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An Investigation of a Particular Weldment Failure

Byron Clow

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AN INVESTIGATION OF A
PARTICULAR WELDMENT FAILURE

by
Byron Glaw

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BUTTE

A Thesis
Submitted to the Department of Metallurgy
in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Science in Metallurgical Engineering

MONTANA SCHOOL OF MINES
BUTTE, MONTANA
MAY 18, 1947
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ABSTRACT

Two sets of weld-test coupons, supposedly made under identical conditions, were submitted to this institution last year for approval and certification under the A.S.M.E. Welder's Qualification Code. The first set of coupons was unsatisfactory. The second set, made by the same operators one month later, was satisfactory.

The object of this investigation was to determine by laboratory procedure the reason for the failure of the first set of test coupons.

The conclusion was that the failures were due to faulty technique on the part of the operators.
INTRODUCTION

Early in 1946, a Montana industrial concern applied to the state for a license to manufacture fusion welded tanks for the storage of petroleum gases under pressure. The state granted the license under the provision that the tanks be manufactured in accordance with the A.S.M.E. code for Unfired Pressure Vessels.

The code specifies minimum thicknesses of head and shell for tanks of a given size and pressure, as well as specifying the method of fabrication within certain limits. Section IX of the code is entitled "Standard Welding Qualification Procedure". Part I of Section IX outlines the test procedure to be followed in qualifying the manufacturer in the use of certain welding processes; e.g., arc-welding of mild steel plates up to ½-inch in thickness, or, oxy-acetylene welding of mild steel plates over 1-inch in thickness. Part II of this section outlines the test procedure to be followed in qualifying welding operators to perform the processes in Part I. Only certified operators, who have successfully passed the required test in Part II, Section IX, of the code, may do the welding on a tank that is to bear the A.S.M.E. stamp.
In order to qualify for the welding process that this company was going to use in the manufacture of its tanks, the operators had to make a flat, butt weld in a piece of 3/8-inch mild steel plate, using a coated electrode of standard manufacture, with current, joint design, speed of travel, etc., as recommended by the manufacturer of the particular electrode used. Two coupons, each approximately 1-inch by 6-inches (the 6-inch dimension being perpendicular to the direction of welding) were then cut from each operators test plate. The coupons were then smoothed off with a planer and subjected to a guided-bend test. One coupon of each set was subjected to a root bend, whereas, the other coupon was subjected to a face bend. All bend test specimens were then sent to Montana School of Mines for inspection and certification. The criterion for certifying an operator was that neither of his specimens should contain a crack or a blowhole greater than 1/8-inch in any dimension.

In March of 1946, the first set of specimens were submitted. The following information accompanied them:

Plate: 3/8-inch, A.S.T.M. Specification A410
Electrode: Fleetweld No. 5

* See appendix for manufacturer's recommended procedure in welding 3/8-inch mild steel plate with "Fleetweld 5".
In addition, a third coupon had been cut from each operators test plate and subjected to a tensile test. Failure occurred in the base metal at 72,000 p.s.i. The operators who took the test were all experienced welders, yet none of them had made welds of a quality that merited issuance of a certificate.

One month later, the same operators submitted a second set of specimens with the following information:

**Plate:** 3/8-inch, A.S.T.M. Specification A-70
**Electrode:** Fleetweld No. 5

All of these specimens were satisfactory and a qualification certificate was issued to each operator.

The difference in plate specification (see appendix) is negligible from the standpoint of weldability; in fact, recommended welding procedure is the same for both steels. The question naturally arose as to why the first set failed and the second set did not when, supposedly, they were made by the same men under identical conditions. That was the subject of this investigation.

Visual inspection showed that the failure was in the root-bend specimen of each set, so, for purposes of simplification, the root-bend coupons of one operator were selected for the investigation. Operator number 22 was selected. The root-bend specimen that
failed shall hereinafter be designated as 22-1, and the root-bend specimen that passed shall be designated as 22-2.

FIG. 1- Weld Test Coupons After Guided-Bend Tests
FIG. 2- Root (left) and Face-Bend Specimens of 22-1, as received.

FIG. 3- Root (left) and Face-Bend Specimens of 22-2, as received.
THEORY

When a weldment fails for no immediately apparent cause, we should look to three general sources for the trouble; namely, the physical and chemical properties of the base metal, the physical and chemical properties of the electrode, and the technique used by the operator in making the weld. This last source might well be termed the "human factor", since it entails all the variables, such as preheating, joint design, current strength, number of passes and rate of travel, that are under direct control of the operator.

