Results of Distortion Comparison Trials on Aluminum – 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 aluminum structural components. PPAW equipment consists of “The Box”, “The Wand”, “The Pulsator”, and “The Sensor” as shown below in Figure 1. Multiple Design of Experiments (DOE) were conducted using preferred aluminum welding parameters and midrange PPAW parameters determined using Bonal Technologies recommended guidelines. This report describes the test program as well as the test results.

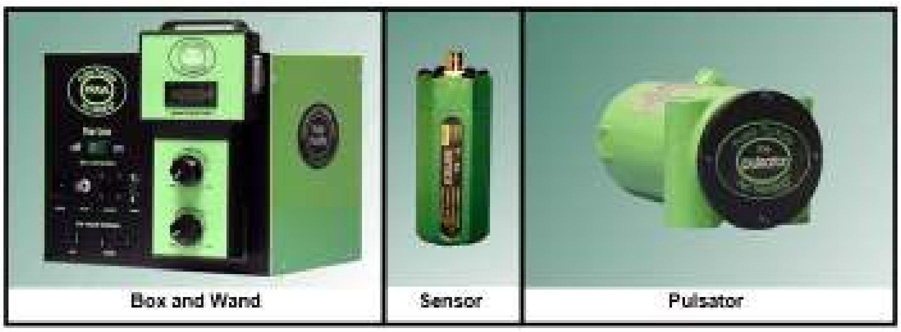

Figure 1. Pulse Puddle Equipment

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 at the various travel speeds, the wire feed speed was adjusted to result in a constant ratio of travel speed versus wire feed speed.

Weld trials were conducted using a Power Master 500P by Thermal Arc, a side beam for automation, and 3/64-in diameter ER5356 filler metal and 100%-Ar shielding gas at a flow rate of 30-cfh. The welding parameters utilized to conduct DOE trials at 25-IPM were 24.9-V and a wire feed speed of 560-IPM. The test plates consisted of a 3/8”x3”x24” type 6061-T6 aluminum alloy vertical plate in which the mating edge was machined to maintain consistent fit-up. The bottom plate was 3/8”x3”x24” type 6061-T6 alloy aluminum. These T-joints were precision fitted and tacked at the ends and in the middle in an identical manner and then 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. 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

An initial screening DOE matrix was used to determine the effect of each variables range and to evaluate the validity of each parameter combination. The screening test matrix is provided in Table 1.

Table 1. Screening Test Matrix

Run	Eccentric Load	Percent Amplitude
1	3	50
2	4	50
3	4	25
4	2	50
5	3	0
6	2	25
7	3	25
8	2	0
9	4	0

As can be seen from this table, three different values were used to evaluate the effects of Eccentric Load and Percent Amplitude. Note that the "Percent Amplitude" refers to the location of the frequency setting with respect to the harmonic curve as shown in Figure 4.

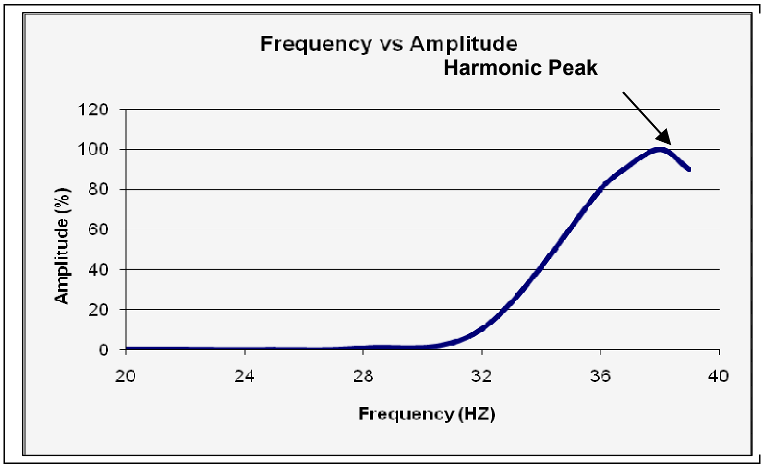

Figure 4. Example of Frequency using Harmonic Peak

After completion of the screening range, the results were evaluated and the trends were used to remove parameter combinations from the matrix that did not have a significant effect on distortion. The matrix was expanded by adding additional variable combinations in pursuit of indicating that the trends showed reduced distortion may be obtainable. The corresponding test matrix is shown below in Table 2

