Parameters for Pressurized Inert Gas Metal-Arc Welding of Aluminum

Rate of filler metal feed is the most significant factor affecting weld appearance, soundness, reinforcement, penetration, width, area and depth-to-width ratio

BY ELDON D. BRANDON

ABSTRACT. This study was designed to establish the significance of various process parameters in *Pressurized Inert Gas Metal Arc* (PIGMA) welding. Specifically, the effects of arc voltage, filler metal speed, travel speed, and chamber pressure were determined. The measured responses were arc mode and stability, weld appearance, soundness, area, width, penetration, reinforcement, and depth-to-width ratio.

Using predetermined combinations of parameters, bead-on-plate welds were made on an 8 in. diameter by 1 in. wall Type 1100 aluminum cylinder. The filler metal was 0.030 in. diameter Type 718 aluminum alloy. The welding was performed in a pressure chamber with the cylinder in the horizontal-rolled position. After welding, the welds were X-rayed and visually and metallographically examined.

For purposes of analysis, the raw data of each response were treated using a multiple regression analysis technique. By this technique, the variability in ratings due to each independent variable and to lower order interactions was determined. Calculated ratings were obtained for each combination of parameters. The results of the study were derived using the trends of the calculated ratings.

Findings are briefly described below:

Chamber pressure, in general, when increased, acts to reduce weld appearance, weld width, and arc stability and increases the depth-to-width ratio. Increased pressure shortens the arc and changes the transfer mode to short circuiting.

Arc voltage, when increased from 22 to 28 v, exhibits relatively minor influence on weld soundness and appearance but did increase weld penetration and area.

Travel speed, when increased from 60 to 120 ipm, decreased weld penetration, width, and cross-sectional area.

Filler metal feed speed, was the most significant factor affecting weld appearance, soundness, reinforcement, penetration, width, area, and depth-to-width ratio. The best appearing and soundest welds occurred at lower filler metal feed rates. As would be expected, the size of the weld increased with filler metal feed rate.

Using criteria of acceptable appearance and soundness, the maximum depth-to-width ratio (1.2:1) was obtained at 29 v, 800 ipm filler metal feed speed, 70 ipm travel, and 82 psi absolute pressure.

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Introduction

Pressurized Inert Gas Metal Arc or PIGMA welding is a relatively new technique being used at the Rocky Flats Plant to reduce weld-metal porosity to extremely low levels when other techniques fail. Other desirable conditions, such as a narrower, more concentrated arc profile, have been realized.

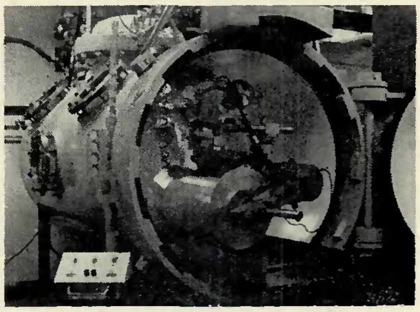

Fig. 1—Welding chamber and fixture used for PIGMA welding study

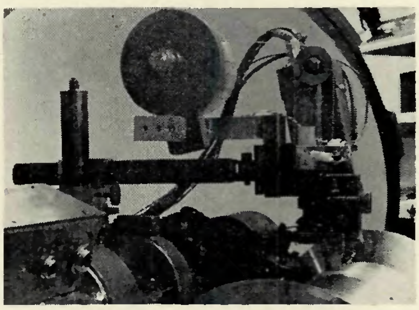

Fig. 2—Close-up of torch/filler metal feeder assembly

The PIGMA process is essentially the same as gas metal-arc welding except that the torch and workpiece are enclosed within a pressure chamber. For welding, the chamber is pressurized to some elevated pressure in the range of 20 to 100 psia. The chamber may or may not be evacuated before being pressurized. Inert gas is normally used to backfill the chamber after evacuation. However, compressed air may be used if an inert atmosphere is not required. After the desired pressure is reached, the welding proceeds in the normal manner except, of course, the operation must be carried out by remote control. The basic process and equipment have been described in more detail by Barker.*

The current program was designed to establish the significance of various process parameters in PIGMA welding. Several response variables were measured to find their relationships to the basic welding parameters. Also, a wide range of variable levels was used. Thus, a set of limits was established wherein acceptable welds could be made.

Experimental

Materials

The selected base metal, type 1100 aluminum, was cylindrical, 8.28 in. outside diameter by 1 in. wall by 13 in. long. 1100 aluminum is a 99% purity alloy containing very small amounts of copper, silicon, and iron. The filler metal was a 0.030 in. diameter 718 aluminum alloy. This alloy consists of 12% silicon, the balance aluminum.

Before welding, the cylinder was

* Barker, R., "PIGMA Welding—A Methold for Reducing Weld Porosity," Welding Journal, 44 (1), Research Suppl., 1-s to 6-s (1965).

Table 1—Summary of Pressurized Inert Gas Metal Arc Welding Procedure

Process	—Automatic gas metal arc
Base Metal	—Type 1100 aluminum cylinder, 8.38 in. O.D. by 1 in. wall by 13 in. long
Filler metal	—718 alloy aluminum (0.030 in. diameter)
Preweld cleaning (base metal)	—Degreased with acetone; nitric acid etch; cold and hot-water rinse; wire brushed before welding
Joint configuration	—Bead-on-surface
Temperature control	—Base metal at room temperature at start of each weld
Welding position	—Cylinder horizontal-rolled; torch vertical at 12 o'clock
Polarity	—Direct current reverse polarity
Shielding gas (torch)	—Ratio of 5:1 helium:argon (by volume) 60 cfh at 12 and 32 psia; 120 cfh at 52 psia; 180 cfh at 72 psia
Chamber gas	—Compressed air
Power supply	—Vickers 500 amp, 3 phase, resistance controlled, d-c variable reactance unit, Model 965, Serial 6511
Welding fixture	—Dow-designed and built; universal orientation for between-centers or turntable operation
Welding chamber	—Horizontal cylinder approximately 3 ft in diameter by 8 ft long; breech-lock door closure; designed for vacuum or pressure
Welding torch	—Dow-designed and built; integral with filler metal drive rolls; water-cooled; gas lens; contact tube bent 9.5 deg into direction of travel

Table 2—Welding Variables

Factor	Level
Voltage, v	22
	24
	26
	28
Filler metal feed speed, ipm	500
	700
	900
	1100
Travel speed, ipm	60
	80
	100
	120
Chamber pressure, psia	12
	32
	52
	72

degreased by wiping with acetone-soaked tissues followed by a light etch by bathing in nitric acid for 25 minutes. After a cold and hot tap water rinse, the cylinder was warmed with an oxyacetylene torch and then stored in the evacuated welding chamber until the welding started.

No attempt was made to clean the filler metal which remained in a mill-applied sealed plastic bag until the welding started.

Equipment

A commercial 500 amp, 440 v, three phase, constant-potential welding power supply was used. An inductance package had been added to the power supply with inductance set at maximum throughout the test.

The welding chamber and fixture are shown in Fig. 1. The torch, torch manipulator, fixture, and sequencing controls were of in-house design and manufacture. Briefly, the torch/filler metal feeder assembly (Fig. 2) was a compact unit using 1 in. diameter, smooth drive, and back-up rolls, and a $2^1/_{16}$ in. long copper contact tube. The filler metal-drive motor utilized a clutch drive to gain faster wire starts. A 9.5 deg bend in the contact tube was used as an attempt to improve the consistency of contact tube-to-filler metal contact.

The fixture/torch manipulator was designed to accommodate a variety of welding positions and weldment configurations. The part-drive motor was connected by a clutch to gain faster part starts.

The sequence control was designed to provide completely automatic control over the welding operation. The operator locates the part in the proper position for welding, sets the controls, including the filler metal feed rate, arc voltage, travel speed, weld time, and gas flow rate, and depresses the "weld-sequence-start" button. For this experiment, the weld time was set to produce a weld approximately 2 in. long.

The welding procedure is summarized in Table 1.

Experiment Design

Bead-on-plate welds are made on the aluminum cylinder. The welds were made with the cylinder in the horizontal-rolled position and the torch vertical in the 12 o'clock position.

The four welding variables and levels are given in Table 2. The values in Table 2 were chosen since they cover the range of, what might be considered, normal welding practice. Atmospheric pressure, 12 psia, was chosen as the lowest pressure.

