Gas Metal Arc Welding Fume Generation Using Pulsed Current

Proper selection of pulsed current welding parameters can reduce fume generation rates compared to steady welding current

BY HARVEY R. CASTNER

ABSTRACT. While the fume generation rate of gas metal arc welding (GMAW) is lower than some other arc welding processes, the further reduction of welding fumes is of interest to companies using GMAW. Several researchers have reported lower fume generation rates for pulsed welding current compared to steady current. However, the range of welding parameters where these reduced fume levels can be expected has not been well documented.

This paper describes a study of the effects of pulsed welding current on the amount of welding fume and ozone produced during GMAW using a range of welding parameters. Fume generation rates were measured for steady current and pulsed current GMAW of mild steel using copper-coated ER70S-3 welding wire and 95%Ar-5%CO_2 and 85% Ar-15% CO_2 shielding gases. The amount of fume generated during welding was determined by drawing fume through a fiberglass filter using the standard procedures contained in ANSI/AWS F1.2.

Results of these measurements show that pulsed welding current can reduce fume generation rates compared to steady current. There is a range of welding voltage that produces the minimum fume generation rate for each wire feed speed with both pulsed and steady current. The data also show that using pulsed current does not guarantee lower fume generation compared to steady current. Welding parameters must be correctly controlled if pulsed current is to be used to reduce fume levels. Fillet welds were made to demonstrate that the pulsed current welding parameters that reduce fume also produce acceptable welds.

No significant difference was found in the chemical composition of fumes from pulsed current compared to steady current. Fumes generated by both types of current are mixtures of iron, manganese and silicon oxides. Measurements of ozone generation rates show that the pulsed current welding parameters that reduce fume also increase ozone generation compared to steady current welding.

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KEY WORDS

Fume Generation Rate
Steady Current GMAW
Pulsed Current GMAW
Fillet Welds
Ozone Generation
Optimum Voltage
Fume Composition
Welding Current
Welding Procedures
Pulse Parameters

Introduction

Health risks for arc welders are generally low (Ref. 1). However, some of the fumes and gases produced during arc welding can be hazardous. The nature of the hazard depends on the composition and concentration of the fume, and the length of exposure. ANSI/ASC Z49.1 (Ref. 2), OSHA (Ref. 3) and The American Conference on Governmental Industrial Hygienists (ACGIH) (Ref. 4) identify the materials that may present hazards and set limits on exposure of personnel to these materials. While the composition of welding fumes and the rate of fume generation can be estimated (if the welding process, filler metal and operating parameters are known), onsite measurements are usually needed to determine welder exposure to fumes. Exposure depends not only on the rate of fume generation, but also on ventilation and the position of the welder's breathing zone.

Companies that rely on arc welding are interested in new methods that will reduce the exposure of welders and other employees to welding fumes. Recent experience shows that permissible exposure limits for personnel can be expected to continue to decrease. There is also a need to limit the escape of process emissions into the environment.

Options available for reducing worker exposure to arc welding fumes include low-fume processes, consumables, and welding procedures, automation, or use of general and local exhaust ventilation. Not all of these options are likely to be practical for a given application. Gas tungsten arc, plasma arc and submerged arc welding processes produce very low fume levels, but these processes do not have the productivity or flexibility required for many applications. Low fume generation consumables may not be available and local exhaust ventilation systems may be cumbersome and expensive, and require extensive maintenance.

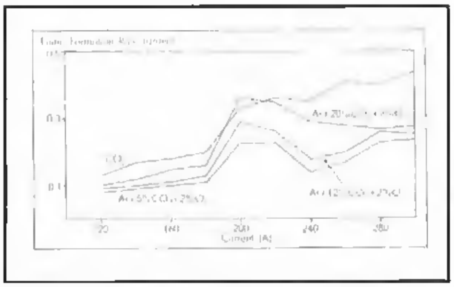

Fig. 1 — Fume generation rate for GMAW (Source: Hilton and Plumridge).

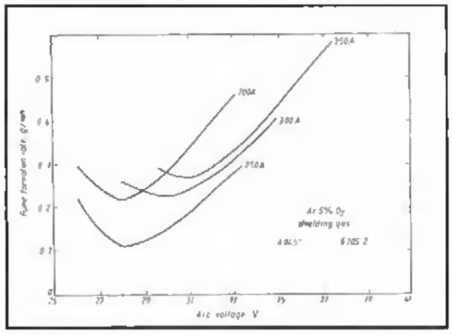

Fig. 2 — Effect of voltage and current on fume generation rate for GMAW with argon-oxygen shielding gas (Source: Heile and Hill).

Gas metal arc welding (GMAW) is one of the most widely used welding processes because of its productivity and flexibility. GMAW usually produces less fume than the shielded metal arc welding (SMAW) or flux cored arc welding (FCAW) processes (Refs. 5, 6). The fume generation rate of GMAW is satisfactory for many applications. However, welding on metals that have very low permissible exposure limits, welding in confined areas, use of high welding current, or high duty cycles can generate higher than acceptable fume levels.

Process controls that can further reduce GMAW fumes would be of great benefit. Studies that are mentioned in the next section of this report describe lower fume generation rates for pulsed GMAW compared with steady current GMAW. However, these studies have not quantified the effect of welding parameters on fume generation nor the range of welding parameters where reduced fume levels can be expected.

