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FATIGUE TESTS OF BUTT WELDS IN STRUCTURAL STEEL PLATES

BY

WILBUR M. WILSON

AND

ARTHUR B. WILDER

PUBLISHED BY THE UNIVERSITY OF ILLINOIS

URBANA, ILLINOIS
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ENGINEERING EXPERIMENT STATION

Bulletin No. 310

FATIGUE TESTS OF BUTT WELDS IN
STRUCTURAL STEEL PLATES

BY

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AND

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PUBLISHED BY THE UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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I. INTRODUCTION

1. Object and Scope of Investigation.—The object of the investigation described in this bulletin was to determine the fatigue strength of butt welds in structural steel plates. The plates were $\frac{3}{4}$ in. thick and from 5\(\frac{1}{2}\) in. to 6 in. wide at the middle where the weld occurred. For one series of 21 specimens the plates were of carbon steel, for a second series of 6 specimens they were of silicon steel. Part of the carbon-steel specimens and all of the silicon-steel specimens were welded with a manually-operated metallic arc; 6 of the carbon-steel specimens were welded by an automatic carbon-arc process.

Metallurgical studies were made of the welds and of the base plate adjacent to the welds to determine variations in the properties of the materials. Several specimens for which the fatigue failure occurred in the weld were examined to determine the path of failure.

2. Acknowledgments.—This investigation was made as a part of the work of the Engineering Experiment Station of the University of Illinois, of which Dean M. L. Enger is the director, of the department of Civil Engineering, of which Prof. W. C. Huntington is the head, and of the Department of Mining and Metallurgical Engineering, of which Prof. A. C. Callen is the head.

The carbon-steel specimens were contributed by the Chicago Bridge and Iron Company and the silicon-steel specimens by the Bethlehem Steel Company.

The fatigue tests were made by Frank P. Thomas and John V. Coombe, Special Research Assistants in Civil Engineering, working under the supervision of Wilbur M. Wilson. The metallurgical studies were made by W. H. Bruckner, Research Associate in Metallurgical Engineering, working under the supervision of Arthur B. Wilder.

II. FATIGUE TESTS

3. Definition of Fatigue Strength.—The fatigue strength of the welded joints has been arbitrarily taken as the maximum stress to which a specimen can be subjected 2,000,000 times without failure. For all tests, the specimen was subjected to an axial stress that varied from 0 to a maximum tension. For a test in which failure occurred at
other than 2,000,000 cycles, the fatigue strength corresponding to failure at 2,000,000 cycles was computed from the actual stress and the actual number of cycles for failure by the use of the empirical equation

\[ F = S \left( \frac{N}{2,000,000} \right)^{0.10} \]

in which \( F \) is the fatigue strength for failure at 2,000,000 cycles, \( S \) is the maximum unit stress in the stress cycle, and \( N \) is the number of cycles for failure.* The fatigue strength was determined on the basis of failure at 2,000,000 cycles rather than at a larger number of cycles because the tests are primarily of interest to the structural engineer, and not many structural members are subjected to more than 2,000,000 applications of the maximum load.

The fatigue strength corresponding to failure at other than 2,000,000 cycles can be obtained by the use of the foregoing formula by substituting for 2,000,000 the number of cycles for failure on which the fatigue strength is to be based. That is, the equation can be written in the form

\[ F_n = S \left( \frac{N}{n} \right)^k \]

in which \( F_n \) is the fatigue strength corresponding to failure at \( n \) cycles obtained from a test in which the maximum stress in the stress cycle was \( S \), and in which failure occurred in \( N \) cycles. The quantity \( k \) is an experimental constant for which the rather limited number of tests available indicate a value of 0.10 to be a good approximation. The empirical character of this equation and the limited amount of experimental data available for determining the value of \( k \) should not be overlooked. It is believed, however, that for a value of \( n \) of 2,000,000, and for values of \( N \) varying between 500,000 and 2,000,000, the error resulting from the use of the equation is very much less than the inconsistencies among tests of identical specimens.

The specimens were made in groups of three identical specimens each, and the maximum stress in the stress cycle was so chosen that, as nearly as could be estimated in advance, one specimen would fail at 500,000, one at 1,000,000, and one at 2,000,000 cycles. The fatigue strength corresponding to failure at 2,000,000 cycles was computed for each test, and the average of the three values thus determined was taken as the average fatigue strength of the group.

The fatigue strength as used in this bulletin is the total axial force divided by the area of the section of the plates connected. That is, it is the average stress on the transverse section of the plate just outside of the weld. It is realized, of course, that, due to stress raisers, there are small areas of the section where the unit stress is greatly in

*For a discussion of this equation, see Appendix B, Univ. of Ill. Eng. Exp. Sta. Bulletin
excess of the average. In addition to the stress raisers known to exist in small machined specimens of continuous metal that have been carefully annealed, welded specimens of rolled plates have additional stress raisers due (1) to the mill scale on the rolled surfaces, (2) to changes in section at the junction of the weld and the base plate, (3) to porosity of the weld, and (4) to gradients of metallurgical properties in the vicinity of the weld. The extent to which these stress...
<table>
<thead>
<tr>
<th>Kind of Plate</th>
<th>Chemical Composition</th>
<th>Physical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>0.15</td>
<td>0.061</td>
</tr>
<tr>
<td>Silicon steel</td>
<td>0.30</td>
<td>0.23</td>
</tr>
</tbody>
</table>

*As determined by drop of beam.
FATIGUE TESTS OF BUTT WELDS IN STEEL PLATES

TABLE 2
WELDING DATA; CARBON-STEEL SPECIMENS

<table>
<thead>
<tr>
<th>Bead No.</th>
<th>Diameter of Rod</th>
<th>Amperes</th>
<th>Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{3}{16}$</td>
<td>180</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{3}{16}$</td>
<td>190</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{3}{16}$</td>
<td>240</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{3}{16}$</td>
<td>330</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>$\frac{3}{16}$</td>
<td>380</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>$\frac{3}{16}$</td>
<td>360</td>
<td>35</td>
</tr>
</tbody>
</table>

TABLE 3
WELDING DATA; SILICON-STEEL SPECIMENS

<table>
<thead>
<tr>
<th>Bead No.</th>
<th>Diameter of Rod</th>
<th>Amperes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{3}{16}$</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{3}{16}$</td>
<td>230</td>
</tr>
</tbody>
</table>

Preparation of edge of plate: Flame cut 40 degrees double bevel; ground bevel surfaces to clean; set up plates with $\frac{3}{8}$-in. opening; pre-heated to approximately 175 deg. F.; welded with reversed polarity.

raisers are additive is one of the uncertainties affecting the fatigue strength of welded joints on which it was hoped these tests might throw some light.

