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Statistical Process Design for Robotic GMA Welding of Sheet Metal

An optimization procedure minimizes cycle time while achieving small fractions of nonconforming welds

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ABSTRACT. A statistical process design method is proposed for robotic gas metal arc (GMA) welding of sheet metal. The proposed method has the objective of minimizing weld cycle time by maximizing welding travel speed, while maintaining predictable weld quality over a range of worst-case processing conditions. This formulation offers a coherent alternative to Taguchi signal-to-noise ratios that permits the use of classically designed experiments that have potential advantages in experimental cost savings. The method is based on recommended choices of independent variables that place all experimental points in the region of interest. Also, a relatively simple weld evaluation approach was included for sheet metal applications. The method was applied on 16-gauge, 409 stainless steel lap joint welds in the horizontal position. The optimization revealed interesting dependencies of achievable travel speeds on root opening and welding gun positioning factors.

Introduction

Industries seeking higher production rates and weld quality improvements are increasingly interested in robotic gas metal arc welding (GMAW). In robotic GMAW, it is important to minimize robot cycle time so the most products possible are produced per hour and maximum return on investment can be achieved. A component of minimizing cycle time is maximizing the welding travel speed, to which the weld cycle time is inversely proportional. A competing consideration to maximizing travel speed is limiting the number of nonconforming welds produced, which generally increases with travel speed. Nonconforming welds cost money due to rework, scrap, and loss of customer goodwill. They also detract from throughput. The occurrence of nonconforming welds depends largely on variability in the conditions. Common sources of variability in the process include variation in part fit-up (root opening) and variation of the location of parts in the fixture (offset).

The objective of this work has been to develop a systematic and easy-to-use method of planned experimentation and formal optimization designed to yield process settings that balance productivity gains with rework costs. Intended outcomes of the methodology include 1) an empirical model for the incidence of weld defects as a function of the process inputs including travel speed, part fit-up and location and 2) settings that maximize the travel speed for a precisely specified worst-case maximum acceptable fraction of nonconforming welds. In our case study example, a simple visual weld inspection procedure was developed for weld evaluation in order to limit the resources required to perform the weld parameter optimization and to make the method more practical. This paper describes and illustrates the method, which was designed to increase profitability more than current statistical process design alternatives by effectively modeling the interplay between the travel speed and the fraction of nonconforming welds. The method was applied to the robotic GMA welding of lap joints between 16-gauge, 409 stainless steel sheets. This is a common welding application in the automotive industry for the manufacture of exhaust system components.

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KEY WORDS

Gas Metal Arc Welding
GMAW
Lap Joint
Statistical Process
Sheet Metal
Stainless Steel

Background

All statistical process design procedures involve the same generic steps as follows:

1) Experimental factors are selected. These are process inputs that likely influence the required outcomes, and in gas metal arc welding are typically the primary factors of travel speed (TS), voltage (V), and wire feed speed (WFS). Sec-

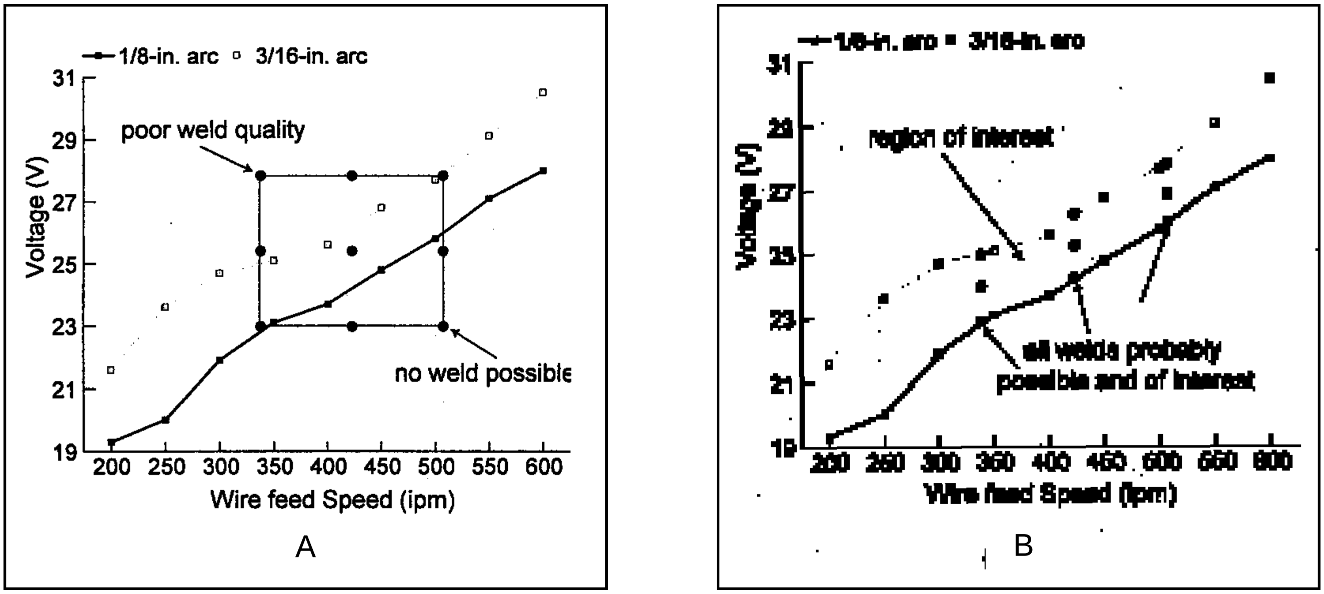

Fig. 1 — Arc length curves. A — Cuboidal variable selection for DOE points; B — the proposed placement of DOE points.

