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, 316, 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, Ferritescope, 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, 316, 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

*DeLong diagram is suggested when nitrogen content is known, and Schaeffler diagram is suggested when nitrogen content is not known.

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Table 1—Summary of Ferrite Measurements by Category

Welding Process	Number of Tests	Stainless Steel Type Filler	Number of Tests	Stainless Steel Types, Base Metals	Number of Tests
Gas tungsten arc	914	308	421	304 to 304	921
Shielded metal arc	303	308L	624	304 to 316	75
Submerged arc	228	316L	90	316 to 316	339
Flux cored arc	2	316	2	304L to 316	25
Gas metal arc	2	Unknown	545	304 to 316L	7
				304 to 304L	8
				Unknown	74
Material Thickness		**Measurement Technique on Production Weld**		**Measurement Technique on Weld Qualification Pad**	
<25.4 mm (1.00 in.)	631	Ferritescope	341	Magne-Gage	485
>25.4 mm (1.00 in.)	273	Elcometer	86	Diagram[a]	419
Unknown	545	Severn gage	477	Unknown	545
		Unknown	545		

[a]Determined from composition with constitution 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

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

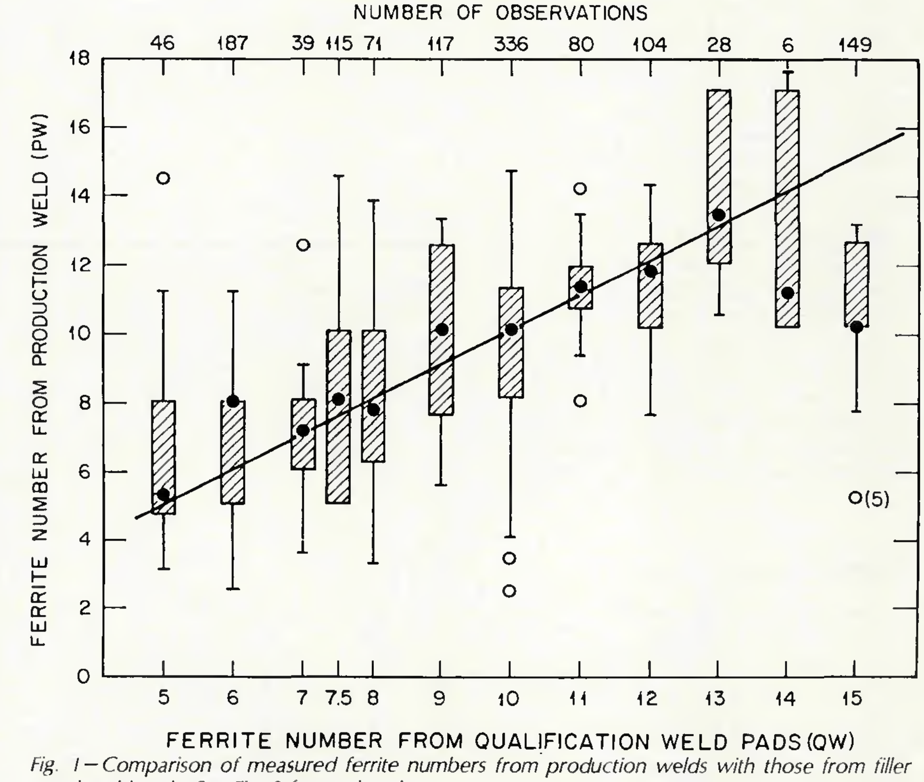

Fig. 1—Comparison of measured ferrite numbers from production welds with those from filler metal weld pads. See Fig. 2 for explanation