4. Description of Specimens.—The shape and dimensions of the specimens and the location in the parent plate of the plates forming the specimen are shown in Fig. 1. The specimens were welded in groups of 3, and then flame cut and machined to size. By this procedure that portion of the bead at the beginning and end of the weld is not included in the portion of the weld tested. The chemical composition and physical properties of the plate material are given in Table 1. The carbon-steel specimens welded with a metallic are contained a single-V weld whereas the silicon-steel specimens contained a double-V weld. Data relative to the details of the welding operation are given in Tables 2 and 3 for carbon-steel and silicon-steel speci-
Table 4
Description of Specimens

<table>
<thead>
<tr>
<th>Kind of Weld</th>
<th>Finish of Weld</th>
<th>Specimen No.</th>
<th>X-Ray Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-Steel Specimens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic carbon-arc</td>
<td>As-welded</td>
<td>A1</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C1</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Stress-relieved by heat treatment</td>
<td>A2</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>One gas pocket</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C2</td>
<td>Few small pockets</td>
</tr>
<tr>
<td>Hand welded; shielded-arc metallic-arc electrode</td>
<td>Each bead peened</td>
<td>A3</td>
<td>Few small pockets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B3</td>
<td>Few small pockets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3</td>
<td>Few small pockets</td>
</tr>
<tr>
<td></td>
<td>Purposely poor weld</td>
<td>A4</td>
<td>Several gas pockets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>Slag</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C4</td>
<td>Slag</td>
</tr>
<tr>
<td></td>
<td>Stress-relieved by heat treatment</td>
<td>A5</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>One gas pocket</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5</td>
<td>Good</td>
</tr>
<tr>
<td>As-welded</td>
<td>A6</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C6</td>
<td>Slight undercut and gas pockets</td>
<td></td>
</tr>
<tr>
<td>Weld planed flush with base plate on both sides</td>
<td>A7</td>
<td>One gas pocket</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7</td>
<td>One gas pocket</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C7</td>
<td>Good</td>
<td></td>
</tr>
</tbody>
</table>

Silicon-Steel Specimens

<table>
<thead>
<tr>
<th>Kind of Weld</th>
<th>Finish of Weld</th>
<th>Specimen No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand welded; metallic-arc electrode</td>
<td>As-welded</td>
<td>A8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C8</td>
</tr>
<tr>
<td>Weld planed flush with base plate on both sides</td>
<td>A9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9</td>
</tr>
</tbody>
</table>

mens, respectively. A shielded-arc electrode was used for both the carbon-steel and the silicon-steel specimens.

The electrode used for the silicon-steel specimens was of the carbon-molybdenum low-alloy type and a representative analysis of deposited weld metal would be

Carbon...........0.10—0.12
Silicon...........0.10
Manganese.......0.64
Molybdenum.....0.40—0.60

As previously stated, the specimens were made up of groups of three identical specimens each. Each group had some feature that was characteristic of that group alone. These characteristics are given in
columns 1 and 2 of Table 4. Thus, for the series of two groups welded with the automatic carbon arc, the group characteristics were as follows: Group 1, as welded; group 2, stress relieved by heat treatment. For the series of five groups of carbon-steel specimens hand-welded with a shielded-arc electrode, the group characteristics were as follows: Group 3, each bead peened; group 4, purposely poor welds; group 5, stress-relieved by heat treatment; group 6, as welded; group 7, weld planed flush with base plate on both sides. Of the two groups of silicon-steel specimens, group 8 was tested in the as-welded condition, and for group 9 the weld was planed flush with the base plate on both sides. The specimens that were stress-relieved by heat treatment were held in the furnace at a temperature of 1200 deg. F. one hour and then cooled in the furnace.

All welds in the carbon-steel specimens were examined for flaws with an X-ray machine, and typical radiographs are shown in Fig. 2. White areas indicate flaws, the small, round areas indicate blow holes, and the larger, irregular areas indicate slag inclusions. An interpretation of these radiographs is given in Table 4. They indicate that all welds, except those which were purposely poor, were good commercial welds.

5. Description of Testing Machine.—The machine used for the tests is shown in Fig. 3. It was originally designed and constructed for use in an extensive series of fatigue tests of riveted joints that has been conducted by the Engineering Experiment Station, University of Illinois, in cooperation with the Department of Public Works, State of California.* The machine was designed to produce an axial force in the specimen and to operate on a stress cycle in which the axial force can be made to vary from 200,000 lb. tension to 200,000 lb. compression (—200,000 lb. tension). Moreover, either the maximum or the minimum stress can be varied independently of the other so as to produce any desired cycle, including a complete reversal, a partial reversal, or a pulsating stress, having any desired relation between the minimum and the maximum stresses. The only cycle that was used in the fatigue tests of the butt welds, however, was one in which the axial stress varied from zero to a maximum tension.

The essential features of the machine are shown in Fig. 3, from a photograph. The force that produces the stress in the specimen originates in the variable-throw eccentric and is measured by the dynamometer. This force is multiplied by the I-beam lever, which has a

---

*Reported in Bulletin 302, University of Illinois Engineering Experiment Station.
(a) Specimen C7
Typical of A6, B6, A5 and C5

(b) Specimen C6

Fig. 2. Radiographs of Butt Welds in Carbon-Steel Plates
Reduced to 0.8 original size
(c) Specimen A7
Typical of B7, B5 and B2

(d) Specimen A4

FIG. 2 (CONTINUED). RADIOGRAPHS OF BUTT WELDS IN CARBON-STEEL PLATES
Reduced to 0.8 original size
(e) Specimen B4

(f) Specimen C4

Fig. 2 (continued). Radiographs of Butt Welds in Carbon-Steel Plates
Reduced to 0.8 original size
(g) Specimen A3
Typical of B3, C3 and C2

(h) Specimen A2
Typical of A1, B1 and C1

Fig. 2 (concluded). Radiographs of butt welds in carbon-steel plates
Reduced to 0.8 original size
multiplication ratio of 18. The specimen is bolted to the pulling heads as indicated in the foreground. The I-beam lever is supported on bearings which provide for the free angular motion caused by the up-and-down movement of the outer end of the beam produced by the eccentric. Similar bearings are provided at the outer ends of both pulling heads so as to give the specimen freedom from angular restraint.

The procedure for beginning a test was as follows: The I-beam lever was placed in a horizontal position and the specimen bolted to the pulling heads, care being taken to have the specimen and the two pulling heads in proper alignment. After the bolts had all been tightened, the throw of the eccentric was adjusted to give the desired stress range, and the length of the connecting rod between the eccentric and the outer end of the I-beam lever was adjusted to give the proper relation between the maximum and the minimum stress. Both of these are cut-and-try processes, and the machine was cranked by hand while the adjustments were being made. The total force on the specimen to be used during a test was determined from the unit stress to be used and the dimensions of the particular specimen being tested. The corresponding deflection of the dynamometer was computed from
the total force on the specimen, the multiplication ratio of the lever, and the calibration constant for the dynamometer. With the required deflection of the dynamometer known, the machine was turned by hand and the stress range and the ratio of the minimum to the maximum stress were noted and compared with the desired values. If the two sets of values did not agree, and they seldom did on the first trial, the throw of the eccentric and the length of the connecting rod were changed and the dynamometer readings again noted. This process was repeated until the desired dynamometer readings were obtained. With a little practice the operator became quite proficient in making these adjustments and the process did not prove to be as tedious as its description indicates.

