# A STUDY OF THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ARC WELDED JOINTS

by

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Director of Thesis Date

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# CHAPTER I

## INTRODUCTION

There has been much work done on deposited weld metals where the entire specimen was deposited metal but there is no authentic information available on the relation between strengths and grain size in the weld zone. It seems then that the following investigation would be of some value to the Engineering profession.

Fusion welding is a comparatively new process and much remains to be learned of its possibilities.

> "Metallurgy of low carbon steel arc welded joints. The essential feature of the fusion welding process is the melting and solidification of small volumes of metal and the flowing of these together to form a unit piece. The bead of deposited metal may or may not be subjected to hot working and heat treatments during welding, by deposition of subsequent beads or peening, or by annealing after welding. The metallurgy of fusion welds may therefore by subdivided into the following headings:
>
> 1. Changes in chemical composition in the molten state.
>
> 2. Microstructure of the fused weld metal produced by the high temperatures of the fusion zone.
>
> 3. The variation in mechanical properties of welded joints due to the varying grain structures."[1]

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1. *A. W. S. Hand Book*, p. 430.

The following work, divided into two parts, is an attempt to correlate the mechanical properties of the varying grain structure and their position in the heat affected zone:

1. Work establishing the grain gradient.

2. Tests and micro examinations to determine the grain sizes and mechanical properties at different points of the heat zone. Microphotographs of areas and sections will be shown throughout.

## CHAPTER II

## GRAIN GRADIENT

A low carbon boiler plate of 5/8" thickness was grooved to 1/2" depth and a 60 degree angle the length of the plate. The plate was of sufficient width to allow the base metal to establish a normal heat gradient. Welds were made in the groove with two popular welding rods manufactured by one of the largest producers of electric welding equipment. One was a general purpose rod and will be designated as Rod #1, the other designed for poor fit ups of parts to be joined and is given the number "2".[1] Both were medium coated electrodes. Six specimens were made with each rod. Three with single pass welds and three with multiple passes. Cross sections were then cut through the welds and base metal and the surfaces polished and etched with a 2% solution of $HNO_3$ in alcohol.

Three specimens were made for each type of weld from which a typical one was selected by microscopic inspection for the photographs of microstructure. A Bausch Lomb and Zeis microphotographic camera was used. Pictures were taken at 100 diameters magnification throughout the weld and heat

1. As this work will be open to the public it would not be ethical to use trade names.

zone to show the grain structures. These were checked with the specimens not photographed to see that they corresponded.

Pictures of the single pass welds will be shown as they are more typical and show the grain gradient much more clearly than the multiple pass welds.

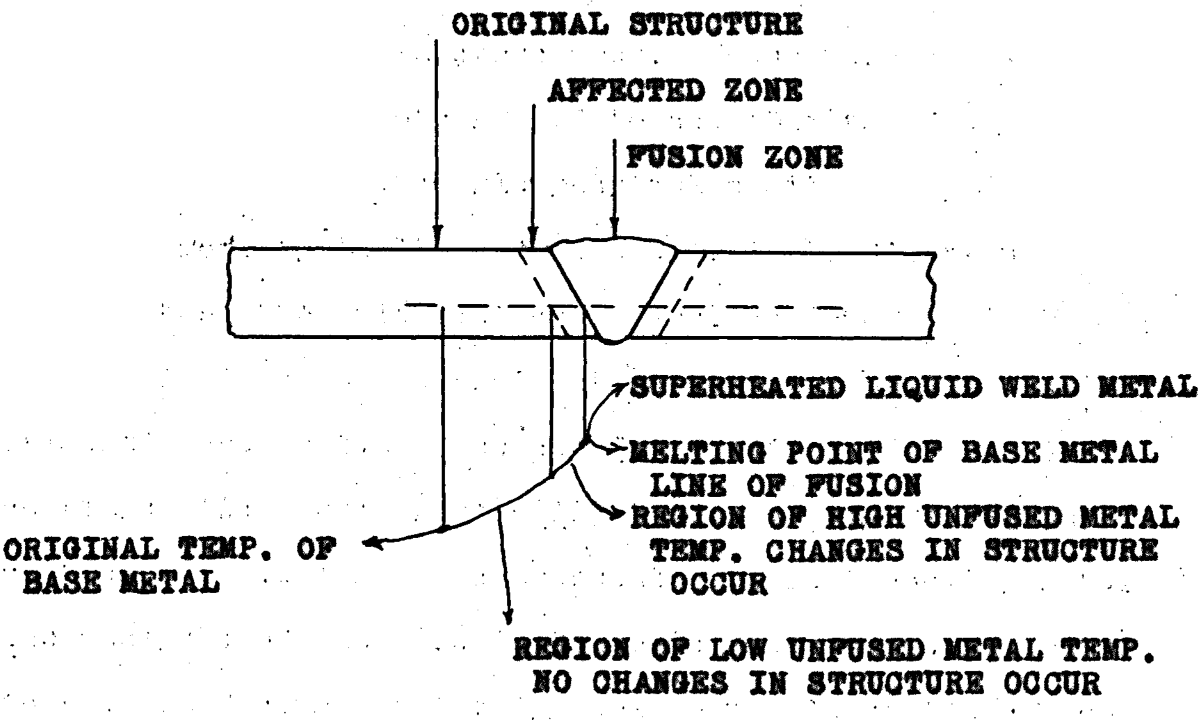
Variations in the grain structure of the two rods is evidently due to the presence of metallic oxides in the coatings which would give a lighter or heavier slag deposit on the weld metal and a consequent different cooling rate. The analysis of the wire in the rods is the same according to the manufacturer but they would not release the composition of the coatings beyond the fact that they were high in metallic oxides. Spectroscopic analysis indicates that these oxides are principally manganese and titanium. The object of the manganese and titanium is to obtain a deposited metal that is high in tensile strength as well as high in ductility.

Photographs and microscopic examination show definitely that there are the following varying grain structures in the weld and heat zone:

1. A coarse grain area in the center of the weld.

2. A small grain area just outside the fusion zone.

3. An area of grain growth in the high critical area of the base metal.




SKETCH A.

Fusion welding involves the heating of the joint edges of the base metal to at least the melting temperature and the formation of a continuous molten pool between the molten surfaces. The heat application is localized establishing thermal heat gradients in the base metal from the melting temperature at line of fusion to the temperature of the base metal at some distance from this line of fusion. Cooling along this gradient occurs rapidly giving different grain sizes beginning with the very small grain of the chill ring at the line of fusion with grain size increasing along the gradient toward the cold plate. The fine grain structure at the line of fusion is called the chill ring and is caused by the quenching action of the cold base metal on the adjacent edges of the molten pool. Sketch (A) shows the affected zones. The area of superheated liquid weld metal cools rapidly, the heat being absorbed by the cold base metal bringing its temperature below the critical range so rapidly that there is insufficient time for large grain growth. The microphotographs, Figures 1, 2, and 3, show this area clearly.

The grain structure of the weld metal is dendritic with the dendrites growing from the joint walls to the surface in the single pass welds resulting in a columnar structure. In the multiple pass welds this structure is broken up by the annealing action of each succeeding bead on the earlier deposit.[2]

It is evident from the above that there is a lack of uniform grain structure in welded joints and parent metal structure and weld metal structure remain dissimilar unless the material is mechanically worked at high temperatures or heat treated in the critical range.

In actual practice it is found that weld failure more often occurs in this small grain area, Figure 2, adjacent to the sides of the weld and on the base metal side of fusion zone. This is particularly true under intermittent loading. Tests show that under tensile loading the weld

2. All welding codes for high pressure vessels call for multiple pass weld due to this, and also to the stress relieving action.

metal is higher in tensile strength and slightly less ductile, also there is increased hardness.[3]

One of the important factors in determining the physical properties of steel is the per cent of carbon. When steels containing under .15% carbon are quenched from a temperature just above their upper critical point, very little increase in hardness is produced. This is one of the reasons that low carbon steel welding is commercially practical without having to be heat treated.

If fine grain structure is desired throughout the welded joint extra beads are added above the surface of the parent metal and then removed.

Microphotographs of weld metal, fusion zone and base metal follow.

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3. These tests were carried out parallel to this work by another group.

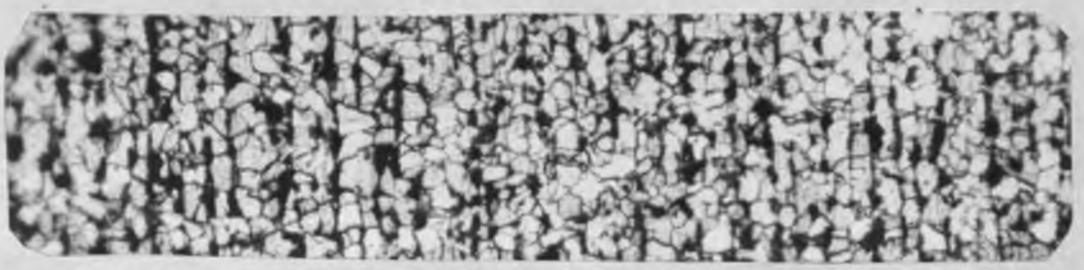


Figure 1

Base Metal: Analysis, .12 - .25% C. .04% Phos. Basic Open Hearth.