Table 1 — Data for Approximate Conversion from Voltage to Arc Length and WFS/TS Preruns

Weld No.	Current Set (A)	WFS	V for 1/8-in.	V for 3/16-in.
1	160	192	19.3	21.6
2	180	222	19.9	21.9
3	200	254	20.2	23.8
4	220	290	21.5	24.5
5	240	315	22.6	24.8
6	260	340	22.9	25.0
7	280	384	23.4	25.6
8	300	422	24.6	25.8
9	320	465	24.9	26.9
10	340	514	26.4	28.2
11	360	604	28.2	30.2

Weld No.	TS	WFS	WFS/TS	Current (A)	V	Appearance
1	40	320	8	244	22.7	Excellent
2	40	400	10	290	23.8	Melt-through
3	40	240	6	195	19.3	Excellent
4	40	160	4	150	19.0	Too small

ondary factors such as contact-tube-to-work distance (CTWD), welding gun travel and work angles, joint type and position, shielding gas type, and wire type and diameter may be included. Noise factors such as joint gaps or wire offset from the joint are important but not often included.

2) What to measure is selected, also called the responses, ***e.g.***, weld dimensions determined from macrosections or defect lengths from radiographs.

3) Experiments are conducted according to an experimental array or design of experiments (DOE), ***e.g.***, the Taguchi L_{18} (Ref. 1) product array, computer-generated arrays, or classical response surface arrays described in, ***e.g.***, Refs. 2 and 3.

4) Empirical models of the responses are created, ***e.g.***, using regression or neural nets.

5) Finally, the process is optimized using the empirical models, ***e.g.***, by inspecting the models, or by using an optimization program.

6) Confirmation tests are performed. The entire procedure is often iterated.

There has been substantial interest in applying statistical process design to arc welding parameter optimization in order to formalize and improve welding process parameter development. The main approaches that have been investigated in past work can be divided into four categories: 1) static Taguchi Methods (Refs. 1, 2); 2) computer-generated or other experimental design methods followed by neural net modeling (Refs. 3–6); 3) heuristic parameter optimization methods, including methods based on "tolerance boxes" (Refs. 7–11); and 4) methods based on so-called classical DOE, which include Bukarov (Ref. 12) and the methods in this paper. For a recent review and illustration of several methods, see Ribardo (Ref. 13).

The first approach, Taguchi Methods (TM), offered several innovations including a widely used procedure for addressing the impact of "noise factors," ***e.g.***, root opening and offset, which can be controlled during experimentation but not during standard operations. Yet, despite the many advantages of TM, at least three limitations remain that motivate the methods proposed in this paper. First, the total number of experimental runs using product arrays can make experimental costs substantially higher than if classical DOEs are used because the total number of runs is often higher for a given number of factors. Second, TM addresses cost considerations such as cycle time only indirectly, with the primary goal being robust quality. This can result in high levels of quality and with highly suboptimal cycle times. Third, standard Taguchi modeling methods do not permit estimation of interactions between control fac-

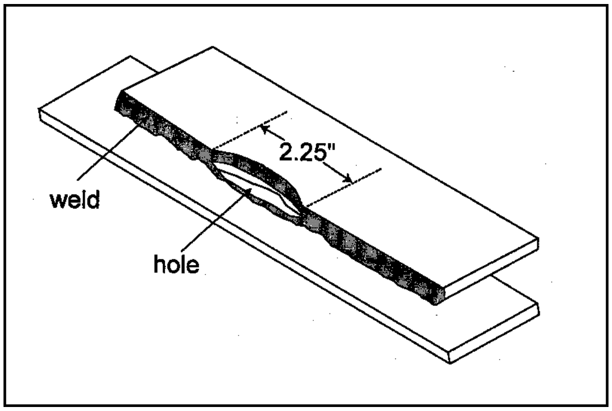

Fig. 2 — Illustration of a weld receiving a melt-through rating of 4.

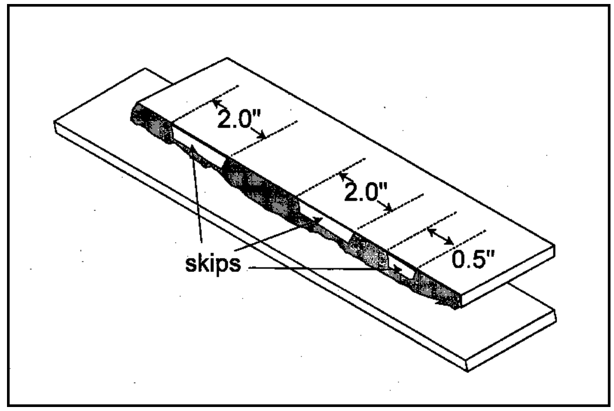

Fig. 3 — Illustration of a weld receiving a fusion rating of 4.

Table 2 — Guidelines for 1 to 10 Ratings of Weld Quality

Score	Penetration Scale Description	Completeness of Fusion Rating Description
10	No visible melt-through of the bottom member along the entire length of the weld	Complete fusion of top and bottom members over the entire length of the weld
9	≤1-in. of visible melt-through	≤1-in. of the total weld can be partially fused
8	>1-in. of visible melt-through	>1-in. of the total weld can be partially fused
7	≤ ¼-in. of excess melt-through	≤ ½-in. incomplete fusion between the members of the joint
6	≥ ¼-in. and <½-in. of excess melt-through	≥ ½-in. and <2-in. incomplete fusion
5	≥ ½-in. and <2-in. of excess melt-through	≥2-in. and<4-in. incomplete fusion
4	≥2-in. and <5-in. of excess melt-through	≥4-in. and <6-in. incomplete fusion
3	≥5-in. and <8-in. of excess melt-through	≥6-in. and <8-in. incomplete fusion
2	≥8-in. and <10-in. of excess melt-through	≥8-in. and <10-in. incomplete fusion
1	Melt-through along entire length of weld	Incomplete fusion over entire length of weld

tors, potentially resulting in poor engineering choices (Refs. 2, 14). McConnell and McPherson (Ref. 1) adapted Taguchi's "sliding levels" technique to GMAW, providing a coherent approach to potentially address the effects of interactions between voltage and wire feed speed. An alternative approach based on effective arc length was evaluated here to attempt to achieve similar benefits.