The machine was operated at a speed of 180 r.p.m. and ran day and night without an attendant. The load was checked and necessary readjustments were made twice each day. Usually, except for a few hours at the beginning of a test, the load remained very constant. The method of measuring the load is not extremely precise but it is believed that in general the indicated load on the specimen was accurate within 2 or 3 per cent. An experimental check* indicated that the inertia of the I-beam lever did not cause an appreciable error in the load as determined from the deflection of the dynamometer when the machine was cranked by hand.

6. Results of Tests; Carbon-Steel Plates.—The results of the tests of welds in the carbon-steel plates are shown in Table 5. For the specimens hand welded with a metallic arc, the fatigue strength of the specimens in the “as-welded” condition was 21,800 lb. per sq. in., and all specimens broke at the edge of the weld where there is a sudden change in section. Contrasted with this, the specimens for which the weld metal was planed flush with the base plate on both sides had a fatigue strength of 27,900 lb. per sq. in., and all specimens broke outside of the weld and at a considerable distance from it. The fatigue strength of the other three groups had values as follows: Specimens stress-relieved by heat treatment, 23,200 lb. per sq. in.; specimens having each bead peened, 22,300 lb. per sq. in.; and specimens with purposely poor welds, 20,600 lb. per sq. in. The number of tests available is not great enough to justify any final conclusions, but it is, nevertheless, of interest to note the relative standing of the various groups. Taking the fatigue strength of the group of specimens

*The load was checked by substituting a calibration bar for a specimen and measuring the elastic stretch of the bar while the machine was running. The value of the force computed from the stretch of the bar checked the value computed from the dynamometer reading within 1 per cent; see Bulletin 302, p. 52.
<table>
<thead>
<tr>
<th>Kind of Weld</th>
<th>Finish of Weld</th>
<th>Specimen No.</th>
<th>Stress Cycle 1000 lb. per sq. in.</th>
<th>Cycles for Failure thousands</th>
<th>Fatigue Strength lb. per sq. in.*</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic carbon-arc</td>
<td>As-welded</td>
<td>A1</td>
<td>0 to 30.0</td>
<td>220</td>
<td>24,100</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1</td>
<td>0 to 27.0</td>
<td>448</td>
<td>23,300</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C1</td>
<td>0 to 22.0</td>
<td>1201</td>
<td>21,000</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress-relieved by heat treatment</td>
<td>A2</td>
<td>0 to 28.0</td>
<td>1864</td>
<td>27,900</td>
<td>Broke in head; weld O.K.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>0 to 32.0</td>
<td>211</td>
<td>25,600</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C2</td>
<td>0 to 30.0</td>
<td>194</td>
<td>23,800</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand-welded; shielded-arc</td>
<td>Each bend peened</td>
<td>A3</td>
<td>0 to 30.0</td>
<td>213</td>
<td>21,000</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td>metallic-arc electrode</td>
<td></td>
<td>B3</td>
<td>0 to 24.0</td>
<td>900</td>
<td>22,200</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3</td>
<td>0 to 20.0</td>
<td>2727</td>
<td>20,700</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purposely poor welds</td>
<td></td>
<td>A4</td>
<td>0 to 26.0</td>
<td>503</td>
<td>22,700</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4</td>
<td>0 to 23.0</td>
<td>601</td>
<td>20,100</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C4</td>
<td>0 to 20.0</td>
<td>914</td>
<td>18,600</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress-relieved by heat treatment</td>
<td>A5</td>
<td>0 to 23.0</td>
<td>1030</td>
<td>21,600</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B5</td>
<td>0 to 26.0</td>
<td>633</td>
<td>23,200</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5</td>
<td>0 to 28.0</td>
<td>609</td>
<td>24,900</td>
<td>Broke at edge of weld and 2 in. from weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-welded</td>
<td></td>
<td>A6</td>
<td>0 to 26.0</td>
<td>300</td>
<td>21,600</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B6</td>
<td>0 to 22.0</td>
<td>927</td>
<td>20,400</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6</td>
<td>0 to 28.0</td>
<td>305</td>
<td>23,300</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld plane flush with base</td>
<td></td>
<td>A7</td>
<td>0 to 30.0</td>
<td>650</td>
<td>26,900</td>
<td>Broke 1 in. from weld</td>
</tr>
<tr>
<td>plate on both sides</td>
<td></td>
<td>B7</td>
<td>0 to 32.0</td>
<td>904</td>
<td>29,600</td>
<td>Broke 3 in. above weld and 1 in. below weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C7</td>
<td>0 to 28.0</td>
<td>1538</td>
<td>27,300</td>
<td>Broke 1.5 in. from weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Fatigue strength based on failure at 2,000,000 cycles in which stress varies from zero to maximum tension, and as computed by the equation \( F = S \left( \frac{N}{2,000,000} \right)^{1/6} \).
in the “as-welded” condition as 100, the rating of the other groups is as follows: Weld metal planed flush with the base plate on both sides 128, stress-relieved by heat treatment 106, each bead peened 102, and purposely poor welds 94. Planing off the excess weld metal so as to eliminate the sudden change in section appears to have had a greater effect on the fatigue strength than stress-relieving by heat treatment or than peening the beads. It is also of interest to note that the fatigue strength of the purposely poor welds is only 6 per cent less than the fatigue strength of the good welds in the “as-welded” condition. This, however, does not justify the use of poor welds. Other types of flaws might more seriously affect the fatigue strength of a joint.

The fatigue strength of the welds in the carbon-steel plates that were welded with an automatic carbon arc was 22,800 lb. per sq. in. for the specimens in the “as-welded” condition and 25,800 lb. per sq. in. for the specimens stress-relieved by heat treatment. These, rated on the same basis as that used in the previous paragraph, have a rating of 105 and 118, respectively. The average strength is a little greater for the specimens welded with an automatic carbon arc than it is for those hand welded with a metallic arc, but the difference is not great. The lowest individual value for the fatigue strength of the 18 welds in carbon-steel plates, not including the welds that were purposely poor, was 20,400 lb. per sq. in. for B6.

As stated in the foregoing, all of the specimens for which the weld was planed flush with the base plate broke outside of the weld. It so happened, however, that the failure occurred at a surface stress raiser in each instance. Strain-gage holes about \(\frac{1}{16}\) in. deep and drilled with a No. 54 drill were provided 1 inch from the center of the weld in both edges of the plate for specimens A7 and B7. Both of these specimens broke through these holes. Because of their effect on the fatigue strength, strain-gage holes were not provided for specimen C7. The number of the specimen, however, was stamped on the specimen about 1.5 in. from the center of the weld and the fatigue crack passed through this stencil mark. These facts are of interest in that they show the effect of small surface indentations upon the fatigue strength of plates.

