UNDERGRADUATE RESEARCH THESIS

A METHODOLOGY FOR THE ROBUST PROCEDURE DEVELOPMENT OF FILLET WELDS

Submitted to:

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Submitted By:

Paul Boulware

Senior, Welding Engineering Program

5720 Aspendale Dr.

Columbus, Ohio 43235

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Executive Summary

Though Gas Metal Arc Welding has been a basic component of fabrication in manufacturing over the last half-century, a standard methodology for optimizing welding procedures is lacking. A new procedure development method which minimizes trial runs, while maximizing accuracy has been recently developed by T.T. Allen, et al, in 2002. The use of the method is presently restricted to lap joint type welds. This work looked to extend this methodology to the application of fillet welds, test its effectiveness with different response variables, and study the effect of increasing the number of response variables.

The development of a robust weld procedure that produces a consistent root penetration was used as the application for the developed methodology. The significance of this application lies in the fact that typical codes and standards currently give no consideration to root penetration when calculating joint strength from a lack of confidence in consistency and robustness. The benefits of incorporating penetration in strength calculations are numerous and consequential for industry. An increase in strength would result allowing welds to be made smaller, thus, resulting in decreases in weld time, filler wire used, and heat input, reducing distortion. Showing the capability of robust penetration through this statistical process procedure is the first step towards inclusion of penetration as a variable in joint strength calculations and the reaping of its benefits.

Fillet welds were made on 12 mm thick A572 Grade 50 steel and cross-sectioned to allow for the critical response variables of penetration, undercut, convexity, maximum and minimum leg length, to be measured. Regression models were created along with

contour plots displaying penetration and quality ratings on a plot of WFS/TS ratio versus travel speed. The optimization of travel speed against penetration and quality restrictions was also performed revealing a set of nominal procedural variables which produce sound welds for a range of noise variables.

The optimized welding procedure included a travel speed of 11.3 in/min, a 1/16" arc length, a WFS/TS ratio of 28.4, and a contact-tip-to-work distance of 22 mm. The low travel speed resulted primarily from a need to maintain a minimum leg length in specification. It was also, observed from the contour plots that the robustness of the process was low from both the minimum leg length and convexity quality response factors.

While the application conclusions show low robustness results, the significance of the developments with the process procedure were significant. The combination of optimization and the contour plots provides the engineer with a tool for determining the nominal input welding variables along with gaining an understanding of the robustness of the certain procedure, according to each significant quality issue. Also, the development of a rating scale based on code adds authenticity to the procedure, while at the same time increasing the ease at which the common scale is developed.

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1.0 INTRODUCTION

Gas Metal Arc Welding (GMAW) is a welding process that involves the striking of an arc between a continuous wire fed electrode, and a base metal. As illustrated in Figure 1, the process melts both the added filler metal, in the form of metal wire, and the base metal, producing coalescence between the two. Since its introduction into industry in 1948, GMAW has developed into an integral part of fabrication in the shipbuilding, construction and agricultural equipment, and automotive manufacturing sectors.[1] However, there is still no standard methodology for optimizing significant weld variables such as the speed of the wire feed into the weld pool (wire feed speed, WFS), the speed of the welding gun along the joint (travel speed, TS), and the length of the arc (arc length), in order to minimize weld defects. Attempts have been made to formalize the process of weld parameter development including Taguchi Methods, ARCWISE™, neural net modeling, and other systematic methods.[2,3,4] All of these methods, while producing some beneficial results, contain individual drawbacks. None have surfaced as the standard parameter development procedure. This work looks to evaluate the capability extension of a statistical process design developed in 2002 by Allen, Richardson, Tagliabue, and Maul.[5] This methodology, called MaxTS, addresses variation in noise variables along with using

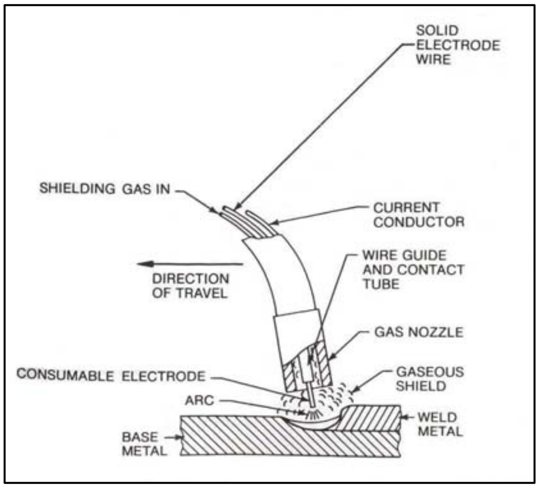

Figure 1 – Illustration of Gas Metal Arc Welding process.[1]

unique welding input variables to increase accuracy and help better focus the region of interest with the experimentation, respectively.

This study looks to increase the strength of this procedural design process by evaluating the inclusion of different response variables along with studying the effect of doubling the number of response variables. Also, included for the developments found through this work is a move away from the user defined rating system for response variables. Greater detail concerning this statistical process design and the development proposed with this work is provided in the following section.

To investigate these proposed improvements the application of a robustness evaluation for an industrial GMAW procedure was chosen. This allowed for the new response variables of joint penetration, undercut, concavity, and weld aspect ratio to be incorporated into the experimental design.

2.0 BACKGROUND

Many methodologies and procedures have been developed and utilized for welding procedural development including the use of Taguchi methods, neural net models, and simple trial and error heuristic methods. While all of these methods have their advantages, the statistical process design procedure included with MaxTS manifests benefits over each. The method avoids the inaccuracy issues of Taguchi Methods, the special software and training of neural net models, and limits the number of necessary trial runs characteristic of heuristic methods.[6] A difference is also seen in comparison to the ARCWISE™ procedure which categorizes welds only into an acceptable or unacceptable range.[3] The new methodology incorporates a more systematic rating scale, resulting in a highly informative tool for determining, not only a clear-cut conclusion of the acceptability of the procedure, but also information on how close the procedure is to such a boundary.

The methodology developed by Allen et al[5], shows significant improvements in welding procedural development through incorporation of noise factor variance and also through unique choices in the selection of independent factors. Permitting variance of the noise factors within the experimental design and analysis makes the procedure comparable to Taguchi signal-to-noise ratios.[2] The advantage, however, is found within this method's ability to allow for the use of classically designed experiments and optimization, in conjunction with noise factor variance. Taguchi methods prevent the utilization of standard designed experiments and optimization.

The second advantage found with this statistical process design is the use of arc length and wire feed speed to travel speed (WFS/TS) ratio in place of voltage and wire feed speed, respectively. Using arc length rather than voltage avoids the inclusion of a significant number of poor welds in the experimental array, while incorporation of WFS/TS ratio allows control of the weld size to be maintained.[5]

Classically designed experiments have the characteristic of running experimentation at the limits of the selected factor ranges. When using voltage and wire feed speed as independent factors, settings composed of high voltage and low wire feed speed, and low voltage with high wire feed speed result. Both of these cases result in extremely poor welds with immeasurable characteristics. This is due to the fact that the first case mentioned results in arc lengths at the extreme high limit while the second condition produces arc lengths at the extreme low limit. Both cases produce unacceptable welds. Simply incorporating arc length in the place of voltage in the experimental design eliminates this problem and helps improve the accuracy of the calculated regression models.

Using the WFS/TS ratio as an independent variable ensures that each experimental weld is of a reasonable size. This incorporates the important factor of wire feed speed in the procedure, but does it in a controlled manner. Again, this leads to concentrating the experimental welds in the region of space desired by the user and also increases the accuracy of the experiment.[5]

It is also important to highlight the background and significance of the application being evaluated through this study. The sponsor of this work has developed a procedure for gaining deep penetration; however, this advantage is currently being rendered useless from the convention of typical standards to give no consideration to penetration in joint strength calculations. The lack of inclusion of joint penetration, defined in Figure 2, is due to the difficulty in achieving a consistent, reliable penetration. It is known that increases in joint strength can be realized with a deeper penetration. However, with the introduction of noise factors that exist in an industrial environment, a lack of confidence has been developed resulting in the exclusion of penetration from joint strength calculations.

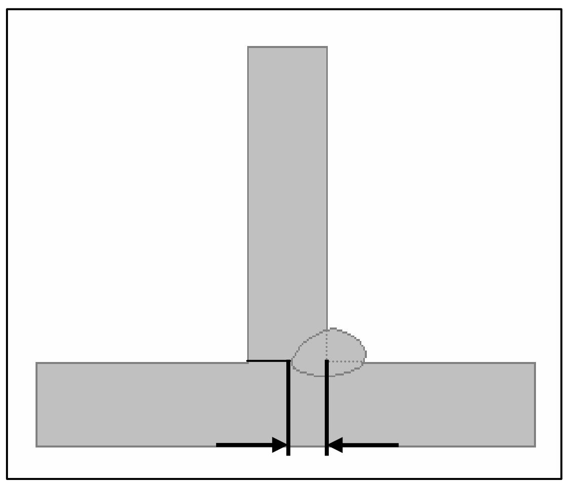

Figure 2 – Definition of joint penetration.

Exhibiting the robustness for this application may be the first step in allowing penetration to be included in these calculations and the realization of its numerous benefits. Smaller weld sizes would be possible, allowing for reduced weld times and filler metal usage. Also, decreases in the heat into the weld would reduce distortion. This would result in substantial savings in mass production industries. Manifestation of a robust process for deep penetration in GMAW is a main step in allowing for the inclusion of penetration in joint strength calculations, and thus a major step towards achieving its monetary benefits.

3.0 OBJECTIVES

The main objective of this work is to further strengthen the statistical process procedure called MaxTS developed in 2002 by Allen et al[5], through extending its range of applications and variables. More specific goals of this study are outlined in the following:

- Demonstrate reliability and robustness in producing welds with a given penetration, allowing the dimension of joint penetration to be considered for the joint strength relationships found in standards and codes.
- Produce empirical models for prediction of joint penetration and the pertinent quality issues for the application of deep penetration GMAW of fillet welds.
- Provide a set of welding parameters to maximize travel speed while holding a level of satisfactory penetration along with quality levels above the limits defined by AWS D14.3.