Artificial neural nets (ANN) offer a coherent approach to model virtually any phenomenon with high degrees of accuracy as long as the DOE or training set is sufficiently large. Ribardo (Ref. 8) reviews applications of neural nets in the context of GMAW. Yet, obvious drawbacks of neural net modeling described in Ref. 8 include 1) the opinion of some engineers that neural nets are relatively complicated to use and to interpret compared with polynomial regression, and 2) typical implementations of neural nets provide relatively limited information about the consistency of the process in yielding acceptable welds at a given combination of input settings. This consistency information is critical for estimating the fraction of defects in optimizing the weld procedure. Furthermore, it is widely known that the accuracy of neural nets is difficult to predict unless the training set is very large because of the many possible ANN implementations and performance sensitivity to the choice of DOE (Ref. 3). Therefore, while ANN may be regarded as promising, the procedure proposed here is based on polynomial regression largely for simplicity.

The third type of approach is heuristic or informal optimization methods. These methods range from basic trial and error to the systematic methods in Harwig (Refs. 7–9), Hardesty (Ref. 10), and Richardson, Hardesty, Yapp, and Paskell (Ref. 11). Key strengths of these methods include that they require relatively little user training and utilize choices of variables that are advantageous, in part, for reasons that are discussed in this paper. The main limitation of these methods is they do not, in general, permit the user to effectively address the effects of variability of noise factors such as root opening and offset on the weld quality.

The proposed method can be viewed as an extension of the classical DOE methods described in Ref. 12 to take advantage of the parameterizations of the GMAW problem introduced in Refs. 7, 10, and 11 and address the effect of noise variables. The method provides a reasonably easy-to-use optimization formulation alternative to Taguchi signal-to-noise ratios (Refs. 1, 2) that allow the user to employ classically designed experiments. These experimental designs can result in substantially reduced experimental costs compared with Taguchi product arrays (Ref. 14) because, in general, classical DOE methods require fewer experimental runs for a given number of factors when noise factors are involved (Ref. 14).

Experimental Approach

The proposed methodology was developed and demonstrated by applying it to GMAW of straight lap joints in the horizontal (2F) position between 16-gauge, 409 stainless steel sheets. The experiments were conducted under laboratory conditions.

Selection of Factors and Responses

Wire feed speed (WFS), weld travel speed (TS), arc voltage (V) and (sometimes) contact-tube-to-work distance (CTWD) may be regarded as the standard, or usual, independent factors chosen for GMA parameter development, ***e.g.***, see McConnell and McPherson (Ref. 1) and Hardesty (Ref. 10). Classical experimental designs are based on cuboidal or spherical regions of interest (Ref. 14). For example, for cuboidal DOEs, such as Box Behnken designs, experimentation occurs at all corners of selected ranges for the independent factors, as indicated by

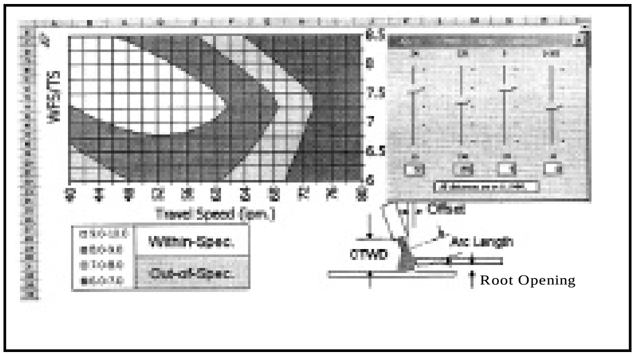

Fig. 4 — The EXCEL™-based software with arc length 3.2 mm (1/8 in.) and CTWD 15.5 mm (0.61 in.) with a root opening (0.5 times wire diameter) and no offset.

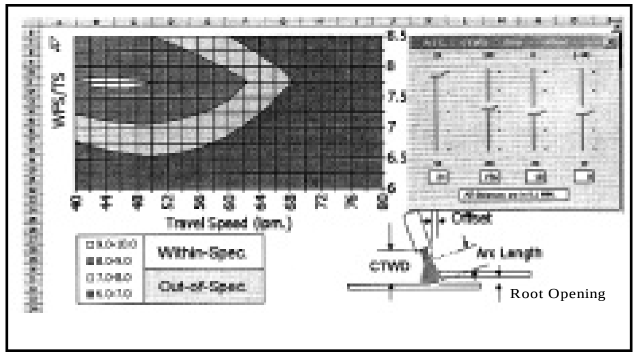

Fig. 5 — Welding window for arc length 2.4 mm (3/32-in.) and CTWD 15.6 mm (0.61 in.) with a root opening (1 times wire diameter) and no offset.

Table 3 — Factors and Levels for the Experiment

Factor	Units	Lowest	Low	Medium	High	Highest
TS	in./min	40	50	60	70	80
Ratio	none	5	6	7	8	9
Arc Length	x 1/32-in. (0.8 mm)	3	4	5	6	7
CTWD	x 0.039-in. (1.0 mm)	13	14	15	16	17
Root Opening	Wire diameters (WD)	0	0	0.5	1	1.5
Offset	Wire diameters (WD)	–1	–0.5	0	0.5	1

Fig. 1A. Yet, as clarified by McConnell and McPherson (Ref. 1) and Harwig (Refs. 7–9), simultaneous selection of high voltages and low wire feed speeds leads to high arc lengths and generally undesirable welds. Also, experimentation at low voltages and high wire feed speeds may result in buried arcs or no weld at all. Similarly, Harwig (Refs. 7–9) and Hardesty (Ref. 10) used the following equation to clarify why high wire feed speeds and low travel speeds can have undesirable effects on weld bead shape:

$$A_{weld} = (WFS^{*}A_{wire}\mathbf{f})/TS = A_{wire}(WFS/TS)\mathbf{f} \quad (1)$$

where A_{wire} is the wire cross-sectional area and ***f*** is deposition efficiency. Some WFS and TS combinations may achieve an excessively larger weld than desired from structural or aesthetic considerations. Therefore, in order to include only welds likely to be of interest to the experimenter and to use classically designed experiments, the experimenter would need to select relatively narrow ranges for voltages, wire feed speeds, and travel speeds. Narrow ranges, in general, lead to empirical models having only small scope applicability and poor optimization results, ***e.g.***, see Ref. 14.