In comparing the interpretation of the radiographs, given in Table 4, with the results of the fatigue tests of the individual specimens, given in Table 5, it is apparent that there is no consistent relation between the small flaws revealed by the radiograph and the fatigue strength of the specimens. This might be interpreted as indi-
cating that the effects of small internal stress raisers and external stress raisers, changes in section, mill scale, etc., are not additive. Even the large internal flaws indicated by the radiographs of B4 and C4, Fig. 2, did not greatly affect the fatigue strength of those specimens.

7. Results of Tests; Silicon-Steel Plates.—The details of the welds and the location of the plates in the parent plate are given in Fig. 1 and Table 3 for the specimens with silicon-steel plates. All specimens were hand-welded with a metallic arc. The first group was tested in the “as-welded” condition but for the specimens of the second group the weld metal was planed flush with the base plate on both sides. The results of the tests are given in Table 6. The fatigue strength of the two groups, the average of three tests in each instance, is 24 000 lb. per sq. in. for the first group, and 23 700 lb. per sq. in. for the second group. The fatigue strength appears to be less for the weld metal than for the base plate as evidenced by the fact that specimen 2 broke through the middle of the weld where the section was much larger than the section of the base plate outside of the weld. All of the specimens of the second group broke at the center of the weld possibly precluding any strengthening effect that might result from planing off the excess weld metal. The weakness of the deposited metal is also indicated by the metallurgical studies of Section 12. The strength of the welds was very nearly the same for silicon-steel plates as it was for the carbon-steel plates of Table 5.

8. Comparison of Fatigue Strength of Butt Welds in Plates with Fatigue Strength of Plates of Riveted Joints.—The engineer is interested, not only in the absolute fatigue strength of butt welds in plates, but also in the relative fatigue strength of welded and of riveted joints in plates. Bulletin 302 of the University of Illinois Engineering Experiment Station contains the results of a large number of fatigue tests of specimens of various shapes including (1) small, round machined and polished specimens; (2) plates with mill scale on two sides and machined on two edges, but with no holes or joint of any character; (3) plates with mill scale on two sides and machined edges and with a 1\(\frac{1}{2}\)-in. drilled hole in the center; and (4) plates of riveted joints. Specimens of these various shapes made of carbon steel, silicon steel and nickel steel were tested and reported on in Bulletin 302. The results of these tests are compared with the results of the tests of butt welds in Table 7. Of the tests of riveted joints, only those for which
### Table 6
**Fatigue Strength of Butt Welds in \( \frac{3}{4} \)-in. Silicon-Steel Plates**

<table>
<thead>
<tr>
<th>Kind of Weld</th>
<th>Finish of Weld</th>
<th>Specimen No.</th>
<th>Stress Cycle 1000 lb. per sq. in.</th>
<th>Cycles for Failure thousands</th>
<th>Fatigue* Strength lb. per sq. in.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand welded; metallic-arc electrode</td>
<td>As-welded</td>
<td>A8</td>
<td>0 to 27.0</td>
<td>353</td>
<td>22,800</td>
<td>Crack began at edge of weld and extended into base plate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BS</td>
<td>0 to 24.0</td>
<td>3015</td>
<td>25,100</td>
<td>Broke at center of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>0 to 26.0</td>
<td>872</td>
<td>24,000</td>
<td>Broke at edge of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av.</td>
<td></td>
<td></td>
<td>24,000</td>
<td></td>
</tr>
<tr>
<td>Weld planed flush with base plate on both sides</td>
<td>A9</td>
<td>0 to 33.0</td>
<td>284</td>
<td>27,200</td>
<td>Broke at center of weld</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B9</td>
<td>0 to 30.0</td>
<td>41</td>
<td>23,400</td>
<td>Broke at center of weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9</td>
<td>0 to 27.0</td>
<td>465</td>
<td>23,700</td>
<td>Broke at center of weld</td>
</tr>
</tbody>
</table>

*Fatigue strength based on failure at 2,000,000 cycles in which stress varies from zero to maximum tension, and as computed by the equation \( F = S \left( \frac{N}{2,000,000} \right)^{0.40} \).
### Table 7

**Fatigue Strength of Structural Steel as Determined by Tests of Various Types of Specimens**

<table>
<thead>
<tr>
<th>Type of Specimen</th>
<th>Strength lb. per sq. in.</th>
<th>Ratio of Fatigue Strength to Static Strength</th>
<th>Ratio of Fatigue Strength to Fatigue Strength of Polished Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static</td>
<td>Fatigue*</td>
<td></td>
</tr>
<tr>
<td><strong>Carbon Steel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round, machined and polished--------------</td>
<td>64 700</td>
<td>47 000</td>
<td>0.73</td>
</tr>
<tr>
<td>Plate with mill scale.---------------------</td>
<td>61 800</td>
<td>30 300</td>
<td>0.49</td>
</tr>
<tr>
<td>Plate with mill scale and 1½-in. drilled hole.</td>
<td>61 800</td>
<td>21 200</td>
<td>0.34</td>
</tr>
<tr>
<td>Plates of riveted joints.-----------------</td>
<td>63 800</td>
<td>25 000</td>
<td>0.41</td>
</tr>
<tr>
<td>Butt weld in ¾-in. plate.-----------------</td>
<td>34 500</td>
<td>24 000</td>
<td>0.43</td>
</tr>
</tbody>
</table>

(18 tests)

<table>
<thead>
<tr>
<th><strong>Silicon Steel</strong></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Round, machined and polished--------------</td>
<td>81 700</td>
<td>56 000</td>
<td>0.69</td>
</tr>
<tr>
<td>Plate with mill scale.---------------------</td>
<td>80 800</td>
<td>35 800</td>
<td>0.44</td>
</tr>
<tr>
<td>Plate with mill scale and 1½-in. drilled hole.</td>
<td>80 800</td>
<td>23 900</td>
<td>0.30</td>
</tr>
<tr>
<td>Plates of riveted joints.-----------------</td>
<td>80 200</td>
<td>25 600</td>
<td>0.30</td>
</tr>
<tr>
<td>Butt weld in ¾-in. plate.-----------------</td>
<td>80 700</td>
<td>23 850</td>
<td>0.30</td>
</tr>
</tbody>
</table>

(6 tests)

*Stress cycle, zero to maximum tension for all specimens. Each value is the average of four or more tests of round, machined, and polished specimens, of 18 tests of welds in carbon-steel plates, of 6 tests of welds in silicon-steel plates, and of 3 tests for all others.

there were identical specimens in carbon steel and silicon steel have been included. Of the tests of welds, all were included except those containing purposely poor welds. It is of interest to note that the carbon content and the ultimate strength were lower for the carbon steel used in the welded specimens than they were for the carbon steel used in the riveted joints.

