Results of Distortion Comparison Trials on Stainless Steel – With and Without *Pulse Puddle Arc Welding®*

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Introduction

Applications Technologies Company LLC (ATC) was contracted by Bonal Technologies, Inc. (BTI) to independently investigate the use of their Pulse Puddle Arc Welding® (PPAW) sub-harmonic technology in terms of its ability to reduce distortion when welding stainless steel structural components. PPAW equipment consists of "The Box", "The Wand", "The Pulsator", and "The Sensor" as shown below in Figure 1. A Design of Experiment (DOE) was conducted using preferred stainless steel welding parameters and midrange PPAW parameters determined using Bonal Technologies recommended guidelines. This report describes the test program as well as the test results.

Figure 1. Pulse Puddle Equipment

Test Program

To determine what PPAW settings produced the best results, the test trials to be performed were established using a Design of Experiments (DOE) approach. Using this method, a minimum number of tests can be conducted to determine the relationship among multiple variables. Those variables selected to change included frequency and eccentric load. However, to produce consistent weld sizes travel speed and wire feed speed were maintained as constants for all DOE trials. An identical DOE was conducted to further validate the data that was received and the average distortion from these tests was compared to control experiments. Weld trials were conducted using a Power Master 500P by Thermal Arc, a side beam for automation, and .045-in diameter 308L-TO-1 filler metal and 90%He-7.5%Ar-2.5%CO2 shielding gas at a flow rate of 35-cfh. The welding parameters utilized to conduct DOE trials at 20-IPM were 27.2-V and a wire feed speed of 440-IPM, herein referred to as Welding Parameters "A". The test plates consisted of a 3/8"x3"x24" type 304 stainless steel alloy vertical plate and a bottom plate that was 3/8"x3"x24" type 304 stainless steel alloy. These T-joints were precision fitted and a one inch long tack weld was positioned at the ends of each sample and in the center in an identical manner. The assembled samples ware clamped such that the bottom plate was in intimate contact with the table and the stem of the tee was free to move. Figure 2 illustrates the use of a precision square to maintain precise and consistent tacking of plates and Figure 3 shows a close-up of the welding gun with respect to the T-joint.

Figure 2. Precision Tacking of Plates

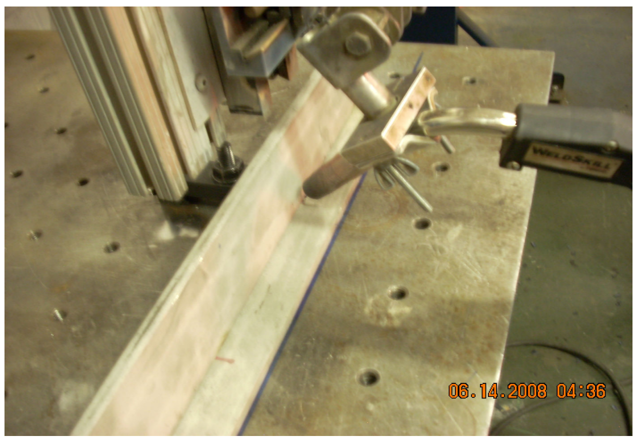

Figure 3. Close-up of Weld Setup

The DOE that was conducted and replicated is a screening matrix used to determine the effect of each variables range and evaluate the validity of each parameter combination. The DOE test matrix is presented in Table 1.

Table 1. DOE Test Matrix

Trial	Eccentric Load	Percent of Peak	Travel Speed (IPM)
1	2	50	20
2	3	25	20
3	4	50	20
4	4	25	20
5	4	5	20
6	2	25	20
7	2	5	20
8	3	50	20
9	3	5	20

As provided by Table 1, it is shown that three different values were used to evaluate the effects of Eccentric Load and Percent Amplitude. Note that "Percent Amplitude" refers to the location of the frequency setting with respect to the harmonic curve as shown in Figure 4