This paper describes studies of the effects of pulsed welding current on GMAW fume and ozone generation rates. The work involved measurement of fume and ozone generation rates for pulsed current and steady current GMAW, using a range of welding parameters and pulse parameters. The goal was to study how pulsed current GMAW parameters influence fume and ozone generation, and to determine to what extent pulsed current can be used to minimize fume generation.

Background Information on GMAW Fume Generation

GMAW fumes are complex oxides and metal vapors that originate predominately from the welding wire. The base metal usually contributes less than 10% to total fume, so the base metal has very little influence on the volume of arc welding fume. Volatile coatings such as paint, plastic, primer, rust, oil, or zinc on the surface of the base metal can cause significant increases in fume. The type of metal being welded also can influence the hazard level of the fume because the base metal and the welding electrode wire are usually similar in composition.

Fume particles are small enough to become suspended in the air and inhaled by welders or other personnel. Ozone is a respiratory irritant that is generated during arc welding by the reaction of ultraviolet light emitted from the arc on the oxygen in the air (Ref. 7). The composition of welding fumes and the rates of generation of fumes and ozone depend on the process and operating parameters as well as the base and filler metals.

A number of studies has been conducted on GMAW fume formation for steady (nonpulsed) welding current (Refs. 5, 6, 8–10). In the mid-1970s, Heile and Hill (Ref. 5) studied the formation of GMAW fume. They reported that elements in the welding wire are vaporized as droplets of the wire are transferred through the arc to the weld pool. These vapors are oxidized by oxygen that may be present in the arc atmosphere or in the air surrounding the arc. Heile and Hill found that the rate of GMAW fume generation was a function of volatile elements in the welding wire, welding current, arc voltage, shielding gas coverage, shielding gas composition and mode of metal transfer. While some condensation of fume particles does occur, Heile and Hill reported (Ref. 5) only 1% of fume particles are larger than 1 micrometer.

Gray, Hewitt and Dare (Ref. 11) divided arc welding fumes into fractionated and unfractionated portions. Fractionated fume comes from vaporized materials in the arc. The formation of this portion of the fume is influenced by the vapor pressure of elements in the welding wire and the oxidation potential of the arc atmosphere. The authors believed that the unfractionated portion of fume comes from evaporation and combustion of ejected spatter particles.

Effects of Major Process Variables on Fume Generation Rate

Welding wire composition: Vaporization in the arc is controlled by temperature, vapor pressure and latent heat of vaporization of the elements involved. The welding wire is the main source of GMAW fume because the elements in the wire are exposed to extremely high temperatures in the arc. Heile and Hill studied the influence of the vapor pressures of elements in the welding wire on the volume and the composition of fume. They found that welding wires that contain the most volatile elements generate more fume than those with less volatile elements. They used the vapor pressures of iron and manganese to explain the percentages of these elements in mild steel welding fume. Vapor pressures also explain why welding aluminum with silicon-aluminum filler metals generates much lower levels of fume than does magnesium-aluminum filler metals.

Welding current: Fume generation rate usually increases with increasing welding current for two reasons: 1) increased welding current increases the arc temperature, vaporizing more of the materials in the arc; and 2) increased welding current increases the melting rate of the electrode so that a larger quantity of material passes through the arc in a unit time. Figure 1 shows that fume generation rate increases continuously with increased steady welding current for GMAW with CO_2 shielding gas. Figures 1 and 2 show that the influence of welding current on fume generation rate is more complicated for argon-based shielding gases. There is one level of steady welding current that produces the minimum fume generation rate for argon-based shielding gases. Pulsed welding current has been reported to produce low levels of fume (Refs. 11–13). Moreton and Spiller (Ref. 12) discovered that pulsed welding current produced very-low fume generation rates for GMAW of stainless steel and suggested that pulsed current offered a way of reducing fume without sacrificing productivity. They also pointed out that pulsed current generally results in increased levels of ozone.

Arc voltage: Fume generation rate increases with arc voltage for CO_2 shielding gas. Increased voltage increases arc temperature and lengthens the arc so that molten droplets are exposed to the arc for a longer time of flight. Both factors increase vaporization and therefore fumes. Figure 2 shows that the fume generation rate goes through a minimum value at a specific level of arc voltage for each level of steady welding current with argon-based shielding gases.

Shielding gas composition: Differences in the oxidation potential of the arc atmosphere affect the rate of GMAW fume generation and the percentages of some elements in fume (Refs. 5, 9). Figure 1 shows that CO_2 shielding gas produces more fume than argon-based shielding gases. This figure also shows that the higher the percentage of CO_2 in the shielding gas the higher the fume generation rate. Heile and Hill found that mild steel fume using CO_2 shielding gas has a higher silicon content than fume from an argon-based shielding gas due to the higher oxidation rate of silicon in the higher oxygen content arc atmosphere. Gray (Refs. 8, 11) believed that a portion of the higher fume generation rate produced by CO_2 shielding gas was due to higher spatter levels.

