EFFECT OF SERVICE ON THE ENDURANCE PROPERTIES OF RAIL STEELS

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ABSTRACT

A series of tests has been carried out to determine the effect of service on the endurance properties of rail steels. In a previous report data were given on the endurance properties of steel from new rails. In the present report data are given on the endurance properties of steel from rails from the same heats after service and from two rails which failed due to a transverse fissure.

It was found that the endurance properties of the steel were not affected by over 20,000,000 tons of traffic. In one group of rails very marked variation in results was found which was shown to be due to the presence of small internal cracks in the rails. Evidence was found which indicated that these rails probably contained small cracks before placing in service.

It was concluded that the service stresses imposed had not measurably affected the endurance properties of the steel, and, therefore, that the service stresses were less than the endurance limit of sound rail steel.

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I. INTRODUCTION

Years of speculation on the causes of transverse-fissure failures in rails have resulted in two schools of thought. Both schools agree that the failure is progressive, starting from a nucleus like any
fatigue failure, and differing from most fatigue failures only in that
the nucleus is inside the rail rather than at the surface. Other cases
of internal nuclei for fatigue failures are, however, well known, as in
the cases of ball bearings and of gear teeth.

Fatigue failures are due to the repeated stressing of the structure
at stresses greater than the endurance limit of the material in that
structure. The endurance limit may be defined as that minimum
stress which, if repeatedly imposed, will cause cracks to develop
which will progress under repetition of that stress, causing ultimate
failure.

One school of thought takes the view that the stresses developed
in rails under present-day wheel loads exceed the endurance limit of
present-day rail steels and, consequently, no matter how sound and
uniform present-day rail steels may be, all may ultimately fail
through fatigue. If this view is correct, there are only two ways
out of the dilemma—one to reduce the wheel loads, the other to
change the type of steel used for rails, abandon the present type, and
go to some type with an endurance limit greater than the imposed
stresses. Since accurate knowledge of the stresses produced within
the rail by the wheel loads is lacking, and since accurate knowledge
of the endurance limit of rail steel under incompletely reversed
stresses is also lacking, this view deserves consideration until it is
definitely disproved. This school of thought might be termed the
"stress school," as it holds that the nucleus for the transverse-
fissure failure is created by the stress.

The other school of thought takes the view that if sound rail steel
under present-day wheel loads is really subjected to repeated stress
above its endurance limit, all rails in similar service would fail through
transverse fissures after the same length of life. Since it is well known
that this is not the case and that of two adjacent rails from the same
heat, laid at the same time, one may fail from a transverse fissure
and on examination may show other fissures in process of formation,
while the other rail may show no sign whatever of any fissure, this
school believes that the nucleus for a transverse-fissure failure is not
created by imposed stress, but is preexistent in the steel before the
rail is laid, in the form of some flaw. If the idea of the "preexistent
nucleus" or "stress-raiser" school is correct, then neither the wheel
loads nor the type of steel used for rails need be changed, if only some
means can be found to produce the present type of steel free from the
sort of flaws that act as nuclei for fatigue-fissure failures.

One difficulty in this theory is that it has not been definitely proved
that nonmetallic inclusions (slag, "dirt," etc.) which are commonly
agreed to act as stress raisers and to form nuclei for fatigue failures in
many steel parts are present at the nuclei of transverse rail fissures, so
that the exact nature of the nuclei is in doubt.
In a recent report it was shown that the endurance limit in rotary bending of specimens cut from unused rails which met all specifications for static tests of rail steel varied from a maximum of 59,000 lbs./in.² to a minimum of 41,000 lbs./in.². If a larger number of samples were examined, this range might be widened. If the extreme endurance range be taken as ±40,000 to ±60,000 lbs./in.², it would appear that, if these values correctly represent the maximum and minimum endurance limits of ordinary rails, repeated rail stresses equivalent in severity to the stress range of 120,000 lbs./in.² (±60,000) applied in testing would result in the failure of all rails by fatigue, and those equivalent to a stress range of 80,000 lbs./in.² (±40,000) would result in no failures.

If, however, stress raisers that can act as nuclei for fatigue failure be present in the rail, but not in the particular specimens cut from it, the calculated applied load might be locally increased to a value above the endurance limit. Unless such stress raisers were met in the most highly stressed portions of the specimens examined, the endurance limit for the rail steel determined by the test would be above the endurance limit for the rail. It is not unreasonable to suppose that the true endurance limit for sound, clean, rail steel is well above 60,000 lbs./in.² and that the amount which actual tests indicate the observed endurance limit to drop below the true value is a measure of the effect of the stress raisers existing in the specimens used.

However, the wide range of endurance limits (40,000 to 60,000 lbs./in.²) does not exist between specimens from comparable locations in the cross section of rails from the same heat in such tests so far made at the Bureau of Standards. Instead of a range of 20,000 lbs./in.², the range is reduced to 6,000 lbs./in.², and ordinarily to a much smaller range.

It would be possible to draw more exact conclusions on the endurance properties of rails were it feasible to use a whole rail, rather than specimens cut from it, for laboratory endurance tests. The construction and operation of an endurance-testing machine capable of applying and of measuring with sufficient accuracy the large loads required in the test of a full-sized rail would be so expensive that it is desirable first to secure as much information as possible from pilot tests of specimens cut from rails made with endurance machines now available.

Were it feasible to subject specimens cut from rails to a type of test in which a larger volume is subjected to the maximum stress than is the case with rotary-beam or rotary-cantilever testing machines, the sampling error would be diminished. Concurrently with the present investigation, the Bureau of Standards is studying the
axial loading, tension-compression endurance test, using a Haigh type of machine, with the expectation of applying that type of test to rail steel. Until that work is farther advanced, the use of such a test would involve uncertainties at least as great as those met in rotary-beam testing.

As was pointed out in the previous report, it appeared that a study of the endurance properties of rail steel before and after service might throw some light on the question as to whether or not service stresses in themselves create nuclei for transverse-fissure failure or whether the nuclei are preexistent. The ground for the hope that such tests would illumine the problem consists in the fact, brought out in the previous report, that, like other steels, rail steels may be strengthened by "understressing" in the endurance test and weakened by "overstressing."

All experimenters working on fatigue of metals agree as to the experimental facts that the fatigue resistance of a steel is increased when the specimen is repeatedly stressed at a stress below, but near to, its true endurance limit. The true endurance limit is found by applying repeated stress to various specimens, starting with a stress which will break the specimen in a relatively small number of cycles, and reducing the stress on successive specimens till a stress is reached at which the specimen will not break no matter how many stress cycles are applied. If such an unbroken specimen is then subjected to a higher stress, one, for example, that would break a fresh specimen in half a million cycles, the specimen that has been under-stressed will withstand many million cycles. It has been shown that understressing in the endurance test raises the static tensile strength if the understressed specimen is tested in tension.

It is not known how near the endurance limit the understress must lie to produce strengthening, how many cycles of stress must be applied, nor whether the specimen must be stressed in the same manner in the understressing and in the later endurance test. For example, it is not known whether understressing by axial loading will strengthen a specimen against higher stress applied by rotary bending, or whether it is only strengthened against higher stress applied in axial loading.

Students of fatigue also agree on the experimental fact that a specimen which has been repeatedly stressed at a stress above the endurance limit which, if applied a sufficient number of times, would break it but which has not yet produced a microscopically detectable crack, has been weakened by overstressing. Not very much is known about the quantitative effect of over-stress. An over-stress of 20 to 30 per cent above the true endurance limit, applied for a few thousand cycles, may reduce the apparent endurance limit for undamaged material quite appreciably, but it is not definitely known how various
stresses and various numbers of stress applications affect various steels.

While the theories to account for these experimental phenomena have been only tentatively put forth, a very reasonable point of view is that of Moore. According to this theory, steel, not being homogenous but being made up of variously oriented crystals, contains tiny places less favorably oriented for withstanding a certain stress applied in a certain direction, and, under stress, the crystals at these locations undergo slip. Slippage in those places hardens and strengthens them much as slip, occurring generally throughout a metal, hardens it on cold working.

This slip so strengthens the unfavorably oriented places that they are able to transmit the load to surrounding metal without themselves undergoing further slip, so that, instead of incipient failure at those places, the result of the application of stress is a strengthening of the specimen. It is postulated that this slip merely moves the layers of atoms in some of the crystal slip planes without breaking down the cohesion between the layers of atoms. The layers are slid along, but not separated, and a crack does not result. The result is local cold working of tiny places within the metal, these places being automatically selected by the stress distribution within the metal. This conception is in accord with the observed phenomena of strengthening by understressing.

If the applied stress is too high, however, the unfavorably oriented areas become overworked before sufficient readjustment has taken place to distribute the load to surrounding material and slip and motion within the affected grain are so great that the layers are separated beyond the distance through which atomic cohesion can operate. In that case an incipient crack is formed which may at first be of submicroscopic dimensions and later grows into a visible crack. Instead of increased strength due to cold working, there is now a tiny flaw which acts as a "stress raiser," like any crack, so that damage, instead of being prevented by redistribution of the load, is concentrated because of increase in local intensity of stress. This conception agrees with the experimental facts of overstressing. This idea of the effect of overstress is somewhat analogous to that held by some students of transverse-fissure failures who postulate the development, under repeated stress, of "zones of exhausted ductility." The mental picture of these zones, however, calls for larger volumes of metal being affected than does that of submicroscopic incipient cracks.

