice from the lower part of the head of the rail No. 3, which has been treated with the iron dust after magnetizing and the same specimen after deep etching. It is extremely difficult to photograph the specimen so as to clearly show the results of the treatment with iron dust. They are much more readily seen upon visual examination than might be inferred from the photograph. Comparison of Fig. 10, *a* and *b*, however, shows the presence of a very fine crack or discontinuity in the unetched specimen (Fig. 10, *a*) corresponding to each of those revealed by deep etching (Fig. 10, *b*).

The appearance of the cracks located by the magnetic method is more clearly shown in Fig. 11, somewhat magnified, in which the surface was viewed obliquely. Crack *b* (Fig. 10, *a*) was located by means of iron dust after magnetizing the specimen. Its position was then recorded by punch marks at each end of the crack. Fig. 11, *b*, shows the specimen after the iron dust was wiped off; no crack can be detected between the punch marks. Fig. 11, *c*, shows the same specimen after a second treatment with iron dust.

[9] This method for the examination of polished surfaces suspected of containing surface cracks was developed at the Bureau for the inspection of precision gages.



(*a*) Longitudinal section of the head of rail No. 3 (Table 4) parallel to the tread. The specimen was magnetized and then immersed in kerosene in which iron dust was suspended. The cracks indicated by *a*, *b*, *c*, *d*, and *e* were located



(*b*) Same specimen as (*a*), deeply etched with concentrated hydrochloric acid. The cracks revealed by deep etching correspond with those in (*a*). ×1

FIG. 10.—*Defects in rails containing transverse fissures revealed by deep etching*

Although it is known with certainty that a discontinuity exists in the metal between the two punch marks, it is extremely difficult to find evidence of it in the microstructure even after light etching. In Fig. 12 is shown the best indication found of the presence of such a crack. This is very faint, however, and would be disregarded in the ordinary microscopic examination as of little or no importance. The faces on the opposite sides of the discontinuity or fissure are in such intimate contact that even at a magnification of 500 diameters the crack is relatively very inconspicuous, as is shown in Fig. 13. The course of the crack which has been indicated by arrows is hardly more conspicuous than the dark boundaries of the pearlite masses.

In Fig. 14 is shown a slice cut from the head of rail No. 1, parallel to the tread, in which two defects have been located by

(*a*) (*b*) (*c*)

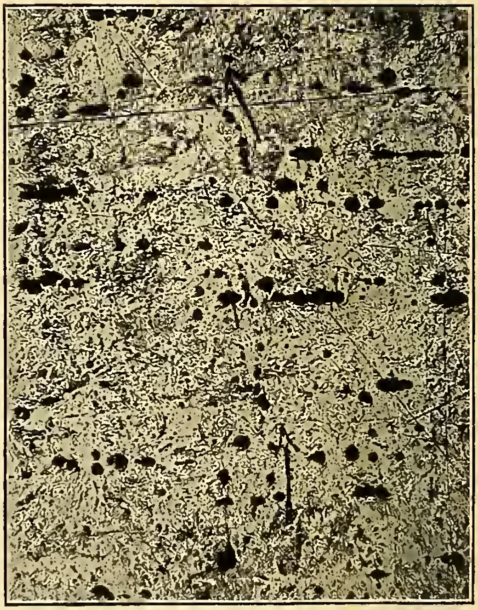
(*a*) Crack (*b*) of Fig. 10, *a*, viewed obliquely. ×3
(*b*) Same specimen as (*a*). The line of the crack shown in (*a*) was located by a punch mark at each end of the crack and the iron dust wiped off. No crack is visible. ×3
(*c*) Same specimen as (*b*), treated a second time with iron dust. Compare with (*a*). ×3

FIG. 11.—*Interior cracks existing in rails of the transverse-fissure type*

means of iron dust after magnetization of the specimen. By means of punch marks *close* to the ends of the crack it was found possible to open the fissure as is shown in Fig. 14, *b* and *c*. The slice containing the defects was then cut as shown by the lines in Fig. 14, *a*, and each strip broken transversely along the line of the defect. The break was localized by means of a slight saw cut on each side in line with the crack. The appearance of the fracture is shown in Fig. 14, *d*. A definite area which is easily distinguished from the surrounding sound material corresponds to the defect previously located. The strip containing crack *b* showed a similar characteristic spot when broken. This area, semicircular in Fig. 14, *d*, is identical in appearance with the nucleus of transverse fissures and with the gray spots often revealed in the transverse breaks of the heads of defective rails of this kind.