Table 2. Expanded Task Matrix

Trial	Eccentric Load	Peak Location
A	4	50
B	4	25
C	3	75
D	3	0
E	3	50
F	4	75
G	3	25
H	4	0

The test matrices were executed and all of the welds were considered visually acceptable. The welding parameters used resulted in a spray transfer deposit, with excellent appearance and freedom from undercutting at the upper weld toe. Once welds were produced and allowed to cool 10 minutes, a 1” weld cross section was then removed 7-in from the termination end of the weld for evaluation. Figure 5 provides a representative macroscopic image of the resulting welds. Angular distortion was then measured using digital imaging software as shown in Figure 6. Linear distortion was mathematically extrapolated and recorded for each DOE Trial as defined in Figure 7.

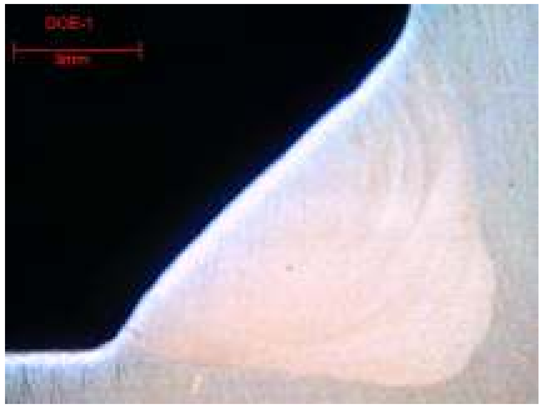

Figure 5. Macroscopic Image of Weld Cross Section

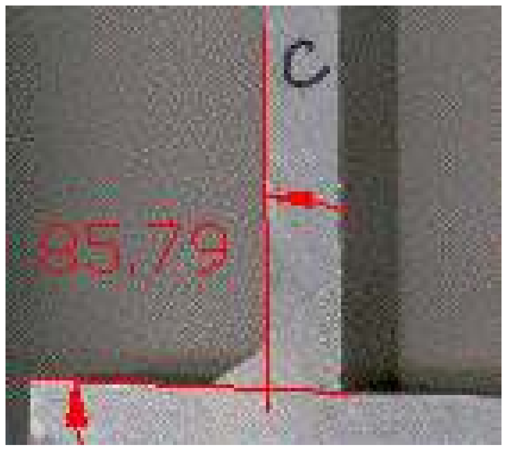

Figure 6. Measuring of Angular Distortion using Imaging Software

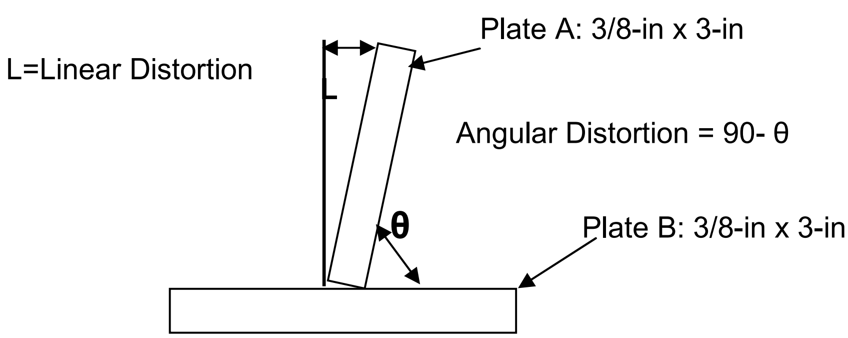

Figure 7. Illustration of Angular Distortion

Test Results

It was noted above that the purpose of these trials was to both verify which settings of the PPAW system are preferred for welding aluminum as well as compare the amount of distortion in the test pieces with and without PPAW.