Under repeated stress there are, then, two opposing factors, one tending to strengthen the material, one tending to weaken it. At

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such a stress that the weakening tendency is so overcome by the
strengthening tendency that no localities are stressed to the point
where development of a real crack can occur, we have the true
endurance limit. At any higher stress failure will ensue unless the
metal has previously been improved by understressing.

Overstressing to the point where an actual crack starts should be
quite readily detectable. Moore 3 says that once a fatigue crack is
started it will spread under subsequent cycles of a stress much lower
than the true endurance limit, and that relatively few cycles of over-
stress are required to start the crack. It would appear that the
development of a crack or an incipient, submicroscopic separation,
since it forms a stress raiser and intensifies the local stress, would
more readily show its effect upon subsequent application of repeated
stress, even though that stress were not applied in exactly the same
direction as the stress causing the damage, than the development of
tiny strengthened areas produced by a certain prior stress would show
its effect on subsequent test.

From this point of view it appeared possible that the endurance
testing of specimens from used rail and the comparison of the endur-
ance limit of used-rail specimens from a given heat or ingot with the
endurance limit of specimens from unused rail from the same heat or
ingot ought to give a useful indication whether or not service had
created overstressed volumes and incipient nuclei for fatigue failure
throughout the rail. If rail steel that is originally sound and flawless
has flaws created within it by overstress due to too high wheel loads,
irrespective of the presence of stress raisers, such as inclusions and
cracks in the steel before service, but due merely to the random ori-
tentation of the grains of the steel, then weakening of the steel due to
overstressing should be readily apparent by a materially reduced
endurance limit. Any microphotograph of rail steel will show such a
number of differently oriented grains that grains unfavorably oriented
to withstand a stress applied from any direction should be present
throughout.

The effect of the application of stress below the endurance limit
would be harder to detect, since it appears that many applications of
understress, and of understress fairly close to the endurance limit at
that, are required to produce appreciable change in properties, while
fewer applications of over-stress appear to be required to cause detect-
able damage. Stresses far below the endurance limit would not be
expected to produce any detectable effect whatever.

Endurance of Metals Under Repeated Stress, p. 16; 1927.
The question whether excessive wheel loads above the endurance limit of sound rail steel are actually being applied in present-day practice is of fundamental importance in the transverse-fissure problem. If they are, the metallurgist must either provide a new type of steel with higher endurance limit or the railways must reduce the wheel loads. If they are not, and the evidence points to pre-existent nuclei due to the steel and not to the service, then a possible field for improvement of present-day types of rail steel presents itself if the source of the nuclei can be determined.

It was not expected that a complete and positive answer, such as might be gotten were it feasible to make endurance tests on whole rails under controlled conditions, would be obtained from the testing of random specimens taken from used rail with no record of the actual stresses that had been applied to that location within the rail represented by the breaking section of a specimen cut from the rail, since, beside the difficulties always met in sampling by which random samples may prove of better quality than the poorest part of the lot or object sampled, the cutting of the specimen from the rail would release internal stress that might be present in the rail itself.

As experience is accumulated in the detection of transverse fissures in the track itself by the Sperry rail flaw detector 4 or other devices and the progress of fissures in actual rail has been more closely followed, some of these questions may be answered on the basis of evidence so accumulated, from the point of view of actual service.

However, the importance of the transverse-fissure problem is so great that all possible lines of attack should be followed simultaneously. With due regard to its limitations, a study of the endurance properties of rail steel before and after service may be expected to throw some light on the fissure problem.

Through the cooperation of E. Stimson, chief engineer of maintenance of the Baltimore & Ohio Railroad and J. M. R. Fairbairn, chief engineer of the Canadian Pacific Railway, rails from some heats which had been tested before service were removed from track after approximately one and a half to two years' service and returned to the Bureau of Standards for a redetermination of the endurance limits of the steel.

II. MATERIAL STUDIED

The record of the rails returned from service on the Baltimore & Ohio Railroad and Canadian Pacific Railway are given in Tables 1 and 2, respectively.

TABLE 1.—Record of rails returned from service on the Baltimore & Ohio Railroad

<table>
<thead>
<tr>
<th>Railroad company No.</th>
<th>Manufacturer heat No.</th>
<th>Bureau of Standards heat No.</th>
<th>Ingot No.</th>
<th>Position in ingot of rail tested</th>
<th>Location and service conditions as given by railroad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>After service</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before service</td>
<td></td>
</tr>
<tr>
<td>L-15</td>
<td>203264</td>
<td>18</td>
<td>13</td>
<td>BC</td>
<td>Bridge, 323; low rail 8° 2.5' curve with superelavation of 5 1/4 inches; 21,738,000 tons of traffic.</td>
</tr>
<tr>
<td>L-17</td>
<td>203264</td>
<td>18</td>
<td>15</td>
<td>BC</td>
<td></td>
</tr>
<tr>
<td>8-13</td>
<td>203266</td>
<td>19</td>
<td>10</td>
<td>BC</td>
<td>Yellow dog tangent; 20,502,000 tons of traffic; 8-13 in south and N-14 in north track.</td>
</tr>
<tr>
<td>N-14</td>
<td>203266</td>
<td>19</td>
<td>10</td>
<td>BC</td>
<td></td>
</tr>
<tr>
<td>S-22</td>
<td>212226</td>
<td>22</td>
<td>1</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>H-29</td>
<td>203264</td>
<td>20</td>
<td>12</td>
<td>AB</td>
<td>Yellow dog curve; high rail; spiral of 3° 6' curve with superelavation of 3 1/4 inches; 20,502,000 tons of traffic.</td>
</tr>
<tr>
<td>H-30</td>
<td>203264</td>
<td>20</td>
<td>10</td>
<td>AB</td>
<td></td>
</tr>
<tr>
<td>H-15</td>
<td>212226</td>
<td>22</td>
<td>1</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

1 These numbers correspond to same heats previously studied. (B. S. Tech. Paper No. 363.)
2 These rails in previous tests (B. S. Tech. Paper No. 363) were taken from "a middle ingot" of the heat.
3 This nomenclature of AB and BC is the same as was used in the previous report. Because of the relatively large crop the manufacturer marked the top rail the B rail and second rail the C rail. To distinguish these, they were called the AB and BC rails, respectively.
4 No specimens from rails from this heat, which was a standard heat, were tested before being placed in service. It is comparable to heat 21 of previous report.

TABLE 2.—Record of rails returned from service on the Canadian Pacific Railway

<table>
<thead>
<tr>
<th>Railroad company No.</th>
<th>Manufacturer heat No.</th>
<th>Bureau of Standards heat No.</th>
<th>Ingot No.</th>
<th>Position in ingot of rail tested</th>
<th>Date removed from service</th>
<th>Total service tonnage, including locomotive</th>
<th>Service condition as given by railroad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>After service</td>
<td>Before service</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5157-5-A...</td>
<td>5157</td>
<td>1</td>
<td>5</td>
<td>A</td>
<td>Jan. 19, 1923</td>
<td>12,130,000</td>
<td>All rails laid on tangent in north line of rails in eastbound track of double-track Winchester subdivision immediately east of Dorval, Province of Quebec, July 30, 1923.</td>
</tr>
<tr>
<td>5157-12-A...</td>
<td>5157</td>
<td>1</td>
<td>12</td>
<td>A</td>
<td>Jan. 27, 1923</td>
<td>12,330,000</td>
<td></td>
</tr>
<tr>
<td>5157-8-B...</td>
<td>5157</td>
<td>1</td>
<td>8</td>
<td>B</td>
<td>Jan. 10, 1923</td>
<td>12,130,000</td>
<td></td>
</tr>
<tr>
<td>5157-13-B...</td>
<td>5157</td>
<td>1</td>
<td>13</td>
<td>B</td>
<td>Jan. 27, 1923</td>
<td>12,330,000</td>
<td></td>
</tr>
<tr>
<td>5159-10-A...</td>
<td>5159</td>
<td>3</td>
<td>10</td>
<td>A</td>
<td>Jan. 10, 1923</td>
<td>12,330,000</td>
<td></td>
</tr>
<tr>
<td>5159-21-A...</td>
<td>5159</td>
<td>3</td>
<td>21</td>
<td>A</td>
<td>Jan. 19, 1923</td>
<td>12,130,000</td>
<td></td>
</tr>
<tr>
<td>5159-1-B...</td>
<td>5159</td>
<td>3</td>
<td>1</td>
<td>B</td>
<td>Jan. 19, 1923</td>
<td>12,130,000</td>
<td></td>
</tr>
<tr>
<td>5159-21-B...</td>
<td>5159</td>
<td>3</td>
<td>21</td>
<td>B</td>
<td>Jan. 19, 1923</td>
<td>12,130,000</td>
<td></td>
</tr>
<tr>
<td>5157-13-D...</td>
<td>5157</td>
<td>1</td>
<td>13</td>
<td>D</td>
<td>Jan. 10, 1923</td>
<td>17,030,000</td>
<td></td>
</tr>
<tr>
<td>5159-21-E...</td>
<td>5159</td>
<td>3</td>
<td>21</td>
<td>E</td>
<td></td>
<td>17,305,000</td>
<td></td>
</tr>
</tbody>
</table>

1 These heat numbers correspond to same heats previously tested (B. S. Tech. Paper No. 363).
2 The rails in previous tests were taken from "a middle ingot" of the heat.

