Analysis of δ-Ferrite Data from Production Welds on Stainless Steel Pipe

Requirements on ferrite measurement in production welds are revised as a result of task group investigation

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ABSTRACT. An American Society of Mechanical Engineers task group on stainless steel weld materials was organized to determine the need for ferrite measurements of production welds required by the U.S. Nuclear Regulatory Commission Regulatory Guide 1.31 (Ref. 1). The task group studied paired ferrite measurements, i.e., both calculated and measured ferrite numbers (FNs) for the material qualifications, versus measured ferrite numbers for corresponding production welds (PWs). Our purpose was to compare δ-ferrite content as measured in the filler metal weld qualification pad with that in the resultant PW. Welds made predominantly by three common processes (submerged arc, shielded metal arc, and gas tungsten arc) were included in the study. Weld metals investigated included types 308, 308L, 316L, and 316L stainless steel. An initial evaluation of the paired ferrite measurements was made by the task group, and specific conclusions and recommendations were made. We describe the analysis of the data and the conclusions drawn.

The data base consisted of a heterogeneous collection of 1449 paired ferrite measurements for several forms and combinations of types 304 and 316 stainless steel pipe qualification pad and production welds. Qualification pad values ranged from 5 to 15 FN, and corresponding values for the PWs ranged from 2.3 to 17.5 FN. Only two PW ferrite numbers were less than 3. For qualification weld ferrite numbers less than 14, the median PW ferrite number was in reasonable agreement. However, the results show a wide scatter.

As a result of this analysis and the task group evaluation, we concluded that the requirements of Regulatory Guide 1.31 on the measurement of ferrite in PWs are not necessary and that a minimum ferrite number of 5 in the qualification welds will, in most cases, result in PW ferrite contents greater than 3 FN.

Introduction

To minimize the susceptibility of austenitic stainless steel welds to fissuring, a small percentage of δ-ferrite is generally required in the room-temperature microstructure. For construction of class 1 nuclear components, Sect. III of the American Society of Mechanical Engineers' ASME Boiler and Pressure Vessel Code requires that welding material qualifications include determination of ferrite content expressed as ferrite number (FN) (Ref. 1). All austenitic stainless steel weld materials, except cladding materials and SFA5.4 type 16-8-2, are required to have at least 5 FN as determined from a constitutional diagram* or from measurements by a magnetic measuring device (Ref. 1). Previously, the Interim Regulatory Position to the U.S. Nuclear Regulatory Commission Regulatory Guide 1.31 (Ref. 2) required that 10% of production welds (PWs) over 25.4 mm thick (1 in.) be tested to ensure that the weld metals contain sufficient δ-ferrite to provide 3 FN. The ferrite number in PWs is measured by magnetic devices (Magne-Gage, Ferritoscope, Severn gage, Elcometer, etc.) calibrated to secondary standards traceable to the National Bureau of Standards.

An ASME task group was organized to determine the need for measuring the ferrite content of PWs, as required in the Interim Regulatory Position (Ref. 2). The task group conducted a study of paired ferrite measurements, that is, calculated and measured ferrite numbers for the material qualifications versus measured ferrite numbers for the PWs. The purpose of this study was to compare δ-ferrite contents, as measured in the filler metal weld qualification pads (qualification welds, QWs), with those in the resultant PWs. Welds made primarily by three processes — submerged arc (SA), shielded metal arc (SMA), and gas tungsten arc (GTA) — were included in the study. Weld metals investigated included types 308, 308L, 316L, and 316L stainless steel. The QW and PW ferrite measurements were first evaluated by the ASME task group, and specific conclusions and recommendations were made. This paper describes an analysis of the data and presents the conclusions drawn from the analysis.