4.0 EXPERIMENTAL PROCEDURE

The experimental approach was established to test the adaptiveness of the statistical process design procedure, MaxTS, to a new weld and joint type, along with distinctively different response variables. The total process is detailed in the following sections.

4.1 Selection of Variables: Factors and Responses

4.1.1 Factors: Input Variables

It has been observed that the use of the standard welding input variables of travel speed (TS), wire feed speed (WFS), arc voltage (V), and contact-tip-to-work distance (CTWD) can result in the production of an overabundant amount of defective welds when using classically designed experiments. The reason for this resides with the tendency of the designed experiments to test the limits of a poorly selected factor, which results in extremely negative interactions with the other welding factors at certain levels.

For example, classically designed experiments test the limits of a cuboidal or spherical region that is specified by the experiment designer. In a cuboidal designed experiment using the standard welding input factors, welds would be made with very high voltages and low wire feed speeds which lead to unacceptable lack of fusion issues. Also, welds with low voltages and high wire feed speeds resulting in miniscule arc lengths would be included in the experimental results. These welds exhibit buried arcs, or simply no weld at all due to small arc lengths.

The typical method of combating this negative effect of the DOE is to limit the ranges of the experimental factors. This technique is normally successful in reducing the number of defective welds from the values discussed above, but it also results in the narrowing of the factor ranges. With narrow ranges, empirical models carry less significance because they are only applicable to a small window of input values.

This work along with the standard input variables of travel speed and CTWD looked to use the factors of arc length, and WFS/TS ratio to replace voltage and current, respectively. Using arc length as opposed to voltage allows the experiment to avoid including heavily defective welds resulting from excessively high or low magnitudes of arc length.

The selection of the WFS/TS ratio over just wire feed speed resulted from a desire to control the weld size. Harwig's ArcWise equation:

$$A_{weld} = \left(\frac{WFS}{TS} \right) \cdot A_{wire} \cdot f_1 \qquad \text{Eq. 1}$$

defines the relationship for weld area (A_{weld}) as a function of wire feed speed, travel speed, and the cross-sectional area of the electrode wire (A_{wire}), and deposition efficiency (f_1).[3] The weld area is simply a function of wire feed speed and travel speed when the wire cross-sectional area and deposition efficiency are constant. Using this relationship as a factor in the experimental design allows for the DOE to be more precisely developed to fit the region of interest.

4.1.2 Noise Variables

In order to simulate industrial conditions the noise variables were chosen to be root gap and wire offset. Root gaps come into play in production, due to poor fixturing, ineffective clamping, or part variance. The occurrence of wire offset is seen in automated industrial applications from either poor robot programming, or part variance and inadequate fixturing and clamping. It is important to include these difficult to control variables in the experimental environment because most applications of the procedural development being tested in this work are industrial applications. The successful inclusion of industrial noise factors in this experiment increases the confidence of engineers to use this process as a tool for welding procedure development.

4.1.3 Response Variables

The response variables chosen for this work came directly from the application used to test this statistical process design procedure. The application was an evaluation of the robustness of deep penetration welding in fillet welds. Therefore, the first response variable was joint penetration, defined as the distance from the root to end of the weld nugget along the face of the bottom plate (Figure 2). Other essential factors for this process were determined by preliminary welding to be undercut on the low end of wire feed speed values and excessive convexity and uneven fillet leg lengths at the high end of wire feed speed. Due to this finding it was decided to measure, record, and include all three defect responses along with penetration.

4.2 Preliminary Testing

Preliminary welds were preformed for two main purposes, the first being the development of a correlation between voltage and arc length, and the second being to provide aid in the determination of levels and cutoff values for the designed experiment. These preliminary welds were simple bead-on-plate welds made with increasing wire feed speeds and corresponding increases in travel speed to hold the WFS/TS ratio constant.

Table 1 displays the parameters used for each preliminary weld along with the acquired voltage readings. In order to correlate certain voltage values to an arc length a tungsten pointer was attached to the welding torch in a position to place its tip at a desired distance from the base metal as illustrated in Figure 3. This allowed for the arc length to be easily determined while welding. A typical tungsten electrode used for Gas Tungsten Arc Welding (GTAW) was utilized by heating its tip with an oxyacetylene

Table 1 – A spreadsheet displaying the inputs for the first set of preliminary welds along with the desired voltage values and a weld description.

Run	Fillet Size	Fillet Size	Ad	Ad	WFS	WFS	TS	TS	Arc Length	Voltage	Current	Characteristics
	(mm)	(in)	(mm^2)	(in^2)	(mm/min)	(in/min)	(mm/min)	(in/min)	(inches)	(Volts)	(Amps)	
1	6	0.23622	18	0.0279	2669.51	**108.96**	203.2	**8**	3/16	-----	-----	Did not perform - WFS too high for spray
2	6	0.23622	18	0.0279	3336.89	**136.20**	254	**10**	3/16	-----	-----	Did not perform - WFS too high for spray
3	6	0.23622	18	0.0279	4004.27	**163.44**	304.8	**12**	3/16	-----	-----	Did not perform - WFS too high for spray
4	6	0.23622	18	0.0279	4671.65	**190.68**	355.6	**14**	3/16	48.4	229	Short circuit transfer - perfect arc length was unattainable
5	6	0.23622	18	0.0279	5339.03	**217.92**	406.4	**16**	3/16	30	263	Globular - perfect arc length was unattainable
6	6	0.23622	18	0.0279	5339.03	**217.92**	406.4	**16**	3/16	29.9	260	Globular - perfect arc length was unattainable
7	6	0.23622	18	0.0279	6006.41	**245.16**	457.2	**18**	3/16	28.3	273	Spray Transfer
8	6	0.23622	18	0.0279	6673.79	**272.40**	508	**20**	3/16	30.1	300	Spray Transfer
9	6	0.23622	18	0.0279	7341.16	**299.64**	558.8	**22**	3/16	31	320	Spray Transfer
10	6	0.23622	18	0.0279	8008.54	**326.88**	609.6	**24**	3/16	31.9	340	Spray Transfer
11a	6	0.23622	18	0.0279	8675.92	**354.12**	660.4	**26**	3/16	33.1	362	Spray Transfer
11b	6	0.23622	18	0.0279	9343.30	**381.36**	711.2	**28**	3/16	33.6	380	Spray Transfer
12	8	0.31496	32	0.0496	4745.80	**193.71**	203.2	**8**	3/16	-----	-----	Short circuit transfer - perfect arc length was unattainable
13	8	0.31496	32	0.0496	5932.25	**242.13**	254	**10**	3/16	28.3	265	Spray Transfer
14	8	0.31496	32	0.0496	7118.70	**290.56**	304.8	**12**	3/16	30.9	306	Spray Transfer
15	8	0.31496	32	0.0496	8305.15	**338.99**	355.6	**14**	3/16	32.6	348	Spray Transfer
16	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	3/16	33.9	380	Spray Transfer
17	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	3/16	33.9	375	Spray Transfer
18	8	0.31496	32	0.0496	10678.06	**435.84**	457.2	**18**	3/16	35.3	410	Spray Transfer
19	8	0.31496	32	0.0496	11864.51	**484.27**	508	**20**	3/16	36	448	Spray Transfer
20	8	0.31496	32	0.0496	13050.96	**532.69**	558.8	**22**	3/16	38	478	Spray Transfer
21	8	0.31496	32	0.0496	14237.41	**581.12**	609.6	**24**	3/16	38.6	509	Spray Transfer
22	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	1/4	35.1	385	Spray Transfer
23	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	1/8	32.5	375	Spray Transfer
24	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	5/16	36.9	390	Spray Transfer
25	8	0.31496	32	0.0496	9491.61	**387.41**	406.4	**16**	1/16	31.5	363	Spray Transfer

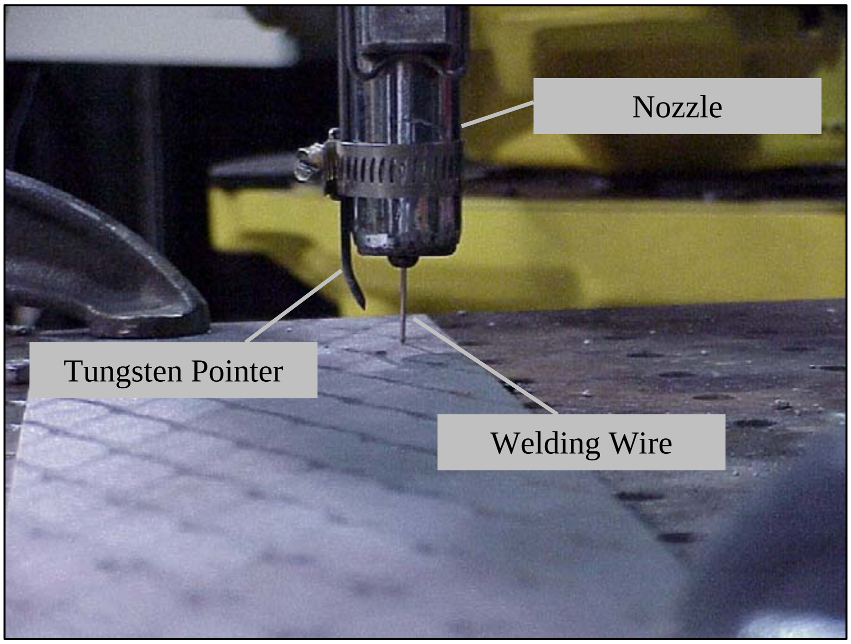

Figure 3 – Experimental setup for preliminary welding illustrating the use of a tungsten pointer to mark arc length.

torch and bending it with pliers to an angle large enough to reach the center of the arc from the weld torch.

While welding, a function on the robot controller was utilized to vary the voltage until the desired arc length was reached by visual alignment of the wire tip with the tungsten pointer. This voltage value was then recorded for each WFS and used in preliminary analysis for the development of arc length curves.