The method developed here selected arc length and weld size as independent factors. Figure 1A and Table 1 show results from preliminary bead-on-plate experiments with 18 arc length and wire-feed-speed combinations. This data was used to establish the approximate relationship between voltage, WFS, and arc length. Other factors were held at mid-range values, ***e.g.***, CTWD of 15 mm (0.60 in.) and travel speed of 40 in./min (102 cm/min.). When these other factors were varied, voltage interpolations based on Fig. 1A only approximately predicted the actual arc length.

Other process conditions were held constant as follows. The lap welds were made with a gun work angle of 45 deg and a torch travel angle of 15 deg push. Shielding gas was 98% argon and 2% oxygen. The wire was 0.045-in.-diameter (1.2-mm), E409T-2G metal-cored wire. A robotic cell was used with conventional DC constant voltage and constant wire-feed speed GMA system. In practice, producing the arc length curves (Fig. 1) required various welding currents to be programmed (the robot system accepted current, which it then converted to a wire-feed-speed command). The voltage was manually adjusted during welding until the arc length matched a visual sight gauge set at either 1/8 in. (0.32 cm) or 3/16 in. (0.48 cm) above the flat workpiece. The sight gauge was a tungsten pointer attached to the welding gun and set to be 1/8 in. or 3/16 in. from the plate with the programmed CTWD. The voltage was increased or decreased from the robot teach pendant using the adjustment feature built into the robot control. The wire feed speeds and voltages were recorded for each of the two arc lengths at the different programmed currents as listed in Table 1. An arc data acquisition system was used to record the actual voltage and wire feed speed for each condition.

Choosing approximate arc length as a factor meant the arc length curves were used to set the voltage for an arc length-wire-feed-speed combination as specified by the DOE. Voltages for 3/32-in. (0.24-cm), 5/32-in. (0.40-cm), and 7/32-in. (0.56-cm) arc lengths were estimated by rough interpolation and extrapolation, ***e.g.***, at WFS = 420 in./min (1067 cm/min) the voltage for an approximate 5/32-in. (0.40-cm) is 25.1 V. This usage of a nontrivial rule for adjusting factors to address odd-shaped regions of interest was apparently new to the DOE literature. It results in an allocation of experimental runs similar to the Taguchi sliding levels approach as evidenced by the similarities of the plot in (Ref. 1) to Fig. 1B. Both approaches concentrate the experimental design points into the region of interest to the experimenter prior to the experiment.

The WFS/TS ratio was selected as the independent factor, instead of travel speed, in order to ensure that all conditions result in a reasonable weld deposit area for the application, ***i.e.***, to again concentrate the DOE points in the experimenter's region of interest. Preliminary tests were also performed to determine the range of WFS/TS that produced reasonable weld sizes on the thin-gauge stainless steel. The same nominal CTWD of 15 mm and travel speed of 40 in./min were used for each weld as for the arc length tests. The welds were made on actual lap joints with a gun work angle of 45 deg and a gun travel angle of 15 deg push. A midvalue arc length of 4/32-in. (0.32 cm) was used. Since WFS/TS was partially related to heat input with other parameters fixed, excessively high WFS/TSs tended to result in large weld deposits and excessive melt-through of the material. Since

Table 4 — The Six-Factor, Experimental Array and Response Data

Run	Day	x 2.54 cm/min (IPM) TS	x2.54 cm/min (IPM) WFS	Ratio	0.8 mm (1/32 in.) Arc Length	mm CTWD	mm Root Opening	Offset WD	(0–10) Burn	(0–10) Bridge
1	1	70	420	6	6	16	1	–0.5	8	3
2	1	70	560	8	6	14	0	0.5	5	5
3	1	60	420	7	5	15	0.5	0	10	8
4	1	50	400	8	6	14	0	–0.5	9	8
5	1	50	300	6	6	14	0	0.5	10	4
6	1	50	400	8	4	16	0	–0.5	10	10
7	1	50	300	6	6	16	1	0.5	9	2
8	1	60	420	7	5	15	0.5	0	9	8
9	1	70	420	6	4	14	1	–0.5	8	3
10	1	70	560	8	6	16	1	0.5	4	4
11	1	60	420	7	5	15	0.5	0	9	8
12	1	50	300	6	4	16	0	0.5	10	8
13	1	50	400	8	4	14	1	–0.5	8	8
14	1	70	420	6	6	14	0	–0.5	9	8
15	1	60	420	7	5	15	0.5	0	9	8
16	1	70	560	8	4	14	1	0.5	2	8
17	1	70	420	6	4	16	0	–0.5	9	8
18	1	50	300	6	4	14	1	0.5	9	3
19	1	50	400	8	6	16	1	–0.5	8	8
20	1	70	560	8	4	16	0	0.5	5	8
21	2	50	400	8	4	16	1	0.5	5	7
22	2	70	420	6	4	14	0	0.5	7	7
23	2	50	300	6	4	16	1	–0.5	10	8
24	2	60	420	7	5	15	0.5	0	9	9
25	2	70	420	6	6	16	0	0.5	8	6
26	2	70	560	8	6	16	0	–0.5	6	8
27	2	50	400	8	6	16	0	0.5	8	9
28	2	70	560	8	6	14	1	–0.5	4	5
29	2	60	420	7	5	15	0.5	0	9	8
30	2	70	560	8	4	14	0	–0.5	4	8
31	2	70	560	8	4	16	1	–0.5	8	8
32	2	60	420	7	5	15	0.5	0	9	9
33	2	50	300	6	6	14	1	–0.5	9	2
34	2	50	400	8	6	14	1	0.5	5	7
35	2	50	300	6	4	14	0	–0.5	10	9
36	2	70	420	6	6	14	1	0.5	8	2
37	2	70	420	6	4	16	1	0.5	8	2
38	2	50	400	8	4	14	0	0.5	8	9
39	2	50	300	6	6	16	0	–0.5	9	7
40	2	60	420	7	5	15	0.5	0	10	8
41	3	60	420	7	5	15	0.5	0	10	8
42	3	60	300	5	5	15	0.5	0	10	8
43	3	60	420	7	5	15	0.5	–1	10	8
44	3	60	420	7	3	15	0.5	0	9	8
45	3	60	540	9	5	15	0.5	0	8	10
46	3	60	420	7	5	15	0.5	1	8	8
47	3	40	280	7	5	15	0.5	0	9	8
48	3	60	420	7	5	13	0.5	0	5	8
49	3	60	420	7	5	15	–0.5	0	10	8
50	3	60	420	7	5	17	0.5	0	8	8
51	3	80	560	7	5	15	0.5	0	8	5
52	3	60	420	7	5	15	1.5	0	8	2
53	3	60	420	7	5	15	0.5	0	10	9
54	3	60	420	7	7	15	0.5	0	10	8

