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STATISTICAL EVALUATION OF A ROUND-ROBIN EXPERIMENT: UNCERTAINTIES IN FERRITE MEASUREMENT IN WELDMENTS

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ABSTRACT

A round robin was organized to measure FN (ferrite) levels in the weld metal of five stainless steel weldments, including: types AISI 308H (with controlled ferrite), 2205 (22 % Cr duplex), 309Mo, 16-8-2 (316H - a lean composition with controlled ferrite), and 316NF (with negligible ferrite). Each weldment was sliced into several pieces, and various locations on the surfaces of these pieces were specified for measurements. In addition, some locations on the weld caps and weld roots were given different finishes (as-welded, lightly polished, ground flush, and filed flush) to assess the effect of these surface finishes on the measurements. The specimens were circulated to 17 different laboratories in 9 different countries around the world. A Summary Report (distributed to two Commissions within the International Institute of Welding in 2001, as IIW Documents II-1440-01 and IXH-512-01) presented the data and some preliminary analysis of the data. That report recommended a more comprehensive statistical analysis, which is the subject of this report.

First, a two-way analysis of variance showed that the laboratory and area (location within the specimen) were both statistically significant variables and so both were considered in further analyses. Next, Tukey analyses showed the large number of statistically distinct subsets into which both the laboratory and area data could be divided. Box-and-whiskers plots for these weldments show the distribution of the data, both by laboratory and by area. The data for each location in the weldments were combined to show the variation (as standard deviations) in the values of FN, to estimate the variation that might be expected among laboratories. Finally, the surface finish was found to be significant, but the effect varied from weld to weld.

KEYWORDS

box-and-whiskers plots; ferrite; FN; round robin; statistical analysis; weldments; welds

BACKGROUND

The amount of ferrite phase in austenitic steel weldments has substantial commercial significance, as various standards specify maximum or minimum FN (ferrite) levels that have been shown to avoid undesirable behaviour, such as cracking or corrosion. Most other round robins have been designed around carefully produced laboratory specimens, to estimate the lower bound of uncertainty in the various aspects of the measurement technique.[1] This round robin was designed around realistic weldments that include measurements at the dilutions and composition gradients that occur when electrodes and base plates of differing compositions interact. Therefore, the data in this round robin represent the ranges in measurements that might be found between commercial laboratories, such as between the producer and user of a welded stainless steel structure.

This round robin was organized to measure ferrite (FN) levels in the weld metal of five weldments, designed for different nominal FN levels, identified as follows:

- 308H - A controlled ferrite 308H type,
- 2205 - A 22 % Cr duplex stainless steel type,
- 309Mo - A 'mixed welding', 309Mo type,
- 16-8-2 - A controlled ferrite 'lean 316H' type, and
- 316NF - A 316 type with negligible ferrite.

These were designed as weldments (with realistic dilutions from the base plates), not research-grade FN pads (with negligible dilutions). Each weldment was sliced into several pieces, and various areas on the surfaces of these specimens were identified for measurements by the round robin participants. In addition, some locations on the weld caps and weld roots were finished by common surface preparation processes (namely as-welded, lightly polished, ground flush and filed flush) to allow an assessment of the effect of these surface finishes on the measurements.

The summary report (IIW Documents II-1440-01 and IXH-512-01) of this set of tests was divided into three parts: [2]

- Part I - Results of FN Measurements. Each laboratory was asked to carry out FN determinations for each of the 22 areas shown in Figure 1, using their own in-house equipment calibrated against IIW secondary standards, and using the procedure outlined in Ref. 1. The participants were asked to make 5 or 10 measurements in each area, and supply the mean value as well as maximum and minimum values for each area.

- Part II - Results of Chemical Analyses. In addition, each laboratory was asked to carry out a chemical analysis using optical emission spectroscopy (OES) on a slice of each of the weldments. For those elements (e.g. nitrogen) for which OES is not considered sufficiently accurate, sample metal chips of the weld areas were supplied so that a dedicated-element analysis technique could be used.

- Part III - Prediction of FN values. Finally, each participant was asked to use their own analysis to predict an FN using their own preferred method, e.g. WRC-92 diagram, commercial software, etc.

The summary report recommended “a more comprehensive statistical analysis to establish the significance of laboratory-to-laboratory variations and the influence of surface finish and position of measurement” for part I of that report. This document, accordingly, presents further analyses of the FN measurements only, not a study of the variations in the chemical analyses or FN predictions.

THE RESULTS OF FN MEASUREMENTS FROM THE SUMMARY REPORT

A brief commentary on the results from each weld was included in the preliminary report [2], and is repeated here, as follows:

308H The results fell into three groups. The bulk of the data are in the range 3 to 6 FN, but there are two groups of higher values at ~8 and ~10 FN, which are from the high dilution root area. With the exception of one or two outlying points, the data are all within about ±1.5 FN of the mean for each area. Some laboratories appear to consistently overestimate FN level, whilst others underestimate.

The dilution effect is picked up on the cross sections with increasing FN towards the root. However, the effects of position on the cap, and of surface finish, are not immediately obvious and require more detailed analysis.

2205 The mean values for the areas range from 30 FN to about 42 FN with some slight increase in scatter between the various laboratories as the FN increases. Scatter is ±7 FN at the 35 FN level, increasing to ±9 FN at the 42 FN level.

This weldment also exhibited increased FN levels in the root area, whether measured directly either on the root or on the cross sections.

Again, there is evidence that some laboratories consistently overestimate the FN, whilst others underestimate. This aspect, together with variations due to position and surface finish (if any) requires further detailed analysis.

309Mo This sample was a mild-steel to stainless-steel dissimilar joint made with type 309Mo consumables. The effects of dilution are most marked in the root (with FN values down to 1), and a similar trend is evident on the cross sections. Interestingly, the effects of dilution on the mild steel side are more evident in the samples with weld reinforcement (as-welded and lightly polished) than in those where the reinforcement was removed by grinding or filing.

For areas that produced means between 1 and 5 FN, the scatter of results about the mean is fairly small – with the exception of one laboratory – at the 1 to 5 FN level, and is about ±1.5 FN. The other data are in the range 13 to 18 FN with a scatter of ±3 FN.

This weldment presents the clearest evidence that some laboratories consistently overestimate the results, whilst others underestimate, and this is particularly apparent in the root area.

16-8-2 The base material for this sample was type 316L plate, and the root area as measured directly and in the cross sections show an increase in FN in the range 4 to 5.5 FN, again with a scatter of about ±1 FN (ignoring two outlying results). The results fall into two populations, with the bulk weld metal values in the range 1.5 to 3 FN. Scatter at this level is similar to other samples at about ±1 FN.

As with the other samples, there is evidence of laboratory variation, but no obvious effect of surface finish. These factors will be the subject of more detailed analysis.

316NF This sample was made with a nil ferrite type 316 consumable. All laboratories reported either zero ferrite or very small fractional values in all positions.

These observations from the preliminary report form a baseline upon which the following additional analyses were designed.

FURTHER STATISICAL ANALYSES OF THE DATA

We suspected that a number of the variables in the round robin were interacting to produce the range in variations reported in the section above. For example, the preliminary analysis did not attempt to separate the possible effect of variations in weld dilution at the various locations, from the effects of laboratory procedures (calibration procedures or the effects of different measuring instruments). Therefore, we began with a two-way ANOVA (analysis of variance) for each of the welds. A main-effects two-way ANOVA evaluates the separate effects of the laboratories and of the areas (the locations in the welds). This analysis assumes that there are no interactions between the lab and the area. Table 1 (below) summarises the results from the analyses of the five weldments.

Table 1 Two-way ANOVA data (lab and area) for each of the five welds

Weld	308H	2205	309Mo	16-8-2	316NF
Significance of lab	> 99.999%	> 99.999%	> 99.999%	> 99.999%	> 99.999%
Significance of area	> 99.999%	> 99.999%	> 99.999%	> 99.999%	> 99.8%

This table indicates that both the laboratories and the areas have a highly significant effect on the results, and so both factors needed to be considered in the following analyses.