As exhibited in Table 1 a number of welds were made with a 3/16” arc length. The data points for these welds are displayed in Figure 4A along with a trendline equation for these points calculated using Excel™. Interpolation and extrapolation was then utilized with this trendline equation and values taken for five other arc lengths, at the nominal input values, to produce the following equations for a range of arc lengths:

1/16 inch:	$V = (0.0292 \cdot WFS) + 19.82$	Eq. 2
3/32 inch:	$V = (0.0292 \cdot WFS) + 20.32$	Eq. 3
1/8 inch:	$V = (0.0292 \cdot WFS) + 20.82$	Eq. 4
5/32 inch:	$V = (0.0292 \cdot WFS) + 21.52$	Eq. 5
3/16 inch:	$V = (0.0292 \cdot WFS) + 22.22$	Eq. 6

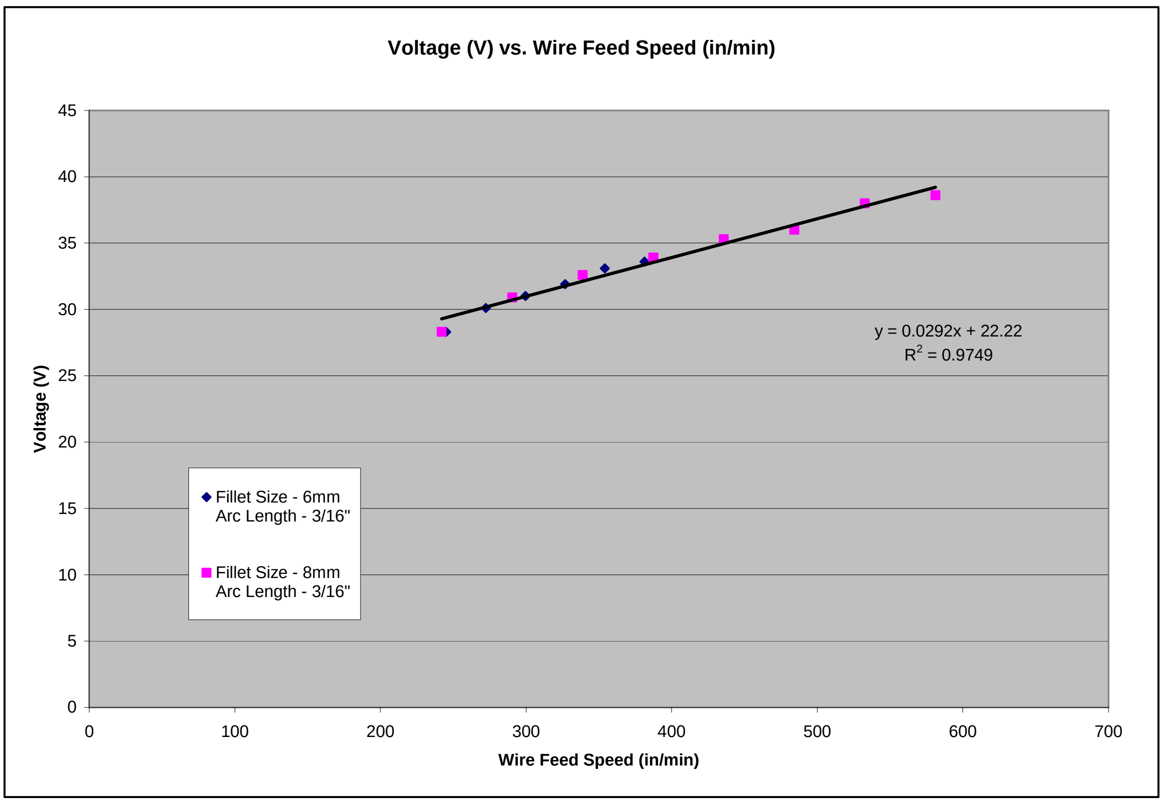

Figure 4A – Plot of experimental data mapping voltage versus wire feed speed readings for 3/16" arc length.

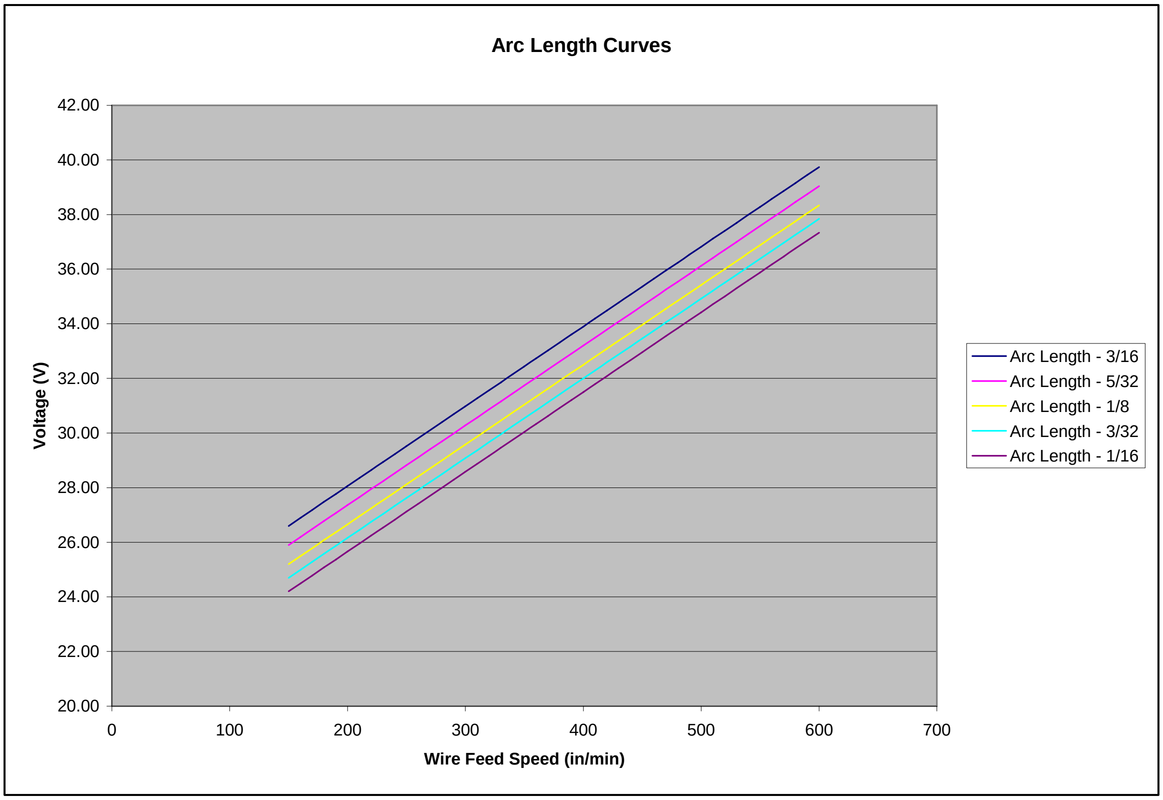

Figure 4B – Plot graphically displaying the five arc length equations produced from experimental data.

Figure 4B plots these arc length curves for voltage as a function of wire feed speed. These plots allow voltage values to be input into the welding robot during the experimental welding to give the desired arc length.

The second goal of the preliminary welding was to gain a greater understanding of the limits needed in the design of experiment. Fillet welds with increasing WFS/TS ratio, 13 to 32, were performed with all other essential variables remaining constant and at a nominal magnitude. The values of each response factor were noted at upper and lower limits of wire feed speeds used. Results from the WFS/TS experimental welds are displayed in Table 2.

The combination of these sets of preliminary welds allowed for the experiment to be better designed to include a large portion of acceptable welds, with a small portion of unacceptable welds at the outer limits of the design. The final set of factors and levels used for experimentation can be viewed in Table 3.

Table 2 – Results from preliminary welding concerning the trial fillet welds with increasing wire feed speed and constant WFS/TS ratio.

	WFS	TS	Arc Length	WFS/TS	Characteristics
	(in/min)	(in/min)	(inches)		
26	*192*	**16**	3/16	*12*	Unacceptable undercut on the lower leg of the fillet weld
27	*288*	**16**	3/16	*18*	High bead quality with low penetration
28	*384*	**16**	3/16	*24*	Good penetration with mediocre convexity
29	*480*	**16**	3/16	*30*	Poor convexity and low top fillet leg length
30	*576*	**16**	3/16	*36*	Unacceptable convexity and unacceptable minimum leg length

Table 3 – Factors and levels used in experimentation.

Factor	Units	Low	Medium-Low	Nominal	Medium-High	High
WFS/TS Ratio	--------	*12*	*17*	*22*	*27*	*32*
Travel Speed	in/min	*8*	*12*	*16*	*20*	*24*
Arc Length	1/32 inch	*2*	*3*	*4*	*5*	*6*
CTWD	mm	*18*	*19*	*20*	*21*	*22*
Gap	wire diameters	*0.0*	*0.0*	*0.5*	*1.0*	*1.5*
Wire Offset	wire diameters	*-2.0*	*-1.0*	*0.0*	*1.0*	*2.0*

4.3 Experimental Design

The choice between experimental designs was narrowed down to the central composite and Box Behnken designs from a desire to produce second-order regression in the final analysis. Between the two, the central composite design was chosen due to its ability to define the region of interest as space surrounding what is initially believed to be the nominal parameters with its boundaries being the extremes of each variable as defined by the user. In comparison, the Box Behnken design forces the number of levels to be three. In this experiment it was desired to analyze a small number of points at the high and low ends of each variable range, and the central composite design allows for this, while the Box Behnken experimental design does not.

The central composite structure is broken down into the center, factorial, and axial points. As is expected the center points include the nominal values of each variable. The factorial points on the other hand include those points that are neither nominal nor extreme. In reference to Table 3, these values would be the medium-low and medium-high values. The design structure is completed with the axial points which lie at the extremes of the variable ranges. To minimize the number of experimental runs a half design was chosen. This limited the number of interactions obtainable in the resulting regression models, but it was assumed that the terms dropped did not have a strong enough interaction to be included in the model. The central composite design resulted in 54 total runs, with 10 replicates taking place at the center point and two at the axial, or star, points. Minitab 14, a statistical software tool, was utilized to develop the DOE. The resulting total experimental array is displayed in Table 4.

