Data Acquisition and Analysis for EB Welding in Perspective

A computerized data acquisition system was shown to be a reliable means of verifying and monitoring the EBW process

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ABSTRACT. Data acquired using a computer-controlled data acquisition system (DAS) on an electron beam welding machine were analyzed. Statistical tests were developed to determine the usefulness of the DAS by comparing the DAS-determined parameter values with the parameter values as set using the machine's meters. Additional analyses were used to investigate the feasibility of the DAS, providing information not otherwise available. In both regards, the DAS was found to be beneficial. Drift was seen on all parameters, a beam current-weldment material interaction was identified, and useful statistical tests were identified for application to data generated by a DAS on an electron beam welding machine. The DAS provides a reliable and meaningful method of verifying and monitoring electron beam welding parameters.

Introduction

We presently have a reliable data acquisition system (DAS) on an electron beam welding machine (EBW) (Refs. 1, 2) and are in the process of evaluating its performance and the usefulness of the resulting data for monitoring machine performance and weld parameters. The availability of personal computers and off-the-shelf data acquisition systems, which are both easy to operate and inexpensive, makes implementation of computer data acquisition straightforward. However, use of the data for statistically valid decisions regarding machine performance requires data analysis by performing standard statistical tests of hypotheses (our approach), or by integrating commercially available statistics software into the data analysis. This report describes the hypothesis testing we have used, results obtained and the analysis of their applicability for determining machine performance and weld parameters. We are restricting our discussion to machine performance and weld parameters verification against the machine's meters. The analysis and comparison is only for DC values, and the DAS sampling rate was set up on that basis. Analysis of transient signals with correlations to weld morphology has been left for future work. In summary, we have found the DAS to be an accurate, reliable and simple means of monitoring certain weld parameters and equipment performance.

Background

The decision to implement data acquisition on welding processes is generally based on the expected benefits of determination of product quality, verification of weld parameters, gaining fundamental information about the process, and gaining information about the performance of the welding equipment. Concern about the equipment's performance generally results when the product has been rejected. This seems to happen frequently enough that verification of the weld parameters is very important. Successful implementation of a DAS onto a welding machine requires a thorough analysis, including both DAS hardware and software, of the entire weld development and fabrication process. Such an analysis should lead to important questions such as, how the data will be analyzed, what the data analysis flow path is, etc., all of which affect the implementation of data acquisition and ultimately how the data is handled.

We continue to use the machine's meters for weld parameter setup and visual monitoring of machine performance. Our data acquisition system is implemented in parallel with the machine's meters. With continued use of DAS, we expect it to become routine to analyze the data and verify machine setup and performance based on the results of the analysis, even though the weld was done based on a setup employing the meters.

To accomplish this, it is important to know what the correlation between the meter values and the DAS measurement is. This study was done to determine if the data taken using a DAS was in agreement with what was expected when the weld parameters were set using the meters.

For this study, the DAS data averages and variances were compared to the corresponding meter values. Several welds and weld simulations (weld parameters run on a tungsten block) were done using the same parameters, and the results were pooled and compared to determine if they were equal. The comparisons were made by using statistically valid tests of hypotheses. The results of these tests are the subject of this report. Throughout the remainder of this report the term "weld" will be used to refer to either a weld or a weld simulation.

KEY WORDS
Electron Beam Welding
Data Acquisition
Acquisition System
Data Analysis
Computer Controlled
Statistical Tests
Weld Schedules
Schedule Monitoring
Equipment Performance
Performance Monitoring

Weld Program and Data Acquisition

Calibration

Prior to any data acquisition, the welding machine and the data acquisition
machine meters (beam voltage, beam current, focus current and filament current) were calibrated, as was the high-voltage system. Each input channel of the DAS was also calibrated. For those parameters that had no meters (X and Y deflection), the monitoring resistors were calibrated. The vacuum gauge tube and readout were also calibrated.

The DAS we used has a digitizing range of 2^12 or 4096 which yields a resolution for ± 10 V of 20/4096 = 0.0049 = 0.005 V/interval. This yields a digitizing accuracy (standard deviation) of ± 0.0025 V. Additionally, the manufacturer’s quoted measurement accuracy is ±0.001 V. Combining this with the standard error of the calibration source shows that the largest error is associated with the digitizing process.