<u>Control Samples</u>

Control samples were first welded without the use of PPAW. Four samples were welded, cross sectioned and evaluated using the discussed procedure. The results are shown in Table 3. It is important to note that the average distortion is 3.94 degrees and a standard deviation of 0.31 degrees. The experimental error is plus or minus 0.93 degrees or plus or minus 3 times the average standard deviation. The average result of these trials will be used to compare welds produced without PPAW to those produce using PPAW.

Table 3. Results of Control Samples Welded without PPAW

Run	θ (Degrees)	Angular Distortion (Degrees)	Linear Distortion (Inches)
C-1	85.79	4.22	0.22
C-2	86.43	3.57	0.19
C-3	86.22	3.79	0.20
C-4	85.81	4.19	0.22
Average	86.06	3.94	0.21
Std Dev	0.31	0.31	0.02

Screening DOE

The initial screening test matrix is shown below. The purpose of the Screening DOE (herein referred to as DOE 1) was to determine the effect of each variables range and to evaluate the validity of each parameter combination. As indicated in Table 1, the variable evaluated include Eccentric Loads of 2, 3,and 4 and Percent Amplitudes of 0, 25, and 50.

Table 4. DOE 1 Test Matrix

Run	Eccentric Load	Percent Amplitude
1	3	50
2	4	50
3	4	25
4	2	50
5	3	0
6	2	25
7	3	25
8	2	0
9	4	0

Table 5 shows the results of DOE 1. The angle (θ) was measured using imaging software and the angular distortion and linear distortion were then mathematically calculated. The data was thus evaluated using Minitab® statistical software to evaluate the effects of both the eccentric load and percent amplitude individually using a main effects graph and interactively using an interaction plot. (Figure 8 and 9)

Table 5. Results of DOE 1

Run	θ (Degrees)	Angular Distortion (Degrees)	Linear Distortion (Inches)
1	87.359	2.64	0.14
2	87.664	2.34	0.12
3	88.038	1.96	0.10
4	86.428	3.57	0.19
5	86.990	3.01	0.16
6	86.211	3.79	0.20
7	87.759	2.24	0.12
8	86.162	3.84	0.20
9	87.030	2.97	0.16

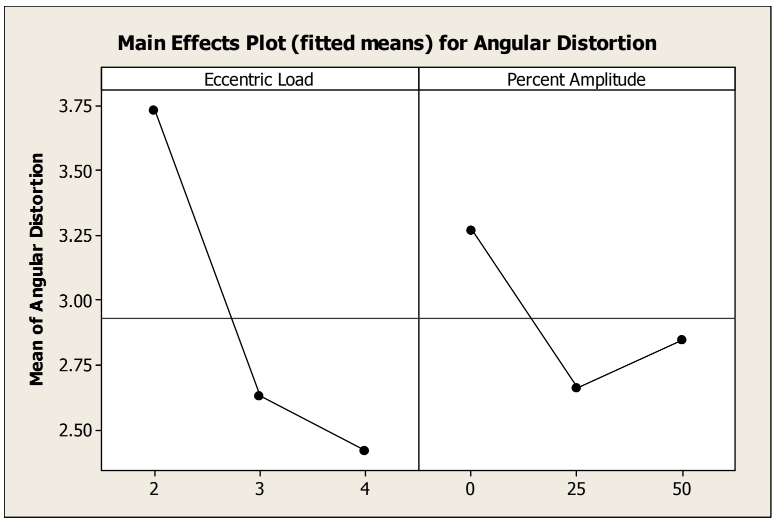

Figure 8. DOE 1 Main Effects Graph

The resulting steepness of the eccentric load portion of the graph shown in Figure 8 indicates that eccentric load has a significant effect. The graph also indicates that an eccentric load of 2 will produce less distortion control than an eccentric load of 3 or 4. The results of percent Amplitude (indicated as Peak Location) displays a parabolic curve with the lowest distortion occurring at 25% amplitude of and the most distortion occurring at the bottom of the harmonic curve or 0 percent amplitude.