It will be noted from Table 1 that the rails returned from the Baltimore & Ohio Railroad were obtained from three heats which had been poured in sink-head ingots, which had been previously tested, and from one standard heat. Unfortunately, it was not possible to locate rails from the standard heat (No. 21) previously tested.

It will be noted from Table 2 that all rails from the two heats returned from service on the Canadian Pacific Railway were rolled from the special heats killed with aluminum and poured in sink-head ingots. Unfortunately, none of the rails from the standard ingot heats could be located.

In the previous work, material was not available to determine the variation in the endurance limits that might be shown between steel from rails from the same position in different ingots from the same
heat. A measure of this difference was desirable in order to be able
to differentiate between any change that might be due to overstressing
or understressing and the differences inherent between rails from the
same position in different ingots.

Accordingly, two A and B rails, respectively, representing each
heat were removed from service. This made possible, the service
conditions of comparable rails having been the same, a comparison
of endurance properties in each instance of the steel from two rails
from the same position in two distinct ingots of each heat and also
a direct comparison with the steel from similar rail before service.
At a later date a D and an E rail from the same ingots as the A and
B rails of heats 5157 and 5159, respectively, were obtained from the
Canadian Pacific for test as discussed more fully later in the report.
For convenience of reference to the earlier work on the new rail, the
same designations have been given in the tables as were previously
used.

The conditions of service for rail removed from track on the Balti-
more & Ohio Railroad were stated by Mr. Stimson to have been as
follows:

* * * For your information I quote the following statement, which indi-
cates rail designation, process, heat number, and ingot number:

Yellow dog tangent:
S-13, Gathmann ........................................ 203286 C 10
N-14, Gathmann ........................................ 203286 C 33
S-22, Regular ............................................ 212256 B 1

Yellow dog curve:
H-29, Gathmann ........................................ 206264 B 12
H-20, Gathmann ........................................ 206264 B 10
H-15, Regular .......................................... 212256 B 2

Bridge 323:
L-15, Gathmann ........................................ 203284 C 13
L-17, Gathmann ........................................ 203284 C 15

The designations S, N, H, and L refer to north, south, high, and low. As
mentioned in my previous letter, the tonnage which traveled over the first six
rails listed was 20,562,000 tons, and over the last two, 21,738,000 tons.

There is, as you will notice, considerable difference in the wear on these rails,
but this is easily explained when it is understood that rails from bridge 323 were
on the low side of a 9° 25' curve with a superelevation of 5½ inches, while the
other rails were either upon the spiral of a 3° 6' curve with a superelevation of
3½ inches or upon tangent.

The conditions of service for the rail removed from track on the
Canadian Pacific Railway were stated by Mr. Fairbairn to have been as
follows:

All of the test pieces sent you were laid on tangent in the north line of rails
in the eastbound track of our double-track Winchester subdivision immediately
east of Dorval, Province of Quebec, July 30, 1926.
The original pieces sent you were removed from the track on January 19, 1928, after approximately 12,130,000 tons, including locomotives, had passed over them.

About 10 per cent of the tonnage in each case was passenger trains hauled by G-1 and G-3 class locomotives. The remainder was freight tonnage handled chiefly by D-10 class locomotives, with occasional N-3 class locomotive. I am attaching wheel-load diagrams of these locomotives.

The diagram of wheel loads mentioned is given in Figure 1.

![Diagram](image)

**Figure 1.**—Wheel load diagram. Canadian Pacific Railway locomotives. Classes D-10, N-3, G-1, and G-3

**III. TEST PROCEDURE**

In order that the test conditions should be as nearly comparable as possible the specimens were taken in the same manner and the same test equipment and test procedure were used as in the previous work.
For convenience, a figure showing location of test specimens is repeated here. (Fig. 2.) Duplicate contiguous (end to end) specimens were taken in each case, as previously, giving 12 specimens at a distance of between 4½ to 6 feet from the end of the rail.

At least one of each series of test specimens was subjected to 18,000,000 to 20,000,000 cycles of stress at a value just under the endurance limit. All other specimens were run at least 10,000,000 cycles if failure did not occur previously and then in some instances tested at a stress appreciably above the endurance limit to determine whether strengthening by understress had occurred during testing.

IV. RESULTS OF TESTS OF RAIL AFTER SERVICE ON BALTIMORE & OHIO RAILROAD

1. ENDURANCE TESTS OF STEEL FROM RAILS RETURNED FROM BALTIMORE & OHIO RAILROAD

The results of all endurance tests on rail steels returned from service on the Baltimore & Ohio Railroad are given in the customary S-N diagrams in Figures 3 to 7, inclusive.

In order to compare the results shown by specimens from the rails removed from service with the similar data on specimens from new rail from the same heats the endurance curves of the latter have been drawn in on the respective charts.
Tests were not made on specimens from new rails of heat No. 22 (fig. 3), which was a standard heat. A comparison of the effect of service on standard ingot rail, however, is available by comparing the endurance curves of the steel from the B rails of heat 22 with the results of similar tests on steel from the B rails from four similar standard heats (Nos. 8, 9, 10, 21, of previous report) tested before service. The range (maximum and minimum values) and average endurance limits shown by these four rail steels are indicated in the chart. (Fig. 3.) The range of endurance limits of all B rails tested before service is also indicated.

![Figure 3](image-url)

**Figure 3.**—Endurance curves of steel from B rails from heat No. 22 after service and indicated range of endurance limits of similar B rails before service

It is evident from the data that the endurance limit of the rail steel after service is well within the limits obtained from similar rail before service.

The conclusion is therefore evident that the service conditions in this instance have had no apparent effect upon the endurance properties of this rail steel.

It is possible in only one instance to make a direct comparison of the endurance limit of steel from a new and serviced rail from the same heat (No. 20) and position (AB) in the ingot. This is shown in Figure 4. The endurance limit of the steel from the AB

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1 The same special nomenclature is used here for these rails as in the previous report.
rail from one of the middle ingots of the heat before service was 53,600 lbs./in.². The endurance limits shown by specimens from similar rails (AB) from two different ingots of the same heat were found, after service, to be approximately 53,000 and 54,400 lbs./in.², respectively.

Specimens from each of these rails that had not failed during test after approximately 20,000,000 cycles were tested at successively higher loads. In one case an endurance limit greater than 60,000 lbs./in.² and in the other greater than 65,000 lbs./in.² was obtained when tests were discontinued. As a result of this repeated under-

![Figure 4](image-url)

**Figure 4.**—Endurance curves of steel from AB rails from heat No. 20 before and after service

stressing, "coaxing," the endurance limits were increased approximately 13 and 19.5 per cent, respectively.

There is therefore no evidence, in this instance also, that the service stresses affected the endurance properties of the steel.

The results of tests on specimens from rails from heats Nos. 18 and 19 are given in Figures 5 and 6. In both instances the rails removed from service were BC rails and are compared with test results from AB rails from the same heat.

The endurance limits shown by the specimens from both of the serviced rails from heat No. 18 (fig. 5) are practically the same at about 56,600 lbs./in.² and are only slightly less (1,100 lbs./in.²) than
the endurance limit of 57,400 lbs./in.\(^2\) shown by the specimens from the AB rail before service.

In the previous work (B. S. Tech. Paper No. 363, p. 292) differences of 2,700 lbs./in.\(^2\) were found in the endurance limits shown by specimens from A and B rails from the same ingot. The difference of 1,100 lbs./in.\(^2\) noted is therefore probably a difference originally present in the steel. It is also to be noted, as indicated in the figure, that the endurance limits of the steel of these serviced rails is considerably higher than the minimum value shown by similar A and B rail steels before service.

![Figure 5](image)

**Figure 5.**—Endurance curves of steel from rails from heat No. 18 before and after service

Evidence is again lacking that the service conditions have in any way affected the endurance properties.

The difference in endurance limits that may exist between rails from the same position in different ingots is shown by the data on the serviced rails of heat No. 19. The endurance limit of the steel from one of these BC rails (ingot No. 10) was found to be about 57,600 lbs./in.\(^2\) and from the other (ingot No. 33) about 53,500, or 4,100 lbs./in.\(^2\) lower.

Both rails were subjected to practically the same traffic conditions. It seems, therefore, a fair assumption that the difference noted was present in the steel before being placed in service.