Thus, if the DAS is calibrated, then an input voltage can be determined with a standard deviation of 0.0025 V. If the DAS is uncalibrated, then a voltage can be determined with a precision of 0.0025 V, but its accuracy is unknown. This means that a comparison cannot be made between a value measured by an uncalibrated DAS and a meter. Calibration of the machine’s meters is essential for the same reasons.

The DAS measurements for beam voltage, beam current and focus current were converted to engineering units of volts and amperes through the use of a software conversion factor. The conversion factor was derived from hundreds of tests by equating the meter reading to the DAS mean and fitting the data to a straight line by the method of least squares. The conversion factor is then the resulting least squares equation. The regression coefficient was always greater than 0.99, indicating a very good fit.

Throughout this work, the effect of electrical noise is not mentioned. From previous work, we know that noise at 60 Hz and 60-Hz harmonics is present on all of the signals. The noise on the signal will not, however, affect the accuracy of the mean value or the validity of the variance of the sample signal. The noise does determine the maximum standard deviation of the parameter analog signal. The result of using the sample variance and not the analog signal variance could affect the outcome of the tests of hypothesis and the deviations calculated in our study. Because we could not sample all signals at a rate high enough to observe the maximum variance, we concluded that the sampling rate used was adequate for developing algorithms to monitor machine performance and weld parameters set up.

Welding with Data Acquisition

During welding, parameters are monitored at a rate determined by the limiting factors of the system. For example, to discriminate 60 Hz signals requires a sample rate of at least 120 Hz. If the weld is 20 s in duration and there are eight input channels, then the amount of memory required for the DAS is (20 s) (120 data points/s) (8 parameters) = 19,200 data points. Each data point is stored in the computer as a binary integer and requires 2 bytes of memory. Thus the computer memory required in this example is 38,400 bytes. This is also the amount of data that must be analyzed. From this it is easy to see that unreasonable data rates can cause excessive amounts of data to be taken and subsequently analyzed. As a general rule, the minimum sampling frequency should be at least twice the maximum frequency analyzed. If the analysis is for DC only, the rule is a minimum sampling frequency of 10 Hz. Once the data rate is determined, filters for frequencies greater than twice the highest sampled frequency should be used to condition the signal.

Calculations and Initial Tests of Hypotheses

Mean values from the DAS are by definition the DC amplitude of the signal. With appropriate conversion to engineering units, they should be the same as any meter reads. The difference, if any, is in the magnitude of the variance, degrees of freedom and time constant of the two measurements. The variance of the DAS must be less than or equal to the variance of the measured data. The degrees of freedom for the DAS data is the weld time multiplied by the sample rate. This is generally a large number and, all things being constant, tends to reduce the variance. The degrees of freedom for the DAS data is the weld time multiplied by the sample rate. This is generally a large number and, all things being constant, tends to reduce the variance. The degrees of freedom for the DAS mean is determined during calibration by the number of observations used to determine the variance. Hypothesis testing of the DAS data against the meter values uses the variance of the meter as determined during the calibration. The time constant on an analog meter, to a certain extent, represents a measure of the degrees of freedom, as does the sample and hold time on a digital meter. These are generally longer than the analog to digital conversion of the DAS, and thus meter values do not represent a value for the parameter during the weld as accurately as a DAS. Additionally, as discussed above, the DAS data has a real-time variance with more degrees of freedom. Thus, a DAS can be considered a replacement for the existing meters based on the usefulness of the numbers only. In most cases, however, it is a supplement since the meters are probably used for set up (the reliability of this arrangement is the subject of this work).

For this study, the means and variances were tested against machine meter values, their associated variances and certain coefficients in a linear regression of the parameter as a function of time. For this latter test, the data for each parameter were fit to an equation of the form:

$$p_1 = (a_1) (i) + b_1$$

to determine if there was linear drift in the parameter during the data acquisition time.

The null hypotheses tested on each parameter were:

1) DAS mean = meter setting (i.e., \(m_{1i} = m_{i}^{*}\))
2) DAS mean = regression constant (i.e., \(m_{1i} = b_{1}\))
3) meter setting = regression constant (i.e., \(m_{1} = b_{1}\))
4) DAS variance = meter variance (i.e., \(d_{1}^{*} = d_{m}^{*}\))
5) DAS variance = regression variance (i.e., \(d_{1}^{*} = d_{r}^{*}\))
6) regression slope = zero (i.e., \(a_{1} = 0\)).