Base Metal

In plain carbon steels, there is only one physical property, detrimental to weldability, which would not manifest itself as an obvious shortcoming during the bend test. This property is the physical distribution of the sulfides in the steel. The presence of sulfur in the usual commercial amounts of less than 0.05 per cent, will have no deleterious effect provided it is evenly distributed throughout the steel. If, however, the sulfides are segregated into banded zones, the sulfur content within these zones may be as high as 0.12 per cent. In such concentration, the sulfides
will ball-up at the weld junction, thus inhibiting contact between the base metal and the weld metal as well as causing brittleness per se. In extreme cases, the sulfides may flow completely out of the lamallae, leaving a void in the base metal, which, if near the surface, will bring about high enough stress concentrations during deformation to cause premature failure.

All of the chemical factors in the amounts usually occurring in commercial steels have little effect on the production of sound welds. It is, however, feasible that one or more of the chemical factors may be "out of line", in which case it may effect the weldability of the steel. The five principal elements to be considered are carbon, silicon, manganese, phosphorous and sulfur.

Carbon is an effective hardener in steel, consequently, increasing amounts of it will tend to pull the elbow of the S-curve to the right, thus favoring the formation of harder structures in the auto-quenched zone immediately adjacent to the weld. Studies have shown that carbon contents up to 0.35 per cent will not effect the weldability of a plain carbon steel, provided the manganese content is less than 0.80 per cent.
Manganese, like carbon, is a hardener, but it has no deleterious effects in amounts up to 0.80 per cent provided the carbon is less than 0.35 per cent. The combined effect of carbon and manganese may result in martensite in the auto-quenched zone with corresponding increase in hardness and loss of ductility.

Silicon in the amounts usually occurring in steels for welding applications (0.15 to 0.35 per cent) is a benefit rather than a detriment in fusion welding. Steels containing as high as 1.0 per cent silicon have been successfully welded by conventional methods.

Sulfur content as high as 0.24 per cent will not affect the weldability of a steel, provided it is evenly distributed. The effect of sulfide distribution has been discussed in an earlier paragraph.

Phosphorous in ordinary amounts is not usually held to exert any influence on the weldability of steel. Phosphorous banding, however, will produce the same detrimental effects as sulfide banding.

There are many other elements present in minor amounts in steel, but their deleterious effects on weldability are the exception rather than the rule, and will not occur unless the elements are present in absurdly large amounts.
Added Weld Metal

The chemical composition of weld rods is usually not specified, except for general type, since nominal analyses alone do not indicate their welding properties. The only real criteria of their satisfactory performance are the results of the actual welding operation and the mechanical properties of the deposited weld metal individually and as a part of the base materials.

The composition of the solidified added weld metal should approach that of the base material where it is desired to avoid any great discontinuity in physical and chemical characteristics. The composition of the rod is based on expected losses of elements and on good welding characteristics 1.

It is not impossible to receive a shipment of poor weld rods, but of the three aforementioned sources of error, this is the least probable. Defects which manifest themselves in the added weld metal are most frequently due to the operator's technique.

The Operator's Technique

This is the most prolific source of error in weldment failures. The ideal way of determining whether or not the operator is using the proper technique is to be present at the time the weld is made. Unfortunately,
this is rarely the case with the investigator, and he
must make what inferences he can from macro and micro-
examinations of the completed weld. Assuming that he
is using the proper materials, the operator has direct
control over the following factors that influence the
soundness of the completed weld:

1. Joint design
2. Cleaness of surface to be welded
3. Preheating of the base metal
4. Current strength
5. Length of arc
6. Number and sequence of weld beads
7. Rate of electrode travel

One or several of these factors, if handled improperly,
may produce the following defects:

1. Incomplete penetration
2. Lack of fusion
3. Slag inclusions
4. Porosity
5. Cracking

Incomplete penetration is the term applied to
describe the failure, for any reason, of the filler
metal and base metal to fuse integrally at the root
of a joint. In a few cases it may be due to failure
to dissolve surface impurities, but more frequently,
it is the heat transfer conditions existing at the
root of the joint. If the metal being joined first
reaches the melting temperature at areas above the base
of the joint, molten metal may bridge between these
areas and screen off the heat source before the metal
at the root melts. In metal-arc welding, the arc will establish itself between the electrode and the closest part of the base metal. All other areas of the base metal will receive heat principally by conduction. If the portion of the base metal closest to the electrode is a considerable distance from the extreme root of the joint, the conduction of heat may be insufficient to raise the metal temperature at the root to the melting point. Conditions favoring incomplete penetration are those which do not allow proper heat transfer in the base metal. The most frequent ones are improper joint design, insufficient welding current, too high rate of electrode travel and attempting to fill a weld groove with one bead where two or more are required.