In both instances the endurance limits are lower than the value shown by specimens from an AB rail from the same heat before serv-
ice. This particular series, however, showed the highest endurance limit of all of the specimens from all rails tested before service, and the value of 53,500 lbs./in.² shown by the BC rail from ingot No. 33 is practically the same as that obtained on similar tests of an AB rail from heat No. 20 before service. Further, as indicated in the figure, the endurance limits in both instances are well within the limits shown by specimens from similar new rail.

In this case, also, specimens were restressed as indicated. In each instance strengthening by understressing of the test specimen had occurred, as shown by the increased endurance limits of approximately 8.5 and 6.0 per cent.

The conclusion is again justified that the service conditions have not affected the endurance properties of the steel.

The results of all of the above-mentioned endurance tests on rail steels returned from service have been plotted in Figure 7. The maximum and minimum values of steel from new rails from the similar heats have also been indicated.

It is apparent that the range of endurance limits shown by the steel from serviced rail is within that of the new rail.

Attention is called to the really random selection of the test specimens representing the cross section of the heads of several rails. If localized defective areas (transverse-fissure nuclei) were present
originally or as a result of service, it would seem probable such areas would have been present in one or more of the test specimens and have caused premature failure.

The grouping of all the test results within the well-defined limits indicated in Figure 7 is strong evidence that such defective areas were not present in the rails tested.

It is also noteworthy that the endurance of steel from the standard rails tested in this instance is lower than that from sink-head rails.

![Figure 7](image_url)

**Figure 7.**—Results of all endurance tests on steel from A and B rails after service on Baltimore & Ohio Railroad

2. **EFFECT OF SURFACE FLOW ON HARDNESS**

Some of the rails returned from service on the Baltimore & Ohio Railroad showed appreciable surface flow of the head of the rail. This is indicated in Figure 8, which is a photograph of a section of rail No. L-15 (Table 1), taken about 10 feet from the end.

Rockwell B hardness tests were made at the points indicated to determine the increased hardness due to cold flow.

The average hardness across the upper edge of the section about one-sixteenth inch from top of rail was found to be 106.7. The average hardness along a line about one-fourth inch below the top of the head of the rail was found to be 104.6. The average hardness of the interior of head of the section, as shown by measurements at points indicated, which were taken in the same manner as in the previous report (p. 340, fig. 30), was found to be 100.2.
Figure 8.—Section of head of rail L-15 showing surface flow and location of Rockwell B hardness tests

Figure 10.—Section of rail L-15 adjacent to location of endurance test specimens

Deep etched in hot concentrated HCl for one-half hour. Surface slightly reground. Dark area indicates region of surface flow.
Tests made along the top edge of new rail from the same heat in the same manner as on the serviced rail indicated no difference in hardness as compared with the interior of the head.

It is evident, therefore, that the surface flow caused an appreciable hardening of a relatively thin surface layer due to the cold working of the metal and that the hardness of the interior of the head was not affected by service.

3. EFFECT OF SURFACE HARDENING ON ENDURANCE PROPERTIES

In view of the surface flow and resultant increase in hardness of the top of this rail, which is undoubtedly a common occurrence in service, it was considered desirable to determine what effect, if any, this surface hardening might have on the endurance properties of the steel adjacent to the cold-worked area.

Nine endurance-test specimens were taken, therefore, contiguously along the length of the rail on the same side from the positions marked G and Z in Figure 9. The Z position is identical with the Z position of tests on other rails. (Fig. 2.) The G position, however, was taken as near the gage corner as it was possible to machine out the test specimens, which was limited by the one-half inch diameter necessary for the tapered end of the specimen. The location of the test area corresponded approximately to the shaded area in Figure 9.

Rockwell B hardness tests on the heads of the broken specimens after test at points corresponding to the periphery of the minimum sections gave a maximum value greater than 100 (102.5) in only one instance, which indicates that the test areas of the several specimens were not in the work-hardened layer, but just beneath it.
The relation of location of test specimens to depth of cold working of the head is evident by comparing with Figure 10, which is a photograph of a section of the same rail deep etched in hot concentrated HCl, the surface of which was ground off slightly after deep etching. The cold-worked layer being more deeply attacked by the acid was not removed in grinding, and is therefore outlined approximately by the dark area at top of section.

The results of these endurance tests are given in Figure 11.

It is evident that the endurance limits of specimens from the G and Z positions are practically identical.

It may be concluded that the degree of cold flow of surface present in this instance has not affected the endurance properties of the steel along the adjacent section from which the G test specimens were taken.

It should be emphasized, however, that it is the endurance properties of the steel per se that are not affected, since machining out the test specimens will in large measure relieve internal stresses that may have been in the rail due to distortion by cold flow. Such internal stresses are probably not present, at least to the same magnitude, in the test specimens. It is known that the endurance limit of steel under reversed axial stresses is affected by the presence of initial stresses in tension or compression. The resistance of the rail,
Sketch of Surfaces and Measuring Points.

Figure 12

A, Method of sectioning rail for internal stress measurements
B, Distribution of internal stress in head of rail after service.  lbs/in.² c, compression; t, tension
therefore, to the fatigue stresses imposed in track might be different from the values indicated in Figure 11, depending upon the magnitude and relative direction of the internal stresses and the service stresses.

The degree of internal stress that may have been present in some of the rails is indicated by the results of tests described below under internal stress.

The data do show, however, that such maximum stresses as may have been developed in service in this instance did not cause incipient internal failure (shattering) of the steel. Had such occurred, a marked "scatter" of the results of the fatigue test would have occurred.

This is of special significance in view of the fact that the internal nuclei from which transverse fissures progress are found predominantly on the gage side of the rail.

It is of interest to note that the endurance limits shown in this case by a curve obtained from specimens taken contiguously along the length of the rail is in agreement with the results (fig. 5) obtained on tests of the same rail in which the specimens were taken across the section of the rail (fig. 2).

4. INTERNAL STRESS IN RAIL AFTER SERVICE

Rail No. L-17 showed the greatest amount of surface flow of the head. It was, therefore, used for the determination of the degree of internal stress that might be present in these rails after removal from service.

The ends of a section approximately 10 inches long were divided into six parts by cutting away about one-quarter inch as shown in Figure 12 (a). The raised surfaces were then ground and lapped flat and parallel and positions identified as shown in Figure 12 (b).

The distances between corresponding points on the end surfaces were then measured in the gage section of the Bureau of Standards.

The six parallel sections were then machined out of the head of the rail. The distances between corresponding points were then redetermined.

The results of the determinations are given in Table 3.

It is evident that the top surface of the rail as represented by the a sections was in compression in a longitudinal direction and the central portion of the railhead as represented by the d sections was in tension.

On the assumption that the modulus of elasticity of the steel is 30,000,000 lbs./in.² and that no bending occurred in the test sections, the internal stresses present in pounds per square inch in the rail were as given in Figure 12 (b) at the points indicated.
### Table 3.—Dimensional changes in cutting head of rail for determination of internal stress

<table>
<thead>
<tr>
<th>Position</th>
<th>Length Before cutting</th>
<th>Length After cutting</th>
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<td>Inch: +0.00318</td>
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<td>f</td>
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</table>

The fact that a change in length occurred in the sections machined out of the rail confirms a previous statement that the endurance limits, as determined on individual specimens removed from the rail, represent the properties of the steel probably relatively free from internal stress.

The internal stresses would, of course, add to or decrease the resultant maximum stresses imposed by service according to their direction, an internal tensile stress increasing the maximum resultant stress imposed in tension but correspondingly decreasing the resultant maximum stress in compression. Internal stresses merely produce a shift in the total range of stress in the rail.

### 5. Relation of Endurance to Tensile Properties

Tensile tests were made using standard 0.505-inch diameter test specimens with 2-inch gage length taken from the O position. The results, together with respective endurance limits and endurance ratios, are given in Table 4.

A comparison of the endurance ratios of serviced rails with those of new rail, as given in Tables 1 and 2, page 283, of previous report, shows that they have approximately the same average value of 0.41.
Endurance of Rail Steels after Service

6. SUMMARY OF RESULTS OF TESTS ON BALTIMORE & OHIO RAILS

A series of endurance tests have been made on specimens taken from eight A and B rails from four distinct heats which had been subjected to over 20,500,000 tons of traffic in track of the Baltimore & Ohio Railroad. Six of the rails were A and B rails from three special heats killed with aluminum and poured in sink-head ingots, from which similar tests had been made on new rail previous to service. The two other rails were B rails from a normal heat cast in standard molds.

Direct comparison of the results of the endurance tests on the steel from the serviced rails from the sink-head ingots with tests of the steel from new rail from the same heats was, therefore, possible. Comparison of the results of tests from the serviced rail from the standard ingots could be made with the results of similar tests on specimens from similar new rails from several standard heats.

The test rails were also chosen so that it was possible to determine the variation in endurance properties of specimens from rails from corresponding portions, A and B rails, of ingots from the same heat. Such comparison before service was not made.

The maximum difference noted in endurance limit between the rail steels from comparable positions in the ingots from the same heat after service was 3,500 lbs./in.² for the B rails from heat No. 19. In the three other instances, where comparison was possible, the differences were found to be 1,500, 750, and 250 lbs./in.², respectively.