A description of these tests is given in Appendix A.

Tests 2 and 6, at first glance, seem to be the same. Note however, that for any set of data, the mean of the data can be equal or unequal to the intercept with the slope equal to zero. Thus, testing the DAS mean against the regression intercept really says nothing about the slope. Testing the slope against a zero value is really a test for simple drift and is but one of the many tests that could be applied. Since the intercept is the DAS parameter at time zero, if the DAS mean is equal to the intercept then the parameter was set correctly, which is important information. If there are any dominant frequency components (colors) in the signal, noise or otherwise, they will not be detected using these tests. Tests for color were not considered because of the sampling rate needed, complexity of the analysis and the difficulty in choosing a valid frequency range.

For our system, meter values were only available for the beam voltage, beam current, focus current and the filament current. We discontinued testing the vacuum because we observed that it was neither constant nor linearly variable during a weld, making testing and comparisons invalid with our current algorithms. This does not imply that vacuum is not important, only that it was not investigated further here.

Deviations

In EBW there is often the question of "did a spike occur?" and if it did, "what was its duration and magnitude?" or more importantly, "what is a spike?" For this report we will use the term spike to refer to an excursion in penetration and the term deviation to refer to the excur-
A deviation can be identified by monitoring the parameters, if its duration is greater than the time between two samples. One may want to know duration and time of occurrence for both spikes and deviations. For deviations it is of interest to know whether it was voltage, current or one of the other monitored parameters? Do deviations in one parameter correlate with other parameters and do they correlate with visual, destructive or nondestructive inspection results? For a spike, one is interested in knowing if it correlates to any parameter or any combination of parameter deviations. The question of the magnitude of the deviation and its significance needs to be addressed, as well as to what extent deviations affect the weld's fitness for service. These last questions are beyond the scope of the present investigation.

Determination of a deviation depends upon the statistics calculated. The total number of deviations is determined by counting, once a deviation is defined. For our study, data values greater or less than the mean plus or minus one standard deviation in the sampled signal were considered deviations. The choice of plus or minus one standard deviation is arbitrary and ultimately it should be determined from the maximum analog signal standard deviations and the resulting weld morphology.

In one case, a deviation was considered to have occurred when the sample mean was statistically equal to the machine setting, and the variance of the sample mean was statistically equal to the machine variance. In this case, a deviation occurs when the measured value is greater or less than the mean, plus or minus the standard deviation. Because the DAS means and the machine meter values, as well as the DAS and machine meter variances, are statistically equal, as a matter of practice, the mean was taken as the average of the DAS mean and meter value and the standard deviation was taken as the numerically greater of the two standard deviations.

A deviation could also have occurred when the sample mean was statistically equal to the machine setting and the variance of the sample mean statistically unequal to the machine variance. The deviation occurred as in the previous case with the same definitions for the mean and standard deviation.

One would be tempted to look at cases of unequal means, but this is not necessary because if the means are not statistically equal then the weld would have been done with the wrong parameter, and it would be rejected from the statistical tests.

The question of when deviations occur can be answered by printing the time of the deviations or by graphically displaying them versus time for visual examination. We used the latter technique by assigning a value of zero to the parameter if the data point was not considered a deviation region and an integral value if it was. An integral value from 1 to 6 was assigned to deviations in each of the respective six parameters monitored. Thus, every deviation for Parameter 1 was assigned a value of 1, for Parameter 2 was assigned a value of 2, etc. An example of this is shown in Fig. 1. Plotting each deviation in this manner, on one graph and for all parameters permitted visual observation of obvious correlations. As seen in Fig. 1, there are some visual correlations particularly between beam voltage and current, as well as X and Y deflection. Filament signal deviations are not plotted for reasons discussed later.

The correlation of weld defects with deviations required the correlation of joint position with time. This was obtained by plotting parameter signals on the same scale as weld longitudinal photomicrographs and superimposing the two for visual correlation. Figure 2 is such a composite for one of the welds. This figure shows that there is some correla-
tion between obvious deviations and weld defects. This is shown in Fig. 2 where the beam current deviations occur at obvious weld spikes. Unfortunately, the correlation is not 100% at the level of one standard deviation.

It is also possible to superimpose the actual signals onto the deviations figure. This allows a visual correlation between the deviations and the signals to further characterize the behavior of the system. As an example, the deviations figure with the beam voltage and current signals superimposed is shown in Fig. 3.