Shielding gas coverage: Effective shielding gas coverage will minimize GMAW fume generation because less oxygen is entrained from the atmosphere. Argon provides better shielding than lower density helium or argon-helium mixtures. Hilton and Plumridge (Ref. 9), and Moreton and Spiller (Ref. 12) found that the rate of GMAW fume generation increased when helium shielding gas mixtures are used to weld stainless steels and aluminum alloys. Helium in the shielding gas also tends to increase arc length and arc energy, which increases fume generation. Larger gas nozzles and higher flow rates of argon-based shielding gases will improve gas coverage and minimize fume. Increased gas flow rates are not effective in reducing fume with helium-based gases because of increased turbulence and the lighter gas density.

Mode of metal transfer and arc stability: Welding conditions that produce a stable arc, droplet spray transfer, and low levels of spatter produce minimum fume. Unstable arcs tend to increase fume generation because they entrain more air in the arc atmosphere. There is some difference of opinion (Refs. 5, 9, 11) on how the mode of metal transfer influences fume generation, but it is agreed that short circuiting transfer and droplet spray transfer generate low fume levels. Globular transfer produces higher fume generation rates than either short circuit or spray transfer modes. Globular transfer in CO_2 shielding gases produces high levels of fume because molten metal droplets are large and remain attached to the tip of the welding electrode wire for relatively long periods of time. This mode of transfer also produces high spatter levels. While droplet spray transfer gives minimum fume generation rates, as welding current and arc voltage increases for spray transfer, fume generation rate also increases to quite high levels.

Summary: Shielding gas composition, welding current, and arc voltage influence the mode of metal transfer and, therefore, the size and temperature of metal droplets transferred through the arc, the time for the droplet to transfer through the arc, and the degree of spatter. Fume generation for steady current GMAW can be summarized as follows:

Fume generation rate is low for short circuit transfer. Metal transfer is by short circuits at low welding currents and low voltages. Deposition rate is low so the total amount of welding electrode wire melted is not large. Spatter occurs, but at a relatively low level.

As steady welding current and voltage increase, deposition rate increases, metal transfer is globular, spatter increases and fume generation rate increases. If the shielding gas is CO_2, the fume generation rate continues to increase with current and voltage. If an argon-based shielding gas is used, increased current eventually results in a transition to spray metal transfer. Spatter and fume generation rate dramatically decrease as metal transfer changes to droplet spray. Heile and Hill (Ref. 5) believe this decrease in fume generation rate is due to a dramatic decrease in the surface area of molten drops exposed to the arc. Gray, Hewitt and Dare (Ref. 11) attribute the decrease in fume generation rate to reduced spatter. Ma and Apps (Ref. 11) state that droplet spray transfer imparts the minimum amount of energy to each molten drop and generates less fume than streaming spray.

Fume generation rate increases in the spray transfer mode with increases in welding current and voltage when argon-based shielding gases are used.

Experimental Procedure

Fume Generation Rate Test Procedure

During this project, fume generation rate (FGR) was measured for steady current and pulsed current GMAW using the standard procedures contained in ANSI/AWS F1.2, *Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes*. Figure 3 shows the general arrangement of the fume chamber. This measurement method draws fume that is generated during bead-on-plate welding through a fiberglass filter. The amount of fume generated during each test is determined by comparing the weight of the filter before and after exposure to the fume.

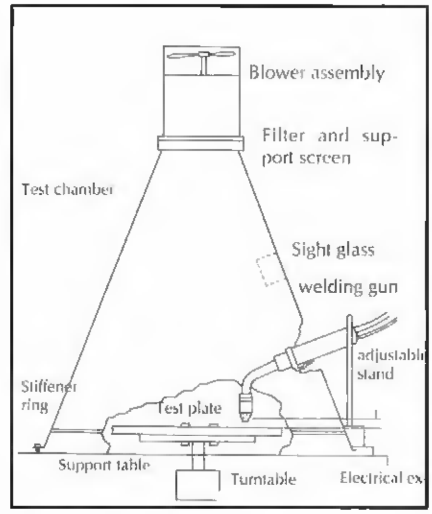

Fig. 3 — Fume generation rate measurement chamber (Source: ANSI/AWS F1.2)

The procedure in ANSI/AWS F1.2 was chosen because it is a U.S. standard, and this facilitates comparisons with data from similar studies. Fume generation rate data in the United Kingdom are usually obtained from fillet welds on T-joints using methods specified in British Standard BS7384. Although the procedures in ANSI/AWS F1.2 and BS7384 are similar, fume collected from T-joints is only 70 to 92% of that collected from bead-on-plate tests because fume accumulates on the vertical and horizontal plates.

ANSI/AWS F1.2 is described as measuring "total fume generation rates," yet not all fume is captured in the filter. Some fume is deposited on the sides of the fume chamber and on the plate being welded. Tests were made to determine the amount of fume deposited on the chamber walls. A clean filter was used to wipe the fume from the walls of the chamber. This filter was weighed before and after being used to wipe the walls. Multiple tests indicated that the weight of fume that is deposited on the walls of the chamber is from 7 to 10% of the weight of fume collected in the primary filter and reported as fume generation rate.