Next, post-hoc data and box-and-whiskers plots were developed for each of the five welds, to study the lab and the area data independently. It seems most logical to explain these two tests and what they mean before we discuss the outcome for each weldment.

Post-Hoc Tests (Tables 2 to 9) - The post-hoc (statistical) analyses (Tukey test) group the data into sets with statistically equivalent means.[3-5] For very homogeneous data, there may be only one set. However, the ANOVA results above indicate that there are significant effects for both the lab and the area, so it is not surprising to find that there are a number of statistically distinct sets for each weldment. These different sets are shown in columns, with a separate column for each statistically similar subset of data.

The first post-hoc test for each weld ranks the results for each area on the specimens, by ascending mean FN value evaluated across all labs. In other words, each row shows the mean FN value determined across all the laboratories for an area, where the rows (areas) are ordered in ascending order. Again, each of the columns in the test indicates which areas produced data that fall into a statistically similar subset. Analogously, the second post-hoc test for each weld ranks the results for each laboratory, by ascending mean FN values evaluated across all areas. Each column of data represents those labs with statistically similar means for each weld. After each table, we include some comments on our conclusions from this data.

Box-and-Whiskers Plots (Figures 2 to 9) - The box-and-whiskers plots show the distribution of the data within its range.[3-5] The first set of box-and-whiskers plots for each weldment shows the ranges of the FN data by area, and again is listed in ascending order, based on mean FN for each area. The data are centred on the median FN value, while the box-and-whiskers lines show measures of the range in the data. Note that while the laboratory and area data are ranked by their mean (average), the horizontal line in the box represents the median (middle value in the set). Thus there are cases in which the medians are not in the same ascending order as the means. The upper and lower edges of the box around the median enclose the middle half of the data. That is, the box excludes the data above the upper quartile (boundary of the upper 25 % of the data) and below the lower quartile (boundary of the lower 25 % of the data). The whiskers extend beyond the box to encompass all data that occur within 1.5 times the length of the box in either direction. However, the whiskers only extend as far as the last data point within this range in each direction. Therefore, they are typically not symmetrical around the box. Any values beyond this box and whiskers (outliers) are shown as circles. If the data were normally distributed, outliers would occur only about 0.7% of the time.[4] The second set of box-and-whiskers plots for each weld show the ranges of the FN data by laboratory, and are also listed in ascending order based on mean FN for each laboratory.

1. Weldment 308H

The Tukey analysis [5] for the areas in weldment 308H (Table 2, at the end of the report along with the remaining figures and tables) indicates that the 22 areas fit into 11 homogeneous data sets. This representation shows the progression from the lowest mean FN in area 16 to the highest mean FN in area 21, and which areas can be grouped into sets. Some of the data sets overlap, but some of the gaps in the sets are quite distinct, such as between areas 17 and 20 (5.6 and 7.6 FN) or between areas 19 and 22 (7.8 and 9.4 FN). Although the means for areas 16 to 17 (3.19 to 5.62 FN) may seem fairly continuous to the eye, the analysis routines group these data into 9 separate sets, each containing 2 to 5 areas with statistically similar data.

The box-and-whiskers plots for the areas in weldment 308H (Figure 2) shows the data from Table 2 in a different format. The box-and-whiskers plots are ranked in ascending mean FN by area. Some prefer this representation for visualizing the statistically significant gaps noted in the post-hoc analysis, such as those between areas 17 and 20 (5.6 and 7.6 FN) or between areas 19 and 22 (7.8 and 9.4 FN). Comparison with the area identifications in Figure 1, reveals that the four areas with the highest FNs are all from the weld roots, and suggests that these high values can be attributed to dilution by the base plate. Also, the box-and-whiskers plots provide much more information about the distribution of the data. For example, areas 6 and 17 have almost identical means, but they vary widely in distribution. Area 6 has a box (range of 25 to 75 % in the data) that is about four times as large as that for area 17, and it has one outlier that is up near 8 FN. Figure 1 shows that area 6 is on the side of the specimen, perhaps near the boundary between the first two weld passes. The first weld pass is in the root, and would be expected to produce an FN near 8 (similar to area 19 or 20). The next pass would have a lower FN (less dilution, and so similar to area 5). This would explain the wider variation for this location in this weldment.

The Tukey analysis of the lab effect in the data for weldment 308H (Table 3) indicates that the data for the 17 labs fit into eight homogeneous sets. Again, the representation shows the progression from the lowest mean FNs (for labs K and A) to the highest mean FNs (for labs L and M). A comparison of Figure 2 and Figure 3 shows that the variation among labs (within any one area) is less than the variation among areas (within any one lab), a situation caused by the few high-FN readings in the weld root (areas 19 to 22), as pointed out in the discussion (above) of Table 2 and Figure 2. Figure 3 shows the effect of the few measurements of weld roots, with the whiskers being longer for the high than the low FN values, and the large number of outliers (circles) above the whiskers.

2. Weldment 2205

The Tukey analysis for the areas in weldment 2205 (Table 4) indicates that these 22 areas also fit into 11 sets. Here, the progression goes from a mean just over 30 FN for area 8 to over 42 FN for area 21. This time, there are not clear breaks in the progression, but at least one trend is evident. Areas 19 to 22 are again near the top end of the FN distribution, and (again) this is attributed to dilution in the root of the weld. The box-and-whiskers plots have fairly narrow boxes, but fairly wide whiskers. This indicates wider tails (greater variations) in the distributions than seen in weldment 308H.

The Tukey analysis of the lab data for weldment 2205 (Table 5) indicates that the data for the 17 labs fit into six sets. The progression goes from the lowest mean FNs for labs A and Q to the highest mean FNs for labs M and L. The fact that lab A was also one of the lowest for weldment 308H and L and M were among the highest suggests that there may be a pattern in lab calibration. We will discuss this after the data are presented for all five welds.

3. Weldment 309Mo

The Tukey analysis for the areas in weldment 309Mo (Table 6) indicates that these 22 areas fit into 13 homogeneous data sets. Here, the progression goes from a mean just under 1 FN for area 20 to over 18 FN for area 14. Areas 19 to 22 (and 3 and 6) are again at the extreme of the data set, this time at the low end. Areas 19 to 22 were previously noted as being in the weld root, and Figure 1 shows that areas 3 and 6 are immediately adjacent (and so the next most likely to be affected by dilution). If these areas were excluded from the data, the remaining areas would fit into only nine sets with a much smaller range (about 13 to 18 FN). The box-and-whiskers plots of the area data (Figure 6) show the distribution more clearly. The first six areas in the ranking are distinctly different from the rest.

The Tukey analysis of the lab data for weldment 309Mo (Table 7) indicates that the data for the 17 labs fit into seven sets. The progression goes from the lowest mean FNs for lab Q to the highest mean FNs for labs M and L. If the data for labs Q, M and L were excluded, the data would fit into only 5 sets. The box-and-whiskers plots of the area data (Figure 7) show that the means appear quite similar. The striking feature here is how close the medians are to the top of the box. The reason is clear from Figure 6, where the data in areas 3, 6, and 19 to 22 pull the lower edge of the box downward from the median, which is in the 15 FN range.

4. Weldment 16-8-2

The Tukey analysis for the areas in weldment 16-8-2 (Table 8) indicates that these 22 areas fit into 12 homogeneous data sets. Here, the progression goes from a mean just over 1 FN for area 13 to over 5 FN in area 6. Areas 3, 6, and 19 to 22 are again at the extreme of the data set, this time at the high-FN end. If these areas are excluded, the data fit into only eight sets. The box-and-whiskers plots of the area data (Figure 8) show the distribution more clearly. The last six areas in the ranking are distinctly different from the rest.