Microscopic examination and photographs show an even distribution of ferrite and pearlite in layers or laminations due to hot rolling of the plate in its manufacture. The grain structure is regular and even and somewhat finer due to hot working than if the metal had been annealed.

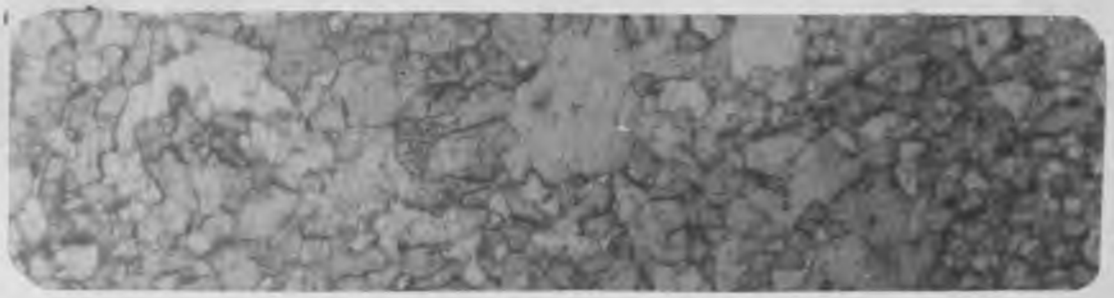


Figure 2, Rod Number One, Weld Zone, Magnification 100 Diameters

ROD ANALYSIS

0.14% C, 0.6% Mn., 0.04% S. 0.06% Si.

PLATE ANALYSIS

0.12% to .25% C. Basic Open Hearth.

WELD DATA

Weld Single Pass
Electrode Positive
Plate Negative
Arc Volts 30
Arc Amps. 200.

Figure 2 shows a large grain irregular structure and a slight alloying with the base metal on the right side of the picture. Laminated structure of the base is partially broken up with a good distribution of ferrite and pearlite. This photograph is taken through the center of weld and the grain structure is coarser than that of the fusion zone shown in Figure 3.

Figure 3, Rod Number One, Fusion Zone, Magnification 100 Diameters

Rod and plate analysis same as Figure 2.

Left side of microphotograph shows a coarse grain structure with a fine grain through the area of fusion and very fine on the right. This fine structure is due to the quenching action of the cold plate on the molten deposit and is often referred to as the chill ring.

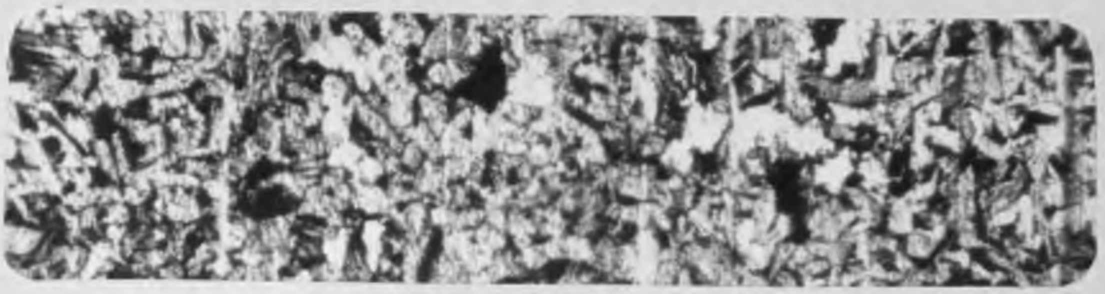


Figure 4, Rod Number Two, Weld Zone, Magnification 100 Diameters.

Rod analysis of core wire same as for Rod Number One.

Plate analysis same.

Grain structure Figure 4 is coarse and dendritic with the laminated structure of the plate not thoroughly broken up. This is to be expected as this rod is designed to give full fusion with shallow penetration. The difference between the two rods is in the coating only.

DATA ON WELD

Arc Volts 25.
Arc Amps. 180.
Polarity Electrode Negative.

Figure 5, Rod Number Two, Fusion Zone, Magnification 100 Diameters

Figure 5. Shows a marked dendritic structure on the right, at the center a coarse grain network and then the fine network structure of the quenched metal follows. This structure shades out to the laminated structure of the base metal.

The foregoing welds were single pass welds and were selected as the variations in grain structure were more marked than in the multiple pass welds. In the multiple pass weld each succeeding bead has a refining action on the structure and a finer grain is the result.

In the test work done in Chapter III dealing with the correlation of grain size and strengths at regular intervals in the weld zone the multiple pass weld was used for three reasons:

1. Thickness of plate was too great for a single bead.

2. The finer grain structure was desired.

3. It was desired to come as close as possible to commercial welds.

This work clearly establishes the fact that there is a definite grain gradient in the weld zone which would indicate points of weakness under different types of loading. Higher tensile strengths would be expected of the finer grain structures and more brittleness under a bending stress.

Heat treatment will even out the grain structure, increase the ductility and make the weld metal less susceptible to fatigue failure or fracture under bending stresses.

## CHAPTER III

## CORRELATION OF GRAIN SIZE AND MECHANICAL PROPERTIES

### Making the Specimens

A low carbon basic open hearth steel was selected as a base metal. Strips were flame cut to 20" x 4½" x 3/4" and flame beveled to 45 degrees on one 20" edge of the plate. Three coated electrodes made by one of the leading manufacturers were used. Rod Number One is a general purpose rod with deep penetrating characteristics.

Rod Number Two is designed for full fusion on poor fit ups. Penetration is obviously shallow.

Rod Number Three is a deep penetrating high speed rod for deep groove high speed welding.

### Welding Procedure

Two scarfed plates were set up as shown in Figure 25 and beads deposited in the order shown in Figure 27. The top or last bead was a weaving bead and the finished weld is shown in Figure 26. An operation sheet showing welding operation and time for the 90 specimens used in the three series is given.[1] A combined operation and time sheet was

1. Appendix.

## MAKING THE WELD

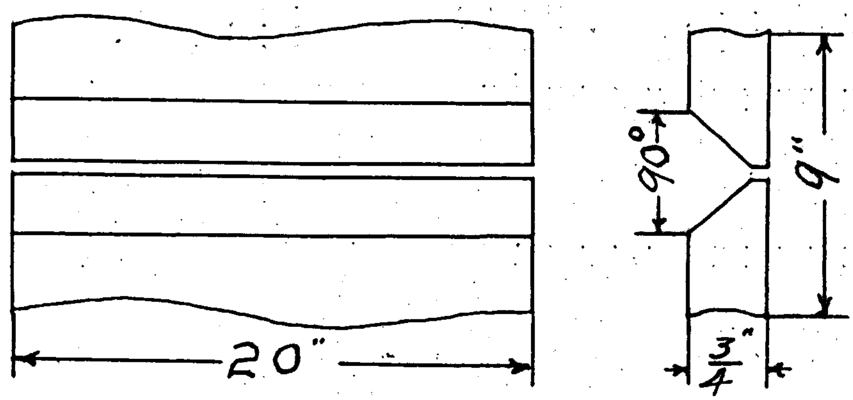



Figure 25

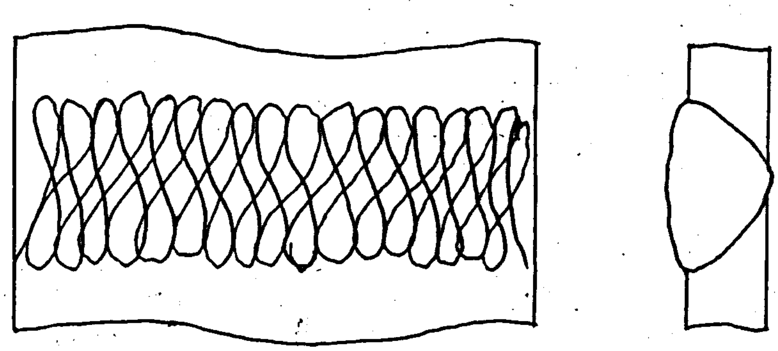


Figure 26

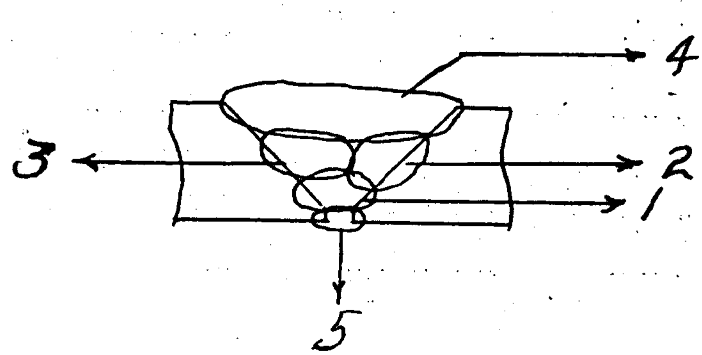



Figure 27

used for the different steps in the tests.[2] The excess material in the bead was removed and the welded plate flame cut into strips 3/4 x 3/4 x 9½ inches preparatory to machining.