A number of tests were made to determine the amount of fume deposited on the test plate itself. The fume was removed by wiping the surface of the plate with a clean filter and weighing the filter. These tests indicate that the test plate collects from 25 to 40% of the weight of fume collected in the primary filter. One argument for not including the fume deposited on the test plate in total fume generation rate data is that this fume will not be released into the atmosphere. If one is concerned with disposal of total fume, however, it may need to be con-

Table 1 — Power Sources Used for Experiments

Power Source	Description	Output Rating	Current Levels
A	CV/CC Inverter	300 A @ 32V 100% Duty Cycle	400A Peak Current 60A Background Current
B	CV Inverter	450 A @ 38V 60% Duty Cycle 350 A @ 34V 100% Duty Cycle	400A Peak Current 50A Background Current
C	CV/CC Inverter	400 A @ 36V 60% Duty Cycle	425A Peak Current 50A Background Current
D	CV/CC Inverter	450 A @ 38V 100% Duty Cycle	650A peak current 50A background current

sidered.

It has been reported that the particle size of fume from pulsed current GMAW is smaller than the particle size from steady current GMAW (Refs. 10, 13). There was some question whether the filter material specified by ANSI/AWS F1.2 was capable of capturing all of the fume generated during pulsed current welding. Tests were conducted using two filters in the fume chamber to determine if any fume passed through the first filter. No fume was collected in the second filter in any of these tests, confirming that the filters used were suitable to capture the fume generated.

Despite the deposition of fume on test plates and chamber walls, the test method specified in ANSI/AWS F1.2 can be used to reliably compare the total airborne fume generation rates for steady current and pulsed current GMAW under the conditions studied.

Calibration of the Fume Chamber

ANSI/AWS F1.2 includes a standard procedure that was used to calibrate the laboratory fume chamber at regular intervals. Calibration involves measuring the fume generation rate for GMA welds under standard conditions with 0.045-in. (1.2-mm) diameter ER70S-3 electrode wire and CO_2 shielding gas at a flow rate of 35 ft^3/h (16.5 L/min). Welding parameters were: a travel speed of 14 in./min (6 mm/s), a wire feed speed of 300 in./min (127 mm/s), and voltages of 24 and 26 V. The calibration tests showed that the fume chamber was within the specified fume generation rate range of $\pm$10% of 0.43 and 0.55 g/min for 24.0 and 26.0 V, respectively.

Welding Equipment and Materials Used for Tests

Fume generation rates for both steady current GMAW and pulsed current GMAW were measured by making bead-on-plate welds using the power sources listed in Table 1. These pulsed current welding power sources represent a range of pulse waveforms indicative of commercial equipment. The peak and background current levels for these power sources are shown in Table 1.

All fume generation rate test welds were made on 0.5-in. (12-mm) thick A36 plate. Typical composition for A36 is: 0.2C, 0.6 Mn, 0.015 S, 0.2 P, 0.25 Si. The surface of each plate was ground to remove scale prior to welding. The welding wire was 0.045-in (1.2-mm) diameter, copper-coated ER70S-3 and purchased from a single manufacturer. A typical composition for this wire is: 0.07 C, 1.1 Mn, 0.015S, 0.015P, 0.5 Si. Shielding gas was 95%Ar-5%CO_2 and 85%Ar-5%CO_2.

Recording Test Conditions and Welding Parameters

All welding parameters, as well as filter weights before and after welding, were recorded for each test. The filter media was 0.5-in. (12-mm) thick Type-1, fiberglass insulation that conforms to MIL-B 5924. Filters were dried in an oven at 250°F (120°C) for at least one hour prior to use. After the filter pads were removed from the oven, they were cooled in still air to room temperature and placed in sealed plastic bags until ready for use. The filters were weighed, exposed to fume in the chamber and reweighed. Fume generation is determined by the change in weight of the filter.

Welding current, voltage and wire feed speed, arc stability, and spatter levels were recorded for each test. Representative current and voltage waveforms were recorded for each power source and test condition with a computerized data acquisition system at a sampling rate of 5000 Hz.

Measurement of Fume Generation Rates

Fume generation rates were measured for steady current GMAW and pulsed current GMAW at wire feed speeds of: 180, 230, 260, 410, 500 and 600 in./min (76, 97, 110, 174, 212, 254 mm/s). These wire feed speeds were selected to cover short circuit metal transfer as well as globular and spray modes of metal transfer. Fume generation rates were measured for a range of arc voltages for each wire feed speed and type of current to determine the effects of voltage on fume generation rate. Tables 2 and 3 summarize the ranges of test parameters. The range of arc voltages studied is much wider than would be of practical use for most welding operations, but was chosen to ensure a comprehensive investigation of the fume generation characteristics of the process and power sources.

At least two tests were conducted for each welding condition. Some test conditions were repeated as many as ten times to confirm results. Test welds were conducted for 60 s each at wire feed speeds of 180, 230, 260 and 410 in./min (76, 97, 110, 174 mm/s), and for 30 s at wire feed speeds of 500 and 600 in./min (212 and 254 mm/s). Welding torch angles and contact tip-to-work distance were constant for all tests. Contact tip-to-work distance was 0.75 in. (19 mm). Travel speeds were 14 or 16 in./min (6 or 7 mm/s). A single shielding gas flow rate of 40 ft^3/h (19 L/min) was used for all tests. The inside diameter of the torch gas nozzle was 0.75-in. (19 mm).

Weld deposition rates were measured for each set of welding conditions so that fume generation rates could be computed in milligrams per gram (mg/g) of deposited weld metal, permitting a comparison of data with those produced by other researchers. The influence of pulse parameters on fume generation rate was studied using power source B by changing pulse width, pulse frequency and peak current. Fume generation rates were measured over a range of voltages at wire feed speeds of 260 and 410 in./min. The influence of changes in contact tip-to-work distance on fume generation rate also was investigated. Fume generation rates were measured using power source B with contact tip-to-work distances of 0.75 in. ±0.25 in. (19 mm ±6 mm) in 0.125-in. (3-mm) increments.