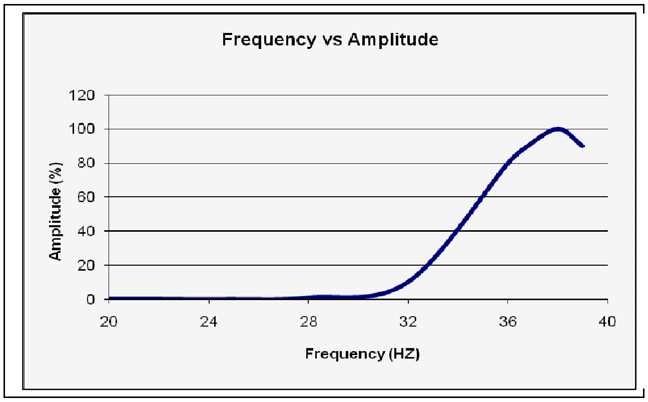

Figure 4. Example of Frequency using Harmonic Peak

All test matrices were executed and all welds were found to be visually acceptable. The welding parameters used resulted in a globular transfer deposit of filler material with excellent appearance and freedom from undercutting at the upper weld toe. Each weld was allowed to cool for ten minutes and a one inch wide cross section was then removed from the trial piece eight inches from the termination of the weld. A representative macroscopic image of the resulting welds is presented in Figure 5. Digital imaging software was then used to measure the angular distortion of each trial as shown in Figure 6. Linear distortion was mathematically extrapolated and recorded for each trial as defined in Figure 7.

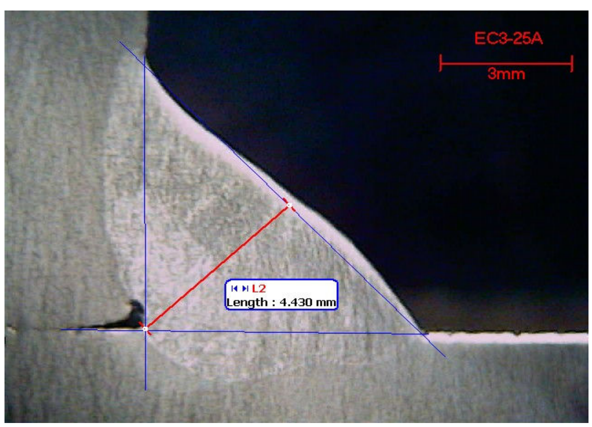

Figure 5. Macroscopic Image of Weld Cross Section

Figure 6. Angle Measurement using Imaging Software

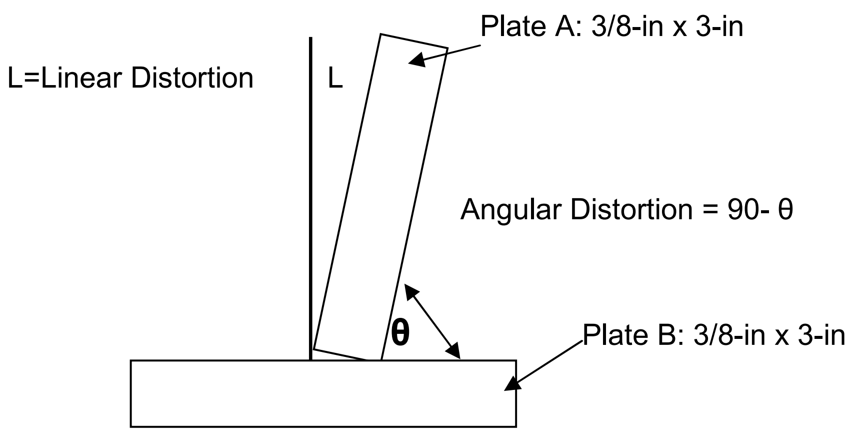

Figure 7. Illustration of Angular Distortion

Test Results

Noted above in this report, the purpose of these trials was to both verify which settings of the PPAW are preferred for welding stainless steel as well as compare the amount of distortion in the test pieces with and without PPAW.

<u>Control Samples</u>

Control samples were welded without the use of PPAW using Welding Parameters "A". Three samples were welded, cross sectioned and evaluated using the discussed procedure. The results are shown in Tables 2 and 3. It is important to note the average deviation of the distortion in the control samples. The average data from these trials will be used to compare welds produced without PPAW to those produced while using PPAW.

Table 2. Control Trials Welded Without PPAW

Trial	Travel Speed (IPM)	Angular Distortion (degrees)	Linear Distortion (inches
C1	20	6.322	.330
C2	20	7.727	.403
C3	20	4.826	.252

Table 3. Control Trials Standard Deviations & Average Distortions

Standard Deviation (degrees)	Average Distortion (degrees)	Average Linear Distortion (inches)	Lower Limit	Upper Limit
1.451	6.292	.328	1.939	10.644

The DOE conducted for this experiment was a full factorial DOE. The experiment consisted of two factors at three levels at a constant travel speed. The welding parameters were identical to those of the control samples (Welding Parameters "A"). The DOE evaluated the effectiveness of Eccentric Load and Percent Amplitude in limiting distortion during welding using flux cored arc welding. The Eccentric Load was evaluated at levels of 2, 3, and 4. The Percent Amplitude was evaluated at 5%, 25%, and 50% amplitude of the harmonic curve. The purpose of this DOE was to evaluate which combination of set variables would be preferred for limiting distortion. Replicating the DOE allowed reduced statistical uncertainty and ability to more accurately predict distortion in stainless steel welding.