WFS/TS also corresponded to cross-sectional weld area, overly low ratios resulted in unacceptably small welds and incomplete fusion of the lap joint. The four welds in Table 1 were used to establish a relevant range of 4 to 9 for the WFS/TS ratio for use in the experimental design.

Noise factors were selected to be the root opening between the upper and lower members making up the joint and the horizontal offset of the welding wire from the root of the lap joint. Root openings were maintained by a clamping fixture design that allowed the top member to be elevated slightly relative to the bottom member by way of shims. Also, stops were designed into the fixture such that the joint edge of the upper member could be repeatedly located. Wire offset was obtained relative to the root of the joint by robot programming an offset into the robot path. Positive offset of the wire was defined to be away from the top edge of the joint. Minus offset was toward the top edge of the joint. The range of root openings used was 0 to 1.5 wire diameters (WD). The range chosen for wire offset was –1 to +1 wire diameters. Preliminary tests indicated root openings or offsets greater than these gave generally poor results.

The choice of continuous responses for measuring the quality of the welds was critical for keeping the number of experimental runs small. In general, sample size requirements for discrete, pass-fail responses are >20 times the number of runs required to achieve comparable information based on continuous responses

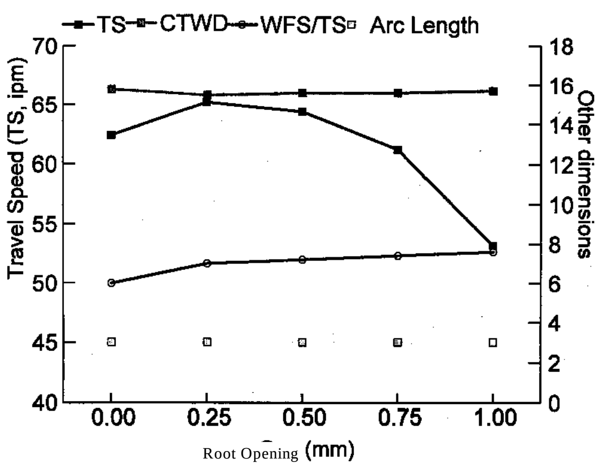

Fig. 6 — Graphical display of optimal settings (wire offset = 0 wire diameter).

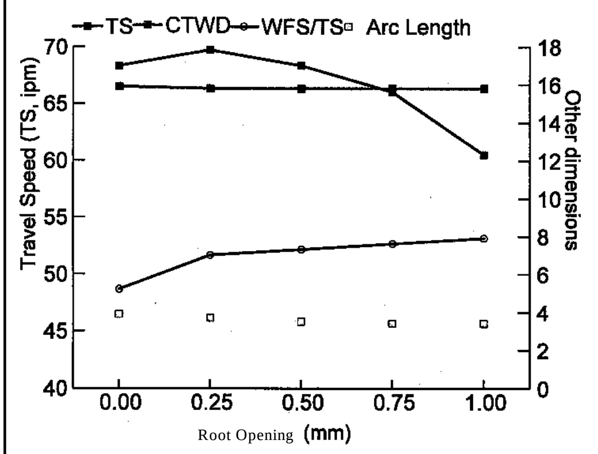

Fig. 7 — Graphical display of optimal settings (wire offset = –1 wire diameter).

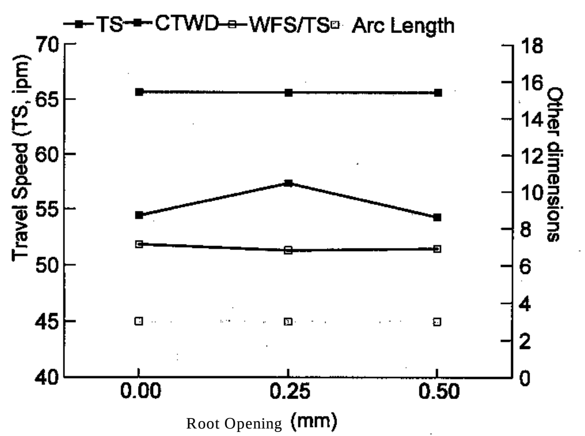

Fig. 8 — Graphical display of optimal settings (wire offset = 0.5 wire diameter).

(*e.g.*, see Ref. 15 in the related context of acceptance sampling). For welding 16-gauge, 409 stainless sheet steel lap joints, two 1 to 10 continuous ratings were used based on visual inspection. One rating characterized the amount of penetration through the lower member, called melt-through, and a different rating characterized fusion of the joint edges. The guidelines for assigning scores to the visual inspections are described in Table 2. In other applications, similar measures could be developed, one for each failure mode with upper and/or lower specification limits, as appropriate. A question for further research is whether assigning a single overall rating to the weld offers empirical model accuracy advantages compared with the assignment of separate measures for failure modes.

Visible melt-through was considered melt-through to the back of the lower member of the lap joint. A weld rating of 10 for the penetration response had no visible melt-through along the entire weld. An 8 had no greater than 1 in. of melt-through (lower specification limit). Welds with a rating of 7 or less had some visible melt-through of various lengths. Ratings were all based on approximately ten total inches of weld from one sample. Figure 2 illustrates a weld having a melt-through rating of 4. A similar rating of scale of 1 to 10 for fusion is shown in Table 2. In this case, the extent to which fusion was achieved with the edge of the top member was characterized. A 10 described a weld with no visible incomplete fusion. A 9 or 8 weld had some amount of partial fusion that was visible along the length of the weld. Welds of 7 or less had some amount of incomplete fusion along the length of the weld. Figure 3 illustrates a score of 4 for incomplete fusion along a total of 4.5 in. of weld. Each weld was given a quality rating for both penetration and completeness of fusion. Any weld with a score of 8 or better for both ratings was considered acceptable. The main practical criterion was a leak-tight weld. Derived weld procedures were ultimately checked for conformance to AWS D8.8.89, ***Specification for Automotive Welding***. The welds were quickly inspected to derive a quality rating from Table 2, a 12-in. scale, and a tabular listing of welds.