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

Partition of Tests with Known Measurement Technique or Filler Metal	Number of Tests in Group	<−4	<−3	<−2	<−1	<0	>0	>1	>2	>3	>4
		Distribution over Ranges of PW−QW (% of Group Total)									
Magne-Gage	485	3.3	3.9	4.3	18.8	35.3	52.2	44.3	12.0	7.4	3.7
Constitution diagram	419	2.1	5.5	20.8	33.4	53.7	42.0	21.7	12.4	9.3	3.6
Magne-Gage and Ferritescope or Elcometer	115	0	0	0	10.4	31.3	63.5	33.9	14.8	7.8	0.9
Constitution diagram and Ferritescope or Elcometer	312	2.9	7.1	14.1	34.0	58.0	36.2	27.5	20.9	8.7	2.9
Magne-Gage and Severn gage	370	4.3	5.1	5.7	21.4	36.5	48.6	47.6	11.1	7.3	4.6
Constitution diagram and Severn gage	107	0	0.9	30.8	31.8	41.1	49.5	33.6	16.8	11.2	5.6
Filler type 308 stainless steel	188[a]	4.3	8.0	18.6	36.7	61.7	36.2	18.6	9.0	7.4	3.7
Filler type 308L stainless steel	624	2.7	4.2	6.6	20.8	39.1	48.9	39.9	13.9	9.5	4.0
Filler type 316L stainless steel	90	0	0	33.3	33.3	37.8	62.2	24.4	6.7	2.2	1.1

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

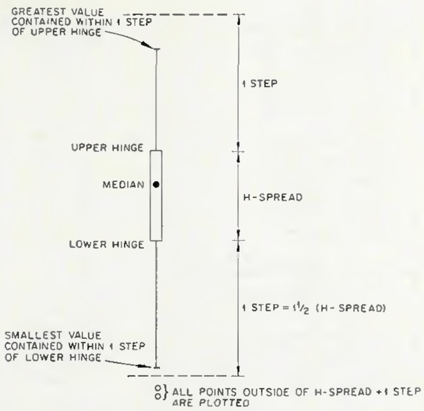

Fig. 2 — Description of box plot method for displaying data. The "hinges" represent quartiles, and the H-spread is the range of values between the lower and upper quartiles

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

Table 3—Distribution of Differences between Ferrite Numbers of Production Welds PW and Filler Metal Weld Pads QW

Ferrite Number Difference (PW-QW)	Raw Count Material Thickness <25.4 mm (<1.00 in.)	Raw Count Material Thickness >25.4 mm (>1.00 in.)	All Data	Total in Category (%) Thickness <25.4 mm (<1.00 in.)	Total in Category (%) Thickness >25.4 mm (>1.00 in.)	All Data
	Distribution of differences (*PW-QW*)					
<−5	1	6	95	0.2	2.2	6.6
<−4	17	7	101	2.7	2.6	7.0
<−3	40	12	126	6.3	4.4	8.7
<−2	91	28	306	14.4	10.3	21.1
<−1	167	75	503	26.5	27.5	34.7
<0	273	124	703	43.3	45.4	48.5
=0	57	16	108	9.0	5.9	7.5
>0	301	133	638	47.7	48.7	44.0
>1	169	79	224	26.8	28.9	15.5
>2	57	52	186	9.0	19.0	12.8
>3	34	40	116	5.4	14.7	8.0
>4	21	12	42	3.3	4.4	2.9
>5	12	5	18	1.9	1.8	1.2
	Distribution of absolute values of differences (*PW-QW*)					
>2	148	80	492	23.5	29.3	34.0
≥2	317	90	709	50.2	33.0	48.9
>3	74	52	242	11.7	19.0	16.7
>4	38	19	143	6.0	7.0	9.9
>5	13	11	113	2.1	4.0	7.8

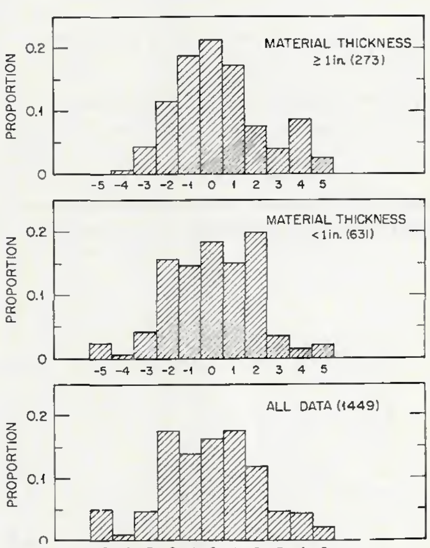

Fig. 3 — Distribution of differences (PW — QW) between production weld and filler metal weld pad ferrite measurements, shown as proportion of tests that fall within specific intervals for two weld thickness ranges and for all available data