Table 4 – Total experimental array used for the DOE.

Run Order	Day	Travel Speed (in/min)	Arc Length (inches)	Voltage (Volts)	WFS (in/min)	Ratio	CTWD (mm)	Root Opening (WD)	Wire Offset (WD)
1	1	12	3/32	29.8	324	27	19	1	-1
2	1	20	5/32	31.4	340	17	19	0	-1
3	1	20	5/32	37.3	540	27	21	0	-1
4	1	20	5/32	37.3	540	27	19	1	-1
5	1	12	5/32	31.0	324	27	19	1	1
6	1	12	5/32	27.5	204	17	19	0	1
7	1	20	3/32	36.1	540	27	21	0	1
8	1	12	3/32	29.8	324	27	21	0	-1
9	1	20	5/32	31.4	340	17	21	1	-1
10	1	16	1/8	31.1	352	22	20	0.5	0
11	1	12	3/32	26.3	204	17	19	0	-1
12	1	12	5/32	31.0	324	27	21	0	1
13	1	20	3/32	30.2	340	17	21	1	1
14	1	20	3/32	36.1	540	27	19	1	1
15	1	16	1/8	31.1	352	22	20	0.5	0
16	1	12	3/32	26.3	204	17	21	1	-1
17	1	12	5/32	27.5	204	17	21	1	1
18	1	20	3/32	30.2	340	17	19	0	1
19	1	16	1/8	31.1	352	22	20	0.5	0
20	1	16	1/8	31.1	352	22	20	0.5	0
21	2	16	1/8	31.1	352	22	20	0	0
22	2	24	1/8	36.2	528	22	20	0.5	0
23	2	16	3/16	32.5	352	22	20	0.5	0
24	2	16	1/8	31.1	352	22	22	0.5	0
25	2	16	1/8	31.1	352	22	20	0.5	0
26	2	16	1/8	31.1	352	22	20	1.5	0
27	2	16	1/8	31.1	352	22	20	0.5	2
28	2	8	1/8	26.0	176	22	20	0.5	0
29	2	16	1/8	31.1	352	22	18	0.5	0
30	2	16	1/16	30.1	352	22	20	0.5	0
31	2	16	1/8	26.4	192	12	20	0.5	0
32	2	16	1/8	31.1	352	22	20	0.5	-2
33	2	16	1/8	31.1	352	22	20	0.5	0
34	2	16	1/8	35.8	512	32	20	0.5	0
35	2	12	3/32	29.8	324	27	19	0	1
36	2	12	5/32	31.0	324	27	19	0	-1
37	2	20	5/32	31.4	340	17	21	0	1
38	2	20	5/32	37.3	540	27	19	0	1
39	2	20	3/32	30.2	340	17	19	1	-1
40	2	20	3/32	36.1	540	27	19	0	-1
41	3	16	1/8	31.1	352	22	20	0.5	0
42	3	16	1/8	31.1	352	22	20	0.5	0
43	3	12	5/32	27.5	204	17	21	0	-1
44	3	20	3/32	30.2	340	17	21	0	-1
45	3	12	3/32	26.3	204	17	21	0	1
46	3	12	5/32	27.5	204	17	19	1	-1
47	3	12	3/32	29.8	324	27	21	1	1
48	3	16	1/8	31.1	352	22	20	0.5	0
49	3	16	1/8	31.1	352	22	20	0.5	0
50	3	20	5/32	31.4	340	17	19	1	1
51	3	12	3/32	26.3	204	17	19	1	1
52	3	20	5/32	37.3	540	27	21	1	1
53	3	12	5/32	31.0	324	27	21	1	-1
54	3	20	3/32	36.1	540	27	21	1	-1

4.4 Experimental Welding

The welding was preformed at the Edison Joining and Technology Center (EJTC) in The Ohio State University Welding Engineering Welding Process Laboratory using a FANUC Robot ARCmate 100i welding robot and a Lincoln Electric 655 PowerWave power supply. Fillet welds on twelve millimeter thick plates of A572 steel in the horizontal, 2F, position were performed with an ER70S-6 electrode wire and utilizing 90-10 Ar-CO_2 shielding gas at 40 CFH. The 18 inch joint length allowed for three experimental welds to be made per joint, as illustrated in Figure 5.

Fixturing was constructed in order to allow for precise and repeatable placement of the joint on the work table, while also acting to prevent distortion during welding. The fixturing utilized in this work is illustrated in Figure 6. Tack welds were made on the ends of the joint following joint placement and clamping onto the makeshift fixture.

As displayed in Figure 7 Shims were placed in the joint before clamping and tacking in order to incorporate the noise factor of root gap into the experiment. Four shims were used on each T-joint, one on each end, and two separating the three experimental welds. Extra tack welds were than added to the joint at each shim to ensure that the gap width remained controlled.

The factor of weld offset was included in experimentation by moving the welding electrode wire up to two wire diameters (0.052”) into and out of the joint. Figure 8 illustrates the coordinate system used to define placement of the wire prior to welding. Positive displacement was taken to be displacement away from the joint, while negative displacement was defined to be displacement into the joint.

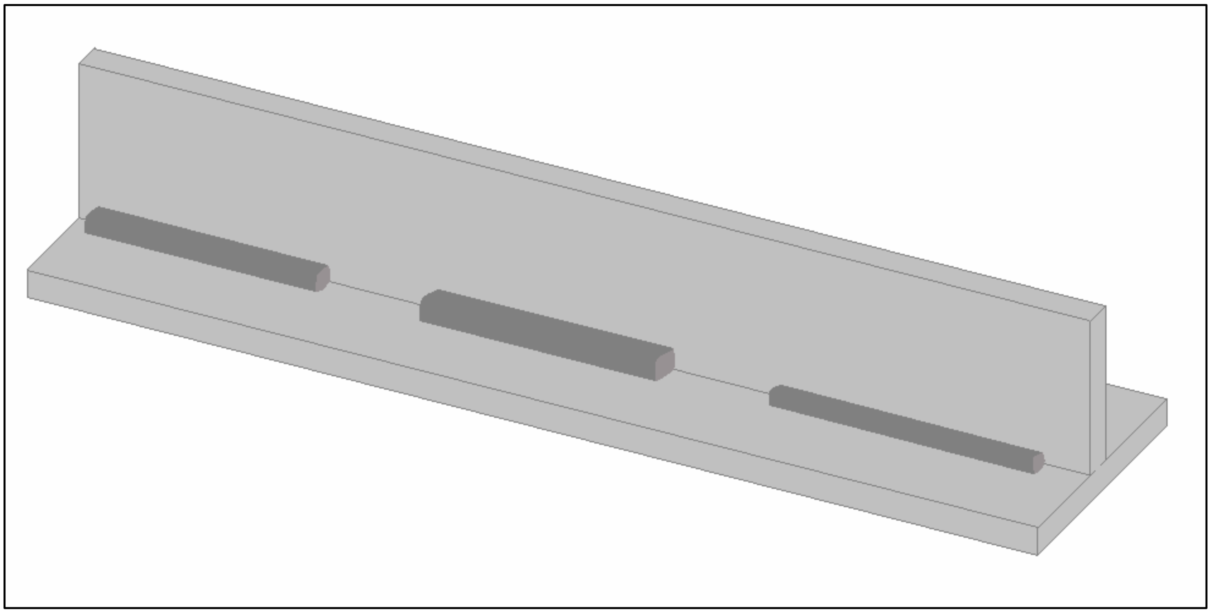

Figure 5 – Experimental T-joint used for the DOE.

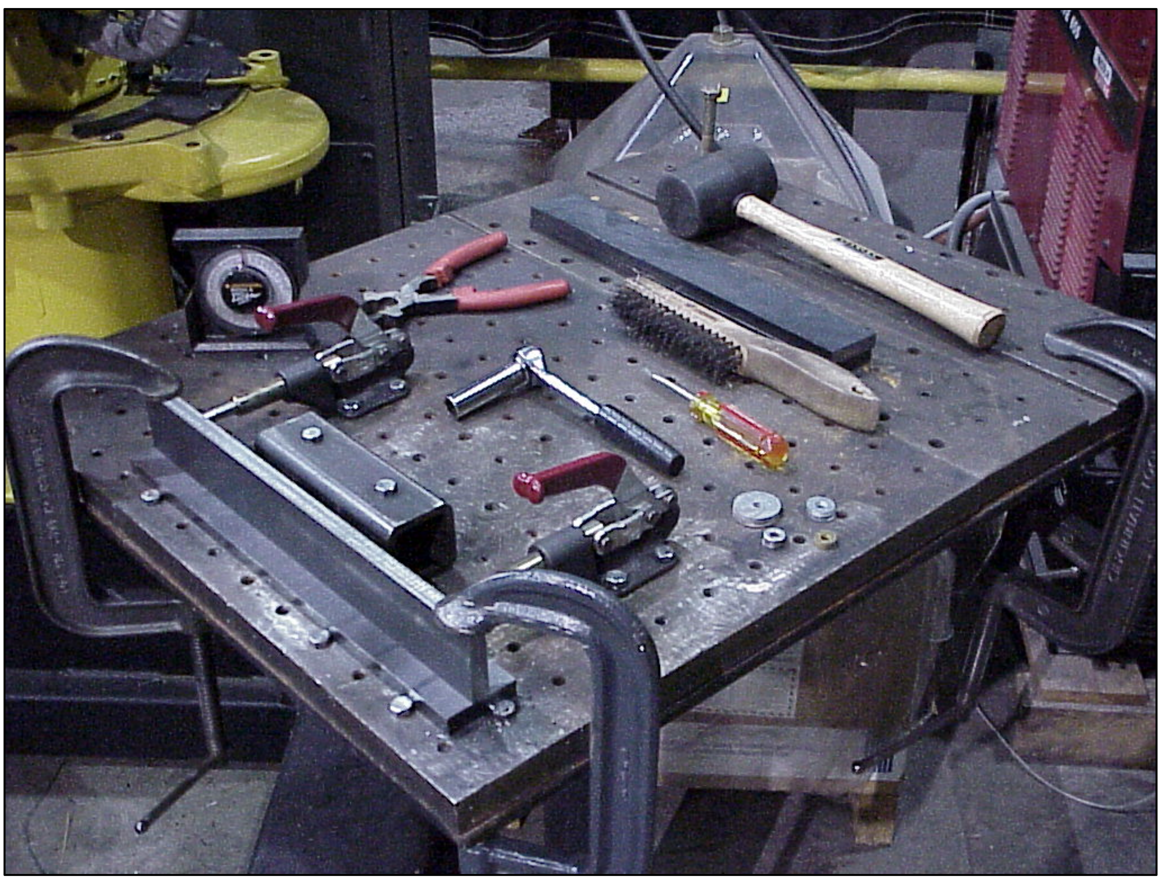

Figure 6 – Experimental setup including clamping, fixturing, and all of the tools used.