A full factorial test plan involving the four factors at four levels would require 4^4 or 256 welds. At the cost of losing information on several higher order interactions, a one-fourth fractional factorial design requiring only 64 welds was used. In addition, 8 duplicate welds were made in order to measure the variability.

The order of making the welds was completely randomized to minimize the effects of uncontrolled and unknown variables such as contact tube changes, etc. The test plan is shown in Fig. 3. The numbers inside the parallelograms refer to the order in which the welds were made.

After welding, the welds were visually examined, X-rayed, sectioned, and metallographically examined. The measured responses were as follows:

1. General appearance.
2. Radiographic soundness.
3. Arc stability.
4. Arc mode.
5. Cross-sectional area of the weld.
6. Weld-bead reinforcement.
7. Weld penetration.
8. Weld width.
9. Depth-to-width ratio.

Evaluation of the first four responses was necessarily subjective.

In rating *general appearance*, each weld was assigned a rating of *1* to *5* with the best welds assigned a *5* and the poorest assigned a *1*. Both types of welds are shown in Fig. 4.

Radiographic soundness was similarly evaluated and each weld was rated with a *1*, *3*, or *5*. A *5* represented a completely sound weld, and a rating of *1*, a weld containing large voids. Visual appearance was disregarded in rating the soundness. Erratic, but sound welds were assigned a *5* rating.

Arc stability was determined and rated *1*, *3*, or *5* according to oscillographic recordings of arc voltage and current. Stable arc action was assigned a *5*, unstable and erratic arcs a *1*.

Arc mode, (spray, transition, or short circuiting) was also determined from the oscillographic recordings. Spray-arc conditions were assigned a *5*; short-circuiting conditions, a *1*; and intermediate conditions, a *3*.

Weld area, reinforcement, penetration, and *width* were measured from a photomacrograph of a cross section of each weld.

The welds which were made are shown in Fig. 5. The 72 welds were subsequently visually examined, X-rayed, and then cut out and metallography examined.

The nine responses were then measured on each of the welds.

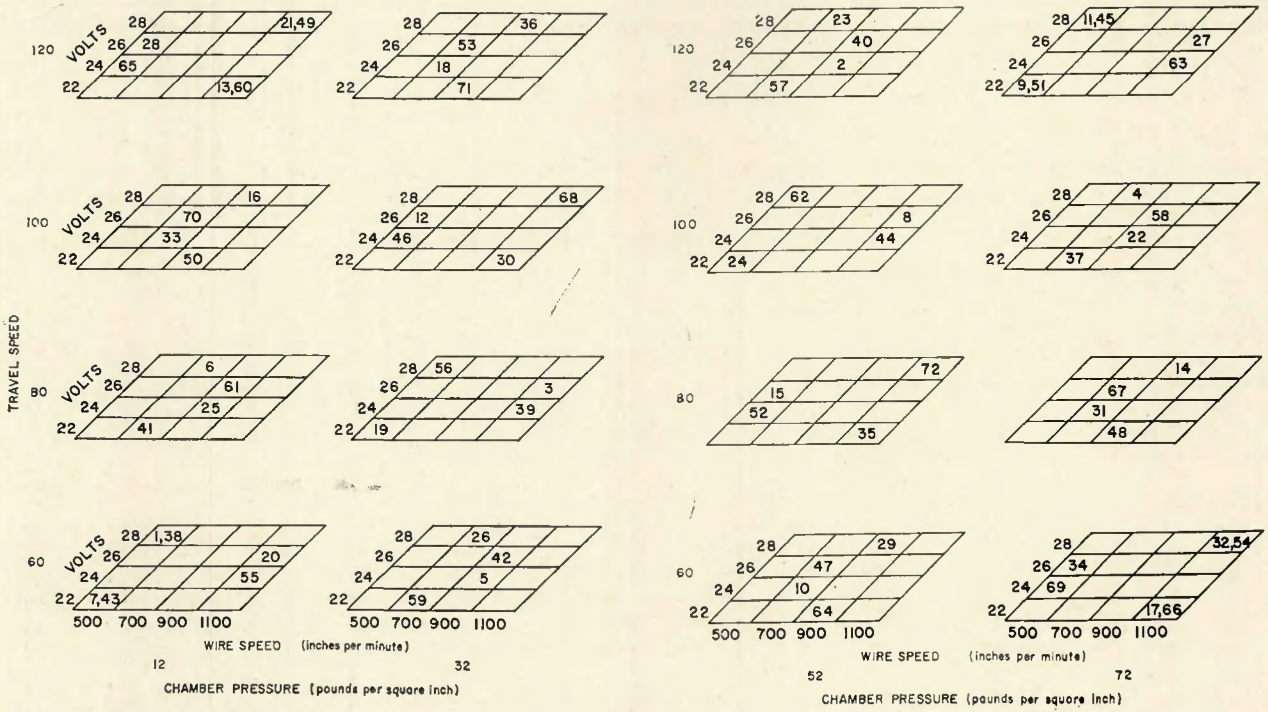

Fig. 3—Test plan for PIGMA welding parameters study

Analysis of Results

For purposes of analysis, the raw data, or ratings, of each response were treated using a multiple regression analysis technique. By this technique, the influence on rating caused by each independent variable and lower order interactions could be determined.

The calculated ratings were determined by applying an equation of the form:

$$R = C_0 + C_1 \cdot V + C_2 \cdot T + C_3 \cdot W + C_4 \cdot P + C_5 \cdot V \cdot T + C_6 \cdot V \cdot W + C_7 \cdot V \cdot P + C_8 \cdot T \cdot W + C_9 \cdot T \cdot P + C_{10} \cdot W \cdot P + C_{11} \cdot V^2 + C_{12} \cdot T^2 + C_{13} \cdot W^2 + C_{14} \cdot P^2$$

where, R = calculated rating; C_x = constants determined by regression analysis; V = normalized voltage; T = normalized travel speed; W = normalized filler metal speed; P = normalized chamber pressure.

In addition to the calculated ratings, the significant factors affecting each of the nine responses were determined using the Student t-Test. The results of this analysis readily show the effects of each factor by itself, as well as the significant interactions.

Table 3 tabulates the welding parameters which significantly affect each of the responses. Of importance here is the magnitude of the t-statistic. The greater the absolute value of the t-statistic, the more influential that factor is in affecting the response.

A negative t-statistic for the single factors indicates an inverse relationship. As the welding parameter is

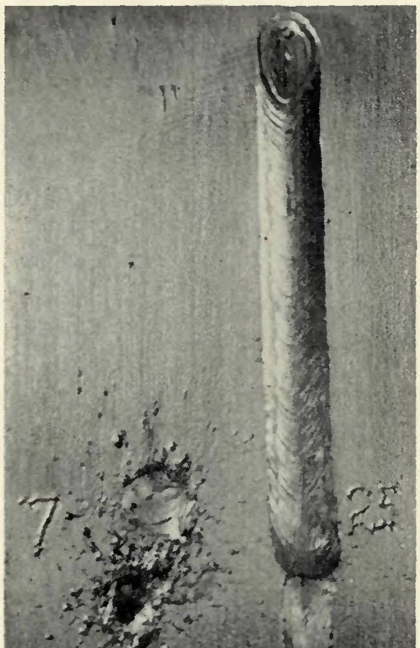

Fig. 4—Example of poor weld rated 1 and good weld rated 5

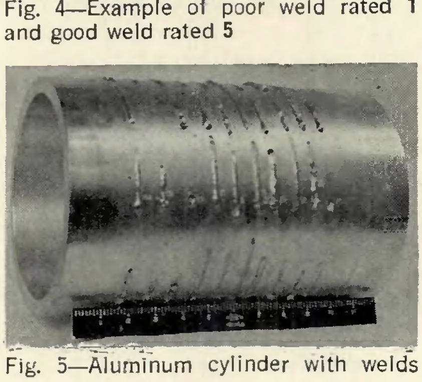

Fig. 5—Aluminum cylinder with welds

increased, the response decreases. A product of two factors indicates an interrelationship. For example, when one of the factors is low, an increase in the other may increase the response. However, when the first factor is high, an increase in the second may decrease the response. A squared single factor simply indicates a nonlinear, second-degree curve relationship between the welding parameter and the response. In this case, the positive or negative sign indicates the direction of curvature.