Tests of Hypotheses 3 and 4

These tests are designed to determine whether or not the means and variances obtained for each parameter from several "identical" welds are actually the same. This part of the study was done to determine the viability of such a test. In practice, one could readily determine if all of the beam voltages for a given production program, between filament changes, during a fixed period of time or for some other identifiable sequence, were the same and had the same variance. This has the effect of adding confidence to the quality of the product, and it could be used to predict required maintenance or to direct the investigation of rejected products. It is important to keep in mind that these tests are only valid if done for some identifiable sequence. For our work, the analysis was done at the end of the weld study.

Experimental

For the work reported here, a commercially available data acquisition system was interfaced between a PC and a Leybold-Heraeus modified Hamilton-Standard electron beam welding machine. The system and its capabilities are described elsewhere (Refs. 1, 2).

The DAS was configured with seven input channels. Data acquisition was triggered when beam current reached a preset level of approximately 1 mA. Sampling was then initiated in Channel 1 after a delay of 0.0082 s, which avoided taking data during the beam current rise. Sampling occurred sequentially, with each parameter acquisition initiation delayed by 170 μs from the end of the previous one. Because of hardware limitation and the fact that we were primarily interested in developing algorithms and methods for testing machine performance and weld parameter setup, signals were only sampled for 10 s at 20 Hz.

The parameters recorded and their sample sequence were beam current (bc), beam voltage (bv), X deflection coil current amplitude (x), y deflection coil current amplitude (y), focus current (fc), high vacuum level (vac) and filament current (fl). The parameters varied were beam voltage and beam current, while all others were held to the following values for each weld: sharp visual focus, 1.27 cm/s (30 ipm) travel speed, 23.5 cm (9.25 in.) gun-to-work distance, X and Y deflections were adjusted to locate the beam at the telescope cross-hair intersection. The chamber was evacuated to 5 × 10⁻⁵ torr before welding, and the filament was peaked for each weld. Each combination of beam voltage and beam current was repeated four times for the following values, respectively: 100, 200 and 140, and 10, 15 and 25. This yielded 36 welds with 27 of them done as simulations on a stationary tungsten block and 9 done on aluminum.

Welds were done on 2-cm diameter × 2.5-cm (0.8- X 1-in.) long tungsten blocks and on aluminum alloy 5083 samples that were 2.54 cm thick × 2.54 cm wide × 25.4 cm long (1 X 1 X 10 in.). Alcohol degreasing was used before each Al weld. These materials were chosen because the aluminum was expected to produce greater variability in weld morphology than many other materials due to its high vapor pressure and outgassing, while the tungsten was expected to be very stable for opposite reasons.

The data obtained from the above welds were analyzed using the hypotheses described previously. The statistics and meter values were tested using Hypotheses 1, 2 and 3 shown in Appendix A. A summary of the tests is shown in Table 1. After all the welds for the study were done, Hypotheses 3 and 4 were tested on the pooled statistics. The parameters for which these were applied are also shown in Table 1.

Results and Discussion

Table 2 shows the results of the tests of hypotheses (TOH) for the beam voltages.
age data after every weld and for the pooled beam voltage data. The results for each parameter are different, but this table serves to illustrate the kind of information that is generated. Information of this type was obtained for each parameter investigated and analyzed to produce Table 3. The results indicated as not tested (nt) were for parameters that do not have DC meters.

In every case we found that the slope of the regression line was not zero. This is shown as row H5 in Table 3. This implies there was drift in the parameter even over the short (10 s) data acquisition time used in this study. This drift probably accounts for the results obtained from the TOH's made against the regression equation. Because the drift is statistically significant, it is not reasonable to test the regression constant against the DAS averages or against the meter values. The drift probably also accounts for the inequality of the pooled regression variances and constants. For this reason, these tests will not be discussed further. This hypothesis should always be tested to verify the drift characteristics of the equipment, which is important when defining the ultimate repeatability and capability of a welding system. Moreover, eliminating this test in this study reduced the TOH's for consideration to those marked with asterisks in Table 3.

The variance of the meters was 1%, as determined by the calibration. Thus, one expects that a test of equality of the variance will show such (row H5 in Table 3). This test is consequently the trivial case and will be ignored.