Table 4. DOE Test Matrix

Trial	Eccentric Load	Percent of Peak	Travel Speed (IPM)
1	2	50	20
2	3	25	20
3	4	50	20
4	4	25	20
5	4	5	20
6	2	25	20
7	2	5	20
8	3	50	20
9	3	5	20

Tables 4 and 5 show the results from the DOE and its replicate. As mentioned previously the standard deviations of the Control Trials in comparison to the DOE trials is significant. A much lower standard deviation, which is present in the DOE trials, allows for a much better prediction of the distortion associated with the welding of stainless steel.

Table 5. Angular and Linear Distortion of DOE Replicate A and DOE Replicate B

	Replicate A	***Replicate B***			
Trial	**Angular Distortion**	**Angular Distortion**	**Average Angular Distortion (degrees)**	**Average Linear Distortion (inches)**	**Standard Deviation (degrees)**
1	5.888	5.526	5.707	.299	0.26
2	4.254	5.092	4.673	.244	0.59
3	5.221	5.391	5.306	.277	0.12
4	6.295	6.206	6.2505	.327	0.06
5	5.882	6.63	6.256	.327	0.53
6	5.044	6.267	5.6555	.296	0.86
7	5.703	5.388	5.5455	.290	0.22
8	5.007	5.307	5.157	.270	0.21
9	5.745	6.45	5.98	.313	0.50

The data from Table 5 was evaluated using Minitab® statistical software to determine the effects of Eccentric Load and Percent Amplitude both independently and interactively. Figure 8 shows the effect of each variable independently throughout its range and Figure 9 is an interaction plot showing both variables. Both figures were derived from the data means from DOE Replicate A and DOE Replicate B.

From Figure 8 one can establish that both Eccentric Load and Percent Amplitude both impact the effectiveness of PPAW in limiting distortion during welding of stainless steel. The figure shows that when assessing at Eccentric Loads only, an Eccentric Load of 3 will produce the least amount of distortion. The plot also shows that when evaluating at Percent Amplitude solely, a Percent Amplitude of fifty percent will produce the least amount of distortion among the three levels.

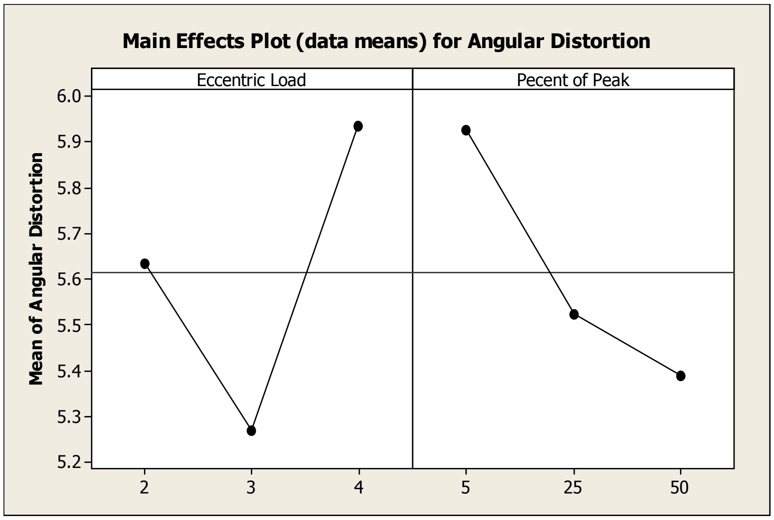

Figure 8. Independent Main Effects Plot of Data Means

Figure 9 shows interaction plot that evaluates Eccentric Load and the Percent amplitude and illustrates the interactions between the two variables. The flatness of the plot for an Eccentric Load of two shows that an Eccentric Load has little effect on distortion for all evaluated Percent Amplitudes. The interaction plot also suggests that 4 it may be possible when using an Eccentric Load to achieve lower distortion with Percent Amplitudes greater than fifty percent. However, this would require additional testing to determine the distortion limitations when using an eccentric load of 4. The plot also indicates that the eccentric load of 3 provides the least amount of distortion when a Percent Amplitude of 25% is used. The plot also suggests any deviation from a Percent Amplitude of 25% when using an eccentric load of 3 may increase distortion.