Figure 7 – T-joint displaying the insertion of shims in the experimental joint

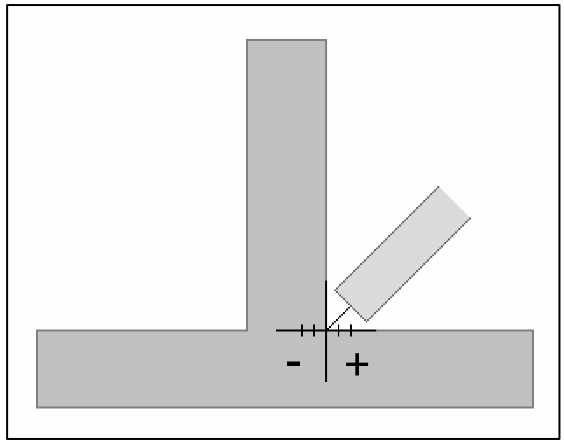

Figure 8 – T-joint displaying the convention for positive and negative wire offset.

4.5 Response Measuring Procedure

The response variables of joint penetration, undercut, convexity, and weld aspect ratio were all taken from weld cross sections. Approximately twelve millimeter cross sections of each experimental weld were cut using a Metal Mizer 2018 table saw approximately two inches from the end of the weld. Calipers and a straight edge were than used to take the measurements from each cross section. The measurements for each response variable are graphically represented in Figures 9A and 9B.

Joint penetration was measured as the distance from the root to the end of fused metal along the direction parallel to the bottom plate's top surface (Figure 2). The undercut value was measured as the maximum distance from the bottom of the undercut gorge to the top surface of the bottom plate. It is also important to note that for the experimental welds exhibiting any undercut, the cutting plane was chosen to be at the location along the weld which visual inspection revealed the maximum magnitude of undercut.

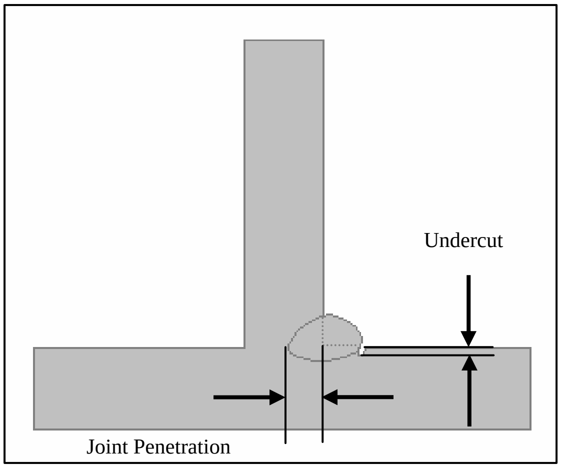

Figure 9A – Definition of convexity, top leg length, bottom leg length, and convexity used for response measurement.

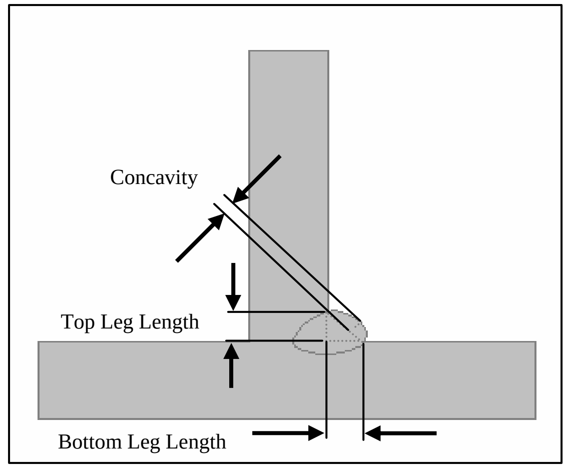

Figure 9B – Definition of joint penetration and undercut used for response measurement

The value for convexity was obtained by measuring the maximum perpendicular distance from a straight line connecting the weld toes to the surface of the weld bead. The final response variable measurement of weld aspect ratio, or the ratio of fillet leg lengths, was obtained by dividing the length of the top leg length by the bottom leg length. The top leg length was measured as the distance from the root to the top weld toe, while the bottom leg length measurement was defined as the distance from the root to the bottom weld toe.

The response measurements were recorded for all of the experimental welds and used to develop regression curves, which defined an equation of each measurement as a function of the chosen input variables.

5.0 RESULTS AND DISSCUSSION

5.1 Regression

Minitab 14 was used to create regression models for each of the response variables. The models consist of equations predicting penetration, convexity, maximum leg length, and minimum leg length ratings as a function of the input and noise variables: travel speed (TS), arc length (AL), WFS/TS ratio (R), CTWD, root gap (RG), and wire offset (WO).

5.1.1 Rating Scale

In this work it was desirable to compare each response variables' effectiveness to each other. For this reason a simple continuous rating scale, exhibited in Table 5 was devised to allow for example, the performance of the penetration response to be compared to the convexity capability on a standard scale.

Table 5 – The final rating scale for each response measurement.

Rating Scale	Penetration		Undercut		Concavity		Max Leg Length		Min Leg Length	
9.0 - 10.0	7.2 - 8.0	mm	0.05 - 0.0	mm	1.0 - 1.5	mm	4.0 - 6.0	mm	1.0 - 1.5	mm
8.0 - 9.0	6.4 - 7.2	mm	0.10 - 0.05	mm	0.50 - 1.0	mm	2.0 - 4.0	mm	0.5 - 1.0	mm
7.0 - 8.0	5.6 - 6.4	mm	0.15 - 0.10	mm	0.25 - 0.50	mm	1.0 - 2.0	mm	0.25 - 0.5	mm
6.0 - 7.0	4.8 - 5.6	mm	0.25 - 0.15	mm	0.0 - 0.25	mm	0.0 - 1.0	mm	0.0 - 0.25	mm
5.0 - 6.0	4.0 - 4.8	mm	0.35 - 0.25	mm	(-0.25) - 0.0	mm	(-1.0) - 0.0	mm	(-0.50) - 0.0	mm
4.0 - 5.0	3.2 - 4.0	mm	0.50 - 0.35	mm	(-0.50) - (-0.25)	mm	(-2.0) - (-1.0)	mm	(-1.0) - (-0.50)	mm
3.0 - 4.0	2.4 - 3.2	mm	1.0 - 0.50	mm	(-1.0) - (-0.50)	mm	(-3.0) - (-2.0)	mm	(-1.5) - (-1.0)	mm
2.0 - 3.0	1.6 - 2.4	mm	1.5 - 1.0	mm	(-1.5) - (-1.0)	mm	(-4.0) - (-3.0)	mm	(-2.0) - (-1.5)	mm
1.0 - 2.0	0.8 - 1.6	mm	2.0 - 1.5	mm	(-2.0) - (-1.5)	mm	(-5.0) - (-4.0)	mm	(-2.5) - (-2.0)	mm
0.0 - 1.0	0.0 - 0.8	mm	2.5 - 2.0	mm	(-2.5) - (2.0)	mm	(-6.0) - (-5.0)	mm	(-3.5) - (-3.0)	mm

The first response variable of penetration was the only factor not to be determined by the welding code. This was simply because as discussed above the codes only require fusion to the root. Therefore, this rating equation was based solely on fitting the data as best as possible and also taking care to ensure that the desired cutoff line between acceptable and unacceptable penetration was in the same rating category as the other variables. In result, it was determined that any penetration above 4.8 mm, (Rating 6.0 – 7.0), would be acceptable while any rating below was deemed unacceptable.

The rest of the response rating equations were based on D14.3: Specification for Welding Earthmoving and Construction Equipment. The first of these variables, undercut, is limited to a value no greater than 0.25 mm. Therefore, this rating was divided among the highest and lowest values found from experimentation and placed 0.25 mm at the bottom end of the 6.0 -7.0 rating range.[6]

The limiting factor for the convexity rating was similar to undercut in the sense that no value could exceed a certain maximum limit, but different in the aspect that this maximum limit was a function of maximum leg length, as displayed in Equation 7. The cutoff value is 0.0 mm because this rating stems from a difference between the limiting number and the actual measurement. If the value is positive the convexity is less than the limit. If the difference is negative than the convexity is over the limit and is thus deemed unacceptable.

Maximum Convexity = (0.1 · maximum leg length) + 0.3 mm   Eq. 7,[6]

The final response variables of maximum and minimum leg length were both determined by taking the difference of the actual measured lengths to the limiting factors determined by code. Equations 8 and 9 display both of the limiting values as determined by code.

Maximum Leg Length = Nominal Leg Length + 3.2 mm   Eq. 8,[6]

Minimum Leg Length = Nominal Leg Length – 0.8 mm   Eq. 9,[6] The nominal leg length used is the equations above are determined from the WFS/TS ratio. Also, because the rating result is taken from a difference between a limiting number and the actual measure, the cutoff value, like convexity, is 0.0 mm.

The final rating scale for the response variables is displayed in Table 5. It should be noted that while the penetration scale is linear, each of the other variables is defined by a nonlinear scale. This was necessary to allow for each cutoff value to be placed at the same rating value while also properly fitting each scale to represent the data taken in experimentation. Figure 10 plots each rating scale illustrating the linearity of the penetration scale and the nonlinearity of the other variable rating scales.