Analysis Technique

The data base consisted of a heterogeneous collection of 1449 paired ferrite measurements on filler metal weld pads...
Table 1—Summary of Ferrite Measurements by Category

<table>
<thead>
<tr>
<th>Welding Process</th>
<th>Number of Tests</th>
<th>Stainless Steel Type Filler</th>
<th>Number of Tests</th>
<th>Stainless Steel Types, Base Metals</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas tungsten arc</td>
<td>914</td>
<td>308</td>
<td>421</td>
<td>304 to 304</td>
<td>921</td>
</tr>
<tr>
<td>Shielded metal arc</td>
<td>303</td>
<td>308L</td>
<td>624</td>
<td>304 to 316</td>
<td>75</td>
</tr>
<tr>
<td>Submerged arc</td>
<td>228</td>
<td>316</td>
<td>90</td>
<td>316 to 316</td>
<td>339</td>
</tr>
<tr>
<td>Flux cored arc</td>
<td>2</td>
<td>316</td>
<td>7</td>
<td>304L to 316</td>
<td>25</td>
</tr>
<tr>
<td>Gas metal arc</td>
<td>2</td>
<td>Unknown</td>
<td>2</td>
<td>304 to 316L</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>304 to 304</td>
<td>8</td>
</tr>
</tbody>
</table>

Material Thickness

| <25.4 mm (1.00 in.) | 631 | Ferritescope | 341 |
|>25.4 mm (1.00 in.) | 273 | Elcometer    | 86  |
| Unknown             | 545 | Severn gage  | 477 |

Table 2—Distribution of Differences between Ferrite Numbers of Production Welds and of Filler Metal Weld Pads with Known Measurement Techniques

<table>
<thead>
<tr>
<th>Partition of Tests with Known Measurement Technique or Filler Metal</th>
<th>Number of Tests in Group</th>
<th>Distribution over Ranges of PW−QW (% of Group Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magne-Gage</td>
<td>485</td>
<td>&lt;4: 3.3, &lt;3: 3.9, &lt;2: 4.3, &lt;1: 18.8, &lt;0: 35.3, &gt;0: 44.3, &gt;1: 12.0, &gt;2: 7.4, &gt;3: 3.7</td>
</tr>
<tr>
<td>Constitution diagram</td>
<td>419</td>
<td>&lt;4: 2.1, &lt;3: 5.5, &lt;2: 20.8, &lt;1: 33.4, &lt;0: 53.7, &gt;0: 42.0, &gt;1: 21.7, &gt;2: 12.4, &gt;3: 9.3, &gt;4: 3.6</td>
</tr>
<tr>
<td>Magne-Gage and Ferritescope or Elcometer</td>
<td>115</td>
<td>&lt;4: 0.0, &lt;3: 0.0, &lt;2: 0.0, &lt;1: 10.4, &lt;0: 31.3, &gt;0: 63.5, &gt;1: 33.9, &gt;2: 14.8, &gt;3: 7.8, &gt;4: 3.9</td>
</tr>
<tr>
<td>Constitution diagram and Severn gage</td>
<td>312</td>
<td>&lt;4: 2.9, &lt;3: 7.1, &lt;2: 14.1, &lt;1: 34.0, &lt;0: 58.0, &gt;0: 36.2, &gt;1: 27.5, &gt;2: 20.9, &gt;3: 8.7, &gt;4: 2.9</td>
</tr>
<tr>
<td>Magne-Gage and Severn gage</td>
<td>370</td>
<td>&lt;4: 4.3, &lt;3: 5.1, &lt;2: 5.7, &lt;1: 21.4, &lt;0: 36.5, &gt;0: 48.6, &gt;1: 47.6, &gt;2: 11.1, &gt;3: 7.3, &gt;4: 4.6</td>
</tr>
<tr>
<td>Constitution diagram and Severn gage</td>
<td>107</td>
<td>&lt;4: 0.0, &lt;3: 0.0, &lt;2: 0.0, &lt;1: 0.9, &lt;0: 30.8, &gt;0: 31.8, &gt;1: 41.1, &gt;2: 49.5, &gt;3: 33.6, &gt;4: 16.8, &gt;5: 11.2, &gt;6: 5.6</td>
</tr>
<tr>
<td>Filler type 308 stainless steel</td>
<td>188(1)</td>
<td>&lt;4: 4.3, &lt;3: 8.0, &lt;2: 18.6, &lt;1: 36.7, &lt;0: 61.7, &gt;0: 36.2, &gt;1: 18.6, &gt;2: 9.0, &gt;3: 7.4, &gt;4: 3.7</td>
</tr>
<tr>
<td>Filler type 308L stainless steel</td>
<td>624</td>
<td>&lt;4: 2.7, &lt;3: 4.2, &lt;2: 6.6, &lt;1: 20.8, &lt;0: 39.1, &gt;0: 48.9, &gt;1: 39.9, &gt;2: 13.9, &gt;3: 9.5, &gt;4: 4.0</td>
</tr>
<tr>
<td>Filler type 316L stainless steel</td>
<td>90</td>
<td>&lt;4: 0.0, &lt;3: 0.0, &lt;2: 33.3, &lt;1: 33.3, &lt;0: 37.8, &gt;0: 62.2, &gt;1: 24.4, &gt;2: 6.7, &gt;3: 2.2, &gt;4: 1.1</td>
</tr>
</tbody>
</table>