## Machining the Specimens

The steps in machining are shown in Figures 28, 29, 30, and 31. Time is shown on machining operation sheet.[3] The nick in the center section of Figure 31 is 1/8" wide and .050 deep. Six specimens were made at the center of the weld for each rod and six for each rod at points 1/8, 2/8, 3/8, 4/8, and 5/8 inches out from the center of the weld. This covers the heat affected area.

## Making the Tests

Specimens were broken under tension in a hydraulic tensile testing machine and yield and ultimate recorded as shown on the accompanying data sheets. Since the break was forced at a desired point, in a very short section, no reduction of area and elongation could be accurately recorded. The break section was polished and etched with a 2% solution of $HNO_3$ and alcohol for microscopic examination and microphotographing. Typical sections for each group were photographed. One photograph was made for each section

2. Appendix.
3. Ibid.

## MACHINING OPERATION

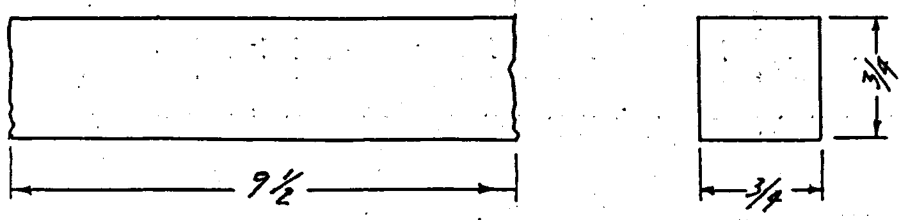



**Figure 28**

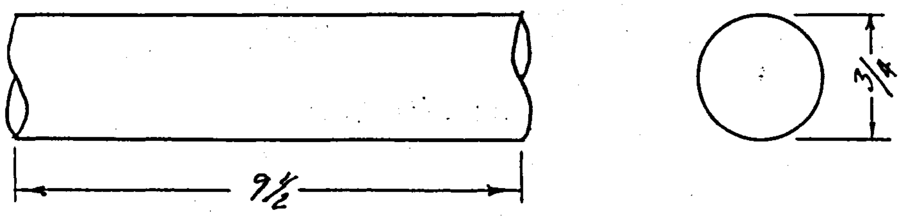



**Figure 29**

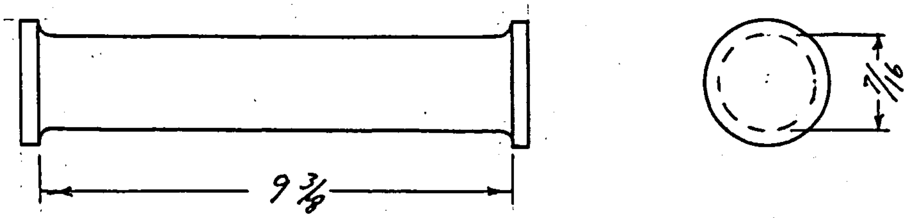



**Figure 30**

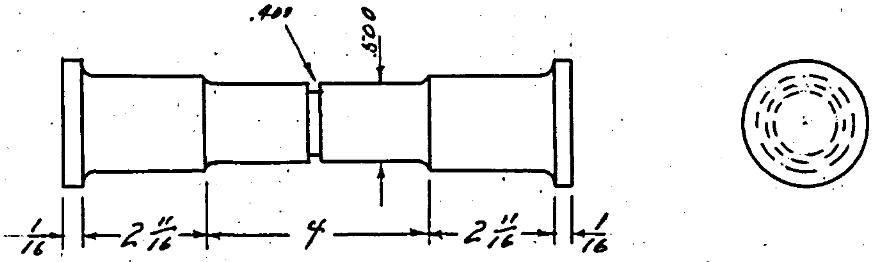



**Figure 31**

of all series. Grain size is the average of the series. Curves for grain size yield and ultimate were plotted against distance from center of weld for each rod.

## Base Metal Tests

Four specimens were made from the base plate to get a comparison of the base and weld metal.

## Equipment and Material

3/4" Basic Open Hearth Plate

Electrode Number One: General Purpose

Electrode Number Two: For Poor Fit Ups

Electrode Number Three: For High Speed Deep Groove Welding

300 Amp. Lincoln S.A.E. D.C. Welding Machine

Oxweld W 45 Cutting Machine

Oxweld Hydraulic Tensile Testing Machine

Lathes, Planers, and Grinders

Polishing and Buffing Machines

Leitz Microphotographic Camera

Bausch and Lomb Microscopes

Specimen number, diameter, yield load and ultimate load are direct readings. Area and unit stress are calculated.

$A = .7854 \times D^2$

$S = \frac{P}{A}$ P = Load $A = .7854 \times D^2$

Graphical interpretation of data sheets are shown following each sheet. These graphs show that for Rod Number One fine grain size, high ultimate and high yield are at the center of the weld. Grain size increases progressively through weld and heat affected zone.[4] Ultimate and yield increase and decrease with grain size except at the point 5/8"out from center where a sharp upturn is found in each of these curves. This is normal as area is decreasing rapidly just before fracture. The nicked section used to force fractures prevented elongation and reduction of area measurements being taken with any degree of accuracy.

4. Photographs and discussion in Chapter II.

Table I gives the result of tests made on specimens of parent metal to establish yield and ultimate to serve as a basis of comparison with the weld metal.

Table II is the result of tests on Rod One; Table III of Rod Two and Table IV of Rod Three. These tables show yield, ultimate and grain size for the three rods at center of weld, and 1/8, 2/8, 3/8, 4/8, and 5/8 inches out from the center respectively.

The parent metal is evidently a 58000 pound steel with a yield of 48000, very ductile and a large reduction of area. Elongation of 3/4" in 2" and a reduction of area of 60%.



## TABLE I

### PARENT METAL

| | Length | | Dia. | | Load | | Unit Stress | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| S6# | init. | Final | In. | Fin. | Yield | Ult. | Yield | Ult. | Elon. | R.A. |
| 1 | 1 63/64 | 2 47/64 | .484 | .298 | 9000 | 11200 | 48900 | 61000 | 48/64 | |
| 2 | 1 63/64 | 2 25/32 | .487 | .296 | 9200 | 10000 | 49700 | 54000 | 51/64 | |
| 3 | 1 63/64 | 2 3/4 | .485 | .294 | 9300 | 11200 | 50300 | 60500 | 59/64 | |
| 4 | 1 63/64 | 2 25/32 | .508 | .315 | 10000 | 12400 | 49500 | 60800 | 51/64 | |
| Total | | | | | 37500 | 44800 | 198400 | 236300 | | |
| Ave. | | | .491 | .301 | 9375 | 11200 | 49600 | 59075 | 3/4" in 2" | .60% |

## TABLE II

## DATA SHEET - ROD #1

### At Center of the Weld

| Speci-men no. | Diame-ter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| 48 | 0.464 | 0.169 | 8200 | 48500 | 12900 | 76400 | | |
| 126 | 0.414 | 0.131 | 7800 | 59500 | 12300 | 94000 | 11000 | Broke out of nick |
| 265 | 0.406 | 0.130 | 8300 | 64000 | 11900 | 91500 | 14400 | B.N.[5] |
| 186 | 0.462 | 0.168 | 8600 | 51100 | 11800 | 72000 | 12000 | B.N. |
| 254 | 0.406 | 0.130 | 8400 | 64300 | 11500 | 88500 | 14200 | B.N. |
| 177 | 0.461 | 0.167 | 8200 | 49000 | 12800 | 76500 | | Broke out of nick |
| Total | | | | 336400 | | 498900 | | |
| Ave. | | | | 56070 | | 83150 | 12900 | |
| 1/8 inch from Center of Weld | | | | | | | | |
| 212 | 0.439 | 0.152 | 7400 | 48600 | 11800 | 77600 | 9200 | B.N. |
| 192 | 0.460 | 0.166 | 8000 | 48200 | 12900 | 77500 | 9100 | B.N. |
| 195 | 0.462 | 0.168 | 8400 | 50000 | 13200 | 78500 | 9000 | B.N. |
| 170 | 0.459 | 0.166 | 8300 | 50000 | 12900 | 77700 | 9300 | B.N. |
| 32 | 0.460 | 0.167 | 8400 | 50200 | 10900 | 65300 | 9000 | B.N. |
| Total | | | | 247000 | | 376600 | | |
| Ave. | | | | 49400 | | 75320 | 9120 | |
| 2/8 inch from Center of Weld | | | | | | | | |
| 184 | 0.470 | 0.174 | 8200 | 46000 | 11900 | 68400 | 5100 | |
| 181 | 0.470 | 0.174 | 8300 | 47600 | 13200 | 75800 | 5700 | |
| 105 | 0.472 | 0.176 | 7900 | 44900 | 12900 | 73100 | 5300 | |
| 45 | 0.472 | 0.176 | 8000 | 45400 | 13100 | 74500 | 5600 | |
| 56 | 0.475 | 0.176 | 8300 | 47100 | 12900 | 73100 | | Broke out of nick |
| Total | | | | 231000 | | 364900 | | |
| Ave. | | | | 46200 | | 72980 | 5425 | |