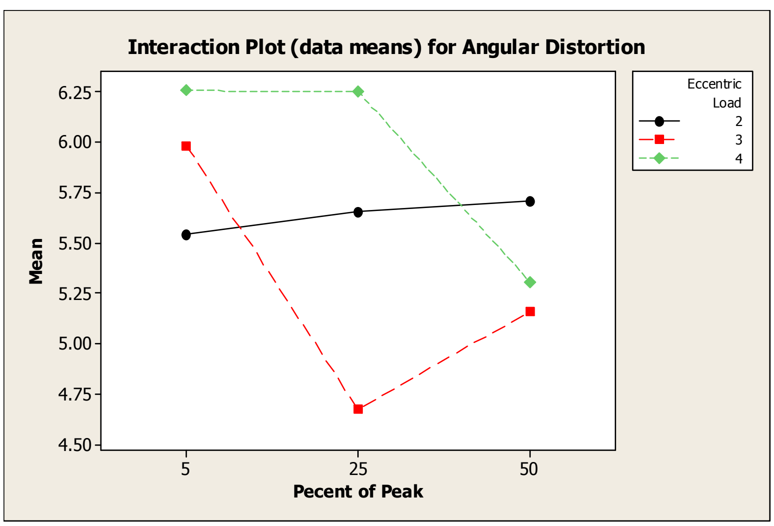

Figure 9. Interaction Plot of DOE Eccentric Load and Percent Amplitude

Figure 10 shows the average amount of distortion measured for each DOE Trial versus the average of the Control Samples. Figure 10 indicates that Trial Number 2 produced the least amount of distortion amongst all DOE and Control Trials. Trial 2 used PPAW parameters with an Eccentric Load of 3 and Percent Amplitude of 25%.

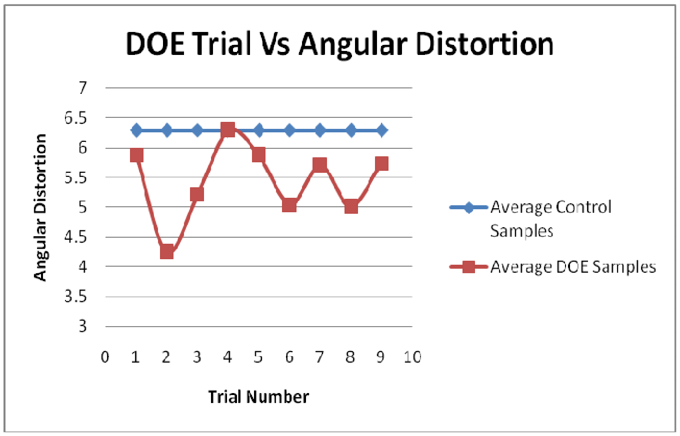

Figure 10. DOE Trials Distortion vs. Controls Distortion

Figure 10 shows the average amount of distortion present in each DOE Trial versus the Average of the Control Samples. Figure 10 indicates that Trial Number 2 produced the least amount of distortion amongst all DOE and Control Trials. Trial 2 used PPAW parameters with an Eccentric Load of three and Percent Amplitude of twenty-five percent.

Manual Welding With and Without PPAW

To further validate the functionality of PPAW in limiting distortion, manual welds on identical plates to those used in the DOE and Control trials were conducted. After concluding that an Eccentric Load of 3 in combination with a Percent Amplitude of 25% were the preferred PPAW parameters, they were applied to manual welds at travel speeds of 25 inches per minute and 25 inches per minute. Welds conducted at a travel speed of 20 inches per minute used Parameters A. Welds conducted at a travel speed of 25 inches per minute used the same filler metal and shielding gas as Weld Parameters "A" but with a voltage of 26.3-V and wire feed speed of 547 inches per minute in order to obtain the same ¼-in fillet weld as obtained using Weld Parameters "A". To produce an accurate comparison, control trials were conducted manually at both of these travel speeds and welds using PPAW were conducted using the preferred PPAW parameters. Data for manual welds follow in Table 6. In Table 6, an Eccentric Load of zero and Percent Amplitude of zero signify that PPAW was not used on this weld.

Table 6. Manual Welds With and Without PPAW

Trial	Eccentric Load	Percent of Peak	Travel Speed (IPM)	Angular Distortion
MPPAW-20	3	25	20	5.209
MC-20	0	0	20	7.883
MPPAW-25	3	25	25	5.745
MC-25	0	0	25	6.283

As illustrated in Table 6, the manual welds conducted with PPAW have less distortion than the manual welds conducted without PPAW. This is similar to those welds conducted automatically in the DOE on the Side Beam.

Conclusions and Recommendations

1. Welds produced using PPAW and preferred parameters exhibit reduced distortion by approximately twenty-six percent compared to welds produced without PPAW.

2. A frequency corresponding to an Eccentric Load of 3 and a Percent Amplitude 25% are recommended for use of PPAW when welding stainless steel.

3. Due to significant difference in standard deviation between DOE trials and Control trials, results indicate that weld distortion is more repeatable when using PPAW then when conducting stainless steel welding without.