Fume Composition Measurements

Fume samples were collected from tests made with pulsed current and steady current for chemical analysis of the fume composition. Sample No. 1 was produced with pulsed current at a wire feed speed of 260 in./min (110 mm/s) and 24 V, and represents the minimum fume generation rate conditions for power source B. Sample No. 2 was produced at the same wire feed speed and a higher voltage. Sample No. 3 was produced with steady current at 410 in./min and 30 V, and Sample No. 4 with pulsed current

Table 2 — Summary of Test Conditions with Argon 5% CO_2 Shielding Gas

Power Source	Wire Feed Speed in./min (mm/s)	Voltage Pulsed Current	Voltage Steady Current
	180 (76)	16–26	20
	230 (97)	20–28	24
A	250 (106)	—	20–32
	410 (174)	32	32
	500 (212)	28–33	28–33
B	260 (110)	23–28	—
	410 (174)	25–31	—

Table 3 — Summary of Test Conditions with Argon 15% CO_2 Shielding Gas

Power Source	Wire Feed Speed in./min (mm/s)	Voltage Pulsed Current	Voltage Steady Current
B	180 (76)	20–25	17–26
	260 (110)	22–29	24–32
A,B,C	410 (174)	24–33	22–32
B	500 (212)	27–32	28–32
D	410 (174)	27–32	27–34
	500 (212)	25–32	28–36
	600 (254)	30–36	30–37

at 410 in./min and 28 V. Both conditions are the minimum fume generation rate for this wire feed speed. These samples were analyzed by x-ray fluorescence spectrometry.

Fillet Weld Tests

Mechanized fillet welds were made using pulsed current and power source B to confirm that the same welding parameters that generate low fume levels also produce acceptable welds. The welds were made on 0.25-in. (6-mm) thick mild steel T-joints positioned flat. Fillet welds were made using welding conditions that produced minimum fume generation rate at 260 in./min wire feed speed and 24 V, and 410 in./min wire feed speed and 27 V. Additional welds were made at a wire feed speed of 260 in./min and at voltages from 22 to 26 V, and at 410 in./min for voltages from 25 to 29 V. Weld bead appearance, spatter, and visible fume were recorded for each weld.

Ozone Generation Rate Tests

Ozone generation during pulsed current and steady current welding was measured using a chemiluminescence ozone meter. Welds were made in a booth to prevent air currents from influencing the measurements. The ozone sensor was placed 18 in. (457 mm) from the arc at an angle of 45 deg from the horizontal. An initial screening test confirmed that 45 deg was the optimum placement of the sensor. This placement gave higher ozone readings than either zero or 90 deg. This sensor placement also agrees with that used by other researchers (Ref. 6). Lower ozone measurements would be recorded if the sensor was moved farther from the arc and higher readings if the sensor was placed closer to the arc. Closer placement of the sensor was precluded because of possible heat damage to the sensor.

Bead-on-plate welds were made on cleaned steel plate with power source B. Shielding gas was 85% Ar-15% CO_2 and the electrode wire was 0.045-in. (1.2 mm) diameter ER70S-3. Ozone levels were recorded at 30 s intervals for 3 min of arc time. Welding conditions were those that produced low fume generation rates. Welds were made with steady current and pulsed current at wire feed speeds of 260 and 410 in./min. The initial voltage was the voltage found to give the minimum fume generation rate for each wire feed speed. Voltage was varied ±2.0 V from the initial value in 1.0 V increments during the tests.

Experimental Results

Fume Generation Rate Test Results

The results of fume generation rate tests in grams per minute are presented graphically in Figs. 4–11. Least-squares curve-fitting algorithms were used to obtain a best fit of data points to first-order through fourth-order polynomial equations. Each figure displays fume generation rates for steady and pulsed current as functions of voltage. Data in each figure represent a single wire feed speed. Some of the figures contain data from one power source and some include data from several power sources. Pulsed current and voltage waveforms are shown in Figs. 12 – 17 for selected power sources, wire feed speeds and voltages. Tables 4 and 5 contain fume generation rate data from selected tests using power sources B and D. The tables list the quantity of fume produced in three ways:

1) Fume generated per unit time in grams per minute (g/min),

2) Fume generated in milligrams per gram (mg/g) of welding wire melted, and

3) Fume generated in milligrams per gram (mg/g) of weld metal deposited.

Fume Generation Rate Results

Figure 4 compares fume generation rates for power source B using steady current with rates with pulsed current for power sources A, B and C. The electrode wire was 0.045-in. (1.2-mm) diameter ER70S-3 at a wire feed speed of 260 in./min. The shielding gas was 85% Ar-15% CO_2. The minimum fume generation rate for steady current at this wire feed speed is about 0.2 g/min and occurs at about 27 V. The minimum fume generation rates for all three power sources with pulsed current are between 0.1 and 0.12 g/min. These minimum values occur at about 26 V for power sources A and C, and 24.5 V for power source B.