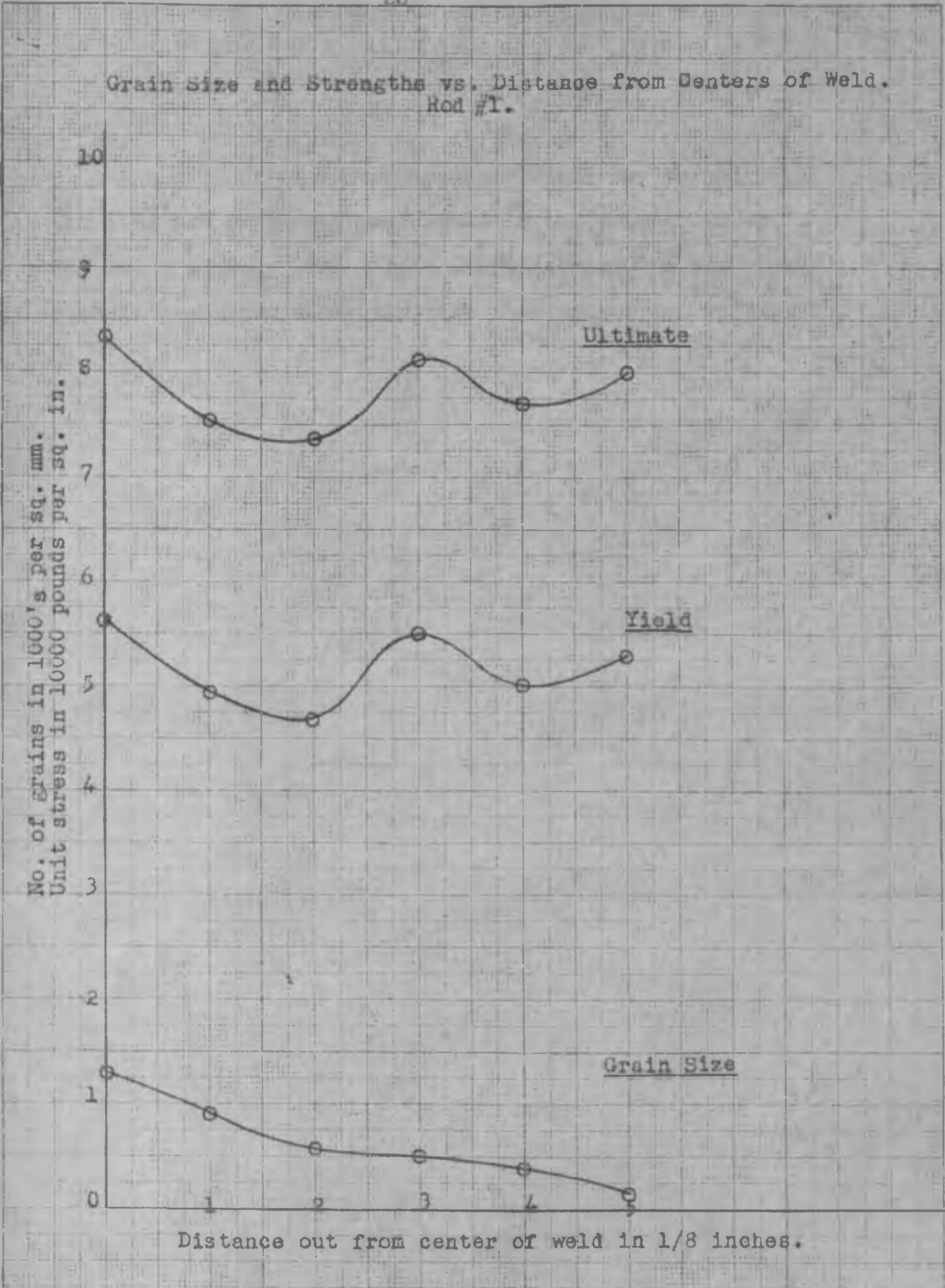
TABLE II (Cont'd.)

DATA SHEET - ROD #1

3/8 inch from Center of Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| 45 | 0.460 | 0.166 | 8100 | 48800 | 11400 | 68600 | | Poor weld |
| 190 | 0.455 | 0.163 | 8400 | 51400 | 13000 | 79800 | 4800 | B.N. |
| 43 | 0.460 | 0.166 | 8300 | 50000 | 13000 | 78300 | 5000 | O.W.-N[6] |
| 266 | 0.406 | 0.130 | 8100 | 62300 | 11700 | 90000 | 6000 | B.N. |
| 247 | 0.403 | 0.128 | 8400 | 65600 | 11500 | 89800 | 5000 | B.N. |
| Total | | | | 278100 | | 406500 | | |
| Ave. | | | | 55620 | | 81300 | 5200 | |
| **4/8 inch from Center of Weld** | | | | | | | | |
| 44 | 0.460 | 0.167 | 8400 | 50300 | 12800 | 76600 | 3800 | B.N. |
| 102 | 0.460 | 0.167 | 8100 | 48500 | 13000 | 77800 | 4100 | B.N. |
| 107 | 0.458 | 0.165 | 8400 | 50900 | 12000 | 72600 | | O.W.-N. |
| 204 | 0.460 | 0.167 | 8300 | 49700 | 13000 | 77800 | 4000 | B.N. |
| 205 | 0.460 | 0.167 | 8300 | 49700 | 12700 | 76000 | | O.W.-N. |
| 215 | 0.460 | 0.167 | 8200 | 49000 | 13000 | 77800 | 4100 | B.N. |
| Total | | | | 298100 | | 458600 | | |
| Ave. | | | | 49700 | | 76430 | 4000 | |
| **5/8 inch from Center of Weld** | | | | | | | | |
| 23 | 0.465 | 0.170 | 8200 | 48100 | 13800 | 81000 | 1500 | B.N. |
| 25 | 0.460 | 0.167 | 8100 | 48500 | 11600 | 69400 | | O.W.-N. Poor weld |
| 64 | 0.425 | 0.143 | 7900 | 55100 | 11900 | 83100 | 1300 | O.W.-N. Good weld |
| 269 | 0.406 | 0.130 | 8400 | 64500 | 11700 | 90000 | 1700 | B.N. |
| 206 | 0.460 | 0.167 | 8200 | 49000 | 12700 | 76000 | 1600 | B.N. |
| Total | | | | 265200 | | 399500 | | |
| Ave. | | | | 53040 | | 79900 | 1525 | |

5. B.N. abbreviation for Breaks in Nick.
6. O.W.-N. " " Necked out of Weld.


Grain Size and Strengths vs. Distance from Centers of Weld.
Rod #1.
No. of grains in 1000's per sq. mm.
Unit stress in 10000 pounds per sq. in.
10
9
8
7
6
5
4
3
2
1
0
Ultimate
Yield
Grain Size
1
2
3
4
5
Distance out from center of weld in 1/8 inches.

A series of pictures showing plainly the varying grain sizes in the different heat zones of the weld is shown in Figures 6 to 11. Microscopic inspection of the six specimens in each case shows that the photographs are typical.

Figure 6

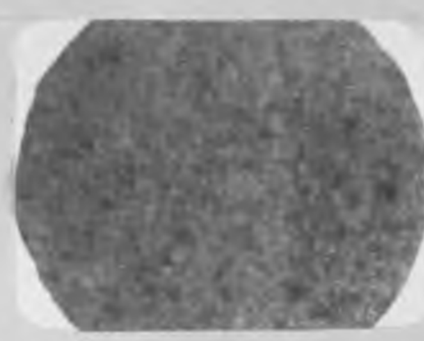


Figure 7

Figure 8

Figure 9

ROD NUMBER ONE

<u>Figure 6</u>, center of weld, shows a very fine grain size, 11000 grains per square millimeter. A fine network with even distribution of ferrite and pearlite.

<u>Figure 7</u>, 1/8" from center of weld shows slightly larger grain size, 9120 grains per square millimeter. Network structure and distribution similar to Figure 6.