The nature of these defects can best be studied in material in which the carbon content is low enough so that the grain boundaries are clearly outlined by ferrite envelopes. Rail No. 2 was found

(a)



(b)

FIG. 12.—*Microscopic appearance of cracks existing in rails of the transverse-fissure type*

(a) Crack (b) of Fig. 10, a, specimen is unetched. ×50
(b) Same specimen as (a), etched with 2 per cent alcoholic nitric acid. The metal is in such intimate contact that only a very faint indication of the presence of the crack could be obtained. ×50

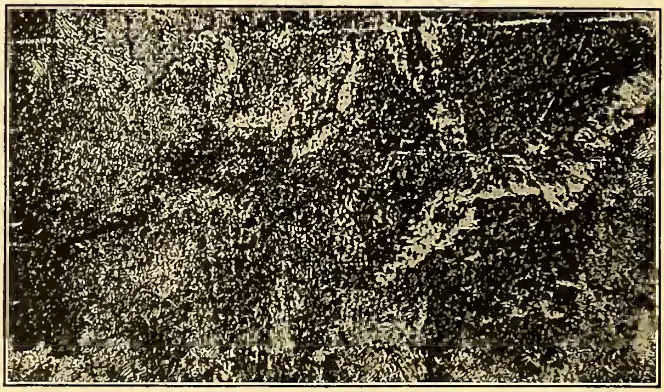
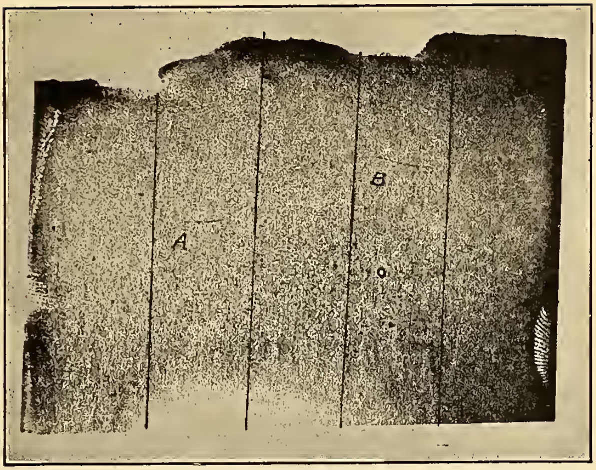
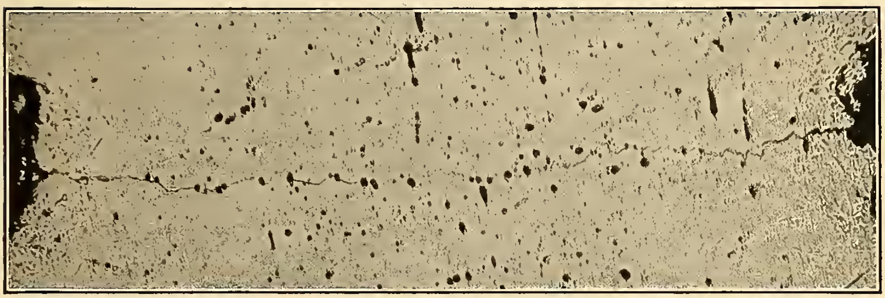


FIG. 13.—*Microscopic appearance of interior cracks existing in defective rails*

Crack (b) of Fig. 10, a, is shown after etching. ×500. The two sides of the crack are in such intimate contact that even at this magnification the course of the cracks (indicated by arrows) is relatively very inconspicuous.