The rating scale adopted allows the user to numerically define the boundary between acceptable and unacceptable welds while also providing insight beyond this distinction. The ratings give an understanding as to the degree of effectiveness or defectiveness with each response along with the go or no-go determination. Also, the quality issues included are all judged according to welding specification and code. This adds to the credibility of the process being developed.

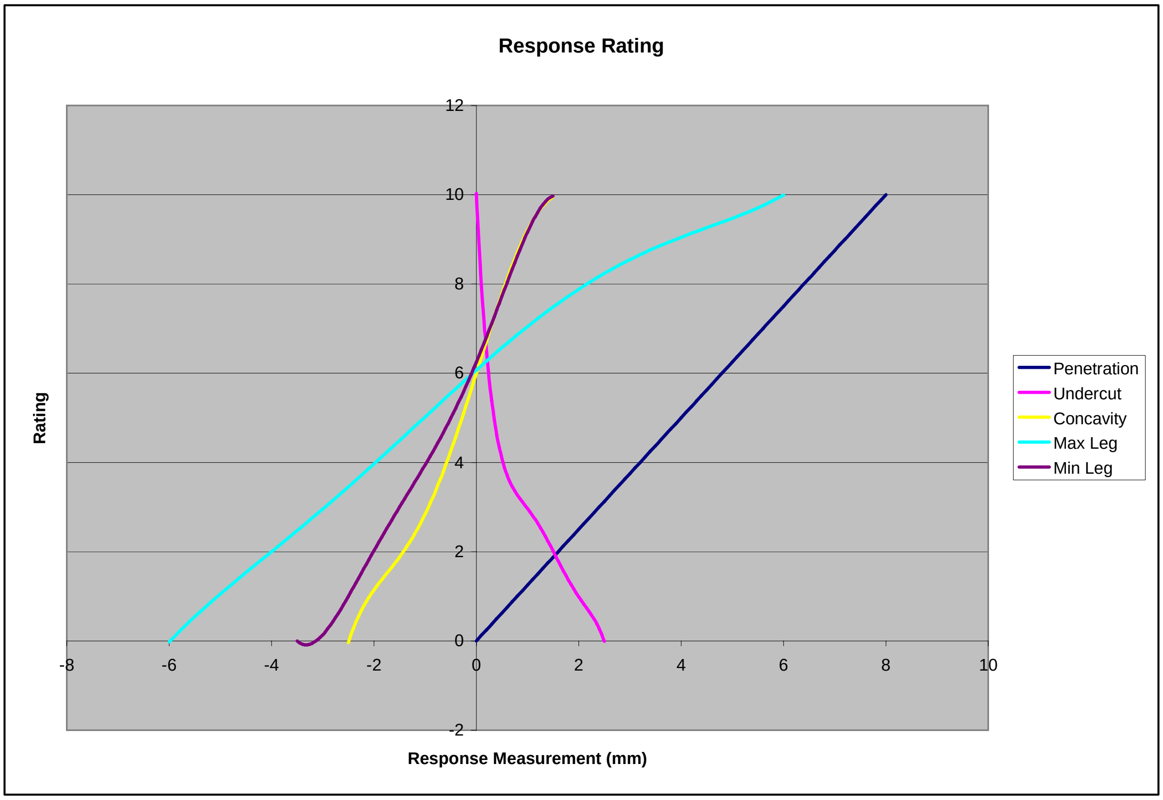

Figure 10 – A graphical representation of each separate response measurement rating equation.

5.1.2 Regression Models

As discussed at the beginning of this section, Minitab 14 was utilized to produce regression models for each response variable. Data on the input values along with the measured response data was used to produce these models which are given in the following equations (Eq. 10 – Eq. 14).

Penetration = 19.69 - (0.18 * TS) + (2.783 * AL) + (0.3531 * Ratio) - (2.691 * CTWD) + (1.77 * RO) - (0.869 * WO) - (0.02661 * TS * TS) + (0.0446 * AL * AL) - (0.009567 * Ratio * Ratio) + (0.039 * CTWD * CTWD) - (1.053 * RO * RO) - (0.0132 * WO * WO) + (0.03545 * TS * AL) - (0.02511 * TS * Ratio) + (0.08382 * TS * CTWD) + (0.085 * TS * RO) - (0.09518 * TS * WO) + (0.04582 * AL * Ratio) - (0.2424 * AL * CTWD) + (0.6015 * AL * RO) + (0.0402 * AL * WO) + (0.03006 * Ratio * CTWD) - (0.03187 * Ratio * RO) + (0.01427 * Ratio * WO)-(0.0919 * CTWD * RO) + (0.0789 * CTWD*WO) - (0.5451 * RO * WO)

Eq. 10

Undercut = 156.2 + (0.812 * TS) - (11.825 * AL) + (1.399*Ratio) - (16.26 * CTWD) + (58.19*RO) - (10.073*WO) - (0.0337 * TS * TS) + (0.4692 * AL * AL) - (0.01646 * Ratio * Ratio) + (0.4692 * CTWD * CTWD) - (5.17 * RO * RO) + (0.4692 * WO * WO) + (0.0666 * TS * AL) + (0.03874 * TS * Ratio) - (0.0528 * TS * CTWD) - (0.1056 * TS * RO) + (0.0579 * TS * WO) + (0.04636 * AL * Ratio) + (0.2762 * AL * CTWD) + (0.5524 * AL * RO) + (0.7748 * AL * WO) - (0.05741 * Ratio * CTWD) - (0.1148 * Ratio * RO) + (0.05328 * Ratio * WO) - (2.546 * CTWD * RO) + (0.222 * CTWD * WO) + (0.4439 * RO * WO) Eq. 11

Convexity = 60.5 - (0.979 * TS) - (12.679 * AL) - (1.365 * Ratio) - (1.02 * CTWD) + (16.27 * RO) + (4.36 * WO) + (0.03154 * TS * TS) + (0.4906 * AL * AL) - (0.02088 * Ratio * Ratio) - (0.0235 * CTWD * CTWD) + (1.369 * RO * RO) + (0.3455 * WO * WO) + (0.03724 * TS * AL) + (0.01048 * TS * Ratio) - (0.03574 * TS * CTWD) - (0.101 * TS * RO) + (0.15331 * TS * WO) + (0.0798 * AL * Ratio) + (0.3501 * AL * CTWD) - (0.7959 * AL * RO) + (0.0056 * AL * WO) + (0.08079 * Ratio * CTWD) + (0.058 * Ratio * RO) + (0.03457 * Ratio * WO) - (0.7181 * CTWD * RO) - (0.3545 * CTWD * WO) - (0.0065 * RO * WO) Eq. 12

Maximum Leg Length = 75.99 - (0.2231 * TS) + (0.699 * AL) - (0.9584 * Ratio) - (5.617 * CTWD) - (1.307 * RO) - (1.644 * WO) - (0.011487 * TS * TS) - (0.1705 * AL * AL) + (0.007047 * Ratio * Ratio) + (0.1189 * CTWD * CTWD) + (0.1429 * RO * RO) - (0.0823 * WO * WO) + (0.04067 * TS * AL) - (0.002554 * TS * Ratio) + (0.02261 * TS * CTWD) + (0.00466 * TS * RO) - (0.07017 * TS * WO) + (0.02099 * AL * Ratio) - (0.0378 * AL * CTWD) + (0.3315 * AL * RO) + (0.0829 * AL * WO) + (0.03051 * Ratio * CTWD) + (0.04917 * Ratio * RO) - (0.02608 * Ratio * WO) - (0.058 * CTWD * RO) + (0.1331 * CTWD * WO) - (0.32 * RO * WO) Eq. 13

Minimum Leg Length = 164.9 - (0.552 * TS) - (8.117 * AL) - (0.886 * Ratio) - (12.76 * CTWD) - (0.22 * RO) - (4.478 * WO) + (0.00368 * TS * TS) + (0.1662 * AL * AL) + (0.01079 * Ratio * Ratio) + (0.2892 * CTWD * CTWD) + (0.416 * RO * RO) + (0.0708 * WO * WO) + (0.07238 * TS * AL) + (0.0052 * TS * Ratio) - (0.01326 * TS * CTWD) + (0.0558 * TS * RO) - (0.03735 * TS * WO) - (0.0321 * AL * Ratio) + (0.3105 * AL * CTWD) - (0.169 * AL * RO) + (0.0416 * AL * WO) + (0.01401 * Ratio * CTWD) - (0.0244 * Ratio * RO) + (0.08002 * Ratio * WO) - (0.0506 * CTWD * RO) + (0.1184 * CTWD * WO) + (0.395 * RO * WO) Eq. 14

As stated above a half central composite design was used in order to decrease the number of total runs for the experiment. However, when cutting down the total number of experimental runs, compensation must be given in the form of a loss of terms in the produced regression models. For this reason the three, four, five, and six order terms have been eliminated from the regression models on the assumption that their impact was less significant than the first and second order terms.

5.2 Contour Plots

The regression models displayed above all contain twenty-eight terms, one coefficient constant term, six first order terms, and twenty-one second order terms. The complexity, or simply the vast abundance of terms results in the need for a more clear, and distinctive method of describing the relationships developed above.

Contour plots are a simple, but effective way of achieving this distinction. An EXCEL™ workbook developed by Allen provides a method for producing one single contour plot to investigate the robustness of a process under the evaluation of two response variables. The plots compare the ratings of two responses as a function of all of the input variables, and plot these ratings on a two-dimensional graph with WFS/TS ratio on the y-axis and travel speed on the x-axis. It is important to note only the minimum rating for the two responses is actually plotted onto the graph. Therefore, the ideal case is for the graph to be split in half with one response dominating one half and the other controlling the second half. Where the contours meet determines the “sweet spot” of the process according to those two response variables.

This is illustrated in Figure 11 which evaluates the rating of penetration and undercut developed in this work for the indicated process settings. As can be seen from the notes in the lower corners of the plot, penetration controls the left side of graph, and undercut dominates the right side. This makes physical sense because penetration is low at slow travel speeds, and undercut becomes more significant at high travel speeds.