The Tukey analysis of the lab data for weldment 16-8-2 (Table 9) indicates that the data for the 17 labs fit into eight sets. The progression goes from the lowest mean FNs for labs R and Q to the highest mean FNs for lab L. If the data for labs R, Q, and L were excluded, the data would fit into six sets. The box-and-whiskers plots of the area data (Figure 9) show that the means appear quite similar. This time, the medians are very near to the bottom of the box. The reason is clear from figure 8, where the data in areas 3, 6, and 19 to 22 pull the upper edge of the box (and the whiskers) upward and away from the median, which is in the 2 FN range.

5. Weldment 316NF

The Tukey analysis for the areas in weldment 316NF (Table 10) indicates that these 22 areas fit into a single data set. The means are all far less than 1 FN, extending from about 0.01 FN for area 1 to about 0.04 FN for area 22. These means are a combination of many readings of zero, with a few small (non zero) readings. Because of the small distribution, no box-and-whiskers plots were produced.

The Tukey analysis of the lab data for weldment 316NF (Table 11) indicates that the data for the 17 labs fit into just two sets. Only lab F reported area measurements that are significantly different from zero.

OBSERVATIONS ON THE WELDS AS A GROUP

Pooling of the analyses presented in Tables 2 to 11 and Figures 2 to 10 reveals additional trends. For example, some labs were consistently near the top of the FN range, while others were near the bottom. Table 12 lists the ranking of the lab data for the four weldments (from Tables 3, 5, 7, and 9). Data on weldment 316NF was excluded because the large number of null readings did not allow a reasonable ranking of the labs. To show the progression in rankings as a function of FN, the order of the weldments was changed, into the order of increasing average FN, shown in Table 12.

In this table (Table 12), the labs are assigned numbers corresponding to their ranks starting from the lowest mean FN for each weldment, as they were ordered in the individual tables. Thus, the lowest FN for each weldment was assigned the value 1 and the highest was assigned the value 17. Also, the average rank (mean rank) was computed as the numerical average of the rankings on the four weldments, and listed in the final column.

The table shows that certain labs are consistently below the mean, while others are consistently above the mean. The further the mean from the middle value (9) for the group, the more bias in the measurements for a lab. (Note that this does not mean that certain procedures are better or worse. We are only comparing to the average of the group.) In addition, we see some skew in the calibration procedures. For example, Lab R was at the bottom of the rank at low FN, but near the top at high FN. Conversely, Lab F was near the top of the ranking at low FN, but near the bottom at high FN. No data on calibration procedures was included, so no reasons for these trends can be proposed.

We also looked at the variations among the labs for each area in the first four weldments. Weldment 316LN was excluded because the large number of null values did not add to the quality of the correlation. Figure 10 shows the standard deviation for each area (22 areas on four weldments) computed from the FN measurements for each of the 17 labs. The standard deviation is in the vertical scale and is plotted versus the mean FN for each area on the horizontal scale. This plot is an estimate of what standard deviation might be expected on actual weldments for a group of laboratories. It could be used to estimate how close the measurements at two laboratories (for example, a producer and a customer) would compare. The figure also includes a straight line fitted (least squares) to the data. This line seems to fit the data reasonably well ($r^2 = 0.914$) and passes very near to the origin. The equation of the line is:

$$STD = 0.06 + 0.08\,FN\ . \tag{1}$$

The labs in this round robin used a variety of instruments to make their measurements, which may have added to the uncertainty in the measurements. To test this, we looked at the types of instruments that were used. These included:

- MP3 (3 labs),
- MP3B (3 labs),
- MP3C (2 labs),
- MP30 (4 labs),
- M10B (2 labs),
- MD11D-FE (1 lab),
- Foerster (1 lab), and
- MagneGage (1 lab).

The first four types of instruments (first 12 labs) dominated the data (about 70 %) and have the most similar designs. Thus, they form a very logical subset of instruments to select for a simple investigation of the effect of instrument on variation. Figure 11 shows the standard deviation for each area (22 areas on 4 weldments) computed from the FN measurements for these 12 labs. The standard deviation is about 30 % smaller and is represented by the line:

$$STD = 0.11 + 0.06FN. \tag{2}$$

Equations 1 and 2 both predict standard deviations that are greater than the variations between machines permitted in Ref. 1. For example, at 20 FN, equation 1 predicts a standard deviation of 1.66 FN, while equation 2 predicts a standard deviation of 1.31 FN. Thus, the two-standard-deviation (95 % confidence interval) bands would be ± 3.32 and ± 2.62 FN, respectively. Meanwhile, Tables 9, 10, and 11 (of Ref. 1) permit ± 0.9, ± 1.0, and ± 1.0 respectively, for the three major instrument types.

OBSERVATIONS ON THE EFFECT OF FINISHES

The experimental design also included four types of surface finishes. Figure 1 shows the locations on the top and bottom of the weldment that had these finishes, which represent typical ways in which the weld might be prepared for service. On the surface of the weld, these combinations were:

- Locations 7, 8, and 9 were ground,
- Locations 10, 11, and 12 were lightly polished,
- Locations 13, 14, and 15, were left as-welded, and

- Locations 16, 17, and 18 were filed.

More details on the precise finishing techniques are included in Ref. 2. Areas 19 through 22 on the bottom surface were also finished, but the greater scatter due to dilution obscured the effects, so only the data on the top surface are presented and discussed.

Even on the top surface, we found effects of dilution at the two edges of the weld. This effect broadened the scatter and made the differences less significant. However, additional ANOVA and post-hoc tests both showed that the finish was a significant factor, even with the dilution effects (data not shown). To more clearly reveal the effect of finish, we reduced the effect of dilution by selecting only the center four locations (8, 11, 14, and 17) on each of the four weldments. This still permitted a good evaluation of the four finishes (on four weldments as evaluated by 17 laboratories).

In weldment 308H, Tukey analysis showed that these four finishes produced mean FNs that were significantly different from each other. As shown in the box-and-whiskers plots in Figure 12, the four finishes produced only a small overlap in the whiskers between the finishes, and in ascending FN, the order is: polished, as-welded, ground, and filed.

In weldment 2205, the mean FN for the ground finish is significantly different from that for the filed, and that for the filed finish is significantly different from that for the polished and the as-welded. However, the mean FNs for the polished and as-welded finishes cannot be distinguished from each other. This is shown in the box-and-whiskers plots in Figure 13. Here, the order in ascending FN is: ground, filed, and then polished and as-welded.

In weldment 309Mo, Tukey analysis showed that the mean FNs for the four finishes fall into four significantly distinct groups. Figure 14 shows the box-and-whiskers plots for this weldment. Here, the order of ascending FN is: ground, filed, polished, and as-welded.

In weldment 16-8-2, Tukey analysis showed that the mean FNs for the four finishes fall into only two distinct groups. The mean FN for the polished finish is less than for the other three (as-welded, filed, and ground), which are not significantly different from each other. The box-and-whiskers plots in Figure 15 show that the first box is much lower than the other three boxes, which overlap.

The effect of surface finish can be summarized as being significant, but variable among the four welds. The two weldments with the lower FN (308H and 16-8-2) both had polished finish at the lowest FN. The two weldments with the higher FN (2205 and 309Mo) both had ground finish as the lowest mean FN. Perhaps the FN of the weldment has a small influence on the effect of the surface finish.

CONCLUSIONS

1. The presence of 11 to 13 homogeneous data sets for the first 4 weldments indicates a wide variation in FN through these weldments. Thus, these weldments are much more variable than the FN pads traditionally used for FN round robins.
2. Most of the variation in the weldments was due to dilution, and is most evident in the measurements made near the weld root.
3. Some labs produced measurements that were consistently near the top or the bottom of the distribution of the labs. Others moved through the ranking as a function of FN. Therefore, both bias and skew are evident in the calibration procedures used by the laboratories.