Figure 10

Figure 11

Figure 8, 2/8" from center of weld, shows a marked increase in grain size, 5425 grains per square millimeter. This is due to the annealing action of the third or weaving bead deposited on top of this section. The structure is a network with even distribution of ferrite and pearlite.

Figure 9, 3/8" from center of weld. Very similar to Figure 8 with slightly larger grain size, 5200 grains per square millimeter. The network structure remains and distribution of ferrite and pearlite is similar to Figure 8.

Figure 10, 4/8" from center of weld. This shows a further increase in grain size and as this and the following Figure 11 are in the top bead, is to be expected. Grains per square millimeter, 4000. There is still good distribution of ferrite and pearlite in a slightly dendritic structure.

Figure 11, 5/8" from center of weld. Grains per square millimeter, 1525. Combination network and dendritic structure with good distribution of ferrite and pearlite.

## TABLE III

## DATA SHEET - ROD #2

### At Center of the Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| S | 0.400 | 0.126 | 7400 | 58700 | 7400 | 58700 | | N.G. |
| T | 0.387 | 0.150 | 7800 | 52000 | 10000 | 66600 | 9800 | |
| U | 0.396 | 0.117 | 7600 | 64900 | 11400 | 97500 | 10000 | B.N. Polish |
| V | 0.396 | 0.117 | 7700 | 64800 | 11500 | 98300 | 10500 | B.N. |
| W | --- | --- | --- | --- | --- | --- | | |
| Total | | | | 181700 | | 262400 | | |
| Average | | | | 60567 | | 87466 | 10100 | |
| 1/8 inch from Center of Weld | | | | | | | | |
| S | 0.396 | 0.117 | 7600 | 64900 | 10900 | 93300 | 8600 | B.N. |
| T | 0.396 | 0.117 | 8100 | 69200 | 11500 | 98300 | 9000 | B.N. Polish |
| U | 0.393 | 0.116 | 8000 | 68900 | 11000 | 95000 | 8800 | B.N. Polish |
| V | 0.396 | 0.117 | 8000 | 68300 | 11500 | 98300 | 9200 | B.N. |
| W | 0.392 | 0.116 | 7700 | 66400 | 11000 | 95000 | 8600 | |
| Total | | | | 337700 | | 479900 | | |
| Average | | | | 67540 | | 95980 | 8840 | |
| 2/8 inch from Center of Weld | | | | | | | | |
| S | 0.395 | 0.122 | 7700 | 63000 | 11500 | 94300 | 6300 | B.N. Polish |
| T | 0.395 | 0.122 | 8000 | 65400 | 11300 | 92700 | 6100 | O.N. Slag |
| U | --- | --- | --- | --- | --- | --- | | |
| V | 0.402 | 0.122 | 8100 | 63800 | 11200 | 88300 | 6000 | Slight Slag |
| W | 0.395 | 0.122 | 7600 | 62200 | 9000 | 74000 | 6500 | Slight Slag |
| Total | | | | 254400 | | 349300 | | |
| Average | | | | 63600 | | 87330 | 6250 | |

TABLE III (Cont'd.)[7]

DATA SHEET - ROD #2

3/8 inch from Center of Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| S | 0.396 | 0.123 | 8000 | 65000 | 11200 | 91100 | 8100 | Polish |
| T | 0.392 | 0.116 | 7900 | 68100 | 10900 | 94100 | 8300 | B.N. |
| U | 0.396 | 0.123 | 8100 | 65900 | 11100 | 90300 | 8000 | B.N. |
| V | 0.392 | 0.116 | 7800 | 67200 | 9600 | 82800 | | N.G. |
| W | 0.392 | 0.116 | 7800 | 67200 | 10900 | 94100 | 8400 | B.N. |
| Total | | | | 266200 | | 369600 | | |
| Average | | | | 66550 | | 92400 | 8200 | |
| 4/8 inch from Center of Weld | | | | | | | | |
| S | 0.412 | 0.133 | 8000 | 60100 | 11700 | 88200 | 3000 | B.N. Polish |
| T | 0.410 | 0.132 | 8100 | 61400 | 11000 | 83400 | 2900 | B.N. |
| U | 0.392 | 0.120 | 7900 | 65700 | 10800 | 90000 | 3200 | Poor Weld-N.G. |
| V | 0.402 | 0.120 | 8000 | 68400 | 10800 | 85000 | | Inc. |
| W | 0.366 | 0.105 | 7400 | 70500 | 9000 | 85600 | 3000 | B.O.N. Poor Weld |
| Total | | | | 326100 | | 432200 | | |
| Average | | | | 65200 | | 86400 | 2970 | |
| 5/8 inch from Center of Weld | | | | | | | | |
| S | 0.400 | 0.126 | 8100 | 64300 | 11000 | 87300 | 1800 | B.N. Polish |
| T | 0.400 | 0.126 | 8000 | 63500 | 10900 | 86500 | 1900 | B.N. |
| U | 0.400 | 0.126 | 8000 | 63500 | 10900 | 86500 | 1850 | B.N. |
| V | 0.395 | 0.122 | 8000 | 65000 | 10400 | 85300 | | Inc. |
| W | 0.395 | 0.122 | 7600 | 62500 | 10700 | 87000 | 1850 | B.N. |
| Total | | | | 318800 | | 432600 | | |
| Average | | | | 63800 | | 86520 | 1850 | |

7. High ultimate and yield are found at point 1/8 out from center of weld. Fine grain at center. The general contour of these curves follow grain size except at this point. Reasons for this are discussed later.