The values reported in Table 7 indicate that the ratio of the unit fatigue strength to the unit static strength is practically the same for butt welds in plates as it is for the plates of riveted joints, the unit fatigue strength being based upon the gross width of the plates of welded joints and upon the net width of the plates of riveted joints.

### III. Metallurgical Studies of Welds

9. **Hardness Survey of Welds.**—The transverse section of a butt weld contains all metallographic structures of fundamental interest in this investigation. The hardness survey of a polished and etched transverse section provides an approximate index to the strength of the various metallographic structures observed in the weld and base plate.
Certain structures occupy a very small area, and it is by means of the hardness test that an indication of the strength of these small areas may be obtained. Sections from all welds were cut to convenient size for macro etching and hardness tests. A boiling 50-percent-water solution of hydrochloric acid was used for etching. Hardness readings were taken on the etched surface of the specimens with a Rockwell hardness testing machine.

The hardness results are summarized in Figs. 4 to 12. A photograph, normal size of each specimen, is shown after hardness testing. Parallel lines of hardness indents transversely across the weld and base plate were spaced one-fourth inch apart; the indents themselves were one-eighth inch apart. A series of hardness indents was also arranged through the center of the weld normal to the top and bottom surface of the weld. The Rockwell B scale (1/16-in. ball, 100-kg. load) was employed for all hardness tests. Hardness values have been arranged to coincide with the relative positions of the indentations on the photograph. A clear impression of the location and method of reporting hardness values will be gained by reference to Figs. 4 to 12.

The heat-affected zone of a weld is in general the most important area of interest with reference to the internal structure. This zone is located at the junction of the base plate and weld metal and lies within the base plate. It consists of that part of the base plate which has been affected by the heat from the welding operation. A variety of internal structures occur in the heat-affected zone because of the existence of a temperature gradient. The hardness of the metal in the heat-affected zone can be readily followed by referring to the photographs.

10. Heat-Affected Zone.—

Carbon-Steel Plates

Table 8 is a summary of the hardness values in the heat-affected zone of the base plate. It will be noted that the automatic carbon-arc weld plates of series 1 and 2 and the metallic-arc stress-relieved weld plates of series 5 are of practically the same hardness, in the heat-affected zone, as the original base plate. This fact may be observed by referring to Figs. 4, 5 and 8. The carbon-arc method of welding consists of butting two square-edged plates together without a gap and fusing them to each other by the heat of the electric carbon arc. The heat-affected zone in the automatic-carbon-arc weld consists of the original base-plate material adjacent to the base-plate material.
FATIGUE TESTS OF BUTT WELDS IN STEEL PLATES

Fig. 5: Hardness Survey of Carbon-Steel Welds—Series 2
Fig. 6. Hardness Survey of Carbon-Steel Welds—Series 3
Fig. 7. Hardness Survey of Carbon-Steel Welds—Series 4
FIG. 11. HARDNESS SURVEY OF SILICON-STEEL WELDS—SERIES 8
FATIGUE TESTS OF BUTT WELDS IN STEEL PLATES

TABLE 8
AVERAGE ROCKWELL B HARDNESS OF HEAT-AFFECTED ZONE IN BASE PLATE

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Hardness</th>
<th>Specimen No.</th>
<th>Hardness</th>
<th>Specimen No.</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>73</td>
<td>A4</td>
<td>79</td>
<td>A7</td>
<td>80</td>
</tr>
<tr>
<td>B1</td>
<td>71</td>
<td>B4</td>
<td>79</td>
<td>B7</td>
<td>77</td>
</tr>
<tr>
<td>C1</td>
<td>72</td>
<td>C4</td>
<td>78</td>
<td>C7</td>
<td>74</td>
</tr>
<tr>
<td>Av</td>
<td>72</td>
<td>Av</td>
<td>79</td>
<td>Av</td>
<td>77</td>
</tr>
<tr>
<td>A2</td>
<td>71</td>
<td>A5</td>
<td>71</td>
<td>A8</td>
<td>97</td>
</tr>
<tr>
<td>B2</td>
<td>67</td>
<td>B5</td>
<td>72</td>
<td>B8</td>
<td>99</td>
</tr>
<tr>
<td>C2</td>
<td>65</td>
<td>C5</td>
<td>73</td>
<td>C8</td>
<td>98</td>
</tr>
<tr>
<td>Av</td>
<td>68</td>
<td>Av</td>
<td>72</td>
<td>Av</td>
<td>98</td>
</tr>
<tr>
<td>A3</td>
<td>79</td>
<td>A6</td>
<td>79</td>
<td>A9</td>
<td>98</td>
</tr>
<tr>
<td>B3</td>
<td>76</td>
<td>B6</td>
<td>80</td>
<td>B9</td>
<td>98</td>
</tr>
<tr>
<td>C3</td>
<td>77</td>
<td>C6</td>
<td>78</td>
<td>C9</td>
<td>96</td>
</tr>
<tr>
<td>Av</td>
<td>77</td>
<td>Av</td>
<td>79</td>
<td>Av</td>
<td>97</td>
</tr>
</tbody>
</table>

which has been melted by the welding process. The heat-affected zone of the carbon-arc weld is heated in such a manner as to give a hardness value comparable to that of the heat-affected zone of the stress-relieved metallic-arc weld. The stress relief treatment applied to series 5 plates lowers the hardness values of the heat-affected zone. This treatment tempers the steel in addition to relieving stresses, hence the carbide particles agglomerate.

The remainder of the welds have an appreciable degree of hardness in the heat-affected zone, and this is caused by a fairly rapid rate of cooling. The metal in the heat-affected zone is heated above the critical range by the deposited metal. The base plate causes rapid cooling by conduction. The rate of cooling, and the application of heat after welding for stress relief, control the hardness of the heat-affected zone. The stress-relieved automatic-carbon-arc welds of series 2 have the lowest hardness values. This would be expected because of the low hardness values before stress relief.

**Silicon-Steel Plates**

The hardness of the heat-affected zone of the silicon-steel welds of series 8 and 9, as shown in Figs. 11 and 12, and as summarized in Table 8, was of the order of 97 or 98 Rockwell B whereas, for the base plate outside of the heat-affected zone, it was of the order of 83 or 84 Rockwell B. Although this is an appreciable increase in hardness, the increase is not of the magnitude usually considered to be harmful.