The next step taken in this work concerning the use of contour plots was to simply add more responses, and thus more contour plots. Because penetration was the variable of interest it was included as one of the two responses in each plot. Four contour plots were constructed: penetration and undercut, penetration and convexity, penetration and maximum leg length, and penetration and minimum leg length.

The significance of this development lies within the realization that it is rare in a process as complicated as welding to completely evaluate a procedure by two responses, or two quality measures. The four plots constructed in this work offered the complete picture of the welding process being investigated. Input variables could easily be varied through a macro incorporated into the workbook, and the resulting change in response measurement could be seen simultaneously for each quality issue along with penetration.

Figure 12 manifests the affect of this development by displaying all four contour plots, similar to what a user would view in process development. It can be seen that at the settings chosen, as indicated in the top-left corner of the spreadsheet, the responses of penetration, undercut, convexity, and maximum leg length all fall within the acceptable rating range at a travel speed of 14 in/min and a WFS/TS ration of 24. However, the minimum leg length response at these inputs lies with the rating of 2.0 – 3.0, far below an acceptable range. A process simply cannot be properly evaluated without taking all of the prevalent quality factors into consideration, and this statistical process procedure displays that exact ability within simple, easy to use software.

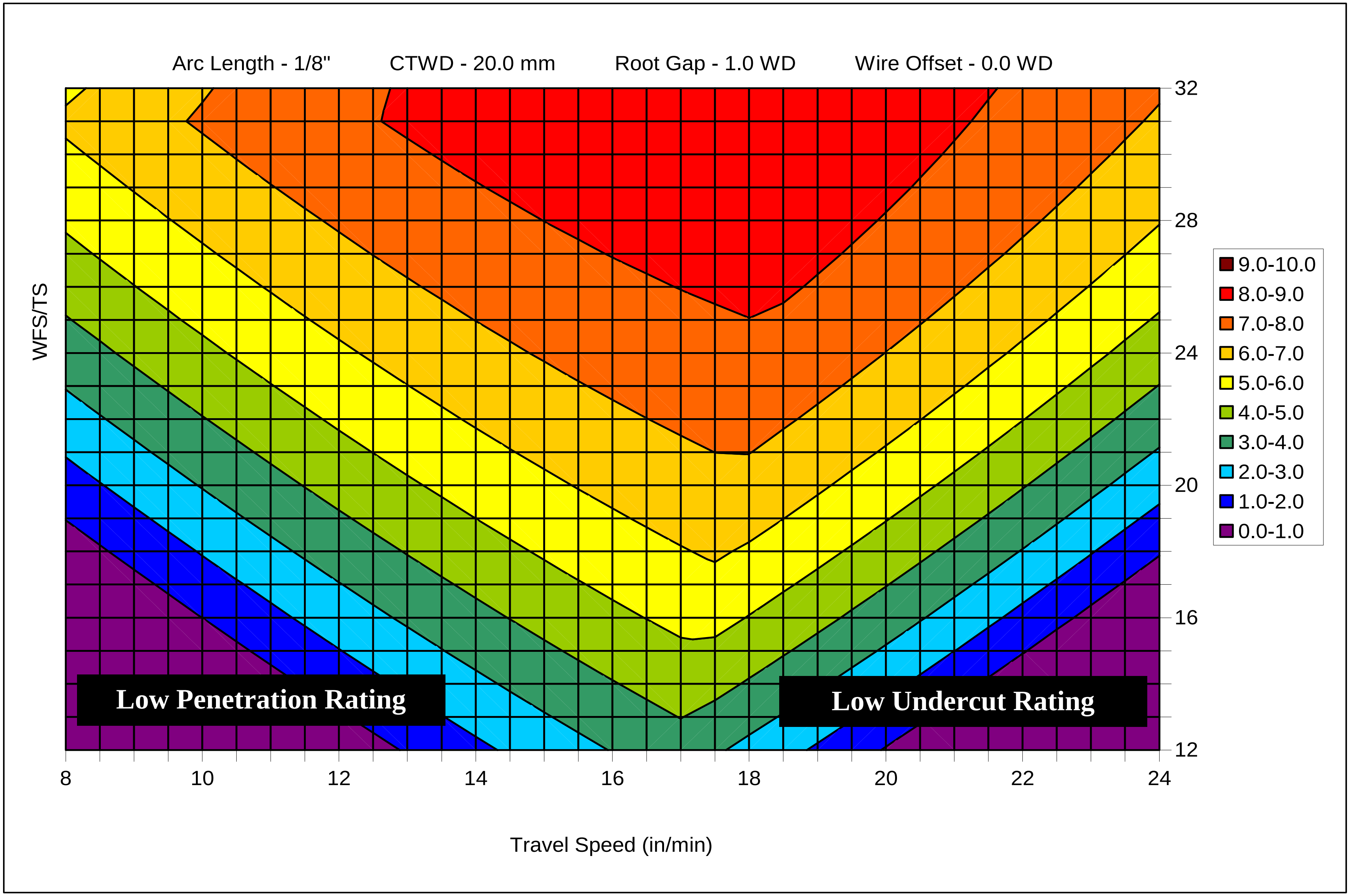

Figure 11 – Contour plot of the minimum rating for penetration and undercut against travel speed and WFS/TS ratio.

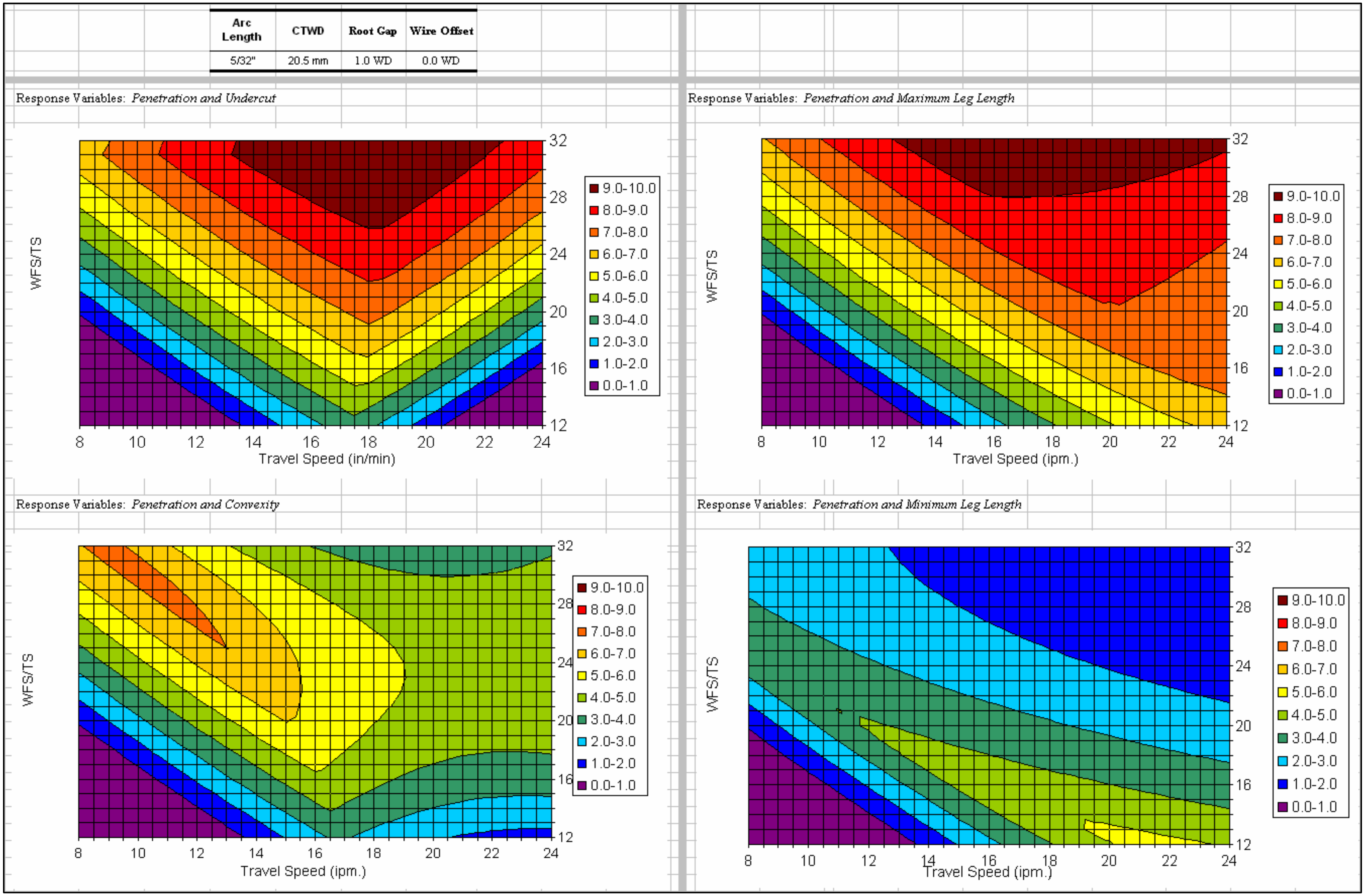

Figure 12 – An example of the contour workbook displaying of the contours created simultaneously.

5.3 Optimization

The optimization process used in this work looked to meet the needs of industry by providing a tool for maximizing travel speed while avoiding certain limits for quality or dimensional values. In this case the limiting factors for travel speed were penetration along with the quality factors of undercut, convexity, and maximum and minimum fillet leg. The rating scale used in the regression and contour plots (Table 5) was developed not only to allow for comparison among the response factors, but also to set in place a distinct cut off rating for acceptable welds. This lower specification limit (LSL) was set to be the rating of 6.0. Therefore, the LSL used in optimization was obviously chosen to be a rating of 6.0 for each of the constraining variables.

For the actual optimization a spreadsheet was developed utilizing the EXCEL™ solver to find the maximum travel speed for six typical sets of root gap and wire offset values. These sets of noise variables act to incorporate the industrial environment into the optimization. The solver program varied each of the controllable input variables (travel speed, arc length, WFS/TS ratio, and CTWD), producing the values for each variable that results in the maximum travel speed for the set of defined noise variables. The constraints on this optimization included holding the resulting response rating at or above 6.0 for each set of noise variables, along with restricting the input variables inside of the space defined in experimentation. The addition of extra responses, again, helps in the overall procedure development by allowing the process to be optimized over all of the prevalent quality issues.