4. Pooling of the data for laboratories allowed the development of an estimate of the variation between laboratories, as a function of FN.
5. Surface finish is a significant variable in determining the FN, but the effect varied as a function of mean FN.
6. The round robin produced standard deviations between laboratories that exceeded those permitted by Ref. 1.

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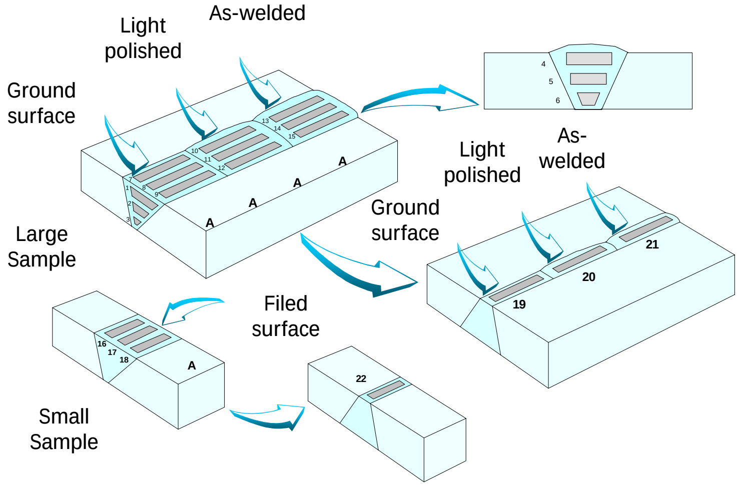

Figure 1. Arrangement of test blocks – Showing areas for ferrite

Table 2. Tukey analysis of weldment 308H, by area

FN[c]

Tukey HSD[a,b]

AREA	N	Subset 1	2	3	4	5	6	7	8	9	10	11
16	17	3.1882										
13	17	3.2000										
11	17	3.2294										
12	17		3.6765									
10	17		3.7294									
1	17		3.9412	3.9412								
14	17		4.0412	4.0412								
9	17			4.2588	4.2588							
15	17			4.2706	4.2706							
4	17				4.5235	4.5235						
7	17				4.5824	4.5824						
2	17				4.6412	4.6412	4.6412					
5	17					4.7529	4.7529	4.7529				
3	17						5.0235	5.0235				
8	17							5.0706				
18	17							5.1176	5.1176			
6	17								5.5235	5.5235		
17	17									5.6235		
20	17										7.6118	
19	17										7.8059	
22	17											9.4059
21	17											9.5588
Sig.		1.000	.201	.388	.135	.941	.135	.201	.075	1.000	.991	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .117.

a. Uses Harmonic Mean Sample Size = 17.000.

b. Alpha = .05.

c. Weld Type = 308H

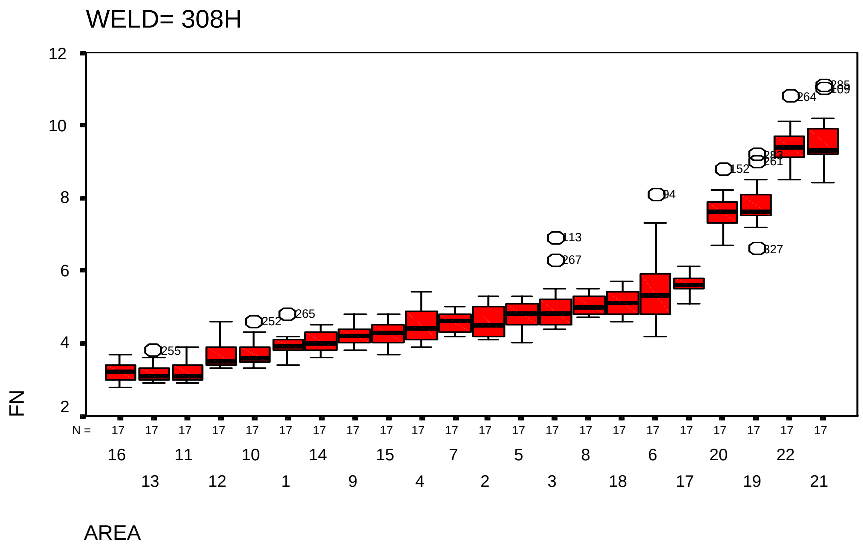

Figure 2. Box-and-whiskers plots for weldment 308H, by area

Table 3. Tukey analysis of weldment 308H, by laboratory

FN[c]

Tukey HSD[a,b]

LAB	N	Subset 1	2	3	4	5	6	7	8
Lab K	22	4.6864							
Lab A	22	4.7136							
Lab N	22	4.7682	4.7682						
Lab R	22	4.8136	4.8136						
Lab Q	22	4.8591	4.8591						
Lab D	22	4.8864	4.8864	4.8864					
Lab I	22	4.9182	4.9182	4.9182	4.9182				
Lab B	22	4.9909	4.9909	4.9909	4.9909				
Lab J	22		5.0909	5.0909	5.0909	5.0909			
Lab P	22		5.1227	5.1227	5.1227	5.1227			
Lab F	22			5.2227	5.2227	5.2227	5.2227		
Lab C	22				5.2500	5.2500	5.2500		
Lab H	22					5.4182	5.4182	5.4182	
Lab G	22					5.4273	5.4273	5.4273	
Lab E	22						5.5273	5.5273	5.5273
Lab L	22							5.6500	5.6500
Lab M	22								5.8000
Sig.		.204	.052	.090	.102	.090	.204	.691	.391

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .117.

a. Uses Harmonic Mean Sample Size = 22.000.

b. Alpha = .05.

c. Weld Type = 308H

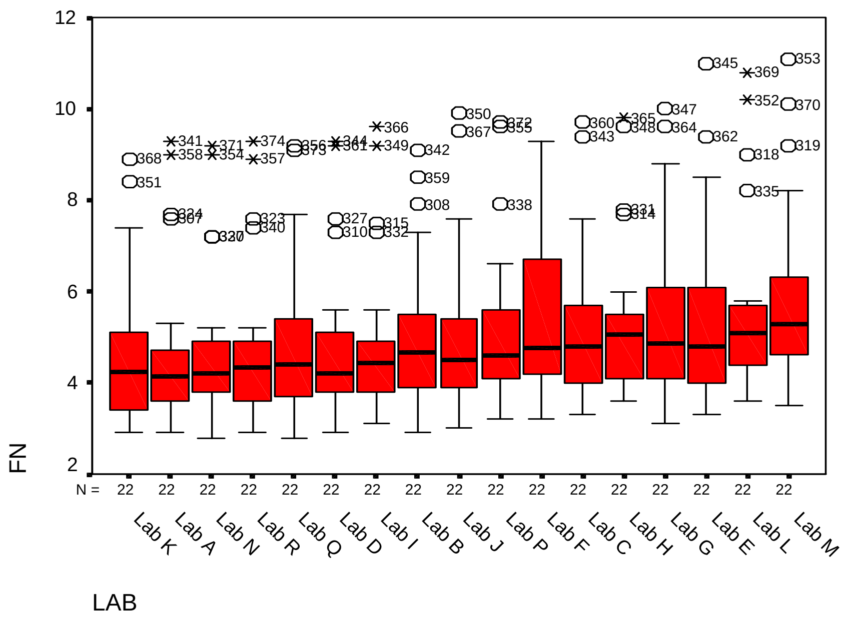

Figure 3. Box-and-whiskers plots for weldment 308H, by laboratory

Table 4. Tukey analysis of weldment 2205, by area

FN[c]

Tukey HSD[a,b]