Experimental Arrays and Response Data

Within the scope of so-called classical DOE, two types of experimental designs exist for developing second-order regression models: central composite and Box Behnken (Ref. 14). Central composite designs were chosen with the adjustable parameter "alpha" set equal to 2. This choice reflected the factor that the region of interest was subjectively decided to be all points in the parameter space around settings believed, preliminarily, to be the best. Box Behnken designs have runs at three levels and would not have allowed us to test a few points at extremes as we subjectively desired. The settings chosen for a six-factor experiment are shown in Table 3. The levels were chosen as previously discussed. The 54-run experimental array and response data for the study are shown in Table 4. An additional column built into the central composite array permitted the tests to be performed over three days (Days 1, 2, and 3). This was not necessary, but the central composite structure leads to minimal effects on the accuracy of the empirical models if the experiments need to be spread over several sessions. Also, it was determined users of this method should consider revising their factor ranges and restarting with a new array if the fraction of nonconforming welds made on runs from Day 1 was greater than 90% or less than 10%. If this was true, then the approach was probably not capturing the relevant failure modes during normal system operation. This could save the cost of performing the runs corresponding to Day 2 and Day 3 twice. The array was obtained from standard statistics software and can also be obtained by simple scaling of central composite designs found in standard textbooks (Ref. 7).

Results and Discussion

The last two columns in Table 4 provide the ratings that resulted from executing the experimental array. The ten center-point runs, repeated in random order, corresponded to the same conditions (Runs 3, 8, 11, 15, 24, 29, 32, 40, 41, 53). These runs allowed an estimate of error that can be used in the optimization to establish the quality rating for 95% acceptable welds. The standard deviations from Table 4 were calculated from the center-points to be 0.49 for the melt-through factor and 0.46 for the fusion factor. Note in Table 4 that welds with an 8 or above rating in both quality responses were considered to be acceptable (not including any provision for experimental error). Inspection showed 30 of the 54 welds resulted in an 8 rating or higher. Advantages of the choice of independent factors discussed earlier were responsible for the large fraction of acceptable welds and the absence of welds that could not be rated due to some "inappropriate" combination of factors, ***i.e.***, combinations that result in no arc and no weld.

Regression

An empirical model was derived that extended the discrete experimental results into a functional relationship that predicts values at all points in the experimental space with estimable accuracy. A second-order polynomial function was chosen here to account for nonlinearity, as is common after experimentation using central composite designs. Ordinary least-squares regression was used to create empirical models for each of the two performance ratings. Regression models below, obtained in EXCEL™ based on the data in Table 4, approximately predict the average fusion rating, y_1, and melt-through rating, y_2.

$$\hat{y}_1(x) = -180 + 0.125x_1 + 0.7x_2 + 4.09x_3 + 23.7x_4 - 2.02x_5 + 5.9x_6 - 0.00346x_1^2 - 0.221x_2^2 - 0.096x_3^2 - 0.846x_4^2 - 0.885x_5^2 - 0.885x_6^2 - 0.0375x_1x_2 + 0.0125x_1x_3 + 0.025x_1x_4 + 0.05x_1x_6 + 0.25\,x_2x_4 - 0.5x_2x_5 - 0.75\,x_2x_6 - 0.25x_3x_4 - 0.25x_3x_5 + 0.5x_3x_6 + 0.25x_4x_5 - 0.25x_4x_6 - 1.0\,x_5x_6 \quad (2)$$

$$\hat{y}_2(x) = -88 + 1.13x_1 + 1.7x_2 - 0.77x_3 + 7.75x_4 - 4.55x_5 + 2.25x_6 - 0.00569x_1^2 + 0.056x_2^2 - 0.194x_3^2 - 0.194x_4^2 - 3.78x_5^2 - 0.776x_6^2 - 0.025x_1x_2 + 0.0125x_1x_3 - 0.025x_1x_4 - 0.025x_1x_5 + 0.0125x_1x_6 + 0.062x_2x_3 - 0.062x_2x_4 + 1.38x_2x_5 + 0.5x_2x_6 + 0.063x_3x_4 - 0.125\,x_3x_5 - 0.125x_4x_5 - 0.5\,x_4x_6 \quad (3)$$

In the regression equation, x_1 is TS, x_2 is WFS/TS, x_3 is arc length, and x_4 is CTWD. The factor x_5 is root opening and x_6 is offset. The ^ symbol means "estimated from response data," in this case using least-squares linear (in the coefficients) regression.

In order to facilitate visualization of the quality and productivity trade-offs, contour plots of the ratings were generated from Equations 2 and 3. WFS/TS was chosen as a function of travel speed for plotting. CTWD, arc length, root opening and wire offset were set. Contour lines were generated and plotted for WFS/TS and TS vs. the minimum of the estimated y_1 and y_2 for different predicted quality factors on intervals of 0.5 — Fig. 4. This plot was generated from our EXCEL™-based optimization software. In the case shown, the root opening between the parts is 0.5 mm (approximately 0.5 wire diameters). The contour lines for constant predicted melt-through rating were displayed in the top half of the plot, and the lines for constant fusion rating in the lower half. Where the lines break was the intersection between lines of melt-through and fusion with the same numerical rating. For example, at a speed of 69 in./min (175 cm/min), WFS/TSs above 7.25 started to produce excessive melt-through (predicted melt-through rating lower than 8). WFS/TSs lower than 7.25 produced incomplete fusion.