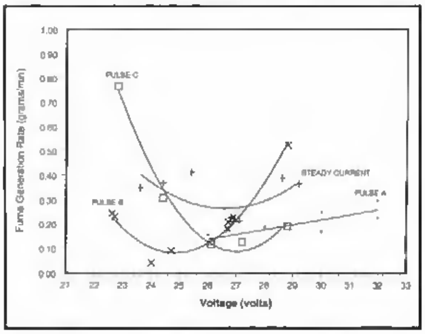

Fig. 4 — Fume generation rate for pulsed and steady current at 260 in./min wire feed speed with power sources A, B and C, ER70S-3 wire and Ar/15% CO_2 gas.

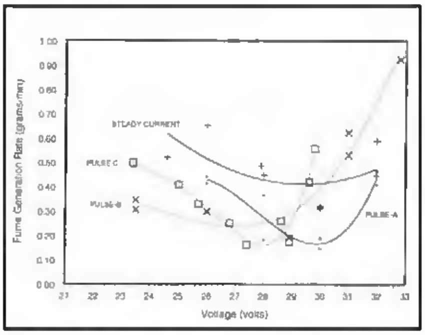

Fig. 5 — Fume generation rate for pulsed and steady current at 410 in./min wire feed speed with power sources A, B and C, ER70S-3 wire and Ar/15% CO_2 gas.

Table 4 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source B, 0.045-in. (1.2-mm) Diameter ER70S-3 Electrode Wire and Argon 15% CO_2 Shielding Gas

WFS in./min (mm/s)	Average Voltage (V)	Average Current (A)	Fume Generation Rate: Per Unit Time[1] (g/min)	Fume Generation Rate: Per Gram of Wire[2] (mg/g)	Fume Generation Rate: Per Gram of Deposit[3] (mg/g)
Pulsed Current					
180 (76)	20.5	131	0.253	6.73	7.07
180 (76)	22.7	135	0.063	1.68	1.76
180 (76)	24.6	144	0.079	2.10	2.12
Steady Current					
180 (76)	17.5	184	0.110	2.93	3.07
180 (76)	20.8	183	0.268	7.13	7.49
180 (76)	22.8	179	0.304	8.08	8.49
180 (76)	25.5	179	0.420	11.17	11.73
Pulsed Current					
260 (110)	22.6	192	0.243	4.47	4.70
260 (110)	24.0	199	0.042	0.77	0.81
260 (110)	24.7	198	0.090	1.66	1.74
260 (110)	26.7	214	0.178	3.28	3.44
260 (110)	26.7	208	0.208	3.83	4.02
260 (110)	26.9	219	0.228	4.20	4.41
260 (110)	28.8	232	0.46	8.47	8.54
260 (110)	28.8	232	0.51	9.39	9.47
260 (110)	29.0	222	0.442	8.14	8.20
Steady Current					
260 (110)	24.4	225	0.369	6.79	7.14
260 (110)	26.8	232	0.225	4.14	4.35
260 (110)	27.1	233	0.211	3.88	4.08
260 (110)	28.4	263	0.491	9.04	9.11
260 (110)	29.6	241	0.508	9.35	9.43
Pulsed Current					
410 (174)	23.5	273	0.304	3.55	3.73
410 (174)	26.0	275	0.297	3.47	3.64
410 (174)	28.9	304	0.189	2.21	2.22
410 (174)	31.0	324	0.529	6.18	6.23
Steady Current					
410 (174)	21.8	292	0.590	6.89	7.24
410 (174)	26.6	315	0.452	5.28	5.54
410 (174)	28.1	300	0.433	5.06	5.31
Pulsed Current					
500 (212)	28.8	334	0.286	2.74	2.88
500 (212)	30.0	340	0.206	1.97	2.07
500 (212)	30.9	328	0.249	2.38	2.40
500 (212)	32.0	336	0.779	7.46	7.52
Steady Current					
500 (212)	28.3	366	0.183	1.75	1.84
500 (212)	30.0	363	0.179	1.71	1.80
500 (212)	31.9	378	0.522	5.00	5.04

1) fume generated per unit time in grams per minute (g/min),
2) fume generated in milligrams of fume per gram of filler wire melted (mg/g) and;
3) in milligrams of fume per gram of weld metal deposited.

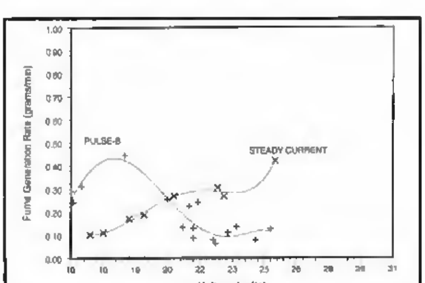

Fig. 6 — Fume generation rate for pulsed and steady current at 180 in./min wire feed speed with power source B, ER70S-3 wire and Ar/15% CO_2 gas.

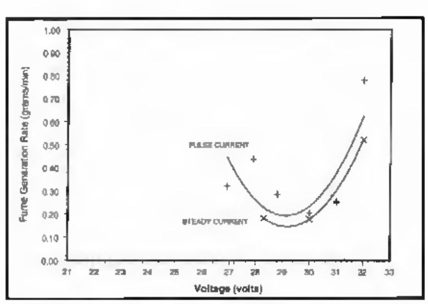

Fig. 7 — Fume generation rate for pulsed and steady current at 500 in./min wire feed speed with power source B, ER70S-3 wire and Ar/15% CO_2 gas.