Lack of fusion is a term used to describe the failure of a welding process to fuse together adjacent layers of weld metal or adjacent weld metal and base metal. The failure to obtain fusion may occur at any point in the welding groove. The causes are the same as for incomplete penetration, but the frequency is reversed; i.e., the most frequent cause of lack of fusion is failure to dissolve oxides and other impurities on the surface of the base metal.

The immediate cause for any slag inclusion is
improper fluxing conditions. Slag from the surface of
the molten weld metal may be forced into the metal by
the blowing action of the arc, it may form within the
weld metal by chemical reactions, or it may flow ahead
of the arc causing molten weld metal to deposit over
it. Also, the heat of the advancing arc causes oxides
to form on the surfaces of the base metal which must
be fluxed and rise to the surface of the molten weld
metal. Any factors such as high viscosity of the molten
weld metal, rapid chilling or too low a temperature
may prevent the release of these slag particles.

Porosity refers to the globular voids free of any
solid material which are frequently found in welds. The
gases forming the voids are derived from gas released
by the cooling weld metal because of reduced
solubility as the temperature drops, and gases formed
by chemical reaction in the molten weld metal. Porosity
has no serious effects on the mechanical properties of
the joint unless present in excessive quantity. If the
current used in welding is excessive, the resultant
high metal temperature will cause more gas to dissolve
which may not be completely released before solidifi-
cation. If the arc length is too great, the deoxidizing elements of the electrode coating may be consumed
before deposition, leaving insufficient quantities
available to combine with the gases in the molten metal.
Cracking is usually due to some inherent metallurgical defect of the base metal, but when a welded specimen is subjected to a bend test, it can be easily seen that an incomplete penetration at the root or a slag inclusion at the surface would be the ideal vehicle for starting a crack. Such cases are quite easily detectable upon close examination of the crack.

It may be observed from the foregoing discussion that heat transfer conditions play an important part in each case. It is appropriate to outline the effects of heat transfer in an ideal fusion weld.

When weld metal is deposited, affected zones in the base metal will be found adjacent to each line of fusion. This affected zone is a region which has been heated to a sufficiently high temperature to cause a change in microstructure. This change varies in accordance with the maximum temperature attained in the thermal gradient that exists back from the line of fusion (see appendix). With deposited single beads, the affected zone shows a gradation in structure varying from a coarse-grained, overheated structure adjacent to the line of fusion to a full-grained zone corresponding to the critical point whose temperature is 910°C. (A2-line on iron-carbon constitutional diagram), to a partly spheroidized zone of granular pearlite corresponding
to 720°C. ( A1-line ), to the original unaffected ferrite-pearlite structure of the steel³.

The depth of the heat-affected zone will vary with the thermal conditions of the individual weld, but the same gradation of structure should exist in all welds. In multiple-bead welds, however, successive beads, when deposited, will have a refining action, and the microstructure at any point will have a grain-size corresponding to the maximum temperature, above the critical range, last attained.

In a microscopic examination, the grain-size observed in any selected area along the junction will indicate the maximum temperature last attained in that area when compared to the original grain-size of the parent material. Further, the structure within the grains ( pearlite, martensite, etc. ) observed will indicate the rate of cooling, provided the composition of the base metal is known ⁴,⁵.

It was with the foregoing facts in mind that the plan for the investigation was drawn up.
PLAN OF INVESTIGATION

It was planned to examine the two weldments, 22-1 and 22-2, according to the following outline:

I. Base metal examination
   A. Carbon by direct combustion
   B. Other elements by comparative spectrograms
   C. Sulfide distribution by contact sulfur printing

II. Weld metal examination
   A. Carbon by direct combustion
   B. Other elements by comparative spectrograms

III. Macroscopic and microscopic examination of a cross-section thru each weldment
   A. Location of cracks
   B. Joint Design
   C. Appearance and extent of the heat-affected zones
   D. Porosity and slag inclusions
   E. Comparative grain-sizes within the heat-affected zones
   F. The structure of these grains
   G. Hardness survey in the heat-affected zones

Inasmuch as the steel used in 22-1 was manufactured to a much more rigid specification than that used
in 22-2 (see appendix), it would seem doubtful that the chemical composition of the base metal was responsible for the failure of 22-1. The weld metal should be of the same composition in both cases. However justified it may seem, this is purely an assumption, and the chemical composition factor should not be fully relieved of responsibility for the failure until a complete analysis is made. As is usually the case, the time factor was an important element in this investigation, and its consideration resulted in the idea of comparative spectrograms.