AREA	N	Subset 1	2	3	4	5	6	7	8	9	10	11
8	17	30.4000										
7	17	31.8765	31.8765									
17	17	32.3471	32.3471	32.3471								
9	17		33.0706	33.0706	33.0706							
1	17		33.4176	33.4176	33.4176							
15	17		33.8176	33.8176	33.8176							
10	17			34.2059	34.2059	34.2059						
13	17			34.3471	34.3471	34.3471						
16	17				34.7588	34.7588	34.7588					
4	17				34.8882	34.8882	34.8882					
2	17				35.0059	35.0059	35.0059	35.0059				
12	17				35.1176	35.1176	35.1176	35.1176				
5	17					35.9706	35.9706	35.9706	35.9706			
11	17						36.5235	36.5235	36.5235			
20	17							37.1235	37.1235	37.1235		
14	17								37.6176	37.6176		
18	17								37.6706	37.6706		
19	17									38.8412	38.8412	
3	17										40.2824	40.2824
6	17										40.6882	40.6882
22	17											41.1529
21	17											42.2765
Sig.		.140	.144	.109	.087	.295	.295	.060	.368	.348	.215	.112

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 3.047.

a. Uses Harmonic Mean Sample Size = 17.000.

b. Alpha = .05.

c. Weld Type = 2205

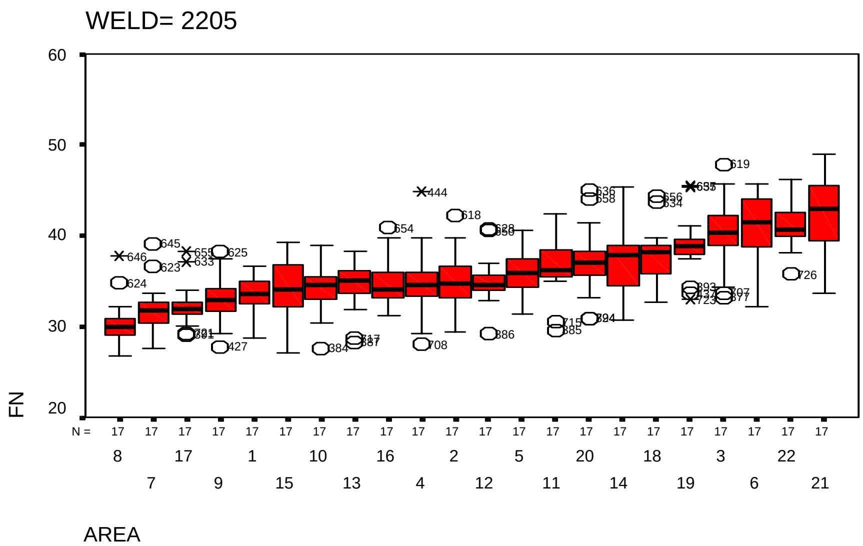

Figure 4. Box-and-whiskers plots for weldment 2205, by area

Table 5. Tukey analysis of weldment 2205, by laboratory

FN[c]

Tukey HSD[a,b]

LAB	N	Subset 1	2	3	4	5	6
Lab A	22	30.6682					
Lab Q	22	30.9682					
Lab C	22		33.6773				
Lab K	22		34.2182	34.2182			
Lab F	22			35.5455	35.5455		
Lab N	22			35.5955	35.5955		
Lab D	22			35.6364	35.6364		
Lab J	22			35.9000	35.9000		
Lab I	22				36.1227	36.1227	
Lab B	22				36.2091	36.2091	
Lab G	22				36.3227	36.3227	
Lab R	22				36.4727	36.4727	
Lab E	22				36.5864	36.5864	
Lab P	22					37.7818	
Lab H	22					37.8091	
Lab M	22						40.8591
Lab L	22						41.1636
Sig.		1.000	1.000	.110	.861	.107	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 3.047.

a. Uses Harmonic Mean Sample Size = 22.000.

b. Alpha = .05.

c. Weld Type = 2205

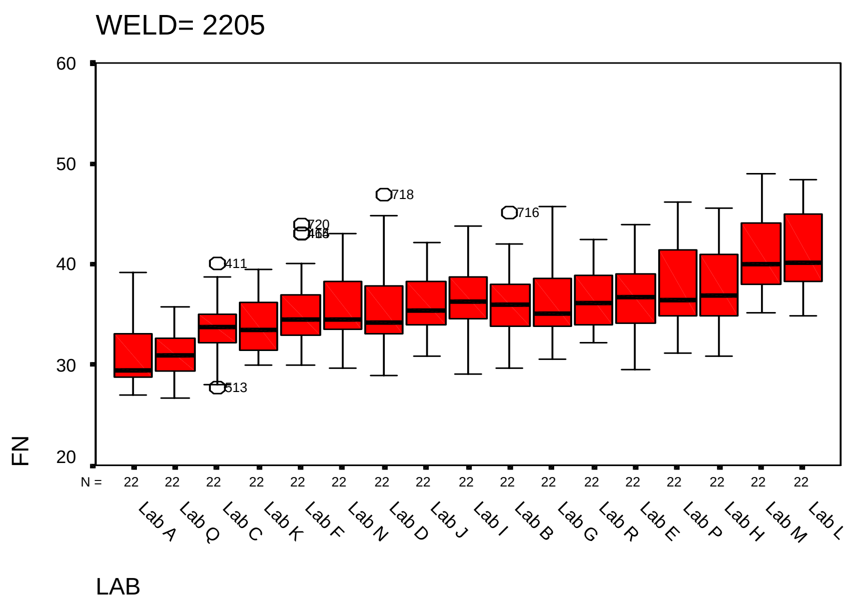

Figure 5. Box-and-whiskers plots for weldment 2205, by laboratory

Table 6. Tukey analysis of weldment 309Mo, by area

FN[c]

Tukey HSD[a,b]

AREA	N	Subset												
		1	2	3	4	5	6	7	8	9	10	11	12	13
20	17	.9235												
19	17	1.1353	1.1353											
21	17		1.9118	1.9118										
6	17			2.1941										
22	17				3.1294									
3	17				3.6941									
10	17					13.6588								
13	17					14.3412	14.3412							
1	17						14.6706	14.6706						
2	17						14.8176	14.8176	14.8176					
9	17							15.3353	15.3353	15.3353				
7	17								15.7000	15.7000	15.7000			
5	17									15.7471	15.7471			
8	17									15.7529	15.7529			
12	17									15.9118	15.9118			
16	17									16.2059	16.2059			
4	17										16.3235	16.3235		
17	17										16.5882	16.5882		
18	17											17.1588	17.1588	
11	17												17.5471	
15	17												17.5882	
14	17													18.6294
Sig.		1.000	.249	1.000	.840	.507	.966	.562	.082	.094	.077	.140	.989	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .560.

a. Uses Harmonic Mean Sample Size = 17.000.

b. Alpha = .05.

c. Weld Type = 309Mo

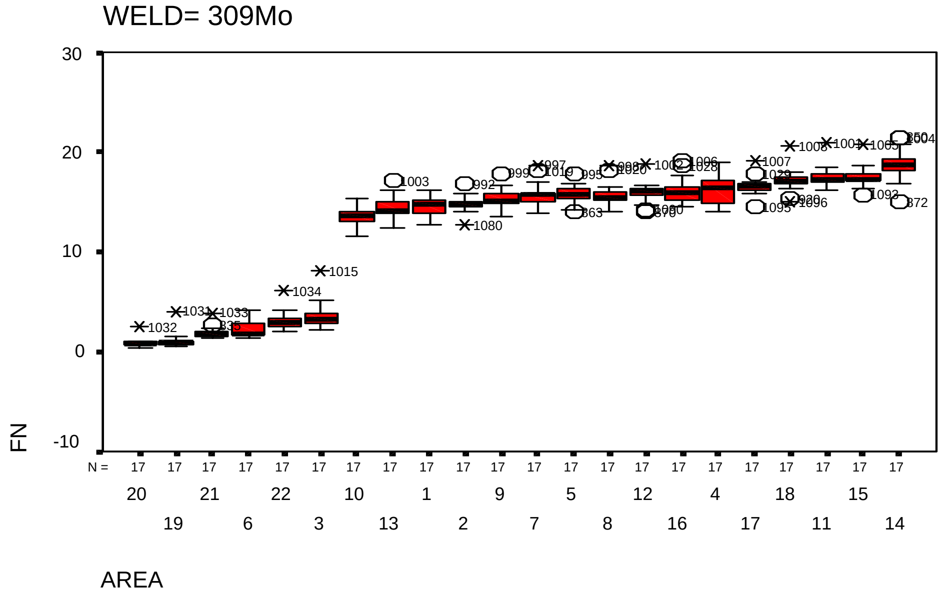

Figure 6. Box-and-whiskers plots for weldment 309Mo, by area

Table 7. Tukey analysis of weldment 309Mo, by laboratory

FN[c]