The real influence of the overheated zone upon the fatigue strength of welds is not generally known. In the case of high hardness values in the overheated zone as compared to those of the base plate, it is
<table>
<thead>
<tr>
<th>Series No.</th>
<th>Zones*</th>
<th></th>
<th>Series No.</th>
<th>Zones*</th>
<th></th>
<th>Series No.</th>
<th>Zones*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>75</td>
<td>75</td>
<td>3</td>
<td>85</td>
<td>80</td>
<td>82</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>77</td>
<td>4</td>
<td>85</td>
<td>79</td>
<td>87</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>79</td>
<td>74</td>
<td>81</td>
<td>92</td>
<td>90</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>86</td>
<td>81</td>
<td>85</td>
<td>92</td>
<td>90</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>79</td>
<td>78</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
possible that small cracks may have formed during cooling, or the zone itself may act as a metallurgical notch (stress raiser) and reduce the fatigue strength.

It should be observed that the silicon steel has a carbon content of 0.30 per cent and a manganese content of 0.91 per cent. The composition of the steel is of first importance with respect to the hardness of the heat-affected zone. Alloys very susceptible to heat treatment will show marked changes in properties after suitable treatment. The
difficulties in welding with respect to mechanical properties increase as the content of carbon or other alloying elements is increased. The influence of changes in chemical composition is clearly shown by comparing the hardness of the carbon-steel and silicon-steel plates. The silicon-steel base plates were preheated in an effort to lower the hardness values in the heat-affected zone. Preheating the base plate retards the cooling rate of the heat-affected zone because the rate of heat conduction from this zone is decreased. This preheating was not of sufficient magnitude to give a low hardness value in the zone affected. It is clear from the photographs that the heat-affected zone is readily susceptible to chemical attack by the etching reagent. This is an indication of the presence of carbon in the finely-divided state causing high hardness values.

11. Weld Metal.—

**Carbon-Steel Plates**

A summary of the hardness values of fused metal is shown in Table 9. Practically no difference in hardness exists between zone 1, which was first formed, and zone 2 of the automatic-carbon-arc welds of series 1 and 2. The structures, however, are quite different, as shown in Figs. 4 and 5, due to the normalizing treatment. The portion fused in welding was not very hard as compared with the original plate. This may be explained as being due to the method of welding. As a rule normalizing, if practicable, improves the physical properties of the weld. Although hardness may remain the same it is possible that other mechanical properties have changed. The chief factor that affects hardness is the rate of cooling, and we know that this has been retarded by the method of welding the specimens of series 1 and 2. It is evident from the macrostructure that a cast structure exists in the zone which has not been normalized. This is a rather definite indication that some of the mechanical properties may be improved by normalizing. In this discussion normalizing is thought of as the result of reheating steel above the critical range and cooling in air. This treatment causes a recrystallization of the metal and in the case of cast metal a refinement of the crystals.

Considering the remainder of the carbon-steel plates which have metallic-arc welds, it will be observed that marked hardness values have been obtained in some of the weld-metal sections. In general the center of zone 2 of the weld, see Fig. 13, has a lower hardness value than zone 1 or zone 3, particularly in the stress-relieved welds of series 5. The center section has been refined by the deposition of ad-
ditional weld metal. This fact is quite evident in the photographs of Fig. 15. When the center weld metal was deposited its hardness was no doubt in the range of that of the sealing bead. Stress relief or its equivalent, reheating by further deposition of weld metal, lowers the hardness values.

It should be pointed out that stress relief is obtained by heating to 1200 deg. F. or lower temperatures below the critical range. Normalizing or reecrystallization occurs when a metal is heated above the critical range. Weld metal may be normalized and retain a high hardness if the cooling rate is rapid enough. Other physical properties may be improved by the normalizing treatment even though hardness does not respond to the treatment. This is in part an explanation of the higher hardness values of the peened weld as compared with the stress-relieved weld. The hardness values for the weld metal of the carbon-steel plates of series 3 to 7 are in general higher than the hardness values in the heat-affected zone of the same plate. This may be accounted for on the basis of the chemical composition of the weld metal as compared with that of the base plate. For the same rate of cooling from above the critical range, steel with the higher carbon content will be harder.

Silicon-Steel Plates

Considering the silicon-steel-weld metal of series 8 and 9 in Tables 8 and 9, it is at once apparent that the weld metal is not as hard as the metal in the heat-affected zone of the base plate. These results are in agreement with what might be expected due to an increase in carbon content of the base plate. Assuming that the carbon content of the weld metal is similar to that of the base plate, it is at once apparent that the rate of cooling in the weld metal was not as rapid as in the heat-affected zone. The type of weld is somewhat different as compared with that for the carbon-steel plates. This fact may be observed by noting the macrostructure of the weld metal in Figs. 4 to 10, inclusive, of the carbon steel plates of series 1 to 7, inclusive, and Figs. 11 and 12 of the silicon steel plates of series 8 and 9. Although a butt weld is dealt with in both cases, the final results with respect to hardness are different. The preheating of the base metal in series 8 and 9 would tend to lower the hardness values of the weld metal due to slower rates of cooling. Diffusion of carbon from the base plate into the weld metal would have a tendency to raise hardness values of the weld metal. A lower carbon content in the weld metal than in the base plate would in general cause a lower hardness in the weld metal.
Fig. 14. Internal Structure of Carbon-Steel Weld No. C1
FIG. 14 (CONCLUDED). INTERNAL STRUCTURE OF CARBON-STEEL WELD NO. C1
12. Microstructure of Welds.—

Specimen No. Cl

The automatic-carbon-arc welds, series 1 and 2, of the carbon-steel plates were examined under the microscope. The as-welded specimens were quite similar to the stress-relieved specimens, and therefore only one specimen, No. C1, as-welded, will be critically discussed. The photographs of macrostructure and microstructure are shown in Fig. 14. The photomicrographs at 100 diameters are numbered 1 to 7, inclusive, and refer to locations as indicated on the photomacrograph at $1\frac{1}{2}$ diameters.

No. 1 of Fig. 14 represents the unheated base metal and shows a typical structure for hot-rolled 0.15-per-cent carbon steel. The grain size is fairly uniform. Banded structure is present to a limited degree and the pearlite consists of fine plates. It is evident that heat treatment may produce a more uniform structure, although indications of banding would remain. The finishing temperature for hot rolling was apparently satisfactory.

No. 2 represents that portion of the unfused base plate that has undergone partial transformation. Small grains of ferrite surrounding the larger grains are evident. The banded structure has been intensified. Small pearlite grains are adjacent to small ferrite grains. The structure is a product of a thermal gradient.

No. 3 is a photomicrograph of material at the junction of the fused and the unfused portions of the base metal. The upper part of the photomicrograph shows a coarse crystalline structure, with indications of the Widmanstatten type of structure. This coarse structure is the last-fused base metal and is not unlike a cast structure. The lower part of the photomicrograph represents the unfused base metal which has been heated to a high temperature. The base metal consists chiefly of large ferrite grains.

The structure shown in No. 4 is interesting because it represents the junction between the two zones of the fused base metal. The upper part of the photomicrograph represents the last zone to be fused, and shows a coarse structure. The lower part of the photomicrograph represents recrystallized metal which exhibits evidence of grain growth. This type of structure would be expected under the conditions encountered during welding.