Figure 9 provides a graphical representation of the interaction plot using fitted means. The results indicate that an eccentric load of 2 provides significantly more distortion than eccentric loads of 3 and 4 over a frequency range corresponding to 0% through 50% amplitude. The curve linearity and flatness of eccentric load of 2 suggests that all parameter combinations using this eccentric load will have minimal impact on the reduction distortion. The corresponding distortion measurements are very similar to those obtained from welds produced without the use of PPAW.

The curves for trails produced with eccentric loads of 3 and 4 are both parabolic in nature and display minimal distortion at amplitude of 25%. The graph also suggests that an eccentric load of 4 can produce welds with less distortion than welds produced with an eccentric load of 3.

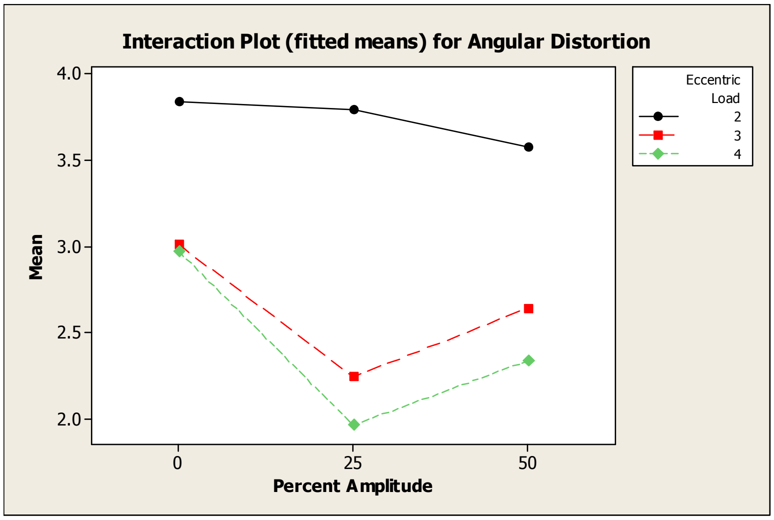

Figure 9. DOE 1 Interaction Plot

<u>Expanded DOE</u>

A second set of DOE trials (referred to herein as the Expanded DOE or DOE 2) was then conducted to further evaluate welds conducted using PPAW. Table 6 summarizes parameters used in the DOE 2 matrix. Eccentric load of 2 was eliminated from the test matrix based on the results of DOE 1 and the lack of effects on distortion. Furthermore, additional parameter combinations were added to the matrix to evaluate eccentric loads of 3 and 4 at 75% amplitude. The goal of adding these trials was to further expand the curve for each eccentric load and gain a better understanding curve trends.

Table 6. DOE 2 Weld Matrix

Trial	Eccentric Load	Percent Amplitude
A	4	50
B	4	25
C	3	75
D	3	0
E	3	50
F	4	75
G	3	25
H	4	0

Table 7 shows the results of DOE 2. As with DOE 1, the data was then evaluated using Minitab® statistical software to evaluate the effects of each the eccentric load and percent amplitude individually using a main effects graph and interactively using an interaction plot. (Figure 10 and 11)

Table 7. Results from DOE 2

Trial	θ (Degrees)	Angular Distortion Degrees)	Linear Distortion (Inches)
A	87.75	2.25	0.12
B	87.58	2.42	0.13
C	87.29	2.72	0.14
D	87.11	2.89	0.15
E	86.55	3.45	0.18
F	87.44	2.56	0.13
G	87.13	2.87	0.15
H	87.88	2.12	0.11

The main effects plot for Eccentric load is very similar to that generated for DOE1 indicating that an eccentric load of 4 provided less distortion than an eccentric load of 3. The steepness of the curve indicates that eccentric load has a significant impact to the amount of distortion.