(1) Of the 421 type 308 weld data listed in Table 1, only 188 had identified welding processes; only these were analyzed.

*Here, QW and PW represent FNs of the respective welds.

Fig. 1—Comparison of measured ferrite numbers from production welds with those from filler metal weld pads. See Fig. 2 for explanation

**Determination from composition with constuction diagram.**

and corresponding PWs for several forms and combinations of types 304 and 316 stainless steel pipe. Ferrite number values ranged from 5 to 15 for the QWs and from 2.3 to 17.5 for the PWs. The tests were partitioned according to six variables: 1) welding process, 2) base material, 3) filler material, 4) base material thickness, 5) ferrite measurement technique used on filler metal weld pad, and 6) ferrite measurement technique used on PW. Other variables such as source of information and welding position were not considered. The number of tests at each variable level is given in Tables 1 and 2. Two measurement techniques—Magne-Gage and the chemical analysis constitution diagram (Ref. 3) contained in Sect. III of the ASME Code—were used solely for QW measurements, and three other techniques—Severn gage (both ranges), Elcometer, and Ferritescope—were used solely for PW measurements.* This confounding makes it impossible to compare directly the qualification and production welds because the variability...
in results necessarily contains unknown biases that may exist between measurement techniques. Although in subsequent treatment of the data we attribute results to differences between QW values and PW values, we must recognize that this confounding is present.

As with most collections of historic information, the confounding of results that exists makes it difficult to draw clear-cut conclusions. No attempt was made to enumerate these except to state that measurement methods, in addition to being confounded with the paired tests, were also partially confounded with data source and thickness of material.

Analysis of Results

The data are illustrated in Fig. 1 with box plots. These plots are generated by determining the median and other appropriate points that display the distribution of values (see Fig. 2 for key to Fig. 1) from an ordered set of data. For example, all data with the same QW measurements are arranged in order from smallest to largest. For each ordered QW set, the median is the middle PW value, and the "hinges" correspond to middle values.

![Fig. 2 — Description of box plot method for displaying data. The "hinges" represent quartiles, and the H-spread is the range of values between the lower and upper quartiles.](image)

![Fig. 3 — Distribution of differences (PW—QW) between production weld and filler metal weld pad ferrite measurements, shown as proportion of tests that fall within specific intervals for two weld thickness ranges and for all available data.](image)

![Fig. 4 — Distribution of differences (PW—QW) between production weld and filler metal weld pad ferrite measurements shown as percent of total in each group for four comparisons of ferrite measurement techniques, (a) Range reading versus dial reading, (b) Range reading versus empirical, (c) Dial reading versus dial reading, (d) Dial reading versus empirical.](image)
Fig. 5 - Distribution of differences (PW—QW) between production weld and filler metal weld pad ferrite measurements for four comparisons of ferrite measurement technique with all weld metals measured. MG, Magne-Gage; DIA, constitution diagram; FS, Ferrite-scope; SG, Severn gage; EL, Elcometer.

Fig. 6 - Distribution of differences (PW—QW) between production weld and filler metal weld pad ferrite measurements for six comparisons of ferrite measurement techniques with type 308L stainless steel weld metal.

Distributions of Differences (PW—QW)

For the remainder of our discussion, we analyze the behavior of the difference (PW—QW) about zero. Ideally, the ferrite number measurements for the QW and PW should be the same for a given set of conditions, so the difference would be zero. It is of interest to determine, for example, if measurement technique or material thickness biases these differences in one direction or another.