The resulting welding procedure is listed in Table 7, and is highlighted by a low travel speed of 11.3 in/min. The slow travel speed produced resulted chiefly from the constraints of minimum leg length and convexity. These quality factors dominated as limiting variables due to the high wire feed speeds used in this application to produce deep penetration welds.

Table 7 – Produced welding parameters from the optimization process.

Control Parameters					
TS	Ratio	Arc L.	CTWD	WFS	Voltage
11.3	28.4	2.0	22.0	321	30.1
(in/min)	-----	(1/32")	(mm)	(in/min)	(Volts)

The advantage of deep penetration welds comes with a price, and that is low fillet leg lengths on the top plate of the T-joint and high convexity. As large amounts of wire is being fed into the weld pool it rolls over onto the bottom leg of the joint causing small values of fused metal at the top leg and large values of leg length on the bottom plate. The extreme restriction of D14.3 on minimum leg length helps to amplify this effect. Along with this effect, high convexity results from the large weld pool simply having no where else to go other than adding to the convexity.

The substantial effect of the minimum leg rating and convexity is detailed in Table 8 which is the identical optimization procedure as described above only with the constraints of these quality measures removed. The resulting travel speed was 24 in/min, an increase of almost 120%.

Table 8 – Optimization table without the quality restraints of minimum leg length and convexity.

Travel Speed =	24.00

Noise Variables		Penetration	Undercut	Concavity	Max Leg	Min Leg	Cutoffs				
Gap	Offset	y_1	y_2	y_3	y_4	y_5	y_{1c}	y_{2c}	y_{3c}	y_{4c}	y_{5c}
0.5	1.0	6.9	13.3	9.8	7.0	4.5	6.0	6.0	0.0	6.0	0.0
0.5	-1.0	9.2	8.8	7.7	8.3	5.6	6.0	6.0	0.0	6.0	0.0
0.0	1.0	6.0	14.2	12.2	6.8	5.0	6.0	6.0	0.0	6.0	0.0
0.0	-1.0	6.8	10.1	10.1	7.8	6.4	6.0	6.0	0.0	6.0	0.0
0.5	0.0	8.1	10.6	8.4	7.8	5.0	6.0	6.0	0.0	6.0	0.0
0.0	0.0	6.0	11.7	10.8	7.4	5.6	6.0	6.0	0.0	6.0	0.0

Low Limit		Parameter		High Limit
8	<=	TS	<=	24
12	<=	Ratio	<=	32
2	<=	Arc L.	<=	6
18	<=	CTWD	<=	22

5.4 Confirmation Runs

To verify the results of the regression analysis the optimal parameters found for the six combinations of noise factors were tested under laboratory conditions identical to that of the experimental welding. Measurements of the response factors were taken and compared to the predicted values. Table 9 displays the results of the confirmation welds.

Table 9 – Comparisons of the actual measurements on confirmation runs to the predicted values from regression.

Noise Variables		Penetration		Undercut		Convexity		Maximum Leg Length		Minimum Leg Length	
Gap	Offset	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
0.5	1.0	6.5	5.4	10.0	10.0	6.0	5.8	8.9	8.2	6.5	3.2
0.5	-1.0	6.5	7.1	10.0	10.0	7.5	6.6	9.4	8.5	6.0	3.0
0.0	1.0	6.0	4.6	10.0	10.0	6.0	7.0	9.3	8.8	7.1	6.3
0.0	-1.0	6.0	4.8	10.0	10.0	7.4	6.0	9.5	7.9	7.0	3.7
0.5	0.0	6.5	6.0	10.0	10.0	6.4	6.9	9.3	8.5	6.2	6.7
0.0	0.0	6.3	5.6	10.0	10.0	6.4	7.3	9.5	8.2	6.9	6.1

All of the results seem to match up well with the predicted values staying within the expected variation of the process except for a number of the minimum leg length values. This is explained through the contour plot of penetration and minimum leg length displayed in Figure 13. As can be seen the area of acceptable quality is miniscule. This means that any small variation in the process will result in a poor rating. Once again, this case exemplifies the usefulness of the combination of the contour plots and the optimization.

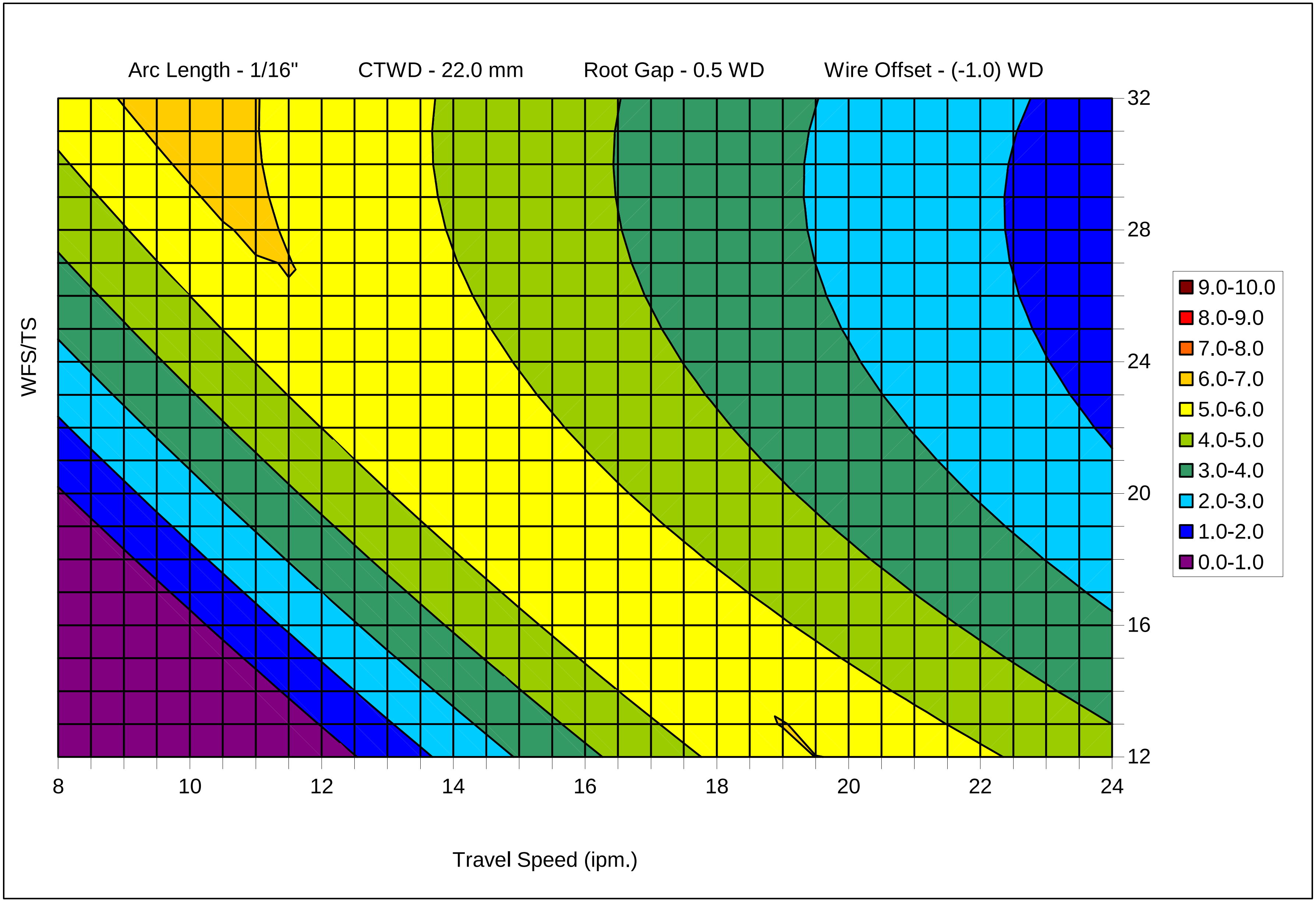

Figure 13 – Contour plot of penetration and minimum leg length for the optimized input variables and a noise factor combination of root gap = 0.5 WD and wire offset = -1.0 WD

4.0 CONCLUSIONS

The conclusions for this work include the main results concerning the development with the statistical process design along with the outcomes for the application, and are listed in the following:

Statistical process design procedure

- This process design can successfully adapt to multiple response variables.
  - Including all of the significant variables allows the user to simultaneously view the effects of varying input variables on output responses.
  - A greater benefit is found in optimizing over all of the critical quality measurements.
- Basing the rating system allows for simple setup of the scale along with easy interpretation of acceptable and unacceptable welds.

Application

- The process for deep penetration GMAW does not exhibit full robustness according to D14.3 welding code.
- More research is needed in decreasing convexity and increasing the top fillet leg length while maintaining the penetration results found in this work.

5.0 FUTURE WORK

The further development of a statistical process design for robotic gas metal arc welding performed in this work was an extension of research performed by Allen et al in 2002. The success found here however, does not mean that opportunities for further advancement are nonexistent. While this work verified its ability to perform under a new joint and weld type, and different response variables there are more options for expansion. Submerged Arc Welding (SAW) and robotic Gas Tungsten Arc Welding

(GTAW) are possible untested process applications, while porosity measurements, weld strength, and weld toe radius are possible response factors.

Along with new processes and variables further study includes developing a method for comparing response variables without a common rating scale. The introduction of a rating scale amplifies the complexity of the process while also weakening its continuity.

Finally, further development needs to take place concerning a standard method for running the preliminary experimental welds. These are crucial to defining the limits of the main DOE along with picking out the pertinent response variables, and thus vital to the overall success of the experiment within the shortest amount of time.

6.0 ACKNOWLEDGEMENTS

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Finally, I would like to thank Brent Holloway for his assistance throughout the project. His help ranged from aiding in fabrication of the tungsten pointer to the shearing

of shim pieces to produce controlled gaps for experimentation. His support significantly decreased to total project time.

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