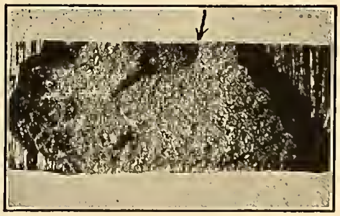


(*a*) Longitudinal section of rail No. 1 (Table 4) parallel to the tread. The two defects *A* and *B* were located by the magnetic method. ×1



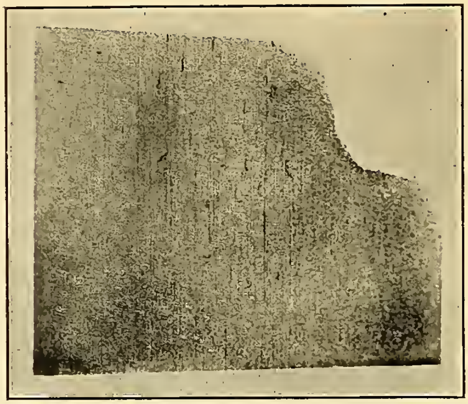
(*b*) Defect *A* of (*a*) above. By means of a punch mark at each end the crack has been opened; specimen is unetched. ×50

(*c*) Defect *B* of (*a*) above. The crack has been opened by means of punch marks as shown. Specimen was slightly etched with 2 per cent alcoholic nitric acid. ×10

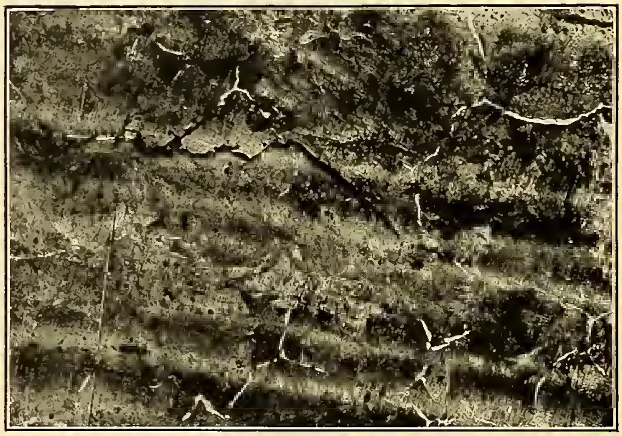


(*d*) Fracture of the strip of specimen (*a*) containing defect *A*. The rail section was cut into strips as shown, and fractured by a transverse break along the line of the defect. The semicircular area, indicated by the arrow, corresponds the to defect.

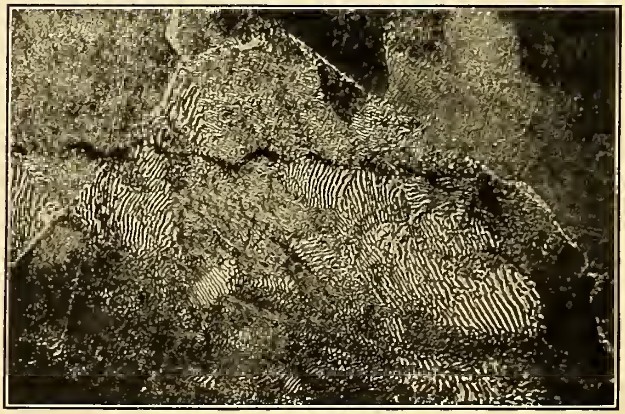
FIG. 14.—*Nature of the interior defects revealed by the deep-etching rails containing transverse fissures*



(*a*) Longitudical section of rail No. 2 (Table 4) parallel to the tread. The interior cracks as they appear after slight etching with concentrated hydrochloric acid. ×1



(*b*) Specimen (*a*) after slight etching in concentrated hydrochloric acid to widen the crack, repolished for microscopic examination. The crack is intracrystalline in its course. There is some evidence of banding due to phosphorus. Etching, 2 per cent alcoholic nitric acid. ×100.