The maximum difference found in the endurance limit between steels from serviced and unserviced rails from the same heat was also in heat No. 19, in which steel from the A rail before service had an endurance limit of 59,200 lbs./in.² and a B rail after service 53,500 lbs./in.², a difference of 5,700 lbs./in.². In the other instances the differences were much less than this, being less than approximately 2,000 lbs./in.² in each case.
The results of all endurance tests of serviced rails (fig. 7) indicated that the service conditions imposed caused no apparent change in the endurance properties of the steel; apparently no "overstressing" or "understressing" had occurred.

Tests were also made which showed that appreciable surface flow and hardening of the top of the rail in service did not affect the endurance properties of the steel in the head of the rail immediately below the work-hardened layer.

It is therefore indicated that the service stresses in the head of the rails were not greater than the endurance limit of the steel.

V. RESULTS OF TESTS OF RAILS AFTER SERVICE ON CANADIAN PACIFIC RAILWAY

1. ENDURANCE TESTS OF STEEL FROM RAILS FROM CANADIAN PACIFIC RAILWAY

The results of all endurance tests on rail steels returned from service on the Canadian Pacific Railway are given in Figures 13 to 16 plotted in the same manner as the similar data on serviced rails from the Baltimore & Ohio Railroad. Comparison of the results with tests of new rails before service is also made in the same manner.

In each case it is possible to make a direct comparison of the endurance properties of the steel from rails from similar positions (A and B rails) in ingots from the same heats both before and after service.
The results of the tests of specimens from the two A rails from heat No. 1 after service are given in Figure 13, together with the results from the A rail from a middle ingot of the same heat before service.

The endurance limits of 44,000 and 41,500 lbs./in.² shown by the serviced material are lower than the value of 47,800 lbs./in.² shown by the steel from the new rail from the same heat.

The difference in value between the two serviced rails of 2,500 lbs./in.² indicates the variation that may occur between rails from similar positions in different ingots within the heat, the service conditions having been the same. This is less than the maximum difference of 4,100 lbs./in.² noted (BC rail, heat 19) in similar tests of the rail from the Baltimore & Ohio. (Fig. 6.)

The lowest value obtained on similar tests of rails before service from all heats was 46,200 lbs./in.² except for the value of 41,000 lbs./in.² indicated by specimens taken contiguously (instead of from adjacent positions (fig. 2) from the U position of the B rail of heat 11 in the previous report (fig. 21, p. 293).

The data for the curve for the A rail from ingot No. 5 are relatively uniform and characteristic of homogeneous material. The data for the A rail from ingot No. 12 are also quite uniform except for the specimens from the Y position which indicate some inhomogeneity.

As was pointed out in the previous report on new rail (pp. 277, 289), this lower endurance value of the Y specimen might be expected and was found in new rails.

The cause for the lower values is not evident. The magnitude of the difference is not great. In view of the relatively small number of tests on new rail by which the range of endurance limits to be expected was determined, the fact that tests were made on only one A rail from this heat before service and the slightly lower value shown by the new B rail from heat 11 all indicate that equally lower values might have been found in new A rail from this same heat had tests been made.

It is, of course, possible that the lower values may be the result of “overstressing” in service. In view of the fact, however, that the specimens that did not fail could be restressed, as indicated in the figure, at values appreciably above their primary endurance limit proves that they were “understressed” as the result of testing and tends to support the above indications that the steel was not in an overstressed condition as removed from track previous to testing.

The results of tests on the specimens from the A rails from heat No. 3 are given in Figure 14.

The data on the steel from the rail from ingot No. 10 indicate an endurance limit of 52,000 lbs./in.², 3,000 lbs./in.² lower than the value indicated by tests of specimens from a new A rail from the same heat.
The individual tests showed some "scatter" indicative of inhomogeneity in the steel.

The test data for the steel from the A rail from ingot No. 21 of this heat showed a very marked "scatter," indicating a corresponding marked inhomogeneity of the steel. An endurance curve has been drawn through the plotted points showing two specimens that had not failed at approximately 44,000 lbs./in.² stress after more than 11,100,000 cycles of stress.

One of these specimens (Y) was restressed at 50,000 lbs./in.² and did not fail after an additional 11,000,000 cycles of stress. The stress was then increased to 55,000 lbs./in.², and the specimen had an endurance life equal to that shown by specimens from the new rail of this heat.

The other specimen, which was from a Z position (fig. 2), was restressed as indicated and finally failed at 60,000 lbs./in.².

A probable cause for the marked scatter of results was the presence of internal cracks in the rail when removed from track, as discussed later in this report.

The results of tests on the steel from the B rails from heat No. 1 are given in Figure 15. In both instances the "scatter" is quite marked. In fact, no endurance limit was determinable from the 12 test specimens from the rail from ingot No. 13, all specimens...
failing. The general trend of the data is indicated by the curve. It is noteworthy that failures occurred in several instances after a relatively large number of reversals of stress—in one instance after 9,000,000 cycles at 40,000 lbs./in.².

The wide "scatter" in this instance was also found to be due to the presence of internal cracks in the rail when removed from service.

In view of the wide scatter of results obtained, an additional group of six specimens was taken from another section of the same rail and tested independently. The results of these additional tests are also included in Figure 15, but distinguished from the first group by the vertical line through the open circle used to indicate the test results of the first group.

The results of the further tests show that the steel at the second location has an endurance limit of approximately 45,000 lbs./in.² and emphasizes the fact that the wide scatter shown by the first group was due to inhomogeneities (cracks) in the steel.

The endurance limit of 45,000 lbs./in.² indicated by the tests from the rail from ingot No. 8 is lower than that of the comparison rail but greater than the values indicated by the tests of the serviced A rails from the same heat.
Figure 16.—a Endurance curves of steel from B rails from heat No. 3 before and after service; b endurance curve of steel from E rail from ingot No. 21, heat No. 3.
The results of tests of specimens from the B rails from heat No. 3 are given in Figure 16 (a). The results in this series are similar to those for the B rails from heat No. 1 after service. (Fig. 15.) There is a marked “scatter” in both instances but particularly for the B rail from ingot No. 21, for which no endurance limit was determinable due to the scatter of results. The approximate trend of the endurance curve is indicated. The cause of this “scatter” was again found to be the presence of internal cracks, as discussed later.

Tests were made at a later date on six additional specimens taken from another section of the same rail. These, except for the Y specimen, gave quite consistent results, indicating an endurance limit of 50,000 lbs./in.²

The endurance limit shown by the tests from the rail from ingot No. 1 at 46,400 lbs./in.² is appreciably lower than the comparison rail steel tested before service but is slightly greater than was shown by one of the B rails from heat No. 1. (Fig. 15.)

Most of the specimens that did not fail during tests were restressed at values appreciably above their indicated respective endurance limits.

(a) CAUSE OF “SCATTER” OBSERVED IN ENDURANCE TESTS

Moore and Koomers⁶ state “Marked scatter of fatigue-test data for a metal may be interpreted as indicating nonuniformity of structure of the metal, dirty metal, metal with minute cracks in it, or badly segregated metal.”

It was thought that the wide “scatter” shown by the test specimens from several of the rails from heats Nos. 1 and 3 might be due to internal cracks in the rail. A careful examination was, therefore, made of some of the test specimens before testing. In specimen C32BY–2, which was from the Y position in the B rail from ingot No. 21 of heat No. 3 (fig. 16 (a)), a crack was apparent at a magnification of about 50 diameters on the surface of the specimen.

This specimen was placed in the fatigue-testing machine and run 10,000 cycles at 46,000 lbs./in.² The computed stress at the location of the crack was approximately 31,700 lbs./in.² Reexamination of the specimen showed that the crack had widened and extended in length to about 3½ mm around the circumference of the test specimen. The appearance of a portion of the crack after stressing is shown in Figure 17.

The specimen was replaced in the testing machine at the same load as previously, 46,000 lbs./in.², and failed at the location of the crack in a total of 155,000 cycles, as indicated in Figure 16.

It is obvious that in machining test specimens from the rails it is entirely a question of chance whether any cracks that might be

---

present would be located at the test section and at the surface or in the interior of the specimen where they would not be detected by visual examination of the polished surface before test.

This was confirmed by examination of specimen No. C32BY1, which failed prematurely, as is evident in Figure 16 (a), after 340,000 cycles at 47,000 lbs./in.²

One of the broken ends was cut longitudinally, polished, and examined microscopically. Several small cracks were found at positions indicated in Figure 18.

The crack at position A appeared appreciably larger than the others. It was approximately one-fourth inch from the surface of specimen and one-fourth inch from the fracture. No evidence of its presence could be found on the surface of the specimen.

A portion of this crack is shown in the photograph in Figure 19 (a). Another portion is shown in Figure 19 (b), obtained after appreciable regrinding and polishing. After etching it was apparent that the crack was principally transcrystalline in character, as is typical of fatigue failures. One portion, however, was apparently intercrystalline, as is evident in Figure 20, which shows the portion of crack included in circle in Figure 19 (b).

The significance of the intercrystalline character of a portion of the crack is discussed later in the report.