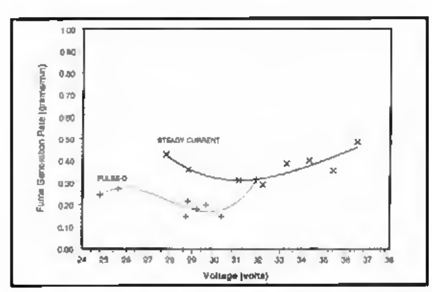

Fig. 8 — Fume generation rate for pulsed and steady current at 500 in./min wire feed speed with power source D, ER70S-3 wire and Ar/15% CO_2 gas.

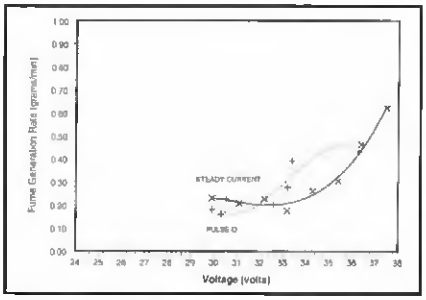

Fig. 9 — Fume generation rate for pulsed and steady current at 600 in./min wire feed speed with power source D, ER70S-3 wire and Ar/15% CO_2 gas.

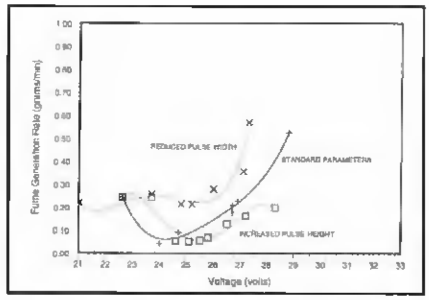

Fig. 10 — Fume generation rate as a function of pulse waveform at 260 in./min wire feed speed with power source B, ER70S-3 wire and Ar/15% CO_2 gas.

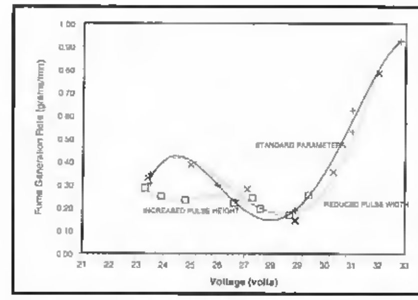

Fig. 11 — Fume generation rate as a function of pulse waveform at 410 in./min wire feed speed with power source B, ER70S-3 wire and Ar/15% CO_2 gas.

Figure 5 shows fume generation rates for 85% Ar-15% CO_2 shielding gas and 0.045-in. (1.2-mm) diameter ER70S-3 wire at a wire feed speed of 410 in./min using pulsed current for power sources A, B and C. The figure also shows the fume generation rate for steady current for power source A. The minimum fume generation rate for power source A using steady current at this wire feed speed is about 0.3 g/min and occurs at about 30 V. The minimum fume generation rates for pulsed current are between 0.15 g/min and 0.19 g/min. These minimum values occur at between 27 and 29 V.

Figure 6 gives fume generation rates for pulsed and steady current using power source B at a wire feed speed of 180 in./min with 0.045-in. (1.2-mm) diameter ER70S-3 wire and 85% Ar-15% CO_2 shielding gas. Fume generation rate is low with steady current at low voltages due to short circuiting transfer. Steady current fume generation rate gradually increases with voltage and the occurrence of globular transfer. Average welding current was between 150 and 180 A for these tests. Voltages below 20 V generated higher levels of fume with pulsed current than with steady current because these low voltages resulted in high spatter levels. It is probably not practical to use pulsed current at these low voltages because of the high spatter levels, but the data show that use of pulsed current alone does not guarantee low fume generation rates. Voltages above 21 V generally resulted in spray metal transfer with pulsed current and fume generation rates were about 0.1 g/min.

Fume generation rates for power source B using 85% Ar-15% CO_2 shielding gas at 500 in./min wire feed speed are shown in Fig. 7. The data show little difference between pulsed and steady current. Power sources A and C produced similar results at this wire feed speed. A wire feed speed of 500 in./min requires an average welding current that is near the maximum current capability of all these power sources. Figure 15 shows the current and voltage waveforms of power source B at a wire feed speed of 500 in./min. These waveforms are not the regular, rectangular waveforms that are generated at lower wire feed speeds.

Figure 8 shows fume generation rates for pulsed and steady current for power source D at a wire feed speed of 500 in./min. The minimum fume generation rate with pulsed current is lower (about 0.2 g/min) than it is for steady current (about 0.3 g/min) with this power source. The current and voltage waveforms are shown in Fig. 16.

Figure 9 contains the fume generation rates for pulsed and steady current using power source D at a wire feed speed of 600 in./min (254 mm/s). There is not a significant difference in the fume generation rates for either type of current at this wire feed speed.