Grain Size and Strengths vs. Distance from Centers of Weld
Rod #2

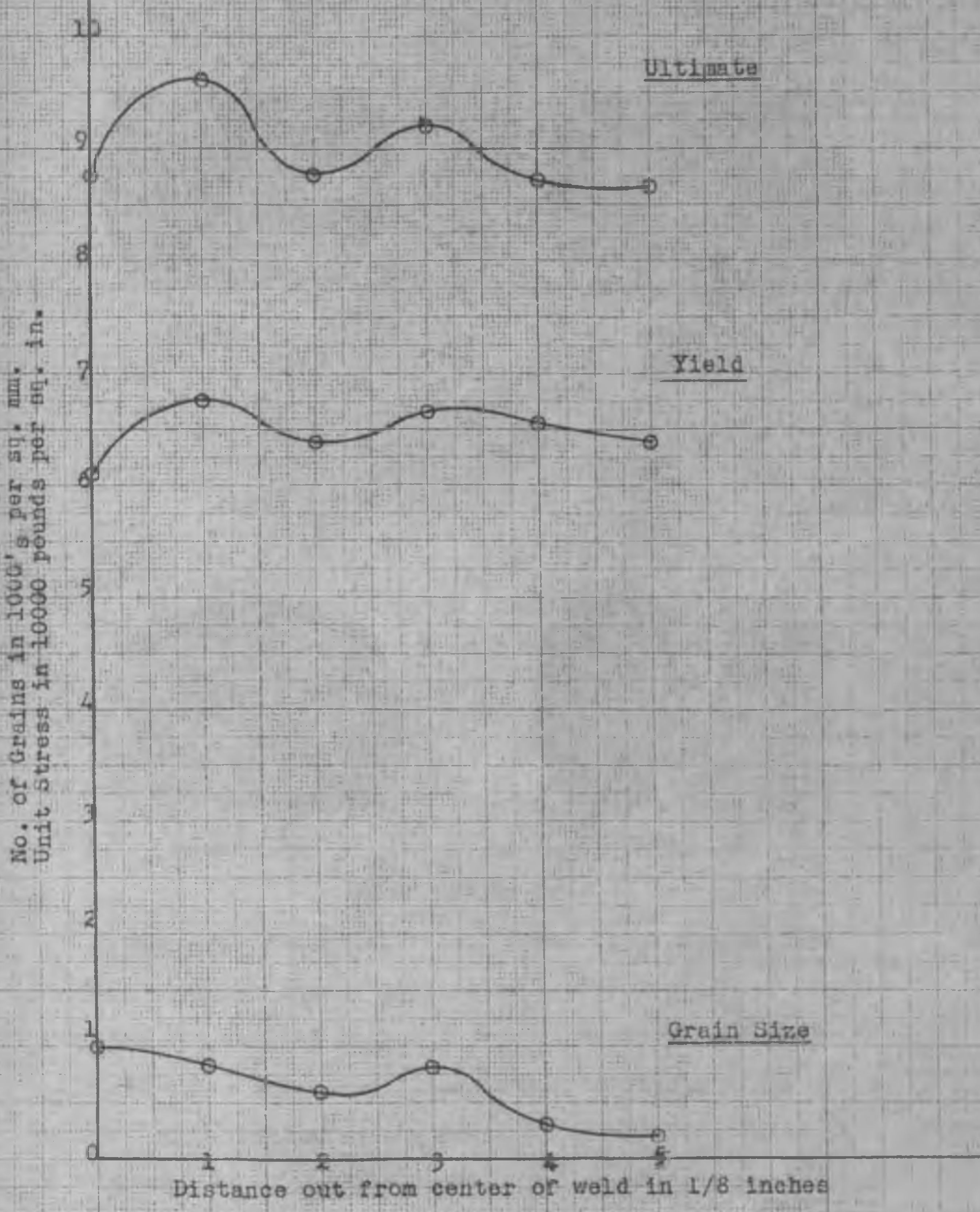


Figure 12

Figure 13

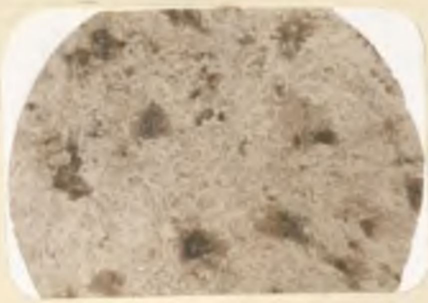


Figure 14

Figure 15

ROD NUMBER TWO

Figure 12: Center of weld. Grain structure is fine, 10100 grains per square millimeter. Distribution of ferrite and pearlite is good in the network. Heavy shaded areas appeared under microscopic inspection to have a slightly colored tint indicating the presence of alloying elements in the coating of the electrode. This condition was apparent throughout this series of specimens.

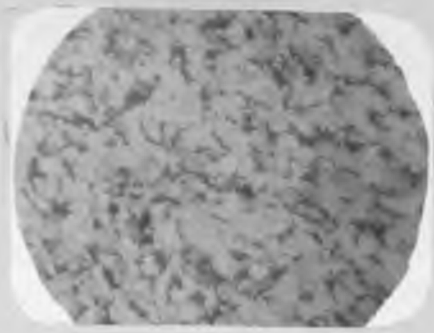


Figure 16

Figure 17

Figure 13: 1/8" from center of weld, shows slightly larger grain size, 8840 grains per square millimeter. Structure is an even network with the shaded areas more noticeable.

Figure 14: 2/8" from center of weld. Grain size slightly larger, 6280 grains per square millimeter. Structure similar to Figures 12 and 13.

Figure 15: 3/8" from center of weld. Grain size smaller than Figure 14 due to quenching action of the cold plate on the heated metal of the succeeding bead. This is a shallow penetrating rod and grain size changes are more noticeable than is seen in the deposited metal from a deep penetrating rod.

Figure 16: 4/8" from center of weld. Grain structure is an irregular network and much coarser than in the preceding structure. A heavy slag is formed on top of the molten metal with this electrode causing a slower cooling

rate. This is the top bead and there is longer time for grain growth, grain size 2970 per square millimeter.

Figure 17: 5/8" from center of weld. This structure is very similar to Figure 16 with slightly larger grain, 1850 per square millimeter.

TABLE IV

DATA SHEET - ROD #3

At Center of Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| A | 0.452 | 0.160 | 8400 | 52500 | 12200 | 76300 | 9000 | B.O.N. Nicked 50 |
| B | 0.453 | 0.161 | 8200 | 51000 | 12200 | 75800 | 8800 | B.O.N. Nicked 50 |
| C | 0.415 | 0.136 | 7600 | 55800 | 10100 | 74200 | | W. Inc. Nicked 90 |
| D | 0.414 | 0.135 | 8400 | 62200 | 11700 | 86700 | 9600 | W. Inc. " " |
| E | 0.410 | 0.132 | 8000 | 60600 | 9700 | 73500 | | Slight Slag |
| Total | | | | 282100 | | 386500 | 27400 | |
| Average | | | | 56400 | | 77300 | 9130 | |
| 1/8 inch from Center of Weld | | | | | | | | |
| A | 0.400 | 0.126 | 8100 | 64300 | 9000 | | | |
| B | 0.400 | 0.126 | 8200 | 65000 | 12100 | 96000 | 12000 | Polish |
| C | 0.400 | 0.126 | 8300 | 65800 | 12400 | 97400 | | O.W.-2 |
| D | 0.400 | 0.126 | 8300 | 65800 | 11700 | 92800 | 11600 | B.N. |
| E | 0.400 | 0.126 | 8400 | 67700 | 12200 | 96700 | 12300 | |
| Total | | | | 328600 | | 382900 | 35900 | |
| Average | | | | 65700 | | 95700 | 11970 | |
| 2/8 inch from Center of Weld | | | | | | | | |
| A | 0.390 | 0.119 | 8300 | 69600 | 11200 | 94000 | | Inc. |
| B | 0.400 | 0.126 | 8300 | 65800 | 11500 | 91300 | 8900 | Slight Slag |
| C | 0.400 | 0.126 | 8000 | 63500 | 11800 | 93600 | 9000 | Polish |
| D | 0.400 | 0.126 | 8400 | 67700 | 11700 | 92800 | 9000 | |
| E | 0.400 | 0.126 | 8400 | 67700 | 10800 | 85700 | | Inc. |
| Total | | | | 334300 | | 457400 | 26900 | |
| Average | | | | 66800 | | 91500 | 8970 | |

TABLE IV (Cont'd.)

DATA SHEET - ROD #3

3/8 inch from Center of Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| A | 0.400 | 0.126 | 7700 | 61200 | 11900 | 94400 | 9200 | |
| B | 0.400 | 0.126 | 8000 | 63500 | 11000 | 86400 | | Inc. |
| C | 0.400 | 0.126 | 7900 | 62700 | 11700 | 92800 | 9000 | Polish |
| D | 0.400 | 0.126 | 7900 | 62700 | 11000 | 86400 | 9000 | |
| E | 0.395 | 0.122 | 7800 | 63800 | 11400 | 93400 | 9100 | |
| Total | | | | 313900 | | 453400 | 36300 | |
| Average | | | | 62800 | | 90700 | 9075 | |
| 4/8 inch from Center of Weld | | | | | | | | |
| A | 0.400 | 0.126 | 7500 | 59600 | 11000 | 86400 | 2500 | B.N. Polish |
| B | 0.395 | 0.122 | 7800 | 63900 | 10700 | 87700 | 2600 | B.N. |
| C | 0.400 | 0.126 | 8000 | 63500 | 11000 | 86400 | 2480 | B.N. |
| D | 0.400 | 0.126 | 7900 | 62700 | 11000 | 86400 | 2500 | B.N. |
| E | 0.395 | 0.122 | 8000 | 66600 | 10900 | 89300 | 2700 | B.N. |
| Total | | | | 316300 | | 436200 | 12780 | |
| Average | | | | 63300 | | 87200 | 2556 | |
| A | 0.400 | 0.126 | 7700 | 61200 | 10800 | 85700 | 1600 | B.N. |
| B | 0. | 0. | --- | --- | --- | --- | --- | |
| C | 0.400 | 0.126 | 7800 | 61900 | 10900 | 86500 | 1550 | |
| D | 0.400 | 0.126 | 7900 | 62700 | 11200 | 89000 | 1600 | Polish |
| E | 0.400 | 0.126 | 8000 | 63500 | 10800 | 85700 | 1500 | Examine Photo |
| Total | | | | 249300 | | 346900 | 5250 | |
| Average | | | | 62600 | | 83800 | 1310 | |

## TABLE IV (Cont'd.)[8]

## DATA SHEET - ROD #3

### 6/8" inch from Center of Weld

| Specimen No. | Diameter | Area | Yield Load | Yield Unit Stress | Ultimate Load | Ultimate Unit Stress | Grains per $mm^2$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| A | 0.400 | 0.126 | 7800 | 61900 | 10800 | 85700 | 1100 | B.N. |
| B | 0.400 | 0.126 | 7900 | 62600 | 11200 | 89000 | 1200 | B.N. Polish |
| C | 0.400 | 0.126 | --- | --- | --- | --- | | N.G. |
| D | 0.400 | 0.126 | 7800 | 61900 | 11000 | 87300 | 1200 | B.N. |
| E | 0.400 | 0.126 | 8000 | 63500 | 11000 | 87300 | 1210 | B.N. |
| Total | | | | 249900 | | 349300 | 4710 | |
| Average | | | | 62500 | | 87300 | 1180 | |

8. Fine grain size, and high ultimate are found at point 1/8" out with high yield at point 2/8" out. Weld metal from this rod is very ductile and this variation from Rods One and Two is not unusual. It will be seen that grain size variations clearly show bead depositions and a marked refinement of grain structure in each case.

Grain Size and Strengths vs. Distance from Centers of Weld Rod #3.