The broken ends of several other specimens which failed apparently prematurely were deep etched in hot hydrochloric acid. In every case transverse cracks were found on the surface of the specimen.

It may be concluded that the wide "scatter" of the test results in this and other rails was due to the presence of minute internal cracks in the rail when removed from service, these cracks causing the premature failure of the test specimens.

In order to confirm this conclusion some of the sections of the heads of several rails were cut as shown in Figure 21. The inner surfaces were polished and deep etched in hot concentrated hydrochloric acid and examined for cracks.

There is given in Figure 22 a photograph showing evidence of the internal cracks in the head of the B rail from ingot No. 21, heat No. 3. These were located in the mid section, somewhat above the

Figure 18.—Location of cracks found in specimen C32BY1 after test
Figure 17.—Portion of crack on surface of fatigue-test specimen from Y position in B rail from ingot No. 21 of heat No. 3 after 10,000 cycles of stress. $\times 100$
Figure 19

A, Micrograph of portion of crack at position A (fig. 18) unetched. × 250
B, Another portion after regrinding and polishing

232–2
Figure 20.—Micrograph of portion of crack included in circle in Figure 19, B, showing intercrystalline nature, 5 per cent picric acid. × 500

Figure 22.—Longitudinal section of head of B rail from ingot No. 21 from heat No. 3

Etched hot concentrated HCl 20 minutes. × 1
Figure 23.—Portion of a shatter crack found in B rail from ingot No. 1 of heat No. 3
Etched 2 per cent HNO₃. × 100
Figure 24.—Portions of cracks shown in Figure 23

A. Portion of crack indicated by arrow "A." × 500

B. Portion of crack indicated by arrow "B." × 500
Figure 25.—Crack in fatigue-test specimen from a new B rail, heat No. 3

Etched in hot concentrated HCl. X 25
junction of the head and the web, corresponding approximately to the Y position. (Fig. 2.) Similar cracks were found in a section from the B rail of ingot No. 1 from the same heat.

Detailed examination was made of some of these small transverse cracks. They were principally transcrystalline in nature, but it is believed significant, however, that at the points indicated by the arrows in Figure 23 and shown at 500 diameters in Figure 24 (a) and (b) that the crack has decidedly intercrystalline characteristics similar to that shown in Figure 20.

It is evident that, had a fatigue-test specimen been taken from the head of the rail in such a manner that this crack or any portion of it had been located in the test area of the specimen, it would undoubtedly have caused premature failure, as has been pointed out above.

A similar examination was made of a section of the head of the rail adjacent to that from which the fatigue-test specimens for the B rail from ingot No. 8, heat No. 1, were taken. No evidence of internal cracks was found. This would indicate, as might be expected, that internal cracks may be more or less localized in certain sections along the rail and explains the wide scatter of fatigue-test results obtained from one section of a rail while similar tests from another section are relatively uniform.

Figure 21.—Method of sectioning head of rail to determine presence of internal cracks. Cut along line AA.
In the results of the nick and break tests given in Table 12, page 328, of the previous report, it is of interest to note that a large number of the A rails showed evidence of pipe or segregation due to the fact that the hot tops used in pouring the ingots of these two heats were too small, as is discussed fully in that report.

It was thought that the presence of internal cracks found in some of the serviced rails from these two heats might be related to this fact. Accordingly, through the cooperation of Mr. Fairbairn, chief engineer of the Canadian Pacific, the D and the E rails from the same ingots of heats Nos. 1 and 3, respectively, were removed from track and sent in to the bureau for test.

These rails had been in track a longer time and, of course, had consequently been subjected to an appreciably greater tonnage of traffic.

The position in the ingot of these rails was such that they should have been free from any segregation effect incident to the too-small hot tops.

Endurance tests were made on these rails.

Results of tests on the D rail from ingot 13 of heat No. 1 have been included in Figure 15. These data also show appreciable scatter but indicate quite definitely an endurance limit at approximately 43,000 lbs./in.², slightly lower than that indicated by the second group of specimens from the B rail from the same ingot.

The "scatter," however, tends to show that the marked scatter shown by the B rail from the same ingot was not essentially related to the use of too small a hot top, but is apparently characteristic of the steel from this ingot.

The results of tests on specimens from the E rail of ingot No. 21 of heat No. 3 are given in Figure 16 (b). Except for the Y specimens, the scatter is small. The endurance limit is very definitely indicated at 52,500 lbs./in.², slightly greater than that shown by the second group of specimens from the B rail of the same ingot.

The results of all tests made on the Canadian Pacific rail have been plotted in Figure 27.

A comparison of these data with the similar data for the Baltimore & Ohio rail (fig. 7) emphasizes the very marked "scatter" of results of tests from the Canadian Pacific rail due to the presence of internal cracks in the rails.

A very careful examination was made of sections from rails L-15, L-17, and H-15 returned from service on the Baltimore & Ohio Railroad to determine if shatter cracks were present in these rails. That none were found tends to further confirm the conclusion that "scatter" in the Canadian Pacific rails was due to the presence of internal cracks.
Figure 26
A and B, Cracks in new B rail from heat No. 3, ingot No. 4, etched in hot concentrated HCl, × 1
Figure 28.—Transverse fissure in rail CN1 which failed in service

Figure 30.—Internal cracks in fissured rail (CN1)
Deep etched in hot HCl. × 1
The ability of some of the specimens tested at the lower stress values to withstand repeated stress at appreciably higher values is also indicated in Figure 27.

It must be borne in mind in considering the results of "restressing" tests that the apparent improvement in stress values is not necessarily entirely the result of the "understressing" of the test specimen but includes the difference in stress between the endurance limit of the specimen and the lowest stress at which the test was started.

Several of the specimens on which the tests were started at or slightly above 40,000 lbs./in.\(^2\) might, therefore, have run indefinitely at appreciably higher stresses. This is quite evident from the test of the specimen from the D rail of ingot No. 13 at 40,000 lbs./in.\(^2\) (Fig. 15.) Another specimen from this rail ran at 43,000 lbs./in.\(^2\) without failing. The fact, then, that the specimen that ran at 40,000 lbs./in.\(^2\) when restressed also ran without failure at 45,000 lbs./in.\(^2\) indicates a known definite increase from the understressing of only 2,000 lbs./in.\(^2\).

In the previous report there was evidence of appreciable "scatter" of the test results, notably in the Y specimens from the B rail of heat No. 3, as indicated in Figure 8 of the previous report (p. 281).

The end of one of these broken specimens from an unused rail that had failed prematurely was cut longitudinally, ground and
polished. Deep etching revealed the presence of internal cracks, as illustrated in Figure 25. In view of this, a section of the head of the B rail from ingot No. 11 of this heat which had not been in service was critically examined by slicing, grinding, and deep etching longitudinal surfaces parallel to the tread.

Evidences of cracks in this new rail were found and are shown in Figure 26 (a) and (b).

This evidence suggests that the cracks found in the rails after service may have been present in the rails before service. In the micrographs (figs. 20, 23, and 24 (a) and (b)) attention was directed to the intercrystalline nature of portions of the cracks.

In general, fatigue cracks are transcrystalline in nature; that is, they traverse the crystals. On the other hand, fractures produced at high temperatures are characterized by intercrystalline cracks. No other known source of intercrystalline cracking, save high temperature stressing, could be acting in this material.

The intercrystalline nature of a portion of the cracks shown in Figures 20, 24 (a) and (b), therefore, suggest the possibility that these portions of the cracks were present in the rail before service and acted as nuclei for the formation of the characteristic transcrystalline type of fatigue crack from service stresses.

The existence of cracks found in an unserviced rail from the same heat supports this hypothesis.

The effect of small internal transverse cracks on the endurance properties of a rail in service is evident. As previously stated and as shown for individual test specimens in this report (p. 210 and fig. 16 (a)), a crack will act as a stress raiser and cause failure under repeated stress at stress values considerably below the true endurance limit of the sound material.

The range of endurance limits shown by all tests of specimens from new rail before service in which the specimens were taken across the section of the head has also been indicated in Figure 27.

It is evident that in many cases the endurance limit of the rail steel after service is apparently lower than the lowest value indicated by the new rail of 46,000 lbs./in.²; the lowest limit indicated by the serviced rail is apparently approximately 42,000 lbs./in.².

It is of interest to note, however, that the endurance limit of steel from a new standard rail in which the specimens were taken contiguous from the U position was found to be about 41,000 lbs./in.², as shown in Figure 21, page 293, of the previous report, and indicated in Figure 27 of the present report.

Apparently, then, the lower limit of endurance indicated by the serviced rails is not less than may be present in some new rail.

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7 See previous report (B. S. Tech. Paper No. 363, p. 332, Table 13, footnote 2) for details of this rail.
2. SUMMARY OF RESULTS OF TESTS ON CANADIAN PACIFIC RAILS

A series of endurance tests have been made on specimens taken from 10 rails from 2 special heats which had been subjected to more than 12,000,000 tons of traffic in track of the Canadian Pacific Railway.