Tukey HSD[a,b]

LAB	N	Subset 1	2	3	4	5	6	7
Lab Q	22	10.7727						
Lab F	22	11.3318	11.3318					
Lab R	22		11.6045	11.6045				
Lab H	22		11.7318	11.7318	11.7318			
Lab D	22		11.7909	11.7909	11.7909	11.7909		
Lab C	22		11.8273	11.8273	11.8273	11.8273		
Lab K	22		12.0227	12.0227	12.0227	12.0227	12.0227	
Lab B	22		12.0727	12.0727	12.0727	12.0727	12.0727	
Lab P	22			12.1273	12.1273	12.1273	12.1273	
Lab A	22			12.2500	12.2500	12.2500	12.2500	
Lab I	22			12.3500	12.3500	12.3500	12.3500	
Lab G	22				12.3864	12.3864	12.3864	
Lab E	22				12.4591	12.4591	12.4591	
Lab J	22					12.5136	12.5136	
Lab N	22						12.6091	
Lab M	22							13.8409
Lab L	22							14.1455
Sig.		.519	.086	.081	.102	.108	.428	.996

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .560.

a. Uses Harmonic Mean Sample Size = 22.000.

b. Alpha = .05.

c. Weld Type = 309Mo

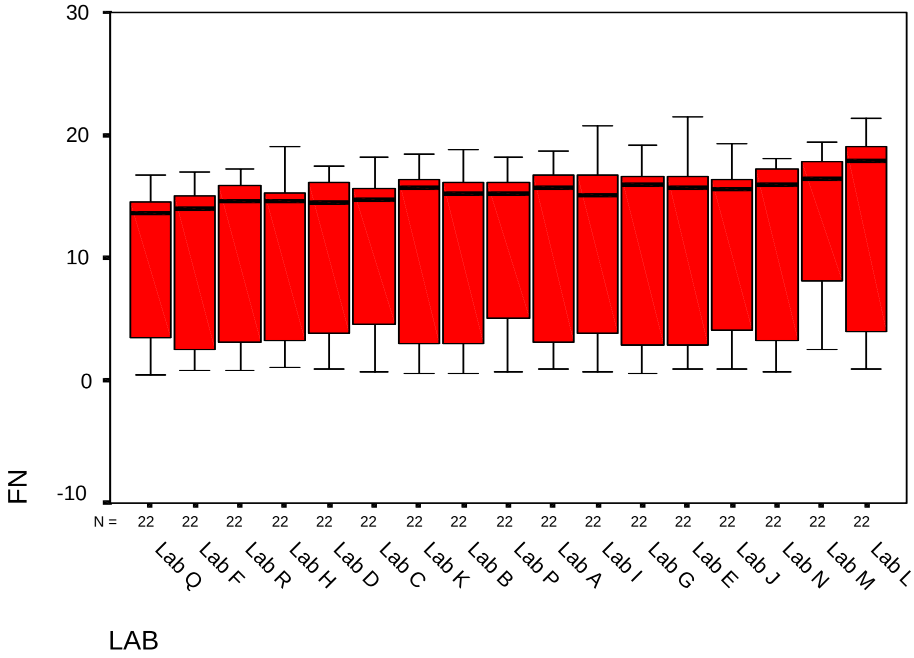

Figure 7. Box-and-whiskers plots for weldment 309Mo, by laboratory

Table 8. Tukey analysis of weldment 16-8-2, by area

FN[c]

Tukey HSD[a,b]

AREA	N	Subset 1	2	3	4	5	6	7	8	9	10	11	12
13	17	1.5588											
10	17	1.7176	1.7176										
11	17	1.8235	1.8235	1.8235									
12	17	1.8353	1.8353	1.8353									
15	17		1.9176	1.9176									
1	17			2.0471	2.0471								
14	17				2.2529	2.2529							
17	17				2.3294	2.3294	2.3294						
8	17					2.3529	2.3529						
5	17					2.4706	2.4706						
4	17					2.4765	2.4765						
7	17					2.5412	2.5412						
9	17						2.6000	2.6000					
2	17							2.8412	2.8412				
18	17								2.9588				
16	17								3.0412				
22	17									4.2941			
20	17									4.5588	4.5588		
21	17										4.6529		
19	17											4.9824	
3	17											5.0882	
6	17												5.4353
Sig.		.107	.693	.468	.087	.070	.131	.313	.693	.159	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 5.797E-02.

a. Uses Harmonic Mean Sample Size = 17.000.

b. Alpha = .05.

c. Weld Type = 16.8.2

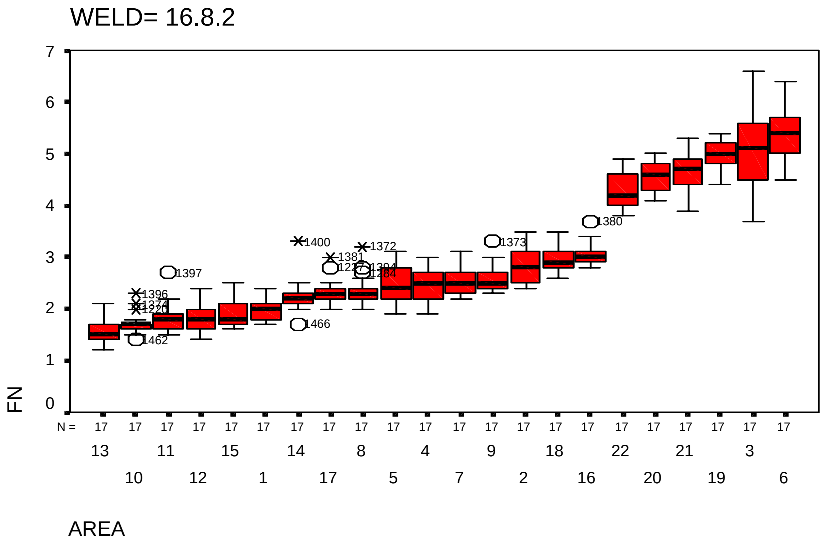

Figure 8. Box-and-whiskers plots for weldment 16-8-2, by area

Table 9. Tukey analysis of weldment 16-8-2, by laboratory

FN[c]

Tukey HSD[a,b]

LAB	N	Subset							
		1	2	3	4	5	6	7	8
Lab R	22	2.6500							
Lab Q	22	2.6955							
Lab K	22	2.7182	2.7182						
Lab A	22	2.7364	2.7364	2.7364					
Lab I	22	2.8136	2.8136	2.8136	2.8136				
Lab P	22	2.8227	2.8227	2.8227	2.8227				
Lab D	22	2.8364	2.8364	2.8364	2.8364				
Lab N	22	2.8591	2.8591	2.8591	2.8591				
Lab C	22		2.9682	2.9682	2.9682	2.9682			
Lab B	22			2.9864	2.9864	2.9864			
Lab J	22				3.0045	3.0045			
Lab F	22				3.0545	3.0545	3.0545		
Lab G	22					3.2045	3.2045	3.2045	
Lab H	22						3.2727	3.2727	3.2727
Lab M	22							3.3545	3.3545
Lab E	22							3.3591	3.3591
Lab L	22								3.4909
Sig.		.244	.052	.052	.077	.093	.182	.775	.182