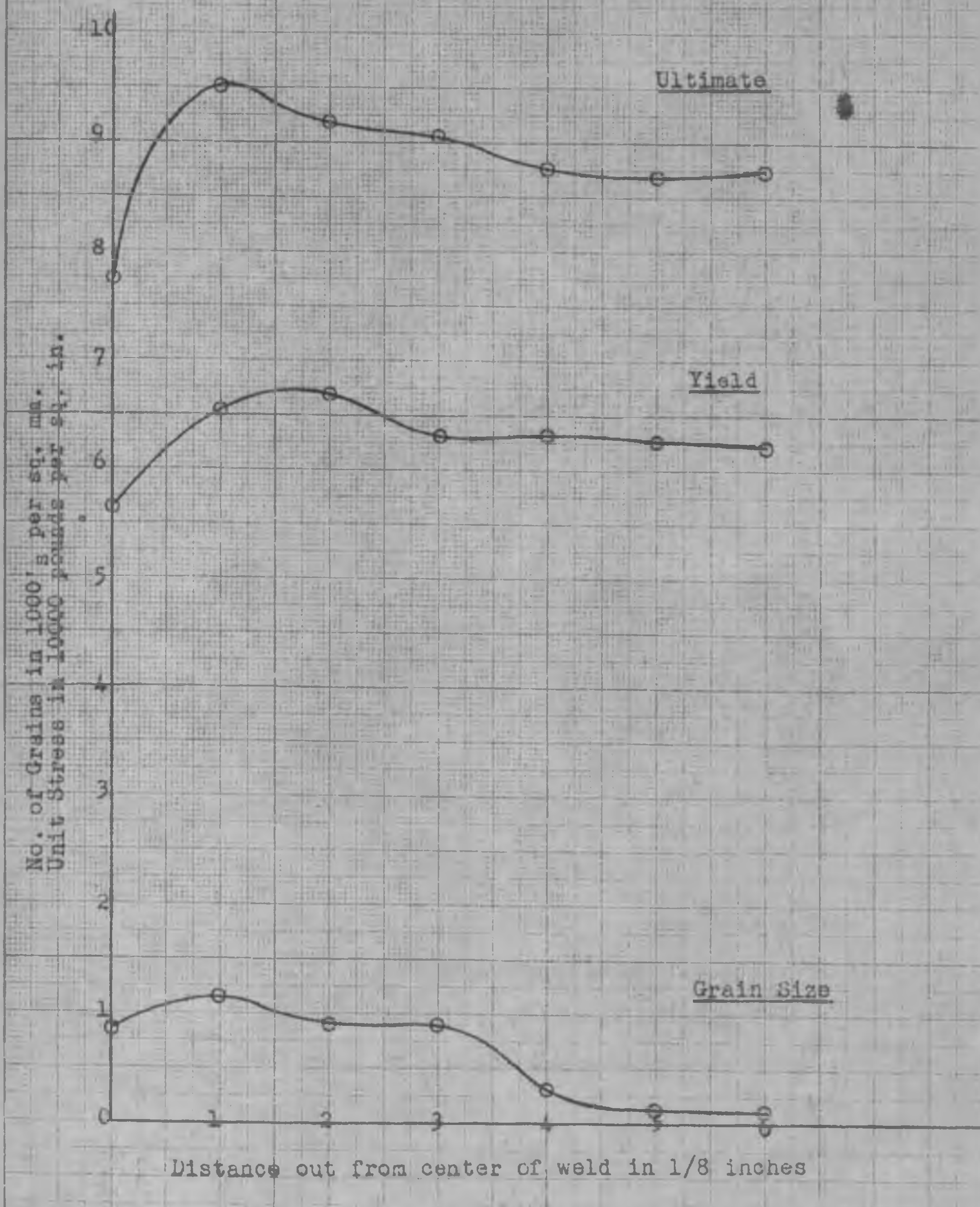


Figure 18

Figure 19

Figure 21

Figure 20

ROD NUMBER THREE

Figure 18: Center of weld. Grain structure is a fine network. Microscopic examination indicates the presence of an alloying element as all specimens were faintly irridescent. Distribution of ferrite and pearlite is even. Grains 9130 per square millimeter.

Figure 19: 1/8" from center of weld. Grain structure

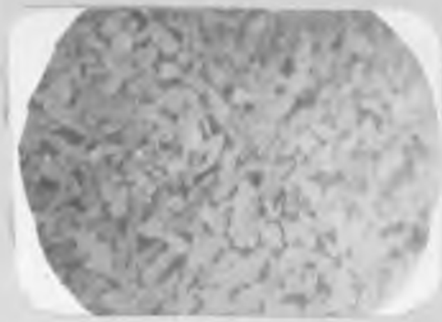


Figure 22

Figure 23

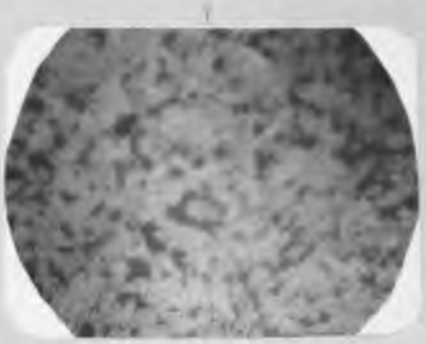


Figure 24

is finer than center section. Except for this is very similar to Figure 18. Grains 11970 per square millimeter.

Figure 20: 2/8" from center of weld. Structure is a network similar to Figures 18 and 19. Grains 8970 per square millimeter.

Figure 21: 3/8" from center of weld. Network structure with a slight tendency toward a dendritic type. Even dis-

tribution of ferrite and pearlite. Grain size slightly finer than the preceding section, 9075 grains per square millimeter.

Figure 22: 4/8" from center of weld. Combination network and dendritic structure, even distribution of ferrite and pearlite with a coarse grain structure. Grains 2556 per square millimeter.

Figure 23: 5/8" from center of weld, shows irregular network structure with grains sharply defined. Even distribution of ferrite and pearlite. Grains 1310 per square millimeter. Very coarse.

Figure 24: 6/8" from center of weld.[9] Laminated structure of base metal shows slightly in the network. Even distribution of ferrite and pearlite. Grains 1180 per square millimeter.

9. This weld section was carried 1/8" further out than the others as this rod is a high speed heavy heat rod.

## CHAPTER IV

## DISCUSSION AND CONCLUSIONS

### Base Metal Tests

Base metal test showed a yield 49800psi. and an ultimate of 58825psi.[1]

### Rod Number One

The deposited metal from this rod has an ultimate maximum for the weld zone at the center of the weld.[2] There is a gradual grain growth from the center through the heat affected zone that follows almost a straight line curve. At the point 3/8" from the center of the weld the grain is somewhat smaller than at 2/8". The yield and ultimate curves are highest at the sections with the smaller grain and conform better than was expected. There is a slight upturn on the end points of the two curves but this is at the edge of the fusion zone and the cold plate quenching action on the molten alloy of rod and base would tend to raise both yield and ultimate. The high yield was at the center of the weld and was 56070psi. Maximum ultimate was at the same point and was 83150psi.

---

1. Table I.
2. Table II.

Rod Number Two

High ultimate and yield are found at the point 1/8" from the center of the weld. Ultimate 95980psi. and yield 67540psi.[3] The grain size at this point is slightly coarser than at the center. Since this is a shallow penetrating rod there would be more alloying with the base metal at this point and the annealing action of the succeeding bead would not give the same grain structure as on the pure weld metal in the center of the weld. There is a distinct rise in the grain size curve at the point 3/8" from the center of the weld due to the refining action of the final weaving bead. Yield and ultimate curves conform to grain size fairly well but not as closely as in the case of Rod Number One, but they are in general of higher values. This would indicate that full fusion is the essential requirement for strength in the arc welded joint and deep penetration is not always necessary. Complete fusion can also be obtained without deep penetration.

Rod Number Three

The smallest grain size, 11970 per square millimeter, is found at the point 1/8" from the center of the weld. The highest yield at the point 2/8" out.[4] The grain size curve is not as near a straight line as is the case in

3. Table III.
4. Table IV.

Rods One and Two. This is a high speed high heat rod with heavy slagging characteristics and the consequent cooling rate variations would be reflected in this curve. There is also a stabilizer in the coating. J. C. Hodge[5] and J. L. Miller[6] say:

> "The addition of a metallic element to iron tends to stabilize the allotropic form of iron most nearly resembling that of the added element. The physical properties are primarily governed by the type of structure resulting from the presence of alloying element or elements. Where austenite forming elements are present in sufficient amounts to produce a stable austenitic steel, the alloy steel is characterized by high ductility and toughness."[7]

Other tests made show that this is typical of this rod and that both manganese and titanium, in the oxide form, are in the coating and alloy with the core wire to give the stabilizing effect.[8]

Microphotographs and microscopic examination of cross sections of the weld zone at regular intervals show that there is a definite grain gradient in the weld and heat zone. The coarse grain size is found at the center of the weld and gradually becomes finer through the fusion zone. On the outer edge of the fusion zone is found a section of fine grain structure due to the quenching action of the

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5. Hodge, J. C., Chief metallurgist Babcock and Wilcox Co.
6. Miller, J. L., Research metallurgist Babcock and Wilcox Co.
7. A. W. S. Hand Book, 1938 edition, p. 429.
8. Lincoln Electric Co., Procedure Hand Book of Arc Welding.

cold plate on the molten metal on the crater. Outside of this section and in the base plate is an area of grain growth. This applies particularly to the single pass weld. In the multiple pass weld grain size does not follow exactly this pattern as the grain structure of the weld zone is much finer than in the single pass weld. This is due to the overlapping of the fine grain areas caused by cold plate quenching.