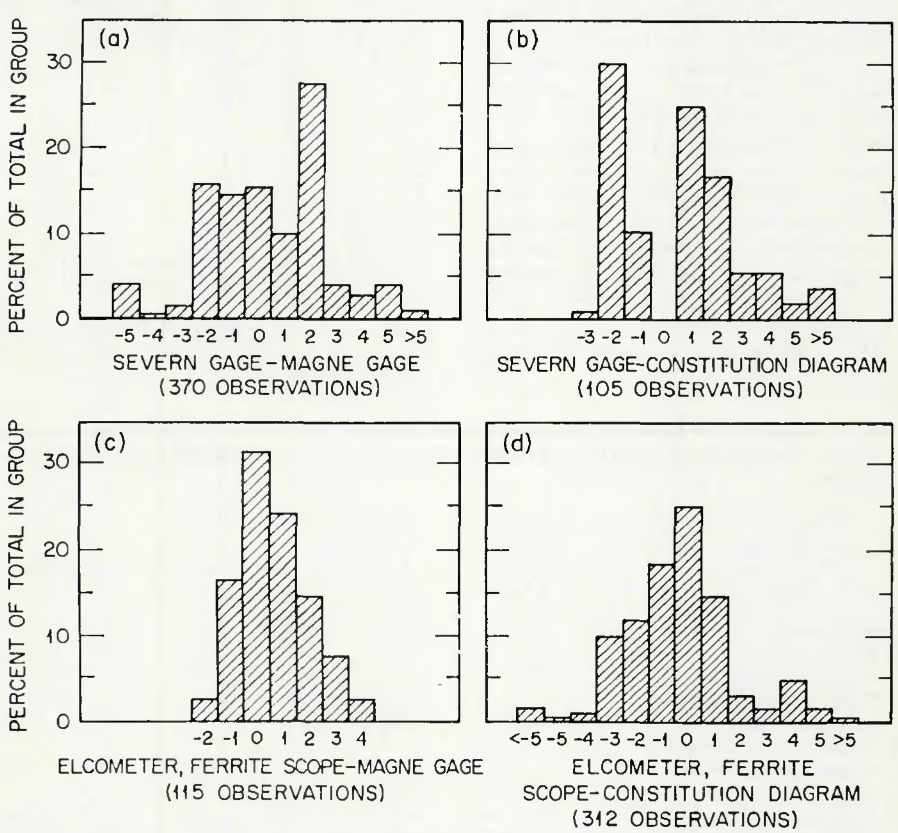

Fig. 4 — Distribution of differences (PW — QW) between production weld and filler metal weld pad ferrite measurements shown as percent of total in each group for four comparisons of ferrite measurement techniques. (a) Range reading versus dial reading. (b) Range reading versus empirical. (c) Dial reading versus dial reading. (d) Dial reading versus empirical

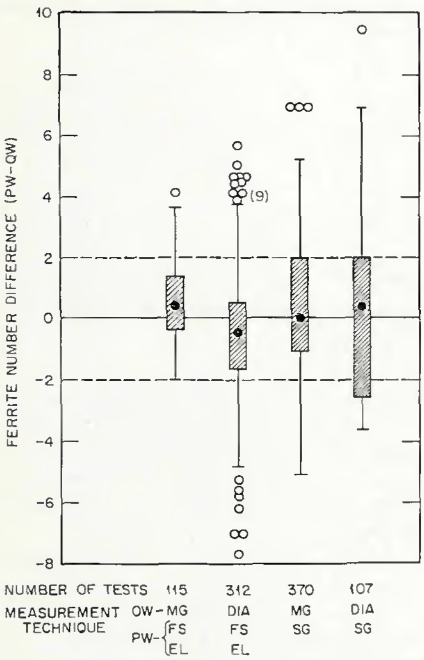

Fig. 5 — Distribution of differences (PW − QW) between production weld and filler metal weld pad ferrite measurements for four comparisons of ferrite measurement technique with all weld metals measured. MG, Magne-Gage; DIA, constitution diagram; FS, Ferritescope; SG, Severn gage; EL, Elcometer