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 5.797E-02.

a. Uses Harmonic Mean Sample Size = 22.000.

b. Alpha = .05.

c. Weld Type = 16.8.2

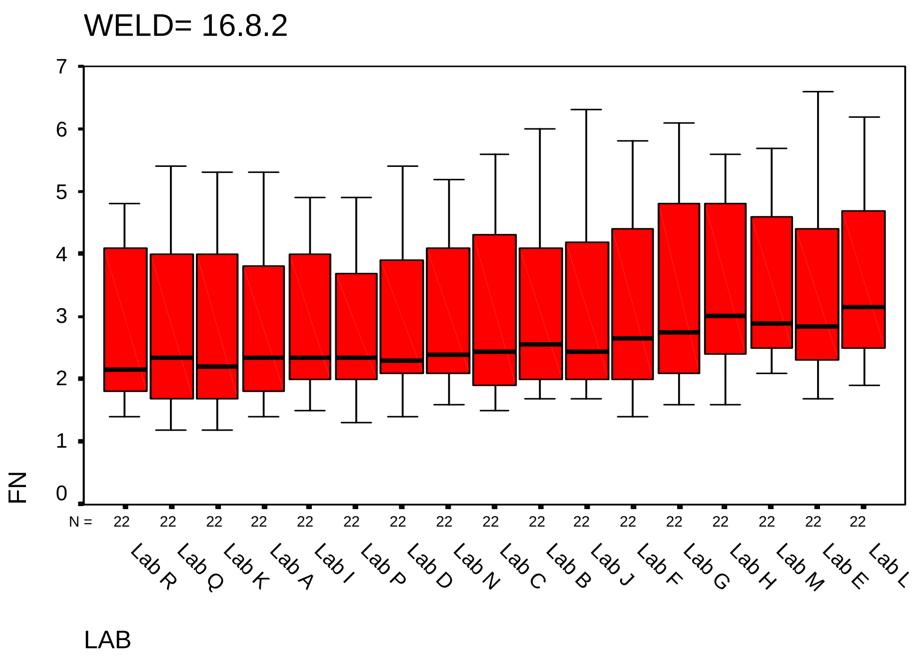

Figure 9. Box-and-whiskers plots for weldment 16-8-2, by laboratory

Table 10. Tukey analysis of weldment 316NF, by area

FN[c]

Tukey HSD [a,b]

AREA	N	Subset 1
1	17	8.824E-03
4	17	8.824E-03
7	17	8.824E-03
11	17	8.824E-03
12	17	8.824E-03
14	17	8.824E-03
15	17	8.824E-03
17	17	8.824E-03
18	17	8.824E-03
20	17	8.824E-03
21	17	8.824E-03
6	17	9.412E-03
8	17	9.412E-03
9	17	9.412E-03
2	17	1.000E-02
5	17	1.000E-02
19	17	1.000E-02
3	17	1.059E-02
13	17	1.118E-02
16	17	2.059E-02
10	17	2.118E-02
22	17	3.882E-02
Sig.		.088

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 6.558E-04.

a. Uses Harmonic Mean Sample Size = 17.000.

b. Alpha = .05.

c. Weld Type = 316NF

Table 11. Tukey analysis of weldment 316NF, by laboratory

FN[c]

Tukey HSD[a,b]

LAB	N	Subset 1	Subset 2
Lab A	22	.0000	
Lab B	22	.0000	
Lab C	22	.0000	
Lab D	22	.0000	
Lab E	22	.0000	
Lab G	22	.0000	
Lab H	22	.0000	
Lab I	22	.0000	
Lab J	22	.0000	
Lab K	22	.0000	
Lab P	22	.0000	
Lab Q	22	.0000	
Lab R	22	.0000	
Lab L	22	4.545E-03	
Lab M	22	1.818E-02	
Lab N	22	1.818E-02	
Lab F	22		.1582
Sig.		.613	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 6.558E-04.

a. Uses Harmonic Mean Sample Size = 22.000.

b. Alpha = .05.

c. Weld Type = 316NF

Table 12 Ranking of mean FNs for the various laboratories

Lab	*16-8-2 (about 2.5 FN)*	*308H (about 5 FN)*	*309Mo (about 10 FN)*	*2205 (about 40 FN)*	*Mean Rank*
A	4	2	10	1	4
B	10	8	8	10	9
C	9	12	6	3	7.5
D	7	6	5	7	6
E	16	15	13	13	14
F	12	11	2	5	7.5
G	13	14	12	11	13
H	14	13	4	15	9
I	5	7	11	9	8
J	11	9	14	8	10.5
K	3	1	7	4	3.5
L	17	16	17	17	17
M	15	17	16	16	16
N	8	3	15	6	8
P	6	10	9	14	10
Q	2	5	1	2	2.5
R	1	4	3	12	5

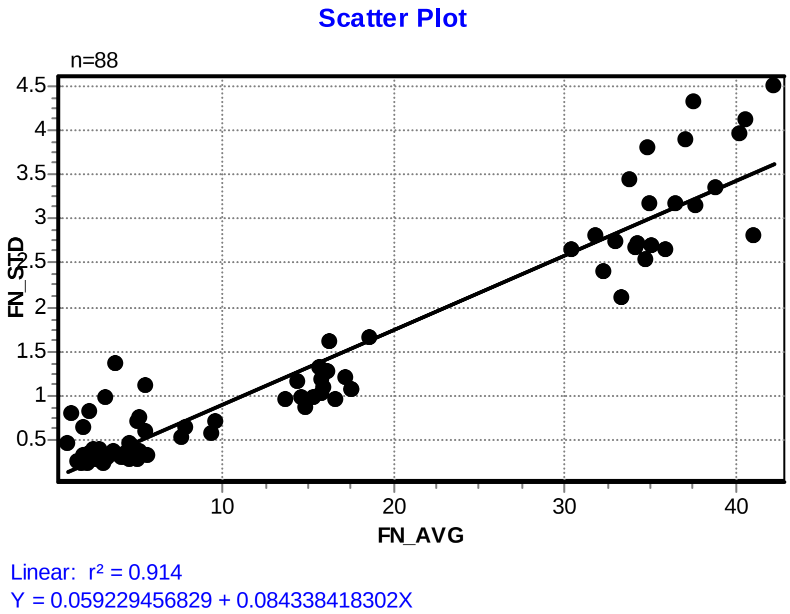

Figure 10. Plot of the standard deviation in the data between laboratories for each area of the first four weldments, plotted at the mean FN for each area.

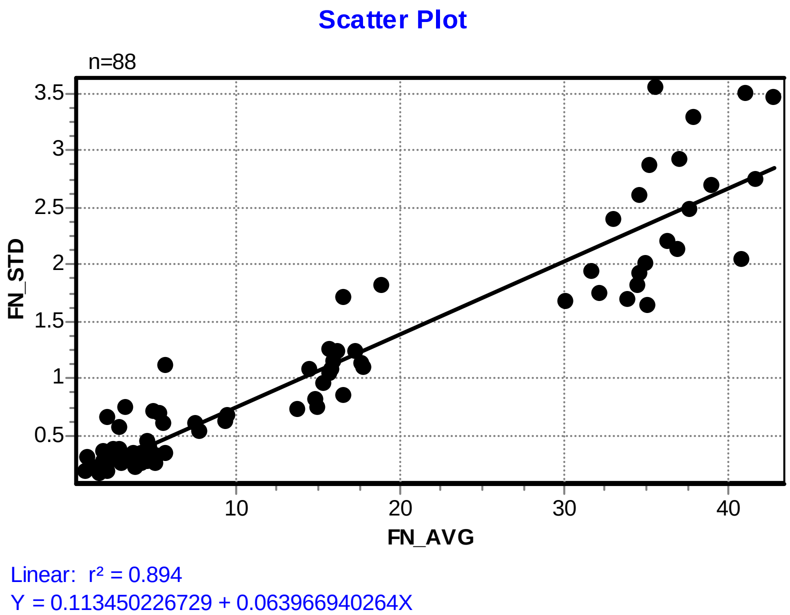

Figure 11. Plot of the standard deviation in the data between laboratories for selected types of instruments and each area of the first four weldments, plotted at the mean FN for each area.