The second graph illustrating the main effect of percent amplitude is significantly different than that obtained from DOE 1. This is believed to be the result of not evaluating trials using an eccentric load of 2 from DOE 2. The graph indicates that percent amplitude has moderate impact on distortion.

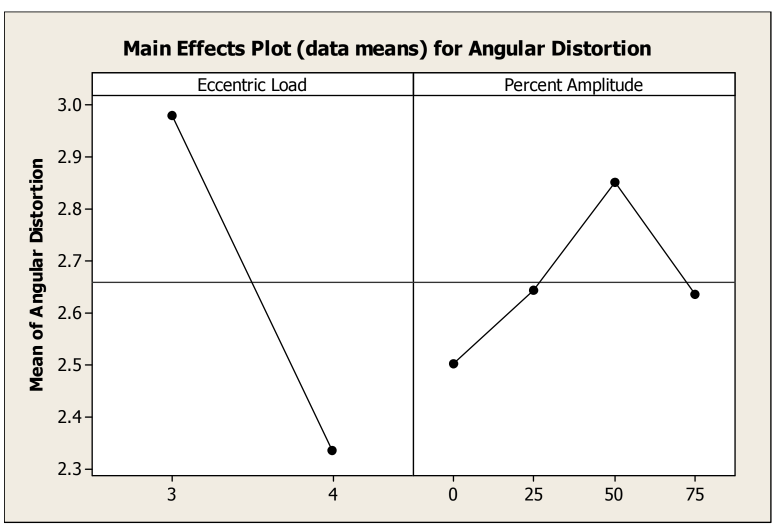

Figure 10. DOE 2 Main Effects Graph

Figure 11 displays the resulting interaction plot using fitted means. The resulting curve for an eccentric load of 3 displays similar trends to the curve for similar parameter combinations in DOE 1. The curve representing an eccentric load of 3 shown in Figure 11 displays a sinusoidal response indicating that there could me multiple optimal parameter combinations.

The resulting curve for an eccentric load of 4 appears to be significantly different than the curve for similar parameters in DOE 2. However, it is difficult to differentiate between the resulting curve in DOE 1 and DOE 2 based on the fact that the experimental error of 0.31 degrees calculated for welds produced without the use of PPAW also applies to welds made using PPAW.

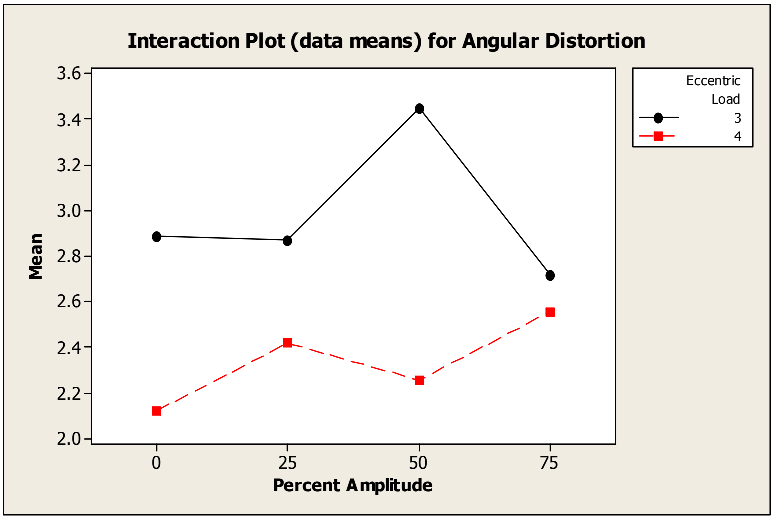

Figure 11. DOE 2 Interaction Plot

Additional statistical evaluation was then conducted using the data generated in DOE 1 and DOE 2. Data for parameter combinations that included eccentric loads of 3 and 4 with percent amplitudes of 0, 25, and 50 were statistically evaluated as a data set consisting of 2 replicates. The results were then averaged and standard deviations calculated for each data set were made, noting that the standard deviation will have significant error due to the size of the data pool. The results are shown in Table 8.