In this type of weld the finer grain structures are found at or near the center of the weld, with a gradual increase in grain size out through the heat zone. This is more noticeable in the welds of this investigation as a backing bead was run at the root of the weld. The curve for grain size approaches a sloping straight line with the variations clearly showing the overlapping of the beads.

Tensile tests of the base metal show a yield of 49800psi. and an ultimate of 58825psi. High yield of 56070psi. and high ultimate of 83150psi. were found at the center of the weld for Rod One. Finest grain size was also found at this point. Yield and ultimate drop with grain size to the point 3/8" out from the center where a slightly smaller grain size is found. This is followed by a rise in both yield and ultimate but these points are lower than at the center of the weld.

Rod Two does not follow this pattern exactly as a lower yield and ultimate are found at the center of the weld than at point 1/8" out with the finer grain size at this point. Yield at center 60567psi. Ultimate 87466psi. Maximums are found at the point 1/8" out and are yield 67540, ultimate 95980psi. From this point grain size and strengths curves conform to the pattern of Rod One.

The low yield and ultimate at the center of the weld for this rod is probably due to the fact that it is a low penetrating low heat rod and the backing bead cratering action is not as deep as in Rod One. This would make the chill ring of this bead less distinct. The strengths of the other points in the weld zone would indicate that welds of this rod are very sensitive to heat treatment.

Rod Three: The fine grain size is found at the point 1/8" out from center of the weld with the maximum ultimate of 95700psi. at this point. Maximum yield of 66800psi. is found at the point 2/8" out. Grain size becomes coarser rapidly through the rest of the heat zone. This is followed by small drops in yield and ultimate. This rod is an alloyed rod for high speed structural welding and and is very ductile. This accounts for the high yield and ultimate not falling at the same point of the weld.

Examination of the data shows that yield and ultimate of the deposited weld metal in every case is much higher than in the parent metal. This is due to the fact that all coated electrodes for low carbon steel welding carry alloying elements in the coatings. It follows then that deposited weld metals can be controlled within very close limits. This will not hold true however unless the proper current and voltage for the electrode involved is used at the arc. Developments in the regulation of D. C. welding generators that enable the operator to cover the range of the machine in very small steps of both current and voltage, with the transient characteristic regulation being inherent to the machine and variable by the operator, makes it possible to obtain and maintain these values within close limits. This assures a deposit of weld metal satisfactory as to its mechanical properties.

The question is sometimes asked: "Does not a weld have coarse and fine grain sizes that will make for strong and weak points in the weld?" The answer is yes. The weld metal however, if proper technique is used, is superior to the base metal in mechanical properties at all points; therefore it is possible to produce a joint that will carry a greater load than the parent metal under either tension or compression. Grain structures would indicate a possible weakness under bending or repeated reversals of stress. This weakness can be overcome by heat treatment to even the grain structure throughout the heat zone.

Welding is the cheapest and fastest method of joining metals and since a joint that is as strong as the base metal is easily obtained it follows that it will soon take the place of the leading process for joining metals. Some manufacturers are at the present time replacing expensive and heavy castings with lighter and stronger all welded steel construction.

## BIBLIOGRAPHY


1. A. W. S. Hand Book.

2. Procedure Hand Book of Arc Welding, Design and Practice, Sixth Edition, Lincoln Electric Company.

3. Engineering Materials and Processes, Clapp and Clark.

4. Engineering Metallurgy, Second Edition, Stoughton and Butts.

5. Principles of Metallography, Second Edition, Williams and Homerberg.

## APPENDIX

### SOME LATE DEVELOPMENTS IN WELDING

Stainless steel welding techniques have been developed recently that bid fair to allow this material to replace to a large extent aluminum alloys in airplane fuselage and wing construction. The steel has a greater deflection in long spans than the aluminum alloy and will have to have stiffeners added.

Boiler shells up to 5" in thickness and working pressure of 1250 pounds per square inch are of all welded construction and are common practice at the present time.

### Pipe Welding

A new plastic process for gas welding pipe lines has been developed and the first line, 1000 feet in length, laid in Tucson, Arizona. Square faces are used in joint preparation. The faces are brought in contact and a clamping machine holds them together under 1000 pounds pressure. This pressure is indicated on a gauge. Heat is applied around the joint by a ring burner oxyacetylene torch with the burner jets about 1/4 inch apart. When the pressure gauge shows a small drop, the pressure is increased and the heat removed. Set up time for 6 inch pipe is 2½ minutes and the welding time is 30 seconds, total time of three minutes per 6 inch joint. This line was sealed and put under a 400 pound gas pressure. At the end of ten days there was no noticeable drop. Comparable time for the same size pipe joined by the Lindeweld process is about 10 minutes.

## PREPARING AND WELDING TIME

| Operation | Time in Min. Set up | Time in Min. Per pc. | No. req. | No. set ups | Time Set up | Time Oper. | Time Total |
|---|---|---|---|---|---|---|---|
| 1. Cut pieces to 20" by $4\frac{1}{2}$" with cutting machine | 30 | 10 | 16 | 2 | 60 | 160 | 220 |
| 2. Cut 45° bevel | 30 | 5 | 16 | 1 | 30 | 80 | 110 |
| 3. Clean slag and grind bevel | 15 | 12 | 16 | 2 | 30 | 192 | 222 |
| 4. Clamp and set up two for welding Weld into 1 plate. | 15 | 105 | 8 | 4 | 60 | 840 | 900 |
| 5. Machine excess bead in planer both sides | 45 | 60 | 8 | 2 | 90 | 480 | 570 |
| 6. Machine to length | 45 | 75 | 8 | 2 | 90 | 600 | 690 |
| 7. Torch machine cut specimens from plate (20" by 9" plate - 15 specimens) | 30 | 60 | 8 | 3 | 90 | 480 | 570 |
| Total welding time minutes | | | | | | | 3260 |
| Total welding time hours | | | | | | | 54-1/3 |

Column 1 - Operation and description
" 2 - Machine set up time
" 3 - Set up time per piece

Column 4 - Number of pieces required
" 5 - Number of machine set ups
" 6, 7, 8 - Summary

## MACHINING TIME

| Operation | Time in min. Set up | Time in min. Per pc. | No. req. | No. set ups | Time Set up | Time Oper. | Time Total |
|---|---|---|---|---|---|---|---|
| 1. Lay out and prick punch centers | 10 | 1-1/6 | 120 | 2 | 20 | 140 | 160 |
| 2. Drill centers | 12 | 2 | 120 | 2 | 24 | 240 | 264 |
| 3. Machine to 3/4" diameter 1/2 way | 25 | 6 | 120 | 4 | 100 | 720 | 820 |
| 4. Machine to 3/4" diameter other 1/2 | 25 | 6 | 120 | 4 | 100 | 720 | 820 |
| 5. Turn to 9/16" diameter 1/2 way | 25 | 4 | 120 | 3 | 75 | 480 | 555 |
| 6. Turn to 9/16" full length | 25 | 4 | 120 | 3 | 75 | 480 | 555 |
| 7. Turn to 1/2" diameter 3½" long | 25 | 4 | 120 | 3 | 75 | 480 | 555 |
| 8. Cut groove .050 deep in weld zone | 25 | 2½ | 120 | 3 | 75 | 300 | 375 |
| Total time machining, minutes | | | | | | | 4104 |
| Total time machining, hours | | | | | | | 68.9 |

## TESTING AND PHOTOGRAPHY

| Operation | Time in min. Set up | Per pc. | Number required | Total time |
|---|---|---|---|---|
| 1. Tensile test | 20 | 6 | 120 | 740 |
| 2. Calculations | | 5 | 120 | 600 |
| 3. Cut off test section to polish stamp number | 35 | 10 | 20 | 270 |
| 4. File and polish 5 grade sand paper | 10 | 40 | 20 | 870 |
| 5. Polish on 2 grades buffing wheels and etch | 30 | 20 | 20 | 430 |
| 6. Micro-inspection | 25 | 10 | 20 | 225 |
| 7. Make negative | 20 | 10 | 20 | 220 |
| 8. Develop film | 20 | 15 | 20 | 320 |
| 9. Make prints | 20 | 4 | 120 | 500 |
| Time Minutes | | | | 3785 |
| Time Hours | | | | 63 |