Because of the amount of information that can be gleaned from this study, each response is discussed separately followed by brief details on optimization of welding parameters.

General Appearance

In Table 3, filler metal speed appears as the most significant parameter affecting weld appearance. Increased filler metal speed, within the limits of this study, is detrimental. Chamber pressure is also inversely related to weld appearance. Arc voltage and travel speed also affect weld appearance.

Figure 6 displays graphically the calculated results. Each of the small squares is a plot of appearance rating as a function of arc voltage and filler metal feed speed at a particular combination of chamber pressure and travel speed. Each contour line represents a particular appearance-rating value. In other words, a weld made with any combination of voltage and filler metal speed along any of the contour lines would be rated similarly.

Table 3—Significant Factors Contributing to Responses (Student *t*-Test Analysis)

	Factor	*t*-Statistic[a]		Factor	t-Statistic[a]
General appearance	Filler metal speed	−8.450	Weld width	Filler metal feed × pressure	−3.685
	Chamber pressure	−3.001		Pressure	−2.997
	Voltage × pressure	2.911		Filler metal feed speed	−2.898
	(Filler metal feed speed)^2	−2.710		Travel speed	−2.709
	Travel × pressure	2.169		Voltage	2.169
				(Voltage)^2	−2.126
Weld soundness	Filler metal feed speed	−9.122			
	(Filler metal feed speed)^2	−3.837	Weld reinforcement	Filler metal feed speed	13.123
				Travel speed	−4.626
Arc Mode[b]	Voltage	9.858		(Filler metal feed speed)^2	3.276
	Pressure	−4.955		Voltage × filler metal	2.305
	Filler metal feed speed	4.854		Voltage × pressure	2.224
	Travel speed	3.234			
	(Filler metal feed speed)^2	2.366	Weld penetration	Filler metal feed speed	16.145
				Pressure	5.516
Arc stability	Filler metal feed speed	−4.637		Voltage	3.053
	Voltage	2.855		Travel speed	−2.998
	Pressure	−2.784		Voltage × pressure	2.823
	Voltage × pressure	2.499		Travel × filler metal	−2.209
Weld area	Filler metal feed speed	9.017	Depth-to-width ratio	Filler metal feed speed	12.553
	Travel speed	−4.441		Pressure	6.450
	Voltage	3.972		Filler metal feed × pressure	4.189
	Voltage × pressure	2.866		(Filler metal feed speed)^2	2.125
	Voltage × filler metal	2.565		Voltage × travel	−2.028
	Voltage × pressure	−2.201		Voltage × pressure	2.025
	Pressure	2.041			
	(Voltage)^2	−2.012			

[a] The 0.05 level of significance—2.000.
[b] Spray mode indicated by high positive *t*-statistic.

Plots wherein the contour lines are relatively vertical indicate that, at that combination of pressure and travel speed, arc voltage is insignificant in affecting the response (in this case, general appearance). Similarly, when the contour lines are relatively horizontal, filler metal speed is insignificant. However, vertical contour lines do indicate that filler metal speed is significant—and, of course, horizontal lines indicate the significance of voltage.

Welds rated better than *4* would normally be acceptable. Welds rated less than *2* would rarely be acceptable. To emphasize these two areas, the plots are shaded.

Going across the chart from left to right corresponds to an increase in travel speed from 60 to 80 to 100 to 120 ipm. Thus, in any horizontal row, any change in appearance of the plots is a result of the increased travel speed only.

Going up the chart corresponds to an increase in chamber pressure from 12 to 32 to 52 to 72 psia. The voltage and filler metal speed scales remain the same. Thus, any change in appearance of the plots in any vertical column is a result of the increased pressure only.

Looking across the bottom row from left to right, the shaded area representing acceptable welds changes only slightly, hence, at atmospheric pressure, weld appearance is relatively insensitive to travel speed. In the bottom-left plot, arc voltage is insignificant. In the bottom-right plot, increased arc voltage is detrimental. In each of the bottom plots, filler metal speed is a significant variable.

Now looking across the top row from left to right, the shaded area increases. Therefore, at 72 psia, increased travel speed is desirable. In each of these plots, low filler metal speed and high voltage are preferred.

Looking at the chart as a whole, in only two plots does the "5" rating line appear. These are both at 72 psia. Hence, if optimum appearance is desired the combination of 72 psia chamber pressure, 120 ipm travel speed, 28 v, and 500 ipm filler metal feed speed would be used.

Weld Soundness

Referring to the X-ray results, Table 3 shows the significant parameters affecting weld soundness. Only filler metal feed speed is significant. Again, the negative sign for the t-statistic indicates that speed and weld soundness are inversely related.

The contour rating chart of Fig. 7 reflects the relative insignificance of chamber pressure, travel speed, and arc voltage. Filler metal speed is significant, as indicated by the close vertical contours. In each of the 16 plots, high filler metal speed is detrimental. Assuming the filler metal speed is appropriate, sound welds can be made at all levels of chamber pressure and travel speed. However, porous welds (the only radiographically detectable defects found in this study) can also be made at each combination of pressure and travel speed by the use of high wire speed.

Arc Mode

Table 3 shows that each of the four main effects are independently significant in affecting arc mode.

In this case, the higher the t-statistic, the greater the tendency for the arc to operate in the spray mode.

As would be expected, increased arc voltage produces a spray arc. Increased pressure produces a short-circuiting arc. Increased filler metal speed and travel speed produce a spray arc. Figure 8 shows this same information graphically. The area between the two shadings represents the transition zone.

Arc Stability

Table 3 shows that filler metal speed is the most significant parameter and is inversely related to arc stability. Increased arc voltage promotes arc stability, while increased pressure is detrimental. Examination of the contour rating chart of Fig. 9 shows a graphical interpretation of the voltage times pressure interaction. The shading in Fig. 9 is used to indicate the region of most stable arc operation.

At low pressures, particularly atmospheric, arc stability is relatively insensitive to voltage. However, at high pressure, increased arc voltage acts to