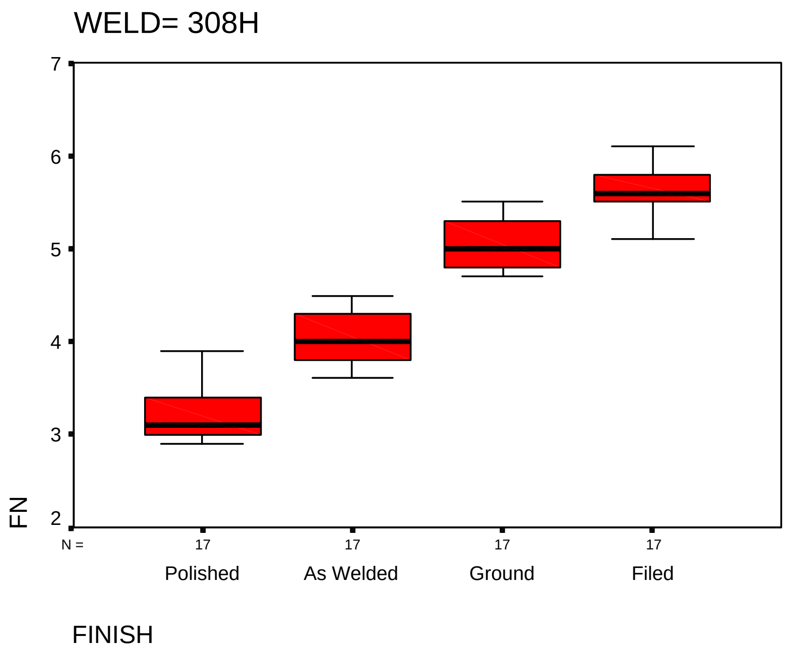

Figure 12. Box-and-whiskers plots for locations 8, 11, 14, and 17 in weldment 308H, by surface finish

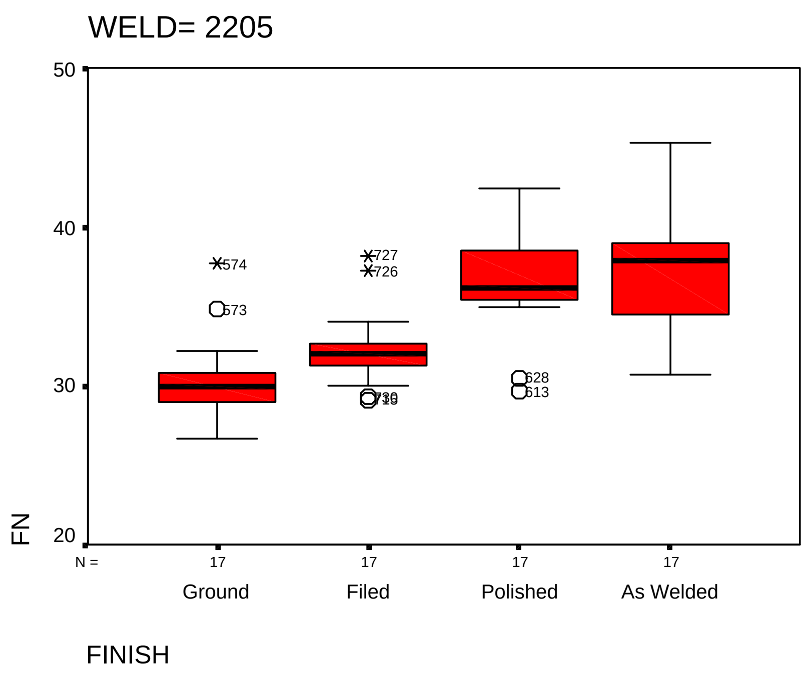

Figure 13. Box-and-whiskers plots for locations 8, 11, 14, and 17 in weldment 2205, by surface finish

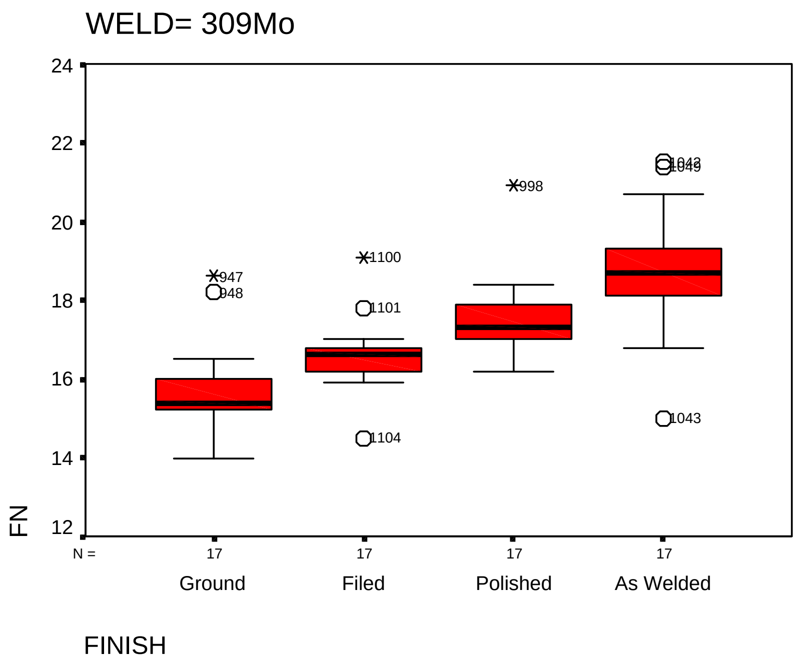

Figure 14. Box-and-whiskers plots for locations 8, 11, 14, and 17 in weldment 309H, by surface finish

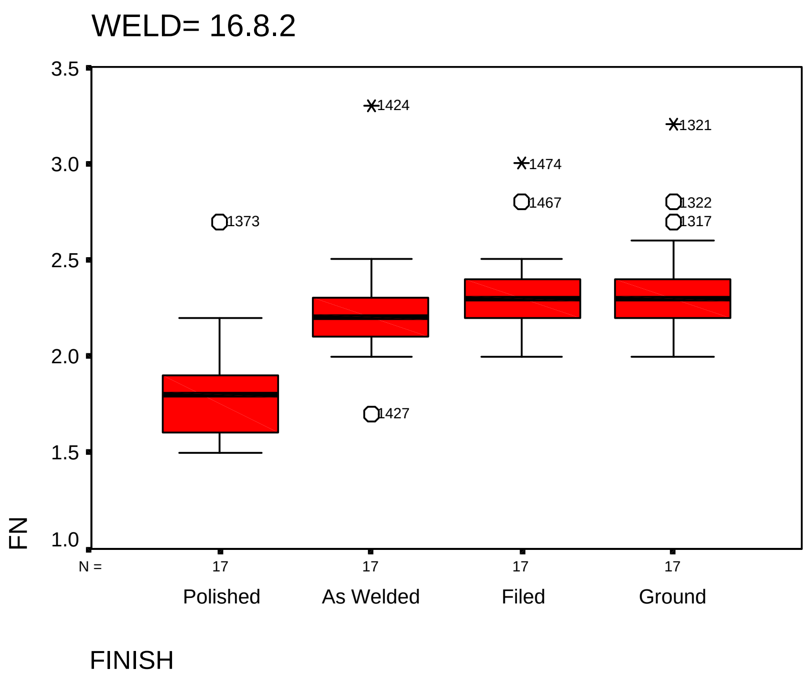

Figure 15. Box-and-whiskers plots for locations 8, 11, 14, and 17 in weldment 16-8-2, by surface finish