The filament current meter is in the AC circuit on the primary side of the filament power supply. The main harmonic of this signal is much greater than the sampling rate used. This is reflected in the TOH's that show that there was no equality for any statistic tested. This is shown as column fl in Table 3. Recall that this signal is on the input side of the filament supply and is AC. For our work, it was rectified and filtered for the DAS input. For this reason, no tests were done against the meter. This work thus shows that additional filtering is needed for this parameter. For this reason, deviations were not plotted in Fig. 1.

The X and Y deflection amplitudes determine the position of the beam on the joint, with the telescope cross hairs as the reference. For the work done in this study, the joint travel was along the X direction, and thus, the only real drift or variations that influenced the beam position on the joint were those in the Y direction. The data showed the mean and standard error of the Y deflection smaller than the X deflection. However, there was drift in both X and Y deflection, and, according to the DAS analysis, it was not possible to repeatedly position the beam on the cross hairs in the telescope. When the gain in the signal conditioning is considered, X and Y deflection coil currents were found to be less than 100 mA with standard errors of less than 1 mA.

A subsequent study, where the X and Y displacement was determined as a function of the deflection coil current, showed that for gun-to-work distances of 15.24, 22.86 and 30.48 cm (6, 9 and 12 in.), the deflections were never greater than 0.005 mm (0.0001 in.) per mA. The study also showed that the coil currents were in the order of several hundred mA, with standard errors of about 1 mA (this agrees with the results of this work). This means that the noise and drift on these signals would only produce beam deflections of approximately 0.005 mm and would probably never be seen visually by the operator or on photomicrographs of welds.

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<tr>
<td>H1: DAS Mean = Meter</td>
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<td>DAS Mean = Reg Con</td>
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<td>Meter = Reg Con</td>
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<td>Meter Variances Equal</td>
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(a) A No. 1 means the hypothesis is rejected.

(b) Weld No.'s 1, 2 and 3 were stationary welds on the tungsten block and Weld 4 was done on Al, for each condition shown.

(c) A blank, 1, x or nt means that the hypothesis was accepted, rejected, had occasions of either or was not tested, respectively.
The results were fit to a straight line, by each voltage), and equating it to the ments and 1, 5, 10, 20, 30 and 40 mA at numerus conditions of beam voltage DAS mean over long times (15 s) and needs reexamination. The conversion factor was developed by determining the many instances when the individual DAS means were always equal to the though the DAS mean is equal to the when the weld was done on the tungsten block, at each condition, the Al sample, the standard deviation was determined to be 1% by the calibration. However, the digital meter has an update frequency of twice per second, while the DAS sample rate is 20 Hz. Because of this difference, the DAS provides a better representation of the parameter value during setup and welding than the meter.

Review of the equality of the DAS means and meter values of the pooled beam voltage data shows the trend we have begun to expect. Namely, that the meter values are the same and there is no trend in the DAS values. This is important since the DAS has been shown to be a better monitor of the parameter than the meter itself, and thus, better control and monitoring could be obtained with the DAS rather than with the meter. It must be kept in mind that this trend is to a certain extent forced because we set the parameter with the meter and monitored it using the DAS. It is expected that by setting the parameter with the DAS, the equality of the pooled data would be obtained.

The DAS variances for the beam voltage were never equal. Review of this data showed that there was no difference between the variances obtained on the tungsten or the Al, and the synergism between parameter and material, seen with the beam current, is not there.

To determine if drift in any of the parameters could be detected in the welds, each of the aluminum weld samples was sectioned along the direction of travel and the penetration measured at
five locations. The measured penetration and a linear least squares calculation of the penetration were plotted versus position along the joint. The data for 140 kV and 10, 15 and 25 mA are shown in Fig. 4. Here it is seen that the penetration is statistically constant for the weld performed using 25 mA but has some drift for the lower currents. It is not possible from this work to relate this penetration variation to the drift in a particular parameter. Of the welds shown in Fig. 4, the one made at 10 mA has the largest variation (as determined by the slope of the regression equation) over the length of the weld.

Conclusion

The work to date has shown that a computer data acquisition system is extremely useful for monitoring the EBW process. The DAS has several attributes which make it a valuable addition to any welding process: It verifies the weld set up, provides information on the behavior of the parameters during the weld, verifies that the weld was run at the desired parameters, and shows interactions between the machine and the material and can help guide an investigation into the cause of a rejected product. In order to take advantage of these attributes, comprehensive analysis of the data must be done. To do this properly, advanced planning and preparation are necessary. This preparation is in the area of hypothesis testing and organizing the computer to do the total job. Without this, the job is too large and cumbersome and there is a great risk that it will not be done correctly and essential tests will be overlooked.