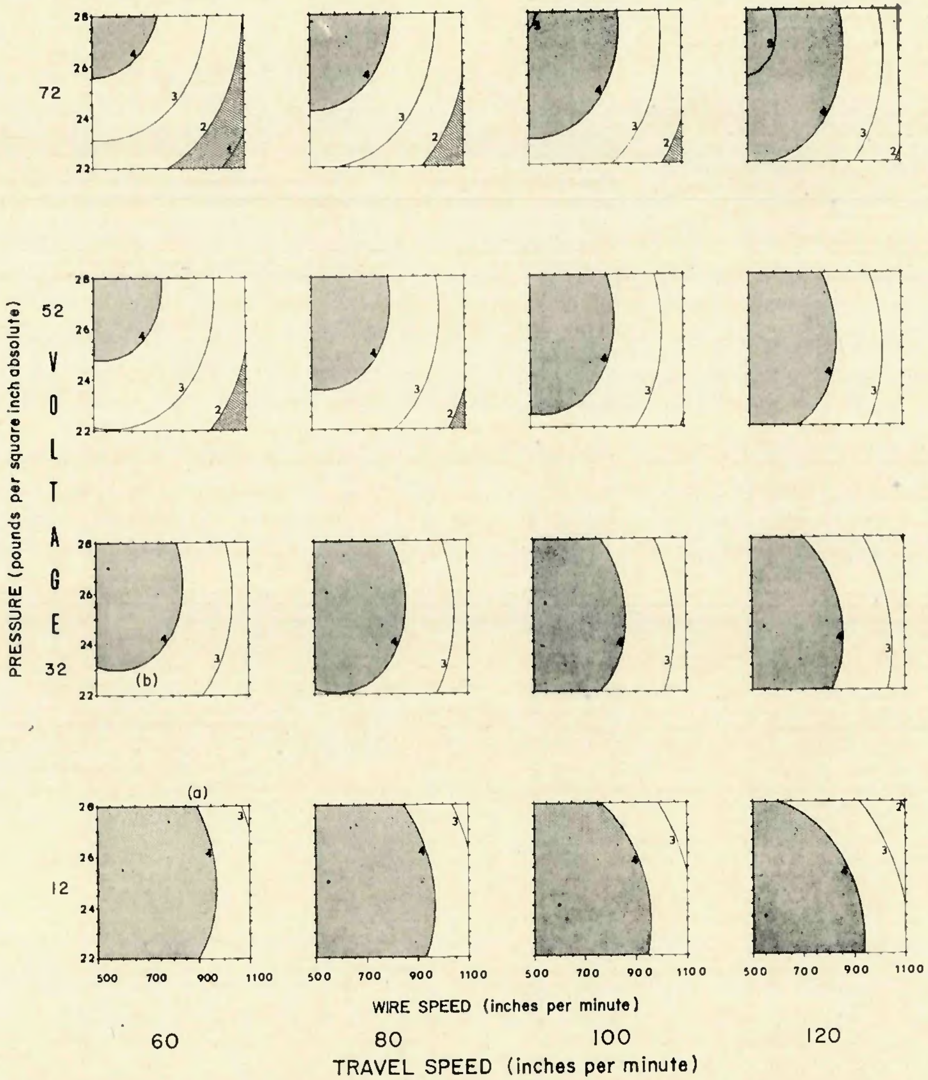

Fig. 6—General appearance, contour chart

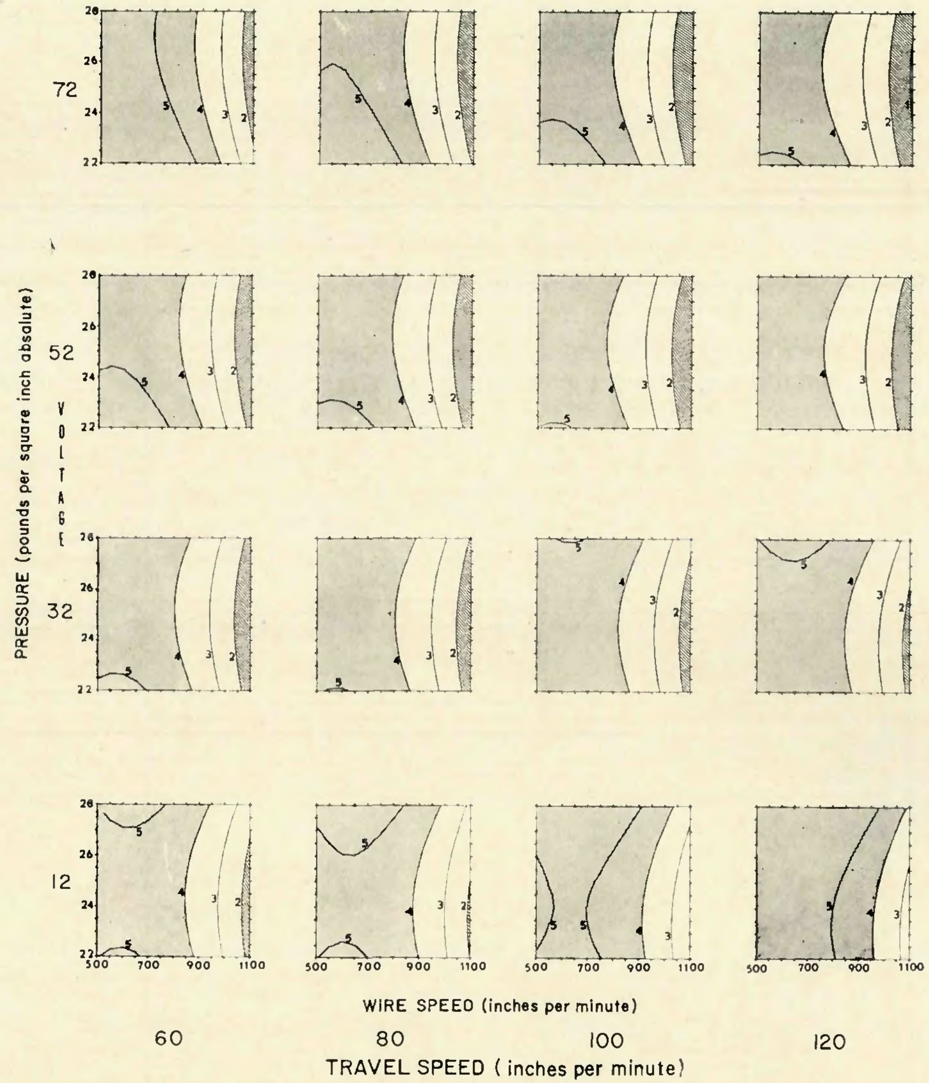

Fig. 7—Weld soundness, contour chart

increase the stability of the arc. This illustrates the requirement of increasing the arc voltage when increased ambient pressure is used.

Again, within the limits of this study, low filler metal feed speeds give the most stable arc conditions.

Weld Area

The mathematical analysis of data in Table 3 shows that the weld cross-sectional area is increased by increasing the filler metal speed, arc voltage, and chamber pressure. Travel speed is inversely related to weld area. Filler metal speed is the most significant parameter.

These same results are shown graphically in Fig. 10. The numbers associated with the contour lines represent square inches of area. The largest area (0.40 sq in.) occurred at 60 ipm travel speed, 1100 ipm filler metal feed speed, and 28 v. At this combination, chamber pressure was relatively insignificant. However, according to Figs. 6 and 7, welds made at this combination were unsatisfactory from the standpoints of appearance and

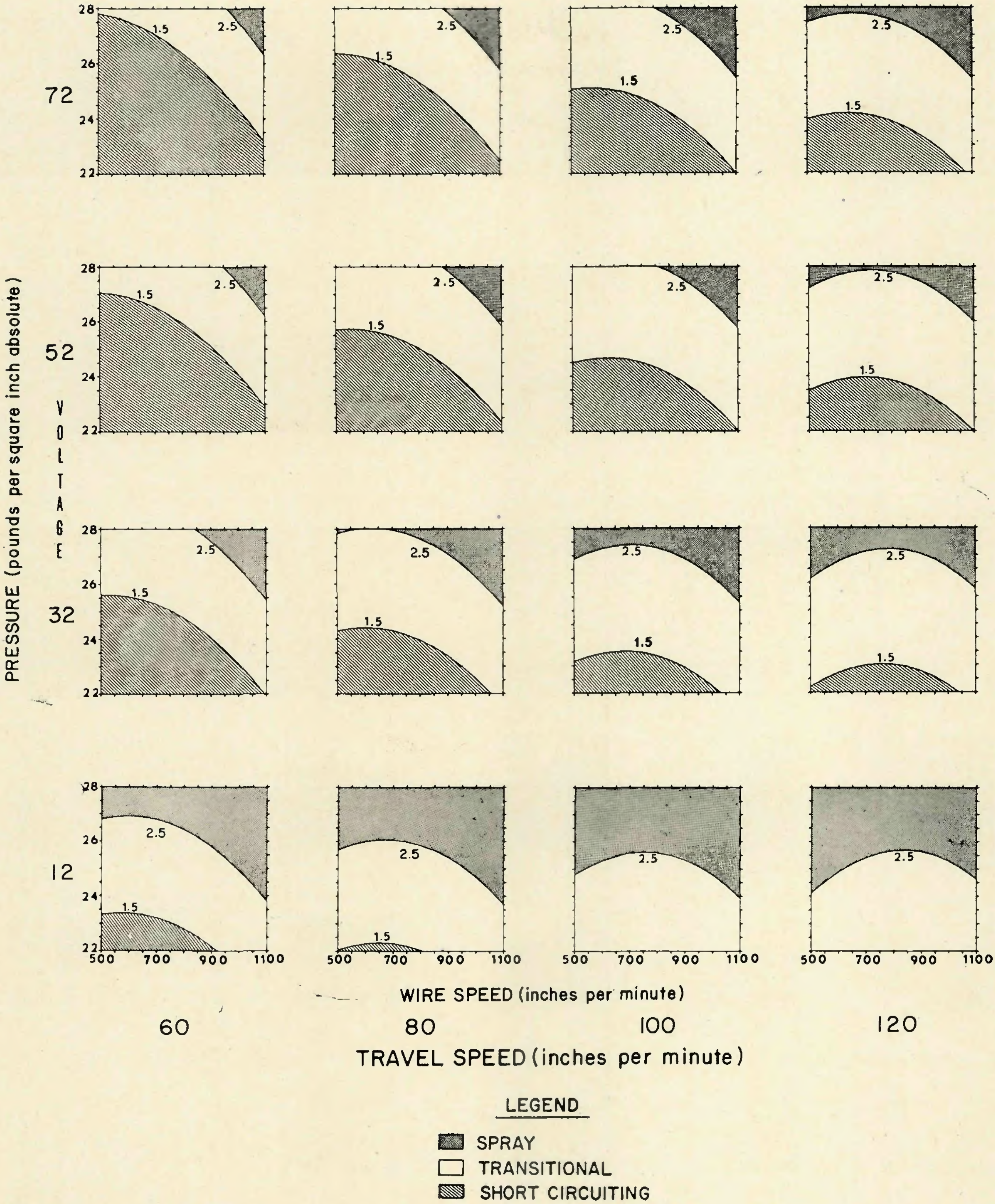

Fig. 8—Arc mode, contour chart

soundness.