If we assumed that the steel of 22-2 was of a satisfactory chemical composition from the standpoint of weldability, and apparently it was; then, by comparing its spectrogram with that of 22-1, we should be able to judge whether or not any of the elements in 22-1 were too far "out of line". It should be realized that such a form of chemical analysis is purely an expedient and may give rise to misleading results.

The hardness survey was contemplated to supplement the findings in III-F.
RESULTS OF INVESTIGATION

The results of the carbon determinations are given in Table I. The carbon content of the base metal of 22-1 is high in comparison with 22-2, but it is well within the accepted limits for good weldability.

<table>
<thead>
<tr>
<th>Specimen 22-1</th>
<th>Specimen 22-2</th>
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<tbody>
<tr>
<td>Base Metal</td>
<td>Weld Metal</td>
</tr>
<tr>
<td>0.27</td>
<td>0.14</td>
</tr>
<tr>
<td>0.30</td>
<td>0.12</td>
</tr>
<tr>
<td>0.285</td>
<td>0.13</td>
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</table>

Sulfur prints were taken to show the distribution of the sulfides (FIG. 4). Specimen 22-2 shows high sulfur and poor distribution, yet, of the two specimens, 22-2 was the satisfactory weld. Apparently, sulfide distribution is not accountable for the failure of 22-1.

The location of the root cracks in 22-1 was found to be at the junction between the weld metal and the base metal, thus indicating the possibility of incomplete penetration.

The joint design appeared to be adequate, although
FIG. 4- Sulfur Print of Specimens 22-1 (below) and 22-2 (above).
positive proof was lacking since the specimens had been deformed.

There was a substantial difference in outline of the heat-affected zones in the two specimens (Fig.'s 5, 6). When the two outlines are compared, it appears that 22-1 was welded in one straight pass, whereas, 22-2 was welded in two passes (one straight and one back-pass) as recommended by the electrode manufacturer.

Porosity and slag inclusion determinations were made on a qualitative basis by visual examination under the microscope. The two specimens were substantially free of both defects, with the exception of one large slag inclusion near the center of the root of 22-1. The slag inclusion was well underneath the surface and could not be accounted for any of the cracking.

Three photomicrographs of each specimen were taken in the positions as shown in Figure 7. The results are shown in Figures 8, 9, 19, 11, 12 and 13. The parent grain-size of each base metal was No. 6 (see Fig.'s 8, 9). The grain-size near the scarf of each specimen was No. 2 (see Fig.'s 10, 11), which indicates that temperatures last attained in these areas were in the neighborhood of 1100°C. The grain-size near the root of 22-2 was No. 3 (see Fig. 12), indicating a final maximum temperature around 1000°C for
FIG. 5 - Cross-section Macrophotograph (3x) of 22-1

FIG. 6 - Cross-section Macrophotograph (3x) of 22-2
this area. The grain-size near the root of 22-1 (see Fig. 13) was No. 8, indicating a final maximum temperature slightly above the lower critical of 720°C. When this is correlated with the outline of the heat-affected zone, it appears that this was not just the final temperature, but the only temperature attained in the root area of 22-1.

An examination of the large grains of figures 10 and 11 at 3000 magnifications revealed a pearlite-sorbutic structure. Good photographs were unattainable.

The results of the hardness survey are given in Table II.

Several attempts were made to obtain spectrophotographs between 3500 and 5500 ˚, but the negatives obtained were entirely unsatisfactory.
FIG. 8- Photomicrograph of Unaltered Base Metal of Specimen 22-1 (100x).

FIG. 9- Photomicrograph of Unaltered Base Metal of Specimen 22-2 (100x).
FIG. 10- Photomicrograph of Weld Junction Near Scarf of Specimen 22-1. Base Metal in Lower Portion of Photo (100x).

FIG. 11- Photomicrograph of Weld Junction Near Scarf of Specimen 22-2. Base Metal in Lower Portion of Photo (100x).
FIG. 12 - Photomicrograph of Weld Junction Near Root of Specimen 22-2. Base Metal in Right Portion of Photo (100x).

FIG. 13 - Photomicrograph of Weld Junction Near Root of Specimen 22-1. Base Metal in Right Portion of Photo (100x).
### TABLE II

**HARDNESS SURVEY**
*Rockwell "B" Scale*

<table>
<thead>
<tr>
<th>Specimen 22-1</th>
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<tbody>
<tr>
<td>60</td>
<td>83</td>
</tr>
<tr>
<td>68</td>
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<td>70</td>
<td>78</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>76</strong></td>
</tr>
</tbody>
</table>

Base Metal Readings 3-inches from Scarf
LABORATORY TECHNIQUE

Carbon determinations were made with the regular carbon combustion train using a Vanier absorption bottle. Despite the fact that the alundum is marketed as being chemically pure, it was found necessary to cure it in a stream of oxygen for several minutes.