No. 5 shows a structure that is desirable. This metal was originally coarse crystalline. Due to the reheating caused by the formation of the last zone, the steel has recrystallized, but, unlike the material of No. 4, the grains did not grow after recrystallization.
Fatigue Tests of Butt Welds in Steel Plates

No. 6 represents material from the junction between the first zone and the unfused base metal. The structure to the left of the photomicrograph is that of metal from the first-fused zone which has been recrystallized. The crystal size is quite similar to that shown in No. 5. The metal corresponding to the right of the photomicrograph represents unfused base metal which has been recrystallized but under conditions permitting grain growth. The unfused base metal of No. 6 before the second zone was formed was not unlike the No. 3 unfused base metal. The formation of the second zone caused recrystallization of unfused metal that had already been recrystallized by the welding operation of the first zone.

No. 7 represents the last zone. The type of structure shown is representative of cast metal with long columnar grains, and has the appearance of a Widmanstatten type of structure.

Specimen No. C3

The hand-welded shielded-metallic-arc welds of the carbon-steel plates were examined under the microscope. The structures of the welds were nearly all alike with the exception of the structure shown in Fig. 16, which will be described later. Due to the similarity of all welds, specimen No. C3, Fig. 15, was chosen for the photomicrographs. The base plate structure was not unlike that described in Fig. 14. The photomicrographs are at 100 diameters and the macrograph at 1½ diameters.

No. 1 of Fig. 15 is from base plate material at the junction of the heat-affected zone and the unaffected base-plate material. The bottom of the photomicrograph shows pearlite which has been partially transformed; the upper part shows pearlite which has passed through the transformation temperature. The ferrite grains in each case remain unaffected. The banded structure is intensified. It will be observed that the material which has undergone transformation consists of very small grains while the large ferrite grains remain unchanged.

No. 2 represents base-plate material which has been recrystallized. Slight evidence of banding is present. The photomicrograph represents material which has been subjected to a double normalizing treatment. The first normalizing treatment due to the original bead adjacent to the base plate produced a material with a much larger grain size than is present in the photomicrograph. Additional layers of weld metal heated the base plate so that it passed through the critical range again, with the formation of a fine grain structure. If the temperature had been higher the crystals would be larger.
Fig. 15. Internal Structure of Carbon-Steel Weld No. C3
FATIGUE TESTS OF BUTT WELDS IN STEEL PLATES

Fig. 15 (concluded). Internal Structure of Carbon-Steel Weld No. C3
No. 3 shows weld metal which has been recrystallized by the heat from an adjacent bead. The material has had sufficient heat to permit slight grain growth.

No. 4 shows weld metal in the center of a heat-treated bead. This structure consists of very small crystals of ferrite and pearlite due to the fact that it was not overheated during the recrystallization process.

No. 5 depicts metal from the junction between the last bead and the previously laid bead. The top of the photomicrograph represents weld metal with large columnar grains. The structure is similar to that of cast metal. The lower part of the photomicrograph represents weld metal originally like that shown in the upper part of the photomicrograph, but recrystallized with some grain growth.

No. 6 shows large columnar crystals in the last bead to be deposited. This material has not received heat treatment. By comparison with No. 4 the effect of heat treatment is emphasized. The structure has indications of the cast Widmanstatten pattern.

No. 7 shows metal from the junction between the lower bead and the base metal. The lower part of the photomicrograph is base plate which has been recrystallized and overheated. The upper part is weld metal with large columnar grains. Columnar structure and Widmanstatten pattern are present in the weld metal.

No. 8 is a photomicrograph of the base plate which shows a continuation of the structure shown in No. 7. The large grain structure gradually tapers into recrystallized-fine-grain metal.

Specimen No. C5

The structures shown in Fig. 15, although those of peened welds, were characteristic of all the hand-welded-shielded-arc welds with the exception of the structure shown in Fig. 16 at 100 diameters. In the middle of the weld, Fig. 15, No. 4, a very fine grain structure is shown. This structure has the characteristics of a peened weld. The remainder of the welds at this location were different from the peened welds. The structure of the unpeened welds, shown in Fig. 16, has slight indications of the original columnar structure. If this specimen had been peened all traces of the original Widmanstatten structure would have been removed by the cold-working operation. Fig. 16, therefore, represents a structure with a slight amount of banding and is what would be expected in the case of normalized weld metal in the center of a bead which has not been peened.
Representative photographs of the butt welds in silicon-steel plates are shown in Fig. 17. The macrograph is at $1\frac{1}{2}$ diameters and the photomicrographs at 100 diameters. All the specimens in this group were hand-welded with a shielded-metallic-arc electrode.

No. 1 of Fig. 17 is a photomicrograph of the base plate which is characteristic of hot-rolled material with 0.30 per cent carbon and 0.91 per cent manganese. Ferrite and fine pearlite are present in the structure. The grain size is not as uniform as would be found in properly normalized material. The ferrite areas within the pearlite grains are due to hot rolling.

No. 2 shows metal from the base plate at the junction of the unaffected and heat-affected zone. The top of the photomicrograph is base-plate material which has been slightly changed by heat from the weld bead. The lower part represents a more distinct change in the pearlite grains with the network of ferrite being retained. This photomicrograph represents a gradual transition in the heat-affected zone with pearlite grains responding to heat treatment before the network of ferrite.

No. 3 shows metal from the junction between the heat-affected zone of the base plate and the middle of the weld metal. The left part of the photomicrograph represents weld metal and the right represents base metal. In both cases the metal has responded to heat treatment with the production of small-grain-size material.
FIG. 17. INTERNAL STRUCTURE OF SILICON-STEEL WELD NO. A8
FIG. 17 (CONTINUED). INTERNAL STRUCTURE OF SILICON-STEEL WELD NO. A8
No. 4 shows metal from the center of the weld metal. The weld metal has been recrystallized by the beads adjoining it, and the structure produced has a very small-grain size.

No. 5 shows metal from the junction between two weld beads. The top of the photomicrograph shows weld metal which has been completely recrystallized and the bottom weld metal which has undergone partial recrystallization. The recrystallization observed is caused by the adjacent weld beads.

No. 6 represents the last bead deposited and shows large columnar grains characteristic of deposited weld metal. The weld metal has received no heat treatment.

No. 7 shows weld metal with large columnar grains at the top of the photomicrograph. The lower part of the photomicrograph shows base metal with large crystalline grains. The base metal has been overheated and cooled rapidly. The rapid cooling produced carbide dispersion throughout the grain within a network of ferrite. This structure is commonly called the network structure, and is found in ferrous materials which have been subjected to a similar heat treat-
Fig. 18. Location of Failure in Test Specimens
Fig. 19. Macrostuctures of Cross-section of Welded Portion of Test Specimen Shown in Fig. 18.
FATIGUE TESTS OF BUTT WELDS IN STEEL PLATES

Fig. 19 (concluded). Macrostructures of Cross-section of Welded Portion of Test Specimen Shown in Fig. 18.
ment. It is evident that a trace of Widmanstatten structure continues to persist.