The smallest welds (0.10 sq in.) generally resulted from the use of 22 v, and 500 ipm filler metal feed speed. In this case, travel speed and chamber pressure were relatively insignificant. This general combination produced sound, good appearing welds.

Weld Width

According to the data in Table 3, each of the main effects is independently significant in affecting weld width. Only voltage is apparently directly related. However, the voltage squared term indicates that the relationship is not linear.

Figure 11 is a graphical presentation of weld width as a function of the weld parameters. The meaning of the interaction term between filler metal feed speed and chamber pressure is shown. The maximum width occurs at the *x* point on each plot. At low chamber pressures, the maximum oc-

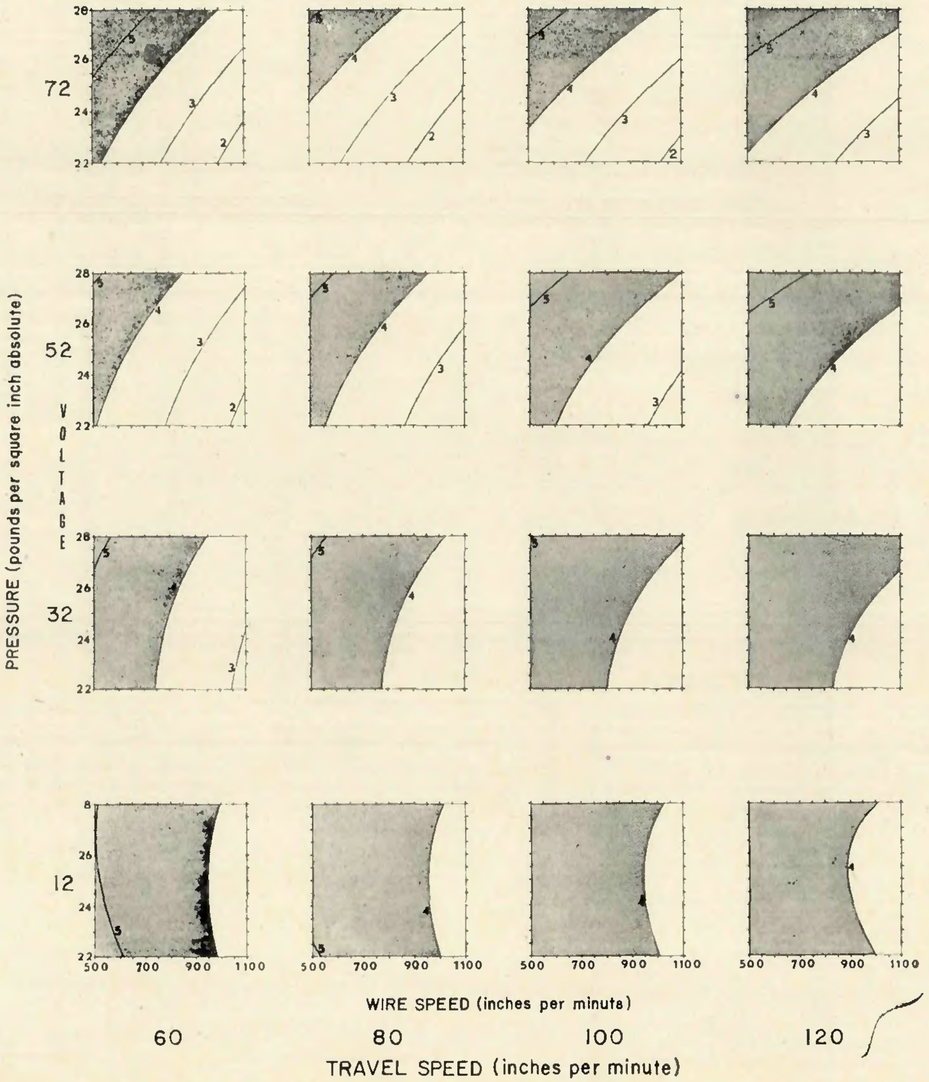

Fig. 9—Arc stability, contour chart

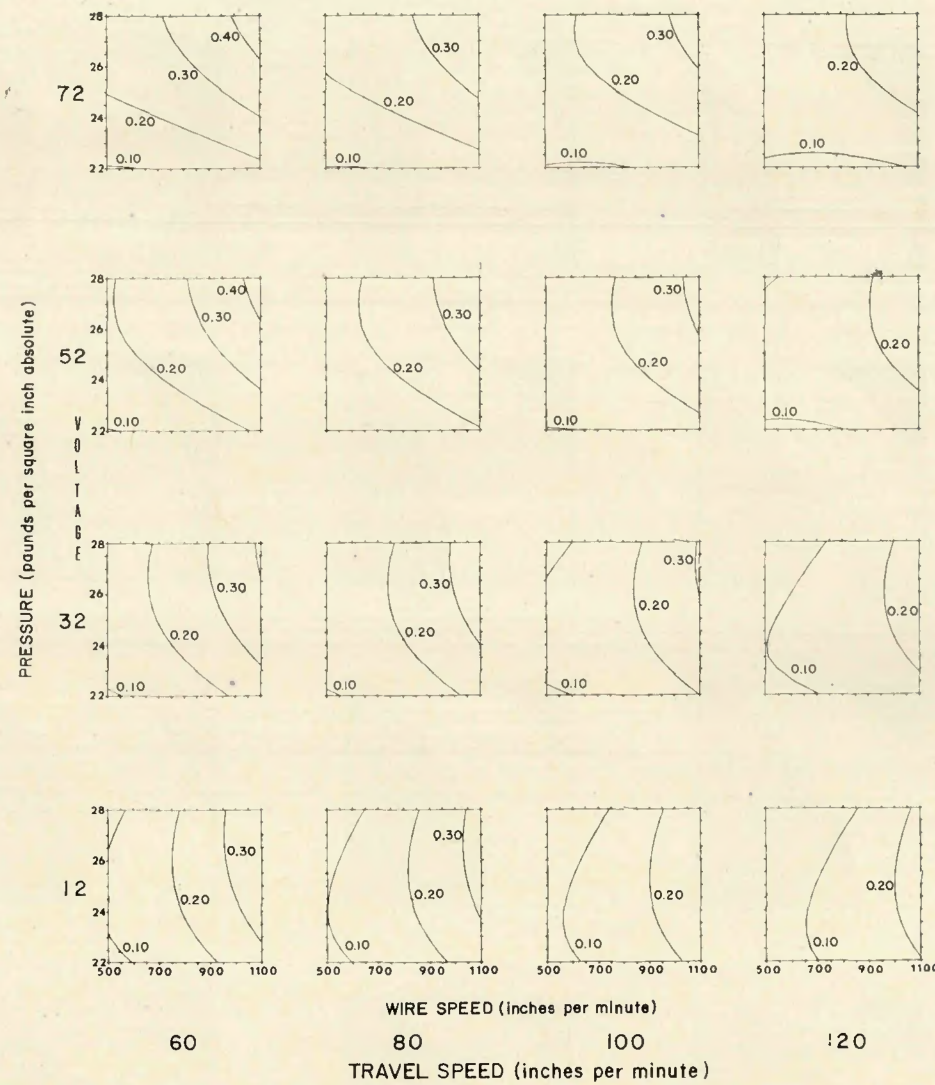

Fig. 10—Weld area, contour chart

curs near the high end of the wire-speed scale. However, at high pressure, the maximum width occurs at low wire speeds.

The widest welds were somewhat greater than ¼ in., actually 0.27 in. The narrowest welds were somewhat less than 0.10 in., but occurred in an area of poor appearance and soundness.