Similar tests had been made on new rails from the same heat before service so that the effect of service on the endurance properties could be determined.

The results of the endurance tests showed considerable "scatter," indicating marked inhomogeneity in the steel.

This marked "scatter" was found to be due to the presence of small internal transverse cracks, so-called shattered zones in the head of the rails.

Evidence was found which indicated that the shattered zones were probably present in the rails before laying in track.

The data indicated that where cracks were not present the endurance properties of the steel were not affected by service.

VI. RESULTS OF TESTS OF TRANSVERSE-FISSURED RAILS

In any discussion of the relation of fatigue strength of rail steels to the development of transverse fissures in service the obvious and important question arises as to what the endurance limit of a rail steel is that has displayed a transverse fissure in service.

Through the courtesy of Robert Job and C. B. Brown, chief engineer of operations, Canadian National Railway, a 10-foot section from each of the following rails, as described by Mr. Job, was obtained:

Rail No. 1.—Failed, due to internal transverse fissure. Manufactured by the Algoma Steel Co., 100-pound A. R. A., 1919–4, open hearth, section 120, heat 6169–19–B. Date of failure, December 4, 1927. Weight of rail, 100 pounds per yard; length of rail, 33 feet; location, 800 feet from mile board 10, Cornwall subdivision, St. Lawrence division, section 2. This rail broke due to transverse fissure.

Rail No. 2.—An adjoining rail removed for your examination. No fissure had been found in this rail. This also was a 100-pound section made by Algoma Steel Co., A. R. A., April, 1919, open hearth, heat 8148–1–A.

The rails were taken from adjoining positions in track and were said to have been subjected to the same conditions of service.

A photograph of the fissure is shown in Figure 28. It is also noteworthy that there is no marked flow of the top surface of the head of the rail as was apparent in rail L–15. (Fig. 8.)

Through the courtesy of E. A. Sperry, president, Sperry Development Co., both rails were examined in his laboratory with the Sperry rail flaw detector for internal cracks.

8 See footnote 4, p. 211.
The results of the examination were reported by Mr. Sperry as follows:

There are no fissures of the size of 1 per cent of the area of the head, or larger. A 1 per cent fissure is the smallest that we can locate with the facilities now at hand.

Mr. Sperry was requested to make the examination with the expectation that other fissures might be located and the endurance-test specimens then taken adjacent to them in order to determine the endurance properties of the steel in the rail at a section adjacent to internal cracks, incomplete fissures.

In view of the apparent freedom of the rail from other internal cracks, 12 fatigue-test specimens were cut from the fissured and unfissured rails in the usual manner (fig. 2) and their respective endurance limits determined. In the unfissured rail these were taken at a section approximately 8 feet from end of rail; in the fissured rail about 8 feet from the fissure.

The results of these endurance tests are given in Figure 29.

It is evident that the endurance limit of the steel from the fissured rail of 56,800 lbs./in.² is appreciably greater than the value of 44,200 lbs./in.² shown by the steel from the unfissured rail. In fact, the value of approximately 57,000 lbs./in.² shown by the steel from the fissured rail approaches the maximum limit of endurance values of 59,000 lbs./in.² (fig. 7) found for any of all the rail steels tested, and the value of approximately 44,000 lbs./in.² is nearer to the lower limit of endurance values of approximately 41,000 lbs./in.² (fig. 27) found for all rail steels tested.

It is apparent from the photograph (fig. 28) that the nucleus of the fissure is near the center of the head of the rail. In view of the data given from the tests of specimens from rail L-15 (p. 222) returned from service on the Baltimore & Ohio Railroad, it is certainly improbable that the nucleus of this fissure originated in service as a result of service stresses, especially when the relative freedom of surface flow of the head of the fissured rail is considered.

A section approximately 4 inches long of the fissured rail, about 7 feet from the fissure, was cut diagonally, as indicated in Figure 21, and the inner surfaces examined for internal cracks by deep etching in hot hydrochloric acid. Evidence of internal failure, shatter cracks, and an incipient fissure, was found as shown in Figure 30. These cracks were located approximately in the center of the head of the rail in the same relative location as the nucleus of the fissure (fig. 28).

The depth of these cracks was small, probably less than one-eighth inch, as measured by grinding off the surface and reetching until the larger ones disappeared. This indicates that the area was probably less than the limit of sensitivity of 1 per cent of the Sperry
The rail flaw detector, which explains their presence not being detected by this instrument.

A similar section taken from the rail immediately behind the fissure showed similar, but smaller, cracks. The endurance-test data were uniform in both cases, showing relatively little scatter except for the Y specimens; in one from the fissured rail and in both from the unfissured rail. In each case the specimen broke at approximately from one-fourth to one-half inch distance from the minimum section, indicating marked inhomogeneity.

The broken ends were deep etched in hot hydrochloric acid. That one from the fissured rail showed the presence of minute cracks in the heavier sections, indicating early failure was probably due to the presence of a crack similar to those indicated in Figure 30. Cracks were not evident in the specimens from the unfissured rail, and deep-etched sections of this rail did not indicate their presence. In one section, however, an unusually heavy segregated streak was apparent, as shown in Figure 31. This section was cut from the rail adjacent to the sections from which the endurance-test specimens were taken. The segregated streak occupied a position in the head approximately contiguous with that from which the Y specimens were taken. On deep etching the broken ends of the specimens a
similar segregated streak was apparent. Due to the curvature of the specimen, a satisfactory photograph could not be obtained. However, the fractured end of one of the specimens was ground flat and deep etched. The end of the segregated streak was apparent, as shown in the photograph in Figure 32. This section was approximately one-thirty-second inch back of fracture.

Undoubtedly the early failure of these Y specimens from the unfissured rail was due to the presence in the test sections of the segregated streaks.

Tensile properties of specimens from the O position of the fissured and unfissured rails were determined, using standard 0.505-inch diameter test specimens, and were found to be as given below.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength</th>
<th>Elongation</th>
<th>Reduction of area</th>
<th>Endurance ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissured rail (CN1)</td>
<td>136,000 Lbs./in.²</td>
<td>11.5 Per cent</td>
<td>14.5 Per cent</td>
<td>41.7 Per cent</td>
</tr>
<tr>
<td>Unfissured rail (CN2)</td>
<td>120,000</td>
<td>12.0</td>
<td>16.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

It is evident that there is no marked difference in the tensile properties of the two rail steels. The endurance ratio of the steel from the fissured rail has very nearly the average value obtained for all rail steels tested (Table 3), while for the unfissured rail it is the lowest value found for all tests made.

Chemical analyses were made on samples taken from the O position of both rails and the composition found to be as follows:

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissured rail (CN1)</td>
<td>.85</td>
<td>.72</td>
<td>.030</td>
<td>.040</td>
<td>.13</td>
</tr>
<tr>
<td>Unfissured rail (CN2)</td>
<td>.75</td>
<td>.73</td>
<td>.030</td>
<td>.030</td>
<td>.17</td>
</tr>
</tbody>
</table>

The relatively high endurance limit of the steel from the fissured rail, the relatively uniform results of the plotted test data for both the fissured and unfissured rail steels when free from cracks or inclusions, the fact that both rails were submitted to the same traffic, the presence of shatter cracks in the fissured rail and their absence in the unfissured rail, all tend to indicate that the transverse fissure, admittedly a fatigue failure, must have started from a preexistent nucleus.

Through the courtesy of Dr. M. E. McConnell, chief chemist, Pennsylvania Railroad, a rail was obtained which had failed due to a transverse fissure after the relatively short service of five months. This was a 130-pound P. S. rail from Bethlehem Steel Co. heat No.
Figure 31.—Section from unfissured rail (CN2) showing segregated streak

Figure 32.—Section of fatigue specimen (CN2-Y1) about one thirty-second inch behind fracture showing section of segregated streak similar to that shown in Figure 31 from same rail

Deep etched in HCl. X 3
Figure 33.—Transverse fissure in rail PO which failed in service. × 1

Figure 34.—Internal cracks in fissured rail PO
Deep etched in hot HCl. × 1
Figure 36.—Portion of crack shown in Figure 29. × 500
Arrow indicates probable intercrystalline portion
Figure 37.—A, B, portions of cracks shown in Figure 23. × 500

Arrows indicate probable intercrystalline portions
72284-8-C. Cushing\(^9\) has reported a detailed study of similar failures of rails from the same ingot and heat in which particular attention was directed to the presence of numerous shatter cracks.

A photograph of the fissure is given in Figure 33. Due to the relatively short life of the rail, the characteristic polished surface usually found in rails failing in a similar manner after prolonged service was not developed.

A longitudinal section of this rail taken approximately between 1 to 5 inches from the fracture was examined for internal cracks by deep etching in the same manner as previously described. Well-defined internal fissures were found, as is evident in Figure 34. Endurance tests were made on 12 specimens taken from this rail in the usual manner. (Fig. 2.) The results are given in Figure 35. It is evident that there is marked "scatter" of the test data, which was found to be due to the presence of internal cracks. A definite endurance limit for the steel, however, was indicated at approximately 67,500 lbs./in.\(^2\) This is the highest value for the endurance limit of a rail steel indicated by any of the steels from either serviced or new rails presented in this and the previous report.