Thus, with the other conditions set as indicated in Fig. 4, the combination of 69 in./min travel speed and 7.25 WFS/TS (7.25 x 69 = 500 in./min or 1270 cm/min WFS) yielded the fastest possible travel speed for quality responses of 8 for both melt-through and fusion. For lower travel speeds, a range of WFS/TSs were predicted to give satisfactory quality factors. For instance, for 64 in./min (163 cm/min) travel speed, WFS/TSs between approximately 6.3 (390 in./min) and 7.75 (496 in./min) were predicted and had average quality factors of 8 or above. Lower travel speeds were predicted to produce a wider range of WFS/TSs for acceptability over the range studied. At a given travel speed, WFS/TS varied proportional to wire feed speed only, thus the plot predicted that incomplete fusion occurred at low wire feeds (and low currents), and excessive melt-though occurred at high wire speeds (and high currents), as would be expected. As travel speed increased, both excessive melt-through and incomplete fusion became more probable. Theoretically, this was consistent with the narrower concentration of heat in the workpiece at higher travel speeds, creating deeper penetration and narrower weld zones. At 69 in./min (175 cm/min) travel speed and above, >50% defects (ratings less than 8) were predicted to be unavoidable. The best welds (ratings of 10) were predicted to be in a small region at around 46 in./min travel speed and between a 7.5 and 8.25 WFS/TS (345 and 357 in./min WFS). These conditions would be appropriate if quality were the only objective. The root opening was fixed at 0.5 mm, and the offset was fixed at zero. A formal approach that yielded the fastest travel speed for a specified worst case quality rating was developed, taking into account a large number of possible combinations of root openings and offset.

Software was designed so any prediction plot could be evaluated based on any

Table 5 — Comparison of the Values Predicted by the Polynomials and Actual Weld Ratings

Noise Variable Settings		Melt-Through Rating		Incomplete Fusion Rating	
Root Opening	Offset	Predicted	Observed	Predicted	Observed
0.0	0.0	9	9	9	9
0.5	0.0	9	9	9	9
1.0	0.0	9	10	9	9
1.5	0.0	8	9	6	8
0.0	–0.5	9	9	9	9
0.0	–1.0	9	10	9	8
0.0	0.5	9	9	9	9
0.0	1.0	9	9	8	9

combination of fixed parameters. Slider input shown in Fig. 4 allowed all four fixed input parameters to be varied interactively to see their effect on the productivity window. Figure 5 shows predictions for a similar set of fixed parameters to Fig. 4, except with a joint opening of 1.0 wire diameter instead of the 0.5 in Fig. 4. Increased root opening was observed to severely shift and shrink the region for acceptable welds. As expected, higher WFS/TSs (larger deposit areas) were required to produce complete fusion with larger root openings. Also, the maximum travel speed was reduced to around 62 in./min from 69 in./min with the 0.5-wire-diameter root opening.

Optimization

Simple optimization based on manual changes to control and noise parameters and plots of the regression predictions may result in suboptimal settings. This follows, in part, because settings that yield a large fraction of acceptable welds at one combination of root opening and offset may yield a large fraction of nonconforming welds at another combination of these noise factors. In this research, an optimization program or solver based on the regression models was utilized. An optimization formulation was used for statistical process design within the context of arc welding: Minimize the cycle time (maximize travel speed) without permitting appreciable incidence of defect formation. To account for a set range of root opening between the parts because of imperfect fixtures, the percentage of nonconforming welds caused by unknown random sources was set less than 5% (1.6σ).

The formulations of the optimization problem with root opening and offset as noise factors, and the two visual ratings for melt-through and fusion were

$$
\begin{aligned}
&\text{Maximize } x_1 \\
&\text{by changing } x_1, x_2, x_3, x_4 \\
&\text{Subject to} \\
&y_1\left(x_1, x_2, x_3, x_4, \begin{array}{l}\text{root opening and}\\ \text{offset combination 1}\end{array}\right) - 1.6\,\sigma_{total,1} \geq LSL_1 \\
&\qquad\vdots \\
&y_1\left(x_1, x_2, x_3, x_4, \begin{array}{l}\text{root opening and}\\ \text{offset combination C}\end{array}\right) - 1.6\,\sigma_{total,1} \geq LSL_1 \\
&y_2\left(x_1, x_2, x_3, x_4, \begin{array}{l}\text{root opening and}\\ \text{offset combination 1}\end{array}\right) - 1.6\,\sigma_{total,2} \geq LSL_2 \\
&\qquad\vdots \\
&y_2\left(x_1, x_2, x_3, x_4, \begin{array}{l}\text{root opening and}\\ \text{offset combination C}\end{array}\right) - 1.6\,\sigma_{total,2} \geq LSL_2 \\
&40 \text{ in./min} \leq x_1 \leq 80 \text{ in./min} \quad 4.0 \leq x_2 \leq 8.0 \\
&\frac{3}{32} \text{ in} \leq x_3 \leq \frac{7}{32} \text{ in.} \qquad 13 \text{ mm} \leq x_4 \leq 17 \text{ mm} \\
&y_1(x), y_2(x) \text{ estimated using regression Equations 2 and 3}
\end{aligned}
\qquad (4)
$$

where LSL_1 and LSL_2 were the lower specification limits for the two responses and C was the number of combinations of the root opening and offset considered. Lower specification limit meant the minimum value for a weld to pass specifications. Both responses for the thin sheet study were ratings such that $LSL_1 = LSL_2 = 8.0$. Also, the ranges for the factors were set to be within the ranges utilized in the experiment to ensure reasonable prediction accuracy of the regression models. Finally, constraints for at least C = 4 root opening and offset combinations were set. For example, (root opening = 0.0 mm, offset = –1.0 mm), (root opening = 0.5 mm, offset = –1 mm), (root opening = 1.0 mm, offset = –1.0 mm), and (root opening = 0.5 mm, offset = 0.0 mm) describe four combinations relevant for this automotive application. However, for the purposes of simplicity in this discussion, the case with a single root opening and offset combination, ***i.e.,*** C = 1, was focused on.