Weld Reinforcement

From Table 3, filler metal feed speed is the most significant factor affecting weld reinforcement. Travel speed is inversely related, and, to a lesser degree, voltage and pressure are significant in interactions. The contour rating chart for weld reinforcement is shown in Fig. 12. The greatest reinforcement was 0.12 in. and occurred at 28 v, 1100 ipm filler metal feed speed, 60 ipm travel speed, and 72 psia pressure. The least reinforcement was 0.01 in. and occurred at 28 v, 500 ipm filler metal feed speed, 120 ipm travel speed, and at atmospheric pressure.

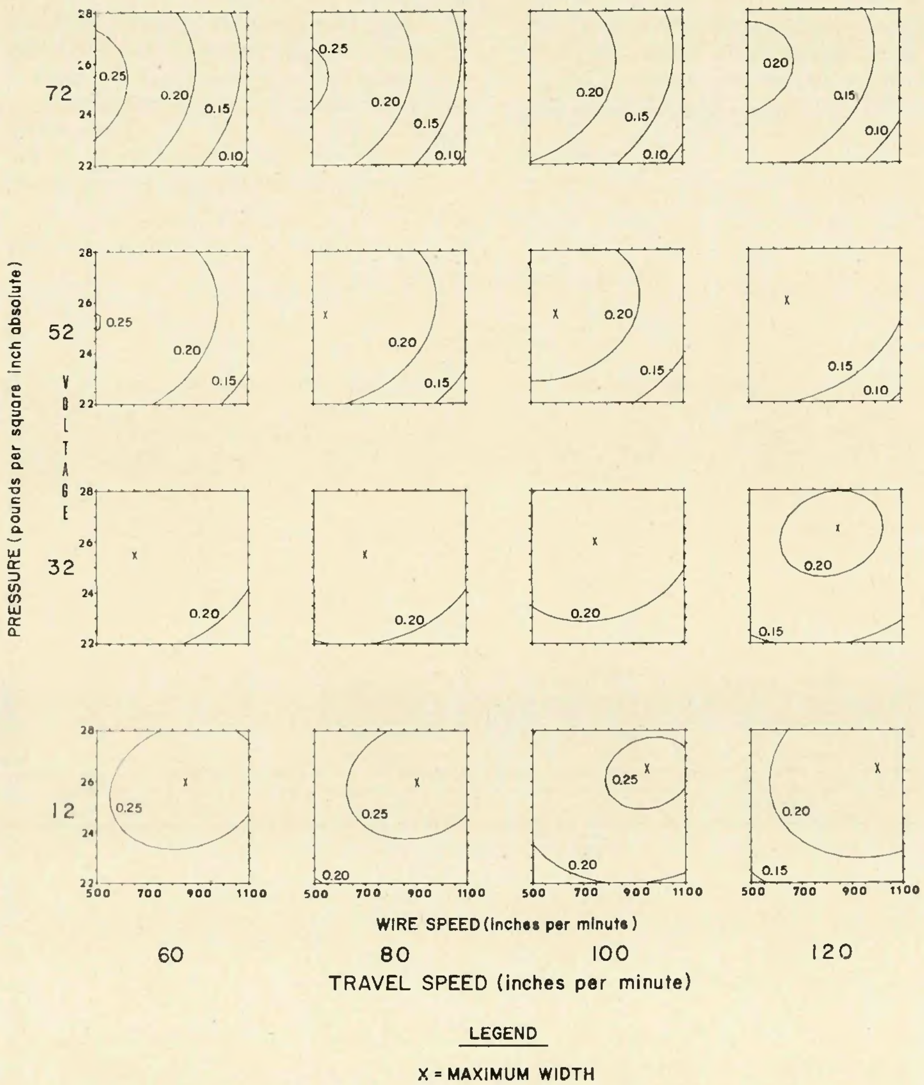

Fig. 11—Weld width, contour chart

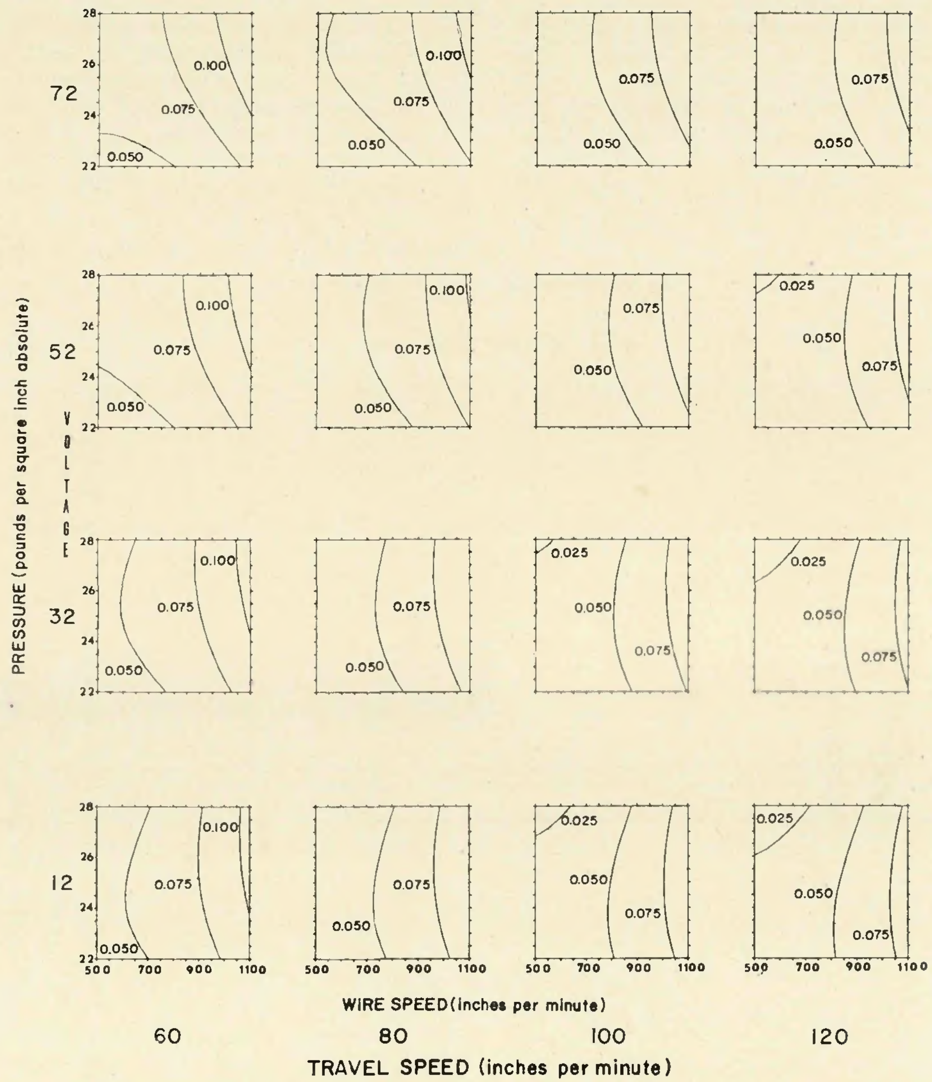

Fig. 12—Weld reinforcement, contour chart

Generally, welds with high reinforcement also exhibited poor appearance and soundness. Filler metal feed speed was the most significant factor related to each of these three responses. High filler metal feed speed gave high reinforcement and also contributed to poor appearance and soundness. By contrast, welds exhibiting low reinforcement were also sound and visually acceptable.

Weld Penetration

From Table 3, weld penetration is most affected by filler metal feed speed, and, to a lesser extent, by the other three main effects. Except for travel speed, all are directly related to the response.

Figure 13 verifies that filler metal feed speed is a significant parameter. In each of the 16 plots, the penetration is at least doubled in going from 500 to 1100 ipm filler metal speed.