No. 8 is a photomicrograph of refined base plate metal. A network structure is present, indicating rapid cooling, and the grain size is rather uniform with some indications of grain growth.

No. 9 is from the base metal near the center of the weld. The left (light area) of the photomicrograph is base metal which has received a double normalizing treatment. The metal at the right of the photomicrograph (dark area) is recrystallized base metal which has received one normalizing treatment.

13. Types of Fatigue Failures.—

Carbon-Steel Specimens

The location of failure and macro sections are shown in Fig. 18. Photomacrographs in Fig. 19 are from the locations indicated in Fig. 18. With the exception of specimen A7, in which the weld has been planed flush with the base plate on both sides, the failure began at the junction of the base plate and weld metal.

The failure with respect to the outside surface followed the junction of the base plate and weld, with the exception of specimens C1, A4, and A7. The path of failure within the weld did not follow the junction between the weld metal and base plate. The photomacrographs indicate that the path of failure within the weld was nearly perpendicular to the outside surface of the weld and hence passed through the base metal. The failure at the junction of the base metal and weld is due to the change in cross section and not to the metallographic structure. If the overheated zone was a factor the failure would follow this zone within the weld.

The gauge mark on Specimen A7 acted as a stress raiser and caused the failure to occur as indicated in Fig. 18. Because of this stress raiser, the fatigue strength of the base plate was lower than the fatigue strength of the overheated zone or weld metal.

With reference to the carbon-steel specimens it appears that the base metal and changes in cross section are controlling factors governing fatigue. It has been shown that the weld metal and the heat-affected zone had variations in internal structure and hardness, but with all the variations in internal structure, it is important to observe that this factor had no appreciable effect upon the fatigue properties. Variations in weld rod might influence the results.
Silicon-Steel Specimens

The nature of several failures in silicon-steel specimens are shown in Figs. 18 and 19. Specimen No. A8 is not unlike the carbon-steel specimens in that failure occurred at the junction of the weld metal and base plate. The path of failure within the specimen was nearly perpendicular to the surface and did not follow the overheated zone. The stress concentration at the surface of the weld was the controlling factor. The internal structure of the weld did not influence the path of failure. If one surface had been planed flush with the plate, it is possible that the internal structure and properties of the weld or overheated zone might have had an influence on the path of failure.

Specimen No. A9 in which the weld was planed flush with the base plate on both sides is the most interesting failure from the viewpoint of internal structure. It will be observed that the failure originated in the weld metal. An examination of the photomacrograph clearly indicates that the junction between the weld metal and base plate within the specimen formed part of the path of failure. Although the failure did not confine its path to the overheated zone it is apparent
that certain parts of this zone offered less resistance than others to fatigue failure.

It would appear from an examination of Specimen No. A9 that the weld metal and heat-affected zone were controlling factors governing fatigue. This would be expected after considering the composition of the base plate. From the fatigue results for all specimens of the silicon-steel series it would appear that the influence of abrupt change in section and the weakness of the weld metal were about equally responsible for fatigue failure. If the change in section caused a lower fatigue value than was found for the machined specimen, it would be practical to consider grinding the surface of welds. The composition of weld metal and base plate are controlling factors which govern the advantages to be secured by machining.

The nature of a fatigue failure with respect to the position of the nucleus is shown in Fig. 20. The section examined shows three nuclei. The major nucleus was located in the center of the weld at the junction of the weld metal and base plate. This type of failure is not associated with the specimens in which failure began on the outside surface at the junction of the base plate and weld metal. Several failures of this latter type, Fig. 18, No. A8, were examined and no internal nucleus was present on the fractured surface. Instead, the nucleus was probably located at the junction of the weld metal and base plate on the surface of the specimen, where the change in section acted as a stress raiser across the full width of the specimen.

IV. Conclusions

14. Conclusions from Fatigue Tests.—The number of tests made in connection with this investigation is not great enough to justify final conclusions relative to the fatigue strength of butt welds in structural plates, and such tendencies as are indicated should be verified by additional tests. The tests reported in Tables 5, 6 and 7, however, seem to indicate:

(1) The fatigue strength in lb. per sq. in. of the joints in carbon-steel plates in the “as-welded” condition was reduced by the stress concentration at the edge of the weld due to the change in section, and it can be increased by planing off excess weld metal.

(2) The fatigue strength of welds of carbon-steel plates was slightly greater for specimens welded with the automatic carbon arc than it was for those welded with the hand-operated metallic arc, but the difference was not great.

(3) The fatigue strength of the filler metal was less than the
fatigue strength of the base plate for the silicon-steel specimen. The electrode used is only one of many alloy electrodes available, and the foregoing statement is not necessarily applicable to all. Additional tests of welds of silicon-steel plates for which other electrodes are used are highly desirable.

4) Peening the beads had practically no effect, and stress relieving by heat treatment had but little effect upon the fatigue strength of the welds.

5) The ratio of the fatigue strength to the static tensile strength was about the same for properly made butt welds in the “as-welded” condition as it was for a plate in a double-strap riveted joint of balanced design, the former being computed on the basis of the gross section and the latter on the basis of the net section. This statement applies to both carbon-steel and silicon-steel plates.

15. Conclusions from Metallurgical Studies.—The results of the metallurgical studies may be summarized as follows:

1) The carbon-steel welds, with the exception of the automatic-carbon-arc and stress-relieved welds, showed an appreciable increase in the Rockwell B hardness in the heat-affected zone of the base plate. The silicon-steel welds exhibited a greater hardness in the heat-affected zone than the carbon-steel welds, but they were not excessively hard.

2) The weld metal in silicon-steel specimens was not as hard as the heat-affected zone of the base plate. The weld metal in carbon-steel specimens gave hardness values equal to or slightly exceeding the values obtained in the heat-affected zone of the base plate.

3) Photomicrographs of the heat-affected zone in the base plate and weld metal indicate a variety of structures depending upon the heat treatment. Peening followed by recrystallization destroys the last trace of original columnar structure. The macrostructure is directly related to the microstructure, and clearly indicates various zones in the specimen.

4) A change in section (stress raiser) and the fatigue strength of the original unaffected base plate, are the chief factors governing fatigue failure in carbon-steel specimens. Low fatigue strength of the weld metal and changes in section appeared to be about equally important as factors tending to cause fatigue failure in the silicon-steel specimens tested. The overheated zone was adjacent to part of the path of failure in the silicon-steel specimens which failed in the weld. Hence grinding the surface of silicon-steel welds did not increase the endurance limit. In the absence of surface geometrical stress raisers, nuclei within the specimen cause fatigue failure.
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