The distribution of differences (in raw counts and percentages) is given in Table 3 for all data collectively and for data from welds with thicknesses less than 25.4 mm (1 in.) and those of at least 25.4 mm. The distribution of absolute differences, also given in Table 3, shows that nearly half (48.9%) of all tests differed by at least 2 FN and that one in ten (9.9%) differed by more than 4 FN. The distribution of differences over equally wide intervals is pictorially displayed in Fig. 3, in which the proportion (X/100 = percentage) of tests falling inside the intervals (as marked by midpoints) is plotted.

Partitioning of Measurement Techniques

The techniques used for measuring ferrite numbers in the PW may be divided into two classes: 1) the “range reading” Severn gage and 2) the “dial reading” Elcometer and Ferrite-scope. That is, each Severn gage response covers a range of values, and the dial reading devices yield a single number on a continuous scale. Ranges magnify the variability, and although in this study all magnets were employed, we used the lower end of the range, i.e., if FN = 5 to 7.5, then 5 FN was used.

These methods were compared separately with results from the dial-reading Magne-Gage and the empirically determined constitution diagram. This compara-
Partitioning of Filler Metals

The data may also be partitioned according to filler metal types 308, 308L, and 316L stainless steel. The two tests on type 316 stainless steel have been omitted from the discussion. The distribution of differences is given in Table 2 and shown as box plots in Figs. 6 and 7. Scatter in the data is substantial and masks any real effects of filler metal type on ferrite measurement.

Partitioning of Base Metal Type, Thickness, and Welding Process

The data were also partitioned to determine the effects of base metal type, thickness, and welding process. In general, scatter in the data masks any real effects of those variables on \( PW-QW \) differences for these welds.

Distribution of Numbers Not Exceeding 10 FN

Because ASME Code Case N47-21 requires that the ferrite number for stainless steel welds be between 3 and 10, it is of interest to look at the distribution of \( PW \) measurements for which the \( QW \) measurement does not exceed 10 FN. The 1034 such paired results are compared below:

1. 129 (12.5%) \( PW \) measurements were equal to 10 FN,
2. 212 (20.5%) \( PW \) measurements were greater than 10 FN,
3. 180 (17.4%) \( PW \) measurements were greater than 11 FN,
4. 93 (9.0%) \( PW \) measurements were greater than 12 FN, and
5. 2 (0.2%) \( PW \) measurements were less than 3 FN.

At specific levels of \( QW \), the number of tests in which \( PW \) exceeds 10 FN is compared in Table 4. It should be noted that only two of the 1449 data points had \( PW \) values less than 3 FN.

**Discussion**

We have demonstrated in this study that wide scatter exists in ferrite number measurements of \( QW \)s compared with \( PW \)s. For any given \( QW \) ferrite number, a large variation in \( PW \) ferrite number values can be expected because of several confounding factors. The largest effect on differences between ferrite number values for \( PW \)s and \( QW \)s was found to be measurement techniques, with the dial-reading techniques providing less scatter than the range-reading and chemical analysis diagram techniques.

However, it is important to note that only two \( PW \) values (0.14%) fell below 3 FN for the 1449 data points with corresponding \( QW \) values of at least 5 FN. Therefore, as a result of the evaluation by the ASME task group, to which this analysis was provided, it was concluded that the requirements of Regulatory Guide 1.31 for measurement of ferrite in \( PW \)s are not needed. The document has since been changed to reflect this conclusion (Ref. 6).

**Conclusions**

1. The median production weld ferrite number is a reasonable measure of the...
qualification weld ferrite number for values less than 14 FN.

2. The dial-reading measurement techniques (Elcometer vs. Magne-Gage and Ferritescop vs. Magne-Gage) produced less scatter in the distribution of differences between \( PW \) and \( QW \) values than did the range-reading techniques (Severn gage for \( PW \)).

3. Partitioning of data according to welding processes, base metal, filler metal, or thickness did not reveal significant effects on the distribution of difference \( PW - QW \).

4. Even though a wide scatter of data exists, the percentage of \( PW \) values less than 3 FN is very low (0.14%) for QWs with 5 FN or more.

Acknowledgments

The authors wish to acknowledge the editorial assistance of Sigfred Peterson and Irene Brogden and composition and makeup by Gwendolyn Sims and Marie Knaff in the preparation of this document.

References