We found that the DAS was a more accurate measure of parameter performance than the meters. Additionally, the DAS can be used to characterize machine performance in relation to parameter repeatability as seen by the results of the pooled analysis. We found that all of the parameters on the machine we studied drifted during the duration of the weld. This could account for some of the penetration variability we see in our welds. However, the real effect of this drift on penetration and joint alignment is not known. This is a matter of concern and will be studied in the future.

Drit was seen in parameters expected to be very stable, such as DC deflection and focus. Subsequent studies showed that the change in beam position per milliampere is less than 0.005 mm/mA (0.0002 in./mA) for the deflection and 0.23 mm/mA (0.009 in./mA) for the focus. It would probably take five to ten times these values to produce noticeable changes in the beam position (deflection or focus). This allows the acceptance range for these deviations to be significantly increased, which would flag fewer deviations and perhaps a better correlation to observed weld defects. The quantization of this remains as work for the future.

Also of importance is the finding that the beam current signal is affected by the material being welded. This was shown by the different beam current variances found. Beam current was the only parameter found to behave this way. This result points to the need for studies to understand beam-weldment interactions.

For this work, a parameter excursion was flagged as a deviation when it was outside the band defined by the mean plus or minus one standard deviation. The width of this band was arbitrary and relates more to the signal variation than to the variation of the resultant weld morphology. There was a reasonably strong correlation between deviations in the beam current and defects in the weld morphology, although it was not 100%.

At this time, no statement can be made about the correlation between deviations in other parameters and weld defects. As a general statement, the study points to the need to determine actual effects of parameter deviations on weldments. Such a study is needed to provide a basis for predicting defects in weld morphology as a result of deviations seen in the parameters.

This study also brought out the importance of signal conditioning for computerized data monitoring. Variances in the data are valid and can be used to determine acceptance ranges and subsequent deviations in parameters. The ranges may not be strictly valid for determining correlations between weld morphology defects and actual parameter signal deviations because the actual parameter signal variance is larger than that of the sampled data, unless the data is sampled at a rate greater than the highest frequency present in the signal. Sampling at a lesser frequency leads to the condition that deviations are determined using an artificially small variance. This must be kept in mind when interpreting the correlations between deviations and defects. In any event, signal conditioning must be used once the sampling rate is determined.

The tests of hypotheses used in this study were all useful in that they provided information otherwise unavailable. The tests were simple to implement and easily programmed for use on the computer. They could be made more interactive, particularly for testing on one set of data. In the development of automated testing of the data generated by the welding process, it is important to have an experienced engineer reviewing the results. Perhaps this type of testing becomes routine and artificial intelligence technology becomes more refined, the correlation of all forms of DAS can be used to more accurately determine weld quality.

During this study, we eliminated some statistical tests. This was done because it could be justified by the basis of the results we obtained. Any future work can and should include these tests because of the information they provide.

References


Appendix A

Hypotheses Used

Various hypotheses used are outlined below with no proof of applicability.

In all the equations that follow:

n is the total number of observations (degrees of freedom) during one run for a parameter.

k is the number of runs made for a parameter.

N is the total number of observations resulting from several runs for the same parameter (N = n*k).

Also, in the following equations, m1 and m2 represent general means and standard deviations with the appropriate nomenclature for the attribute being examined in the text. The mean values for a parameter resulting from several runs are represented by: m1, m2,. . . mk. The corresponding standard deviations will be represented by: σ1, σ2,. . . σk and the variances are (σ1)2,. . . .

HI (i = 1, 2, ..., 5) represents the null hypotheses tested.