The tensile properties were found to be as follows: Tensile strength, 148,000 lbs./in.²; elongation, 8.5 per cent; and reduction of area, 14 per cent.

The endurance ratio is then 45.5 per cent, or slightly higher than the average.

Chemical analysis of a specimen from the O position showed the composition to be carbon, 0.82 per cent; manganese, 0.82 per cent; phosphorus, 0.033 per cent; sulphur, 0.04 per cent; and silicon, 0.24 per cent.

The unusually high endurance limit of this steel, the failure of the rail after only five months’ service in track, the fact that rail steels having a considerably lower endurance limit are known to have given much longer service in track without failure or change in endurance properties, and the presence of cracks in the rail again favor the conclusion that transverse fissures develop from a preexistent nucleus, present in the rail before being subject to service.

As previously stated (p. 236), fatigue cracks are generally transcrystalline in nature; that is, they traverse the crystal. No evidence is available that fatigue failure ever occurs at the grain boundaries in ferrous materials under the frequencies of repeated stress, generally below 2,000 cycles a minute, commonly used in fatigue testing. On the other hand, fracture produced at elevated temperatures is characterized by intercrystalline cracks.

Waring and Hofammann,¹⁰ in their original study of shatter cracks, state that “the defects (cracks) in fissured rails were found to extend through the crystal as well as following the boundary lines”; that is, they were both transcrystalline as well as intercrystalline in nature, the former probably developing from the latter, which must have occurred while the metal was hot.

Detailed microexamination was made of the shatter cracks found in the transverse fissured rails CN1 and PO to determine if intercrystalline failure was present. The locating of any intercrystalline nucleus of a transcrystalline fatigue crack is of necessity rather doubtful, in fact largely a question of chance. The intercrystalline nucleus which is being sought is of microscopic dimensions and may quite possibly be destroyed and entirely lost during the necessary cutting, grinding, and polishing operations incident to the preparation of the specimen for microscopic examination. Rail CN1 had a carbon content very close to the eutectoid composition. The structure showed no free ferrite at the grain boundaries, which made it very difficult to determine boundaries between the pearlite grains. The micrograph shown in Figure 36 illustrates the general appearance of a portion of the crack shown in Figure 30. Along the section indicated it appears to be intercrystalline, but the evidence is not

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conclusive. The difficulty of determining grain boundaries in a steel of this structure is quite apparent.

Similarly, the structure of the steel in the fissured rail PO had no free constituent, making it difficult to determine the path of the fatigue crack, whether across or between the grains.

Figure 37 (a) and (b) show characteristic portions of one of the cracks shown in Figure 34, which at points indicated are apparently intercrystalline.

VII. SUMMARY AND CONCLUSIONS

A series of tests has been carried out to determine the effect of service on the endurance properties of rail steels.

In a previous report, data were given on the endurance properties of steels from new rails from 11 distinct heats. An hypothesis based on the phenomena of weakening by "overstressing" and strengthening by "understressing" was presented whereby it was considered possible to determine whether the steel of the rails in service was subjected to stresses greater or less than its endurance limit by a comparison of the endurance limits before and after service.

Through the cooperation of the Baltimore & Ohio Railroad and the Canadian Pacific Railway, a total of 18 rails from 6 heats tested before service and 1 heat not previously tested were removed from track after being subjected to over 20,000,000 and 12,000,000 tons of traffic, respectively. These were principally A and B rails.

The endurance properties were determined in the same manner as for the rail steels before service.

In the rails returned from service on the Baltimore & Ohio Railroad the endurance properties of the steel were found to be the same as before service.

Tests were also made to determine the effect of appreciable surface flow and consequent hardening of the top of the head of the rail in service on the endurance properties of the steel in that rail. No evidence was found of any weakening by "overstressing" or strengthening by "understressing" having occurred in the steel immediately below the work-hardened layer.

Comparative tests were also made on steel from a rail which failed in service due to a transverse fissure and a similar rail from an adjoining position in track which had been subjected to identical service but had not failed.

It was concluded that under the service conditions to which the rails were subjected on the Baltimore & Ohio Railroad the steel in the head of the rail was not subjected to fatigue stresses greater than its endurance limit.
The results of similar tests of rails after service on the Canadian Pacific Railway were not so definite in their indications. In many cases the test specimens showed a very marked "scatter" in endurance properties, indicating appreciable inhomogeneity in the steel. This "scatter" was found to be due to the presence of groups of minute transverse cracks, or so-called "shattered zones," in the rail as removed from service.

Microscopic examination showed the cracks to be principally transcrystalline, but in a few instances evidence was found of intercrystalline cracking which would not have been produced by alternating stress and therefore must have been formed in the metal while hot, before it was put into service.

Examination of a new rail from one of the same heats showed the presence of shatter cracks. Premature failure of a fatigue-test specimen from a new rail of the same heat was also found to be due to the presence of an internal crack.

Unless cracks were present the steel from rails after service gave, in most cases, endurance limits within the range of those obtained on steel from new rails.

Cracks were not found in the fatigue specimens or the etched sections of rails removed from track on the Baltimore & Ohio Railroad which had been subjected to over 20,000,000 tons of traffic as compared to about 12,000,000 tons for the Canadian Pacific rail, and, as previously stated, no detectable change in the endurance properties of the former was found. The conclusion was unavoidable either that the service on the Baltimore & Ohio rails had not created nuclei for fatigue failure or that the test sections of the endurance-test specimens did not happen to include such nuclei. Certainly no general deterioration of endurance properties occurred as a result of the service to which these rails were subjected or it would have become evident by a more general scatter of the test results.

The conclusion seems justifiable that the service stresses imposed on the Baltimore & Ohio rails were below the endurance limit of present-day rail steels containing the usual amount of nonmetallic inclusions or other internal defects but free from transverse cracks.

The endurance limits of the steel from the used Canadian Pacific rails, while in general within the limits found for the steel from new rails, did show in some cases an appreciably lower endurance limit than the steel from new rails from the same ingot position and heat, although these rails had carried less than 60 per cent as much traffic as the rails from the Baltimore & Ohio.

The scatter of the points on the endurance curves was greater for steel from the used than from the new Canadian Pacific rails from the same heats, and several early failures of test specimens were definitely correlated with cracks in the rail.
Transverse internal cracks, logical nuclei for fatigue failures, were found in the used rails, evidence that detectable deterioration of the rail may have occurred in service.

If there were evidence also that the Canadian Pacific rail had been subjected to track stresses greater than those imposed on the Baltimore & Ohio rails and if it could be shown that the new rails were free from internal cracks or other stress raisers, the results of tests on the steel from the Canadian Pacific rail would tend to support the theory that internal cracks and subsequent transverse fissures may originate in service.

However, the fact that transverse cracks were found in new rail from the same heats and the test results of the steel from the Baltimore & Ohio rails which had been subjected to over 60 per cent more traffic support far more strongly the theory of a preexistent nucleus (shatter crack) in the rail before placing in service, with the subsequent development of the characteristic fatigue failure of the transverse fissure.

The results of tests on specimens from a transverse-fissured rail and a comparison rail in which it was found that the endurance limit of the steel in the fissured rail was appreciably greater than that in an adjacent rail in track subjected to the same traffic confirms the conclusion that a transverse-fissure failure is not due simply to fatigue stresses developed in track. If this were the case, the rail steel having the lower endurance limit should have failed first. The fissure must have progressed from a stress raiser originally present in the rail. The presence of internal transverse cracks, as shown by deep etching in the fissured rail, and absence of similar cracks in the unfissured rail tend to show that one or more of these minute cracks acted as the stress raiser or nucleus of the transverse-fissure failure.

The absence of deterioration in the used Baltimore & Ohio rails with the absence of cracks in the Baltimore & Ohio rails, and the presence of deterioration in the used Canadian Pacific rails with the presence of cracks in the new Canadian Pacific rails, and the absence of cracks in the unfissured and presence of cracks in the fissured rail from the Canadian National Railroad, all appear to corroborate the statement of Moore and Kommers:11 "Transverse fissures seem to develop from some defect which is initially in the rail and which acts as the nucleus of a fatigue failure."

Whether or not this conclusion will ultimately be proved and accepted, the evidence for it is sufficiently strong to justify careful search for the metallurgical factors which tend to produce or to prevent the presence of initial defects which may develop into transverse fissures. Experimental work on one phenomenon met in rail

steel at high temperatures, which may have a possible bearing on the formation of initial defects, is now in progress at the Bureau of Standards.

VIII. ACKNOWLEDGMENTS

The authors wish to express their appreciation and thanks to E. Stimson, chief engineer of maintenance of the Baltimore & Ohio Railroad; J. M. R. Fairbairn, chief engineer of the Canadian Pacific Railway; Robert Job and the Canadian National Railway for their indispensable cooperation; and to Dr. H. W. Gillett, chief, division of metallurgy of the Bureau of Standards, for many helpful suggestions throughout the course of the investigation.

WASHINGTON, March 22, 1929.