Considerable difficulty was encountered in making the sulfur prints. The original procedure adopted was that given by Kehl in his "Principles of Metallographic Laboratory Practice ", but it gave unsatisfactory results. After much experimenting, the final procedure adopted was as follows:

1. Polish the surface of the specimen to be printed on the alumina lap and then etch in nital (5%) for about 15-seconds to roughen the surface slightly.

2. Soak the paper (Azo No.4-glossy) in a 5 per cent solution of \( \text{H}_2\text{SO}_4 \) for approximately 5 minutes.

3. Allow the paper to drain until the liquid film disappears from the surface of the paper (approx. 30 seconds).

4. Place paper on a flat glass surface and set specimen on it, allowing it to rest solely by the pressure of its own weight. Optimum contact time will vary and should be determined by a trial run for each specimen.

5. Rinse in water, fix in hypo bath for 12 minutes, then wash and dry in the usual manner.
6. If a second print is desired from the same specimen, it must be re-surfaced, starting with the No. 1 grit paper.

Figures 1, 2 and 3 were taken with a Leica, 35-mm. camera using Eastman Panatomic X film. The lighting was done with three, bench-type, microscope lamps. Figure 1 was taken with a No. 1 lense attachment, 3.5 opening, and 1/20th-second shutter speed. Figures 2 and 3 were taken with a No. 3 lense attachment, 4.5 opening, and 1/20th-second shutter speed.

Figures 5 and 6 were taken with a non-adjustable, bench-type camera using a 72-mm. lense and three microscope table lamps for lighting. Eastman Ortho Contrast film was used with a 1-second exposure. Prints were made on Azo No. 4 paper.

The specimens in figures 10 and 13 were etched in nital (5%) for 20-seconds. They were photographed on Wratten Metallographic Plates using an 8-second exposure. A green filter was used on the light. Prints were made on Azo No. 4 paper.

The specimens in figures 8, 9, 11 and 12 were etched in Picral for 30-seconds. Photographic data is the same as for figures 10 and 13 except Eastman Ortho Contrast film was used.

Twelve different samples were run on the spectrophotograph, but only one of them gave a satisfactory negative.
This was insufficient, of course, since there was nothing with which to compare it. The recommended exposure time for iron samples is 45-seconds using Eastman Spectral Analysis No. 2 film. The difficult part of the operation is to keep the light from the condensing lense focused on the slit for the entire exposure time. An inexperienced operator, as in this case, will run three samples for the same length of time on one negative and find that he has a different exposure time on each one when he develops the negative. There was insufficient laboratory time remaining to acquire the necessary skill.
CONCLUSIONS

In view of the fact that no chemical analyses were made, the investigation was not complete. The evidence that was assembled leads to the following conclusions:

1. The first weldment made by Operator No. 22 failed because of cracks due to incomplete penetration.

2. The incomplete penetration was the result of trying to make the weld in one straight-pass when one straight and one back-pass should have been used.
BIBLIOGRAPHY


TERMINOLOGY AND GENERAL THERMAL CONDITIONS IN A FUSION WELD (After Rossi)
EXCERPTS FROM A.S.T.M. SPECIFICATION A-10 FOR MILD STEEL PLATES

Chemical Requirements:
Phosphorous ........ 0.04 max.
Sulfur ............. 0.05 max

Physical Requirements:
Tensile Strength 55,000-65,000 p.s.i.
Bend Test - 180° on itself

EXCERPTS FROM A.S.T.M. SPECIFICATION A-70 FOR CARBON STEEL PLATES

Chemical Requirements:
Manganese ........... 0.80 max
Phosphorous ........ 0.04 max
Sulfur .............. 0.05 max

Physical Requirements:
Tensile Strength 55,000-70,000 p.s.i.
Bend Test - 180° on 1/4-diameter

EXCERPTS FROM LINCOLN ELECTRIC COMPANY’S PAMPHLET "FLEETWELDING"

Recommended Procedure for Flat Position Welding of 3/8-inch Mild Steel Plate with Fleetweld No. 5

Joint: 60° V-groove, 1/8-inch shoulder, 1/16-inch gap
Electrode: 1/4-inch Fleetweld No. 5
Current: 300-amperes
Passes: 1st straight, 2nd back-pass-- no preheat
ACKNOWLEDGEMENTS

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