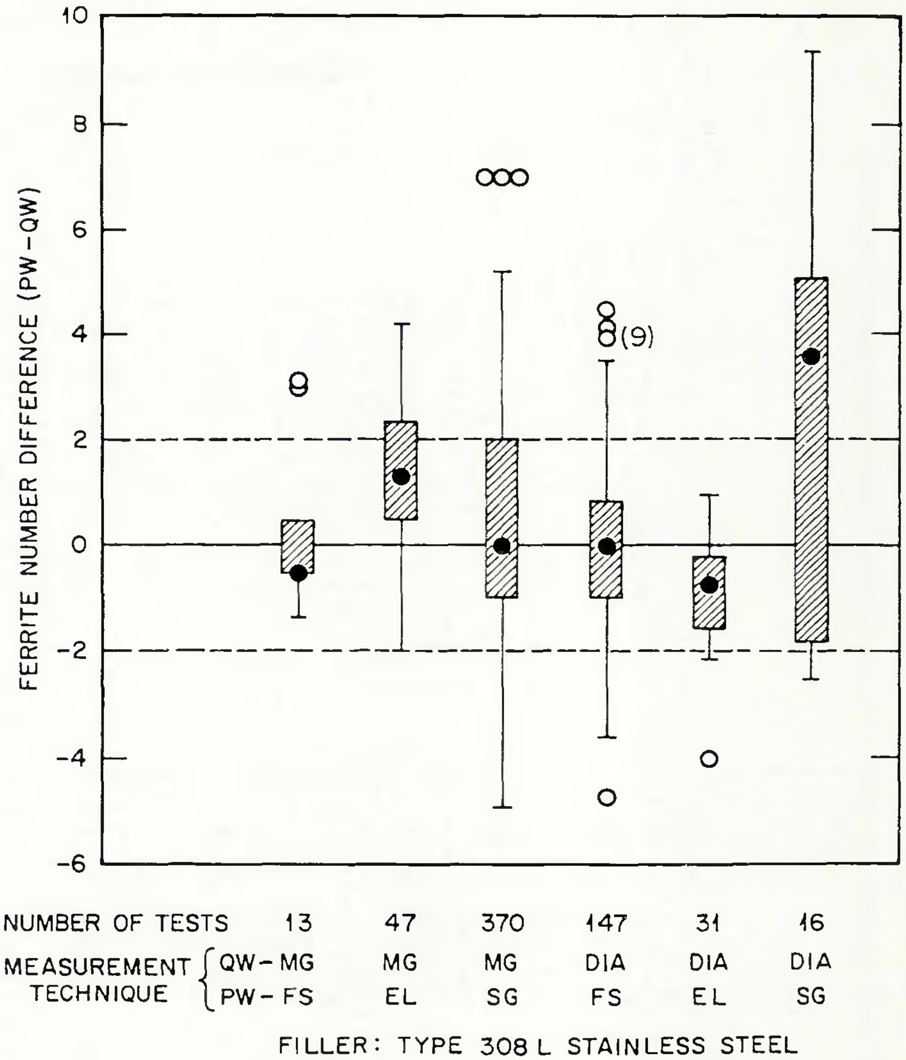

Fig. 6 — Distribution of differences (PW − QW) between production weld and filler metal weld pad ferrite measurements for six comparisons of ferrite measurement techniques with type 308L stainless steel weld metal

between the median and extremes, that is, quartiles. Thus, at most, 50% of the data fall inside the interval spanned by the rectangle (H-spread). If hinge points are included in the H-spread interval, then we can say that at least 50% of the observations are contained in the interval. Unusual plots, such as in Fig. 1 under *QW* of 13, call attention to and summarize important distributional aspects of the observations. Here no upper region is shown because at least 25% of the data are equal to 17 FN. In the extreme case, where all values in a data set are the same, there is no structure, just a median. Displaying data in the foregoing manner has been suggested by Tukey (Ref. 4).

The median *PW* value at each *QW* level below 14 FN is a reasonable measure of the corresponding *QW* value. Figure 1 illustrates the wide scatter in results over the *QW* range from 5 to 15 FN (*PW* ranged from 2.3 to 17.5 FN). At a *QW* level of 15 FN, none of the 149 *PW* values exceeded 13 FN. We omitted 171 tests from the figure because they were scattered at different *QW* levels and their inclusion would be misleading. The only reason for including the six tests at *QW* = 14 was to provide a complete coverage of integral *QW* values from 5 to 15. Of the 1449 *PW* measurements, only two *PW* values were less than 3 FN.