The greatest penetration was 0.28 in. and occurred at 60 ipm travel speed, 72 psia pressure, 28 v, and 1100 ipm filler metal speed. However,

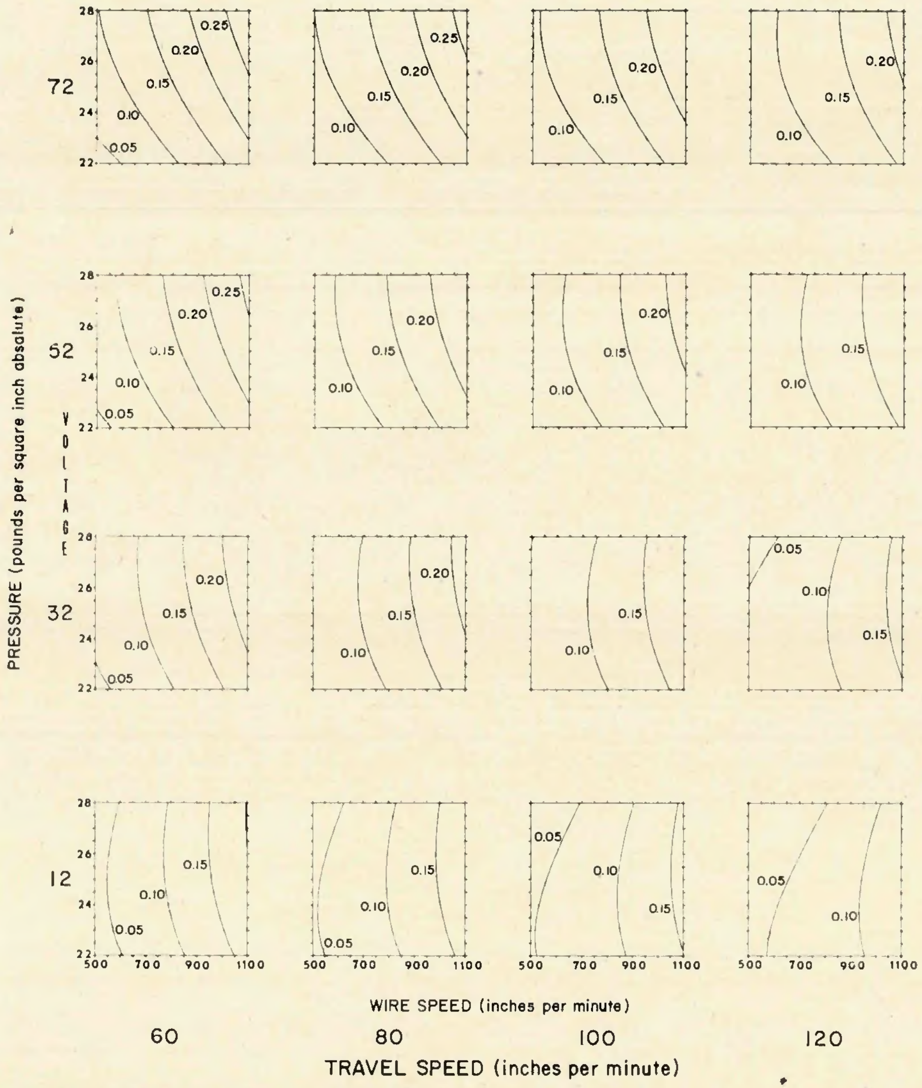

Fig. 13—Weld penetration, contour chart

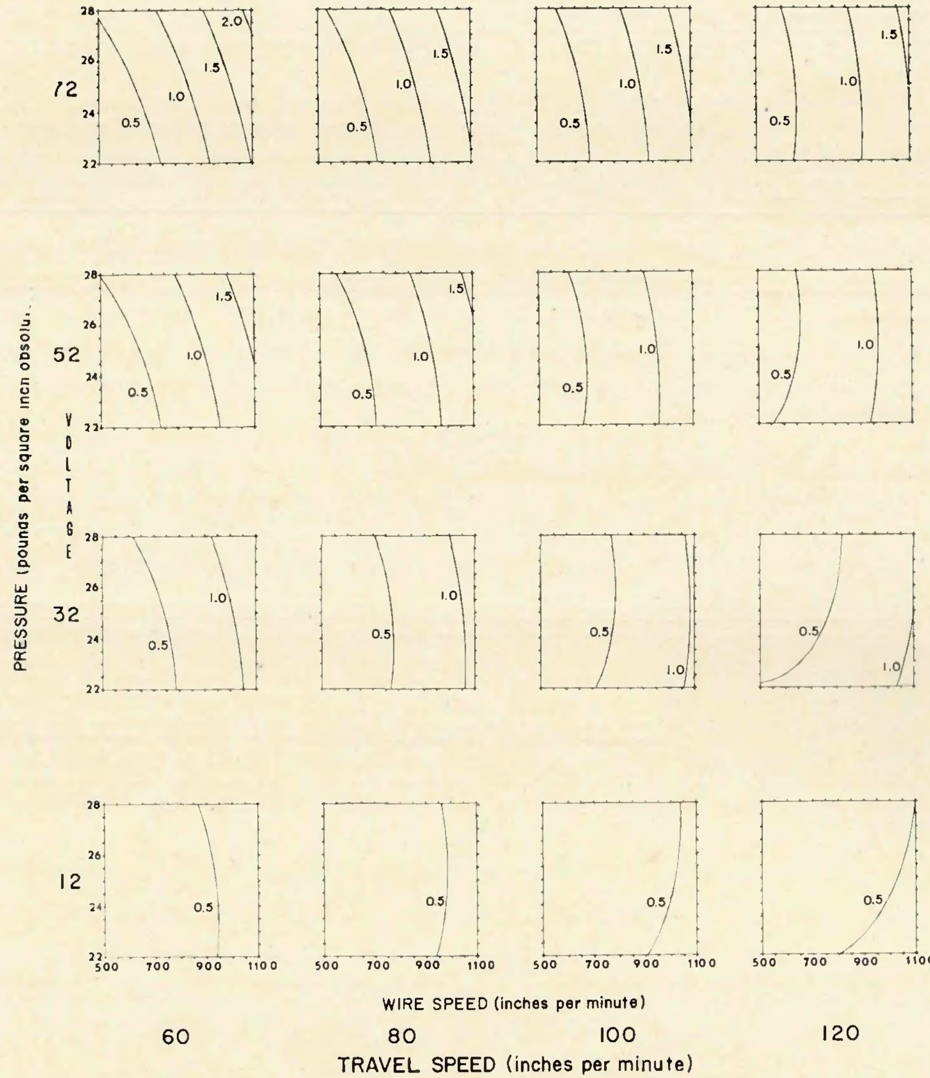

Fig. 14—Weld depth-to-width ratio, contour chart

this is also an unsatisfactory combination to produce sound, visually acceptable welds.

From Fig. 13, the least penetration is predicted to occur at 120 ipm travel speed, 12 psia pressure, 28 volts and 500 ipm filler metal feed speed. The calculated penetration at this point is 0.03 in.

Weld Depth-to-Width Ratio

Table 3 shows that increased filler metal feed speed and chamber pressure increase the weld depth-to-width ratio. Arc voltage and travel speed are also significant, but to a lesser degree. Figure 14 illustrates the trends, and the most obvious trend is that increased filler metal feed speed increases the depth-to-width ratio. Also increased chamber pressure exerts the same effect, particularly at high travel speed.

The maximum depth-to-width ratio (2.1:1) occurred at 60 ipm travel speed, 72 psia pressure, 1100 ipm filler metal speed, and 28 v. At this point, the depth (penetration) was

0.28 in. and the width was 0.13 in. However, the weld was unsatisfactory because of poor soundness and appearance.

Optimization

Finally comes the question: What combination of parameters gives the best overall weld? The question can be answered mathematically by using the equation for the calculated ratings. First, however, several restrictions or criteria must be established.

Appearance and soundness must be acceptable. Minimum responses of *4* can be established for these responses. Weld reinforcement should be minimized. This, however, can be neglected since combinations of welding parameters which resulted in good appearance, also gave low reinforcement. Good arc stability is also desired, but is synonymous with good appearance and can be neglected. For many applications, deep penetration, or more specifically, a high depth-to-width ratio is desired so that this response would be maximized. Finally, the welding parameters are restricted to practical values.

Based on these criteria, a computerized optimization program was run with the results summarized in Table 4. The first optimization gave the welding parameters which would result in a depth-to-width ratio of 1.2:1. This occurred at 29 v and 82 psia chamber pressure which were the maximums allowed for those parameters.

A second run was made with those limits raised to 32 v and 92 psia. The depth-to-width ratio was then predicted to be 1.96:1.