(*c*) Same material as (*b*). The intracrystalline nature of the crack is very evident. Etching, 2 per cent alcoholic nitric acid. ×500

FIG. 15.—*Microscopic nature of the interior defects found in rails of the transverse-fissure type*

to be very suitable for this purpose. Fig. 15, *a*, shows a section of this rail after slight etching with concentrated hydrochloric acid. The interior cracks having been widened by the concentrated acid, the surface was ground down, repolished, and reetched for microscopic examination. In Fig. 15, *b* (×100), and Fig. 15, *c* (×500), a crack is shown passing through the grains and across the grain boundaries. The cracks are intracrystalline, in their course; that is, the break has occurred *through* the grains rather than *between* them.

IV. NATURE OF DEFECTS REVEALED IN RAILS CONTAINING TRANSVERSE FISSURES

The results of the examination given above definitely warrant the conclusion that the defects (gashes, fissures, or cracks), revealed in rails of the transverse fissure type by means of deep etching, exist within the material previously to the etching, as discontinuities within the steel. The function of the acid used for etching is merely to widen and deepen the *preexisting* cracks. The microscopic appearance of these cracks offers some suggestions as to their origin. The course of the crack is intracrystalline and has the general appearance of a fracture produced in normal material; there is no evidence of inherent weakness at the grain boundaries. An answer to the question as to whether the separation occurred while the metal was cold—that is, in the track—or while hot—that is, in the mill—does not appear to be forthcoming from the evidence offered by the examination of the fractures alone. No definite statement can be made on this point. However, the comparison of internal fractures found in ingots and blooms and hence, in all probability, produced at a rather high temperature (Fig. 9, *c*) with those found in rails which developed transverse fissures in service (Fig. 15) is very suggestive. The internal cracks shown in Fig. 9, *c*, are of the *inter*crystalline type. In general, this is a characteristic of fractures produced in metals at elevated temperatures. On the other hand, the cracks shown in Fig. 15 are of the *intra*crystalline type, a feature which, in general, is characteristic of fractures produced in metals broken at ordinary temperatures.

V. SUMMARY AND CONCLUSIONS

1. The method of deep etching of steel by means of concentrated acids was examined in detail. The choice of the acid is a matter

of minor consideration provided it is concentrated enough to produce a vigorous attack of the metal.

2. The metallographic features of steel revealed by deep etching are of three general types: Chemical inhomogeneity, mechanical nonuniformity, and physical discontinuities.

3. Chemical inhomogeneity, usually the result of segregation, shows itself by a more vigorous roughening and pitting of the "impure" portions. Sulphides and other inclosures are rapidly dissolved and the resulting pits are then deepened and widened.

4. Steel which is not mechanically uniform throughout because of the presence of initial stresses, which may be the result of previous mechanical work or of too vigorous quenching during heat treatment, will split when deeply etched, provided the stresses are of sufficient magnitude. Commercial bearing balls of different types were used to illustrate this feature. It was shown that this tendency to crack upon etching may be eliminated by suitable heat treatment. The behavior of steel, in this respect, is identical with the corrosion cracking of brasses and bronzes.

5. Physical discontinuities, such as internal fractures, etc., which may exist in steel, are revealed by deep etching. The acid serves to widen and deepen these discontinuities within the metal.

6. It has been definitely shown that the gash defects found in abundance in rails in which transverse fissures have developed and in similar materials, are physical discontinuities or internal fractures which exist within the material previously to etching. The etching merely reveals the defect. A magnetic method for locating such defects in the unetched specimens is described. This method appears to be the only one for determining the nature of these and similar defects with certainty.

The authors are indebted to Maj. W. E. Hoke, under whose direction the magnetic method described was developed for the inspection of the surfaces of precision gages, and to F. H. Tucker, for the chemical analyses of the materials used.

WASHINGTON, September 20, 1919.