The results indicate a large range of standard deviations which is typical for welding applications due to the number of uncontrollable variable inherent to the process. However, the use of an average standard deviation is more representative of the experiment. The average standard deviation for the weld for the weld trials displayed in Table 8 is 0.32 degrees and is very similar to the standard deviation calculated for the control samples welded without PPAW of 0.31 degrees.

Table 8. Combined Statistical Data

Run	Eccentric Load	Percent Amplitude	Angular Distortion(1) (Degrees)	Angular Distortion (2) (Degrees)	Average (Degrees)	Stdev (Degrees)
1	3	0	3.01	2.89	2.95	0.09
2	3	25	2.24	2.87	2.56	0.44
3	3	50	2.64	3.45	3.05	0.57
4	4	0	2.97	2.12	2.55	0.60
5	4	25	1.96	2.42	2.19	0.32
6	4	50	2.34	2.25	2.30	0.06

Figures 12 and 13 provide statistical results using a main effects plot and an interaction plot. As with the individual analysis of DOE 1 and DOE 2, the main effects graph for eccentric load indicates that the variable has significant impact on distortion. Similarly, the results suggest that when evaluating the variable independently, an eccentric load of 4 is preferred over an eccentric load of 3.

The main effects graph for percent amplitude is significantly more similar to the results of DOE 2 when compared to analysis of DOE 1 versus DOE 2. The steepness of the main effect curve for percent amplitude suggests that the percent amplitude and corresponding frequency influence distortion. However the steepness of the curve is less than that of the Eccentric load indicating that the eccentric load has significantly more impact in the resulting weld distortion.

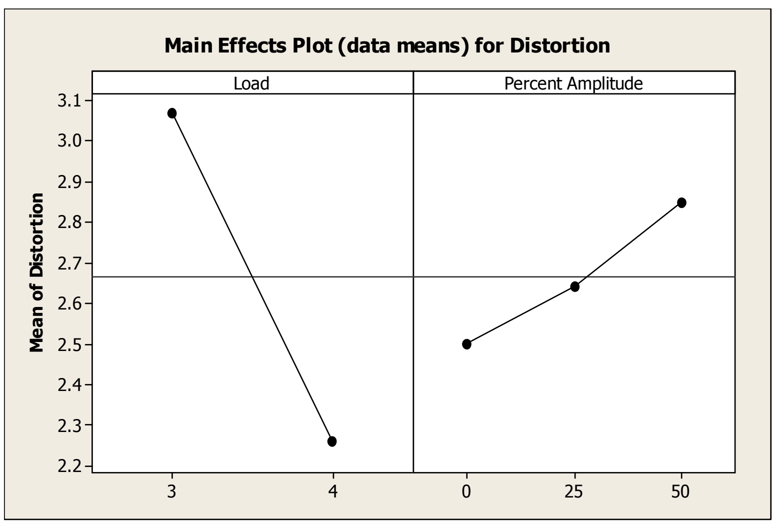

Figure 12. Main Effects Graph for the Combined Data Analysis

Figure 13 displays the interaction plot results as a function of peak location. The results suggest that an eccentric load of 4 is preferred over an eccentric load of 3. The graph suggests that operating in the lower portion of the harmonic curve near 0% amplitude is better when an eccentric load of 4 is utilized. The graph also indicates that the lower portion of the harmonic curve is recommended when using an eccentric load of 3 and that the flatness of the curve between 0% and 25% amplitude suggests that the process should be operating within this range.