A third run was made with the pressure limited to one atmosphere. In this case, the depth-to-width ratio was cut to 0.65:1.

Table 4—Results of Optimization of Parameters
(Criteria: Appearance Rating—4, Soundness Rating—4, Depth-to-Width—Maximize)

	Restrictions	Results of optimization	
1. Voltage	21 to 29	29	Appearance = 4.
Filler metal feed speed, ipm	400 to 1200	800	Soundness = 4.
Travel speed, ipm	50 to 130	70	Depth-to-width = 1.2:1
Chamber pressure, psia	2 to 82	82	
2. Voltage	21 to 32	32	Appearance = 4.
Filler metal feed speed, ipm	400 to 1300	600	Soundness = 6.
Travel speed, ipm	50 to 130	60	Depth-to-width = 1.96:1
Chamber pressure, psia	12 to 92	92	
3. Voltage	21 to 29	21.7	Appearance = 4.0
Filler metal feed speed, ipm	400 to 1200	933	Soundness = 4.4
Travel speed, ipm	50 to 130	123	Depth-to-width = 0.65:1
Chamber pressure, psia	12	12	

Table 5—Standard Errors of Calculated Ratings and Measurements

Response	Ratings or measurements	Standard error[a]
General appearance	1, 2, 3, 4, 5	0.753
Weld soundness	1, 3, 5	1.05
Arc mode	1, 3, 5	0.432
Arc stability	1, 3, 5	0.978
Weld area	0.04 to 0.48	0.055
Weld width	0.110 to 0.338	0.042
Weld reinforcement	0.025 to 0.138	0.012
Weld penetration	0.025 to 0.300	0.025
Depth-to-width ratio	0.14 to 2.73	0.230

[a] Errors are in the same units as the ratings.

Discussion

It is important to realize that, although many data have been collected from the study, the results are applicable to only limited conditions. The investigation covered only one combination of aluminum alloys. No joint or weld groove was involved. The welding was all downhand. Power-supply characteristics were not varied.

An area of particular concern which would supplement the study involves arc shielding. At elevated ambient pressures, different arc-shielding techniques may be required. Also, the use of an inert gas rather than normal air to backfill the welding chamber may be beneficial.

The study was begun with an underlying thought of proving the merits of welding under pressure to eliminate porosity in aluminum welds. The results in Table 3 and Figs. 7 and 9 show there is no significant correlation between ambient pressure and weld soundness.

Added pressure is, however, beneficial for improving the depth-to-width ratio in welds while maintaining satisfactory weld appearance and soundness. Table 4 shows that a depth-to-width ratio of 1.2:1 was realized, while at atmospheric pressure the depth-to-width ratio was 0.65:1. Especially for metals that are sensitive to heat input, welding under pressure may be advantageous.

It was reassuring to find that welds exhibiting good appearance were also internally sound, and that arc stability

Table 6—Conclusions of Study to Establish Significance of Process Parameters[a]

An increase in . . .	Weld appearance	Weld soundness	Arc stability	Arc mode	Penetration	Width	Reinforcement	Area	Depth-to-width
Filler metal feed speed, (ws)	↓	↓	↓	↑	↑	↓	↑	↑	↑
Voltage, (v)	f(p)[c]	[b]	↑	↑	↑	↑	f(ws)[c]	↑	f(p.ts)[c]
Travel speed (ts)	f(p)[c]	[b]	f(v)[c]	↑	↓	↓	↓	↓	f(v)[c]
Pressure, (p)	↓	[b]	↓	↓[d]	↑	↓	f(v)[c]	↑	↑

[a] Affects shown by direction of arrows: ↑—increase in value of response; ↓—decrease in value of response.
[b] No effect on resoonse.
[c] f(p)—direction of change is function of pressure, etc.
[d] Tends toward short circuiting.

is associated with good appearance and soundness. Arc mode was not directly related to appearance, soundness or stability.

Weld metal porosity was the only type of metallographically or radiographically discovered defect. The porosity ranged from small (0.010 in. diameter) pores to larger, irregular voids. The latter were apparently caused by erratic solidification which, in turn, was caused by turbulant arc and puddle action.

Of interest was the definite correlation between even the small porosity and welding parameters. Filler metal feed rate was the only parameter significantly affecting weld soundness. Low filler metal feed speeds gave completely sound welds; high filler metal speeds gave large voids. The small pores occurred between these two extremes. Hypothetically, perhaps even the small porosity is caused by arc turbulence.

The accuracy of the results reported depends largely on the correlation between the experimental results and mathematical model derived from those results. The standard error of the calculated ratings gives an indication of how well the observed values and calculated values agree. Approximately 67% observed ratings or measurements will fall within ±1 standard error of the calculated ratings. Approximately 95% will be within ±2 standard errors. This assumes a normal distribution for the observed ratings.

Table 5 lists the standard errors of the calculated ratings. The standard errors for weld soundness and arc stability appear to be somewhat out of line. Calculated ratings of these responses should not be interpreted to be exact. However, the main objective is not to determine exact values, but to reveal trends. The indicated trends are not invalidated by inexact predicted ratings or measurements.

Conclusions

The following conclusions should be considered applicable only to the particular conditions specified in the paper. The restrictions include material, welding position, arc atmosphere, and range of welding parameters.

1. The conclusions may be summarized as shown in Table 6. The summary shows the reaction of each of the nine responses as each main factor is increased. The responses move in the direction indicated by the arrows.

2. Filler metal feed speed is the single most important factor in gas metal-arc and pressurized inert gas metal-arc welding. Increased wire speed acts to decrease weld appearance, weld soundness, arc stability, and weld deposit width and will increase weld penetration, the depth-to-width ratio, reinforcement, area, and will cause the arc to operate in the spray mode.

3. Arc voltage was the most important factor in influencing the arc mode of metal transfer. As would be expected, increased arc voltage caused the arc to operate in the spray mode. Increased arc voltage also acted to increase arc stability, weld penetration, width, and cross-sectional area.

4. Increased welding travel speed served to decrease weld penetration, width, reinforcement, and area. Spray transfer was encouraged by faster travel speed.

5. Increased chamber pressure resulted in a decrease in weld appearance, arc stability, and weld width, and an increase in depth-to-width ratio, and overall weld area.

6. Using good weld appearance and soundness as criteria, a maximum weld depth-to-width ratio would result at 29 v, 800 ipm filler metal feed speed, 70 ipm travel speed, and 92 psia chamber pressure.

7. High filler metal feed speeds (above 1000 ipm) should be avoided because of poor weld appearance and soundness above this level.

8. Weld appearance and soundness generally occur together. A deterioration in one is usually accompanied by a deterioration in the other.

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• Erokhin, A. A. and Utlinskii, G. G.: The role of nitrogen in the formation of porosity in welding austenitic Cr-Ni steels.—It is shown that the cause of porosity in austenitic welds may be saturation of the weld pool with both hydrogen and nitrogen. In the presence of titanium and aluminum in the austenitic steel the weld porosity is substantially reduced. The authors advance the hypothesis that the beneficial effect of these elements is related to an increase in the nitrogen solubility (6-8).

• Marishkin, A. K. et al.: Electrode wire burn-off in the automatic welding with systematic short-circuiting of the arc gap.—Analytical proof is presented of the independence of the burn-off coefficient of the continuous or discontinuous burning of the arc (9-11).

• Makara, A. M. et al.:Effect of a soft layer on the properties of welded joints in high strength steels.—It is shown that the ultimate strength of welded joints in thermally hardened steels depends on the adhesive strength of the soft layer which is determined by its relative width (12-14).

• Lazko, V. E.: Influence of base metal composition on the susceptibility to brittle failure of joints in high strength steels.—It is shown that the effect of the alloying elements on the mechanical properties of the weld differs from the rules applicable to the base metal. The structure and the mechanical properties of the weld metal have been studied in relation to the alloying of high strength steels with silicon, manganese, chromium and nickel (15-19).

• Gotal'skii, Yu, N. and Struina, T. A.: Carbon distribution in the fusion zone of dissimilar steels in the presence of structural heterogeneity.—Experimental data are presented which show that in the fusion zone between dissimilar steels, where as a result of heating structural heterogeneity has been produced, decarburization takes place on the side of the less highly alloyed metal. The rate of progress of these processes is a func-

(*Continued on page* 537-s)

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