In the remainder of this section, three topics are addressed related to the optimization program specified in Equation 4: 1) the role of process inconsistency, 2) the implementation of the method using a standard spreadsheet solver, and 3) the implications of solutions for the gas metal arc welding of 16-gauge, 409 stainless steel lap joints.

First, referring to Fig. 4, the highest travel speed for at least a predicted average 8 rating on both factors can be seen to be approximately 69 in./min (175 cm/min with a WFS/TS of 7.5). However, this was predicted to result in >50% nonconforming items because the process was not perfectly consistent (due to uncontrollable factors including root opening and offset). Some conservatism was necessary. The 1.6σ terms in Equation 4 were intended to adjust the target quality factor by an estimate of the process inconsistency (caused by factors not included in the experiment). Thus, rather than seek 8s, the optimization algorithm looks for ratings of 8 + 1.6σ. Therefore, the 95% fraction conforming cutoff ratings used were 8.0 + 1.6 x 0.5 ~ 9.0 for both quality ratings. This cutoff gave a 95% fraction conforming welds at all worst-case noise factor conditions, so the actual percentage conforming was expected to be higher. See Ref. 16 for an investigation into the appropriate sigma level considering economic considerations. Since regression model errors were not included in the sigmas, it is important to note the above formulation assumed that, after the experiment, the optimal settings will be confirmed by additional tests. Otherwise an estimate of model prediction error needed to be added to the σs.

Second, an optimization spreadsheet was created based on the EXCEL™ solver to find the maximum travel speed for all combinations of parameters using the formulation in Equation 4. The solver spreadsheet finds the maximum travel speed point with systematic variation of all the parameters (TS, WFS/TS, CTWD, and arc length) for set amounts of joint root opening and wire offset. Referring to the WFS/TS vs. TS plots, this can be described as inspecting all possible plots, like that in Fig. 4 over the range of all parameters. Values for all of the controllable (welding) parameters are found that yield the highest travel speed and acceptable quality regardless of the root opening and offset values.

The solver was used to derive optimum parameter settings for maximum travel speed for joint root openings of 0.0 to 1.5 wire diameters in increments of 0.5 and for wire offsets of –1 to 1 wire diameters, also in increments of 0.5. In each solution of Equation 4, only the constraint shown in the particular row was included. The values found by the solver provided insight into the process. Twelve of these optimums produced acceptable welds of at least predicted 9s for both ratings — Table 5. The unacceptable ratings resulted from large root openings and/or large wire offsets away from the top joint edge. Figures 6–8 show these optimum parameters plotted as a function of joint root opening for wire offsets of 0, –1 (into the plate), and 0.5 (away from the plate) wire diameters, respectively.

For zero wire offset (Fig. 6), the optimum recommended travel speed decreases significantly with an increase in root opening. The recommended WFS/TS (fill area) rose, as would be expected. Recommended CTWD rose slightly and arc length decreased slightly. An offset of one wire diameter into the joint (Fig. 7), decreased the effect of root opening on recommended travel speed significantly for openings of one wire diameter and less. This was a reasonable result since the arc was still concentrated on the upper joint edge. Figure 8 shows recommended parameters for a wire offset of 0.5 wire diameter away from the top edge. A lower travel speed was recommended even with no joint root opening for positive offsets. This would recommend programming of some wire offset into the joint, a point that is also known from practice.

Note that if root opening and offset combinations were included in Equation 4, which have root openings ≥1.5 mm and offset ≥1.0 wire diameters, the regression models predicted that no combination of parameters will produce an acceptable weld at the quality level specified. There were other combinations of root opening and offset (Table 5) of actual welds that met, or exceeded, predictions.

Confirmation of the Results

Welds were made for the first eight of the optimum parameter sets to compare the weld quality factors with the predictions. The results are presented in Table 5, where the predicted and actual quality ratings are shown. The actual ratings were always within 1.6σ of the predicted values. All of the weld samples for the optimum welding conditions were cross-sectioned and evaluated, and found to comply with the AWS D8.8.89 specification.

Conclusions

A method for deriving process settings was developed and demonstrated for its application to robotic GMAW of sheet metal. The method has the following properties:

1) It included an objective formulation (Equation 4) that addressed variation of noise factors, such as root opening, and offset making it comparable to Taguchi signal-to-noise ratios. The method and the formulation permit both experimentation using classically designed experiments and direct maximization of the travel speed of the welding robot, which are both impossible using Taguchi methods, ***e.g.***, see Ref. 2.

2) It incorporated potentially advantageous selections of independent variables, ***e.g.***, arc length instead of voltage and WFS/TS instead of wire feed speed. These choices were shown to concentrate the experimental region onto the region of interest to the engineer, and contributed to the accuracy of the fit model over the region of interest (Ref. 14). Yet, the full implications of the use of these surrogate factors in creating relatively accurate and useful meta-models is an important topic and needs further study.

3) It was implemented with standard spreadsheet software packages since it was based on ordinary least-squares regression. Thus, the method required no special software and minimal training.

4) It involved estimation and constraining of the worst-case fraction nonconforming, which was possible because it involved estimating the process consistency.

5) In its application to the design of 409-gauge, stainless steel lap joints, the procedure achieved 1) predicted optimum parameters that were confirmed by testing, 2) insight into the effect of parameters via plots, and 3) generally reasonable experimental time and cost.

Future Work

The procedure described in this paper in the context of 409-gauge, stainless steel lap joints is expected to generalize well to other welding applications. In order to apply the procedure to additional arc welding applications, different responses may need to be identified. These might, or might not, be based on continuous ratings from visual inspection. Responses could be derived from precise dimensional measurements of sectioned parts or other continuous measures provided by nondestructive measures. Additional factors such as shielding gas composition, travel and work angle, and wire diameter might also be included, and would require only minor modifications to the experimental arrays. These modifications could include selecting a different central composite design, adding factors to the model, or optimizing over additional factors. In addition to adapting the method to other applications, other topics remain for future study. These include a more thorough investigation of independent factor selection based on decision rules (using effective arc length and wire feed speed to set the voltage or using dimensionless numbers) and using separate measures for each failure mode instead of one overall quality characteristic (rating the melt-through of welds that have substantial incomplete fusion).

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