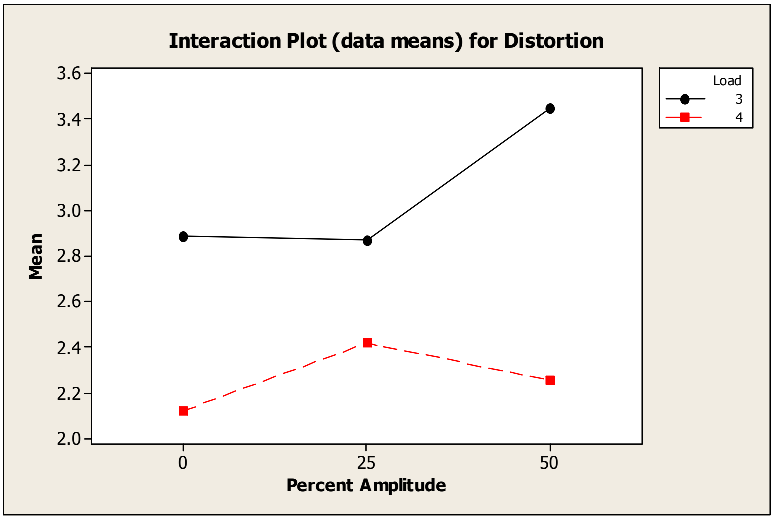

Figure 13. Interaction Plot for the Combined Data Analysis

Figgure 14 provides graphically displays the results in Table 8 and compares those results to the average distortion of the control samples welded without the use of PPAW. The first trend to note is that all welds produced using the PPAW technology had less distortion than welds produced without the use of PPAW. We can also deduct that a frequency relating to 25% amplidude of the subharmonic peak provides perferrable resuls (Runs 2 and 5) . The results also indicate that a parameter combination consisting of an eccentric load of 4 and a percent amplitude of 25% (Run 5) should provide minimal distortion for welding aluminum. However, the difference in distortion between the average for Run 2 and Run 5 is 0.37degrees and the two points are not statistially distiguishable based on an average standard deviation of 0.32 degrees

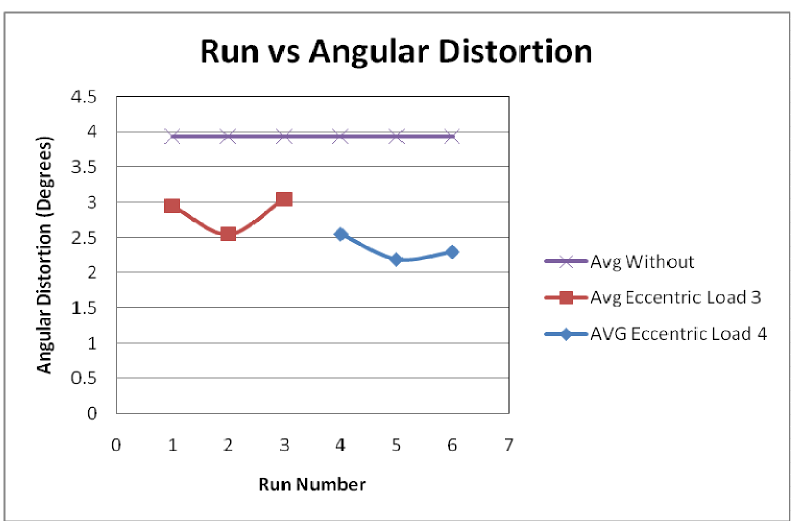

Figure 14. Graphical Representation using Table 8 Combined DOE results.

Conclusions and Recommendations

The following conclusions can be derived from the above study:

1. Welds produced using the PPAW and preferred parameters provided reduced distortion by approximately 50% compared to welds produced without PPAW.
2. A frequency corresponding to 25% of the amplitude is recommended for eccentric loads of 3 and 4.
3. Eccentric load of 4 and an amplitude percentage of 25% were identified as optimal parameters for using the Pulse Puddle for gas metal arc welding of 6061-T6 aluminum.
4. Based on the limited data and the resulting average standard deviation, it is difficult to definitively discriminate between an eccentric load of 3 and amplitude of 25% and an eccentric load of 4 and amplitude of 25%.