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 (×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 Ferritescope. 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 compar-

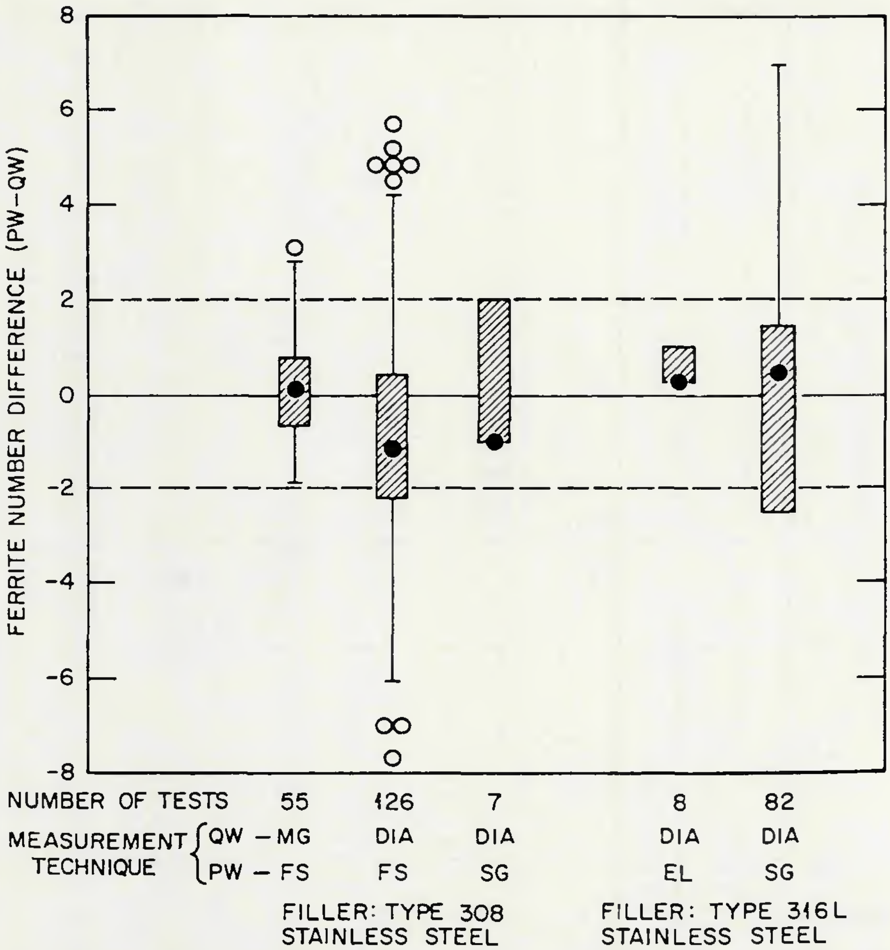

Fig. 7 — Distribution of differences (PW — QW) between production weld and filler metal weld pad ferrite measurements for six comparisons of ferrite measurement techniques with types 308 and 316L stainless steel weld metals

ison is shown by the distributions of differences given in Fig. 4. As expected, the dial-reading results, as seen in Fig. 4(c), exhibited less scatter. All data falling outside the intervals with midpoints of ±5 are placed in a single category labeled >5 or <−5. It must be recognized that the subjective conclusion of less scatter includes a bias due to unequal sample size. In general, scatter (range of data) increases with sample size. Still, the 107 Diagram-Severn gage tests, Fig. 4(*b*), exhibited a large scatter.

Note that Fig. 4(*b*) displays a bimodal distribution of the Diagram-Severn gage differences. None of the tests produced PW values equal to the *QW* results. The distributions in Fig. 4 are plotted as box plots in Fig. 5. Although not readily apparent when the two figures are compared, the tighter central concentration seen in Fig. 4(*d*) emphasizes the wide scatter of the same results when shown in Fig. 5. On the other hand, with the exception of Magne-Gage, Ferritescope and Elcometer, Fig. 5 clearly shows the large spread of data. Note that the bimodal character of Fig. 4(*b*) is hidden in a box plot.

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 (paragraph 2433.2) (Ref. 5), 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.

Table 4

Number of Tests	FN for QW	Number of Tests in which *PW* Exceeds 10 FN
46	5	3 (6.5%)
187	6	8 (4.3%)
39	7	1 (2.6%)
115	7.5	23 (20.0%)
71	8	16 (22.5%)

Discussion

We have demonstrated in this study that wide scatter exists in ferrite number measurements of QWs compared with PWs. 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 PWs and QWs 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 PWs 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 Ferritescope 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.

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