For DAS mean = meter; DAS mean = regression constant; and meter = regression constant

H1: m1 = m2; this is a student’s t test and HI is rejected at the 5% confidence level if the calculated value is greater than 1.96.

\[ t = \frac{(m1 - m2)/\sqrt{\left(\frac{\sigma1^2}{n1} + \frac{\sigma2^2}{n2}\right)}}{\sqrt{\frac{1}{n1} + \frac{1}{n2}}} \geq 1.96 \]

For DAS variance = meter variance; DAS variance = regression variance

H2: (σ1)2 = (σ2)2; this is a double sided F test and F is rejected at the 5% confidence level if the calculated value is outside the range

\[ F = \frac{\sigma_2^2}{\sigma_1^2 - 1} \]

For DAS means = meter values = regression constant = :

H3: m1 = m2 = ... = mk; this is an F
test and $F$ is rejected at the 5% confidence level if $F \geq F_{k-1, n-k, 0.05}$, where $F_{k-1, n-k, 0.05}$ is determined from the tables for $k - 1$ and $n - k$ degrees of freedom.

$$F = \frac{(n - k)/(k - 1)(\Sigma \eta_j m_j - M)/(\Sigma \eta_j)}{(\Sigma \eta_j m_j - M)/(\Sigma \eta_j)} \geq F_{k-1, n-k, 0.05}$$

In the above expression $M = (1/k) \Sigma m_j$ and all sums are from $j = 1$ to $k$.

For $F$ statistics:

$$F = \frac{(n - k)/(k - 1)\left(\frac{\Sigma \eta_j m_j}{(\Sigma \eta_j)} - \frac{M}{(m_j - M)}\right)^2}{\frac{\Sigma \eta_j}{(n_j - 1)(\Sigma m_j - M)^2}}$$

For regression variances $=\cdot$ meter variances $=\cdot$ regression variances $=\cdot$

$$H_4: (\eta_1)^2 + (\eta_2)^2 + \ldots + (\eta_k)^2; \text{ this is a Chi squared (X) test and the hypothesis is rejected at the 5\% level if } X > (X_{\alpha=0.05}, k - 1)^2$$

$$N^*\Sigma (m_j - 1)(\eta_j)^2/N - \Sigma m_j^*\eta_j > (X_{\alpha=0.05}, k - 1)^2$$

These tests constitute the complete set for the data analysis.

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**WRC Bulletin 330**

January 1988

This Bulletin contains two reports covering the properties of several constructional-steel weldments prepared with different welding procedures.

**The Fracture Behavior of A588 Grade A and A572 Grade 50 Weldments**

By C. V. Robino, R. Varughese, A. W. Pense and R. C. Dias

An experimental study was conducted on ASTM A588 Grade A and ASTM A572 Grade 50 microalloyed steels submerged arc welded with Linde 40B weld metal to determine the fracture properties of base plates, weld metal and heat-affected zones. The effects of plate orientation, heat treatment, heat input, and postweld heat treatments on heat-affected zone toughness were included in the investigation.

**Effects of Long-Time Postweld Heat Treatment on the Properties of Constructional-Steel Weldments**

By P. J. Konkol

To aid steel users in the selection of steel grades and fabrication procedures for structures subject to PWHT, seven representative carbon and high-strength low-alloy plate steels were welded by shielded metal arc welding and by submerged arc welding. The weldments were PWHT for various times up to 100 h. at 1100°F (593°C) and 1200°F (649°C). The mechanical properties of the weldments were determined by means of base-metal tension tests, transverse-weld tension tests, HAZ hardness tests, and Charpy V-notch (CVN) impact tests of the base metal, HAZ and weld metal.

Publication of these reports was sponsored by the Subcommittee on Thermal and Mechanical Effects Materials of the Welding Research Council. The price of WRC Bulletin 330 is $20.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Suite 1301, New York, NY 10017.

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**WRC Bulletin 331**

February 1988

This Bulletin contains two reports prepared by the Japan Pressure Vessel Research Council (JPVRC) Subcommittee on Pressure Vessel Steels. The reports are involved with the variation in toughness data for weldments in pressure vessel steel structures.

**Metallurgical Investigation on the Scatter of Toughness in the Weldment of Pressure Vessel Steels—Part I: Current Cooperative Research**

This report covers the background of current cooperative research from 1973 to the present, covering 137 references on toughness and toughness testing of weldments.

**Metallurgical Investigation on the Scatter of Toughness in the Weldment of Pressure Vessel Steels—Part II: Cooperative Research**

The objective of this report was to investigate the variation in toughness of multipass weldments in a welded joint.

Publication of these reports was sponsored by the Subcommittee on Thermal and Mechanical Effects on Materials of the Welding Research Council. The price of WRC Bulletin 331 is $28.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Suite 1301, New York, NY 10017.