The influence of pulse parameters on fume generation rate was investigated using power source B. The results are shown in Figs. 10 and 11. Figure 10 compares the fume generation rate for the original preprogrammed pulse parameters with two modified pulse parameter conditions: 1) reduced pulse width; and 2) increased pulse height. For one set of tests, the pulse parameters were modified by reducing pulse width from 2.2 to 2.0 ms. These changes in pulse width influenced arc stability and, as shown in Fig. 10, increased the fume generation rate. Tests were conducted by increasing the pulse height to the maximum achievable and increasing the peak current from approximately 400 to 420 A. This change caused the fume generation rate curve to shift to the right by approximately 1.5 V but did not make a significant difference in the minimum fume generation rate. Figure 11 shows only a slight change in fume generation rate with similar changes in pulse parameters at 410 in./min. Reducing pulse width shifted the curve to the right by approximately 1 V and increasing the pulse height produced lower fume generation rates only at low voltages. However, the minimum fume generation rate for all three conditions is approximately the same at 410 in./min (174mm/s).

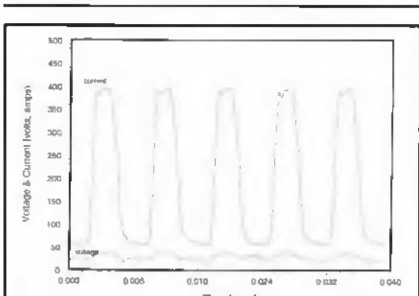

Fig. 12 — Voltage and current waveform for power source A at 260 in./min wire feed speed and 26 V with ER70S-3 wire and Ar/15% CO_2 gas.

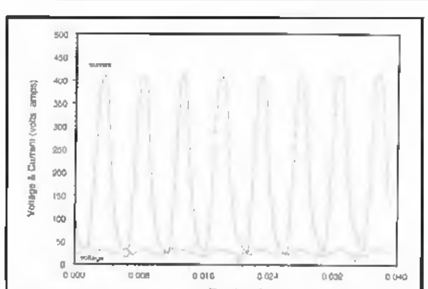

Fig. 13 — Voltage and current waveform for power source B at 260 in./min wire feed speed and 25 V with ER70S-3 wire and Ar/15% CO_2 gas.

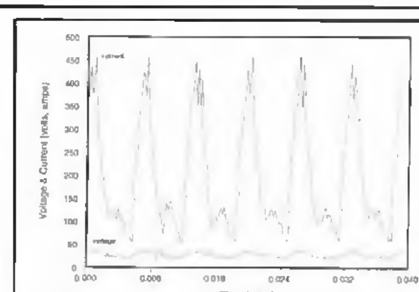

Fig. 14 — Voltage and current waveform for power source C at 260 in./min wire feed speed and 25 V with ER70S-3 wire and Ar/15% CO_2 gas.

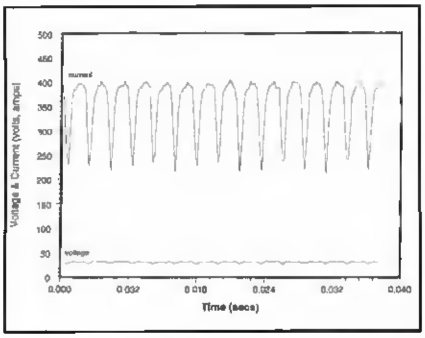

Fig. 15 — Voltage and current waveform for power source B at 500 in/min wire feed speed and 30 V with ER70S-3 wire and Ar/15% CO_2 gas.

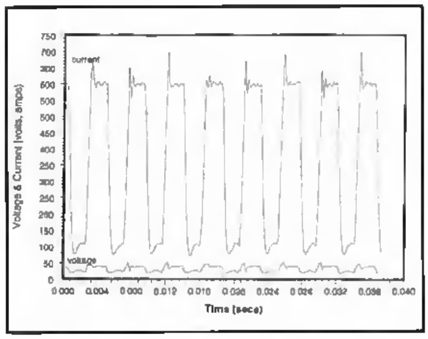

Fig. 16 — Voltage and current waveform for power source D at 500 in./min wire feed speed and 30 V with ER70S-3 wire abd Ar/15% CO_2 gas.

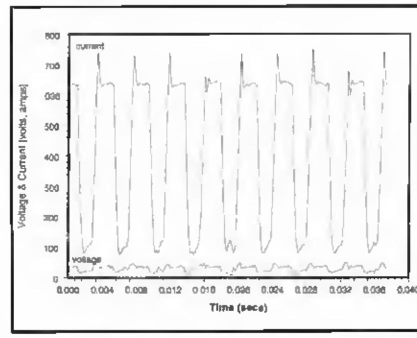

Fig. 16 — Voltage and current waveform for power source D at 500 in./min wire feed speed and 30 V with ER70S-3 wire and Ar/15% CO_2 gas.

Changes in contact tip-to-work distance of as much as ± 0.25 in. did not have a significant influence on the fume generation rate using pulsed welding current, as shown in Table 6. It is reasonable to expect that changes in contact tip-to-work distance would increase fume generation rate if these changes increase welding current, increase arc voltage, reduce arc stability or increase spatter.

Fume Composition Measurements

Table 7 contains the chemical compositions of fumes generated with both pulsed and steady current. Compositions were determined by x-ray fluorescence spectrometry. These fumes are primarily oxides of iron, manganese and silicon. Since the wire is copper coated, a small percentage of copper oxide is present as well. The data show no significant difference in the composition of fume generated with pulsed current compared to steady current. The table also shows that the compositions of the fumes generated during this project agree with the compositions for GMAW fumes from ER70S-3 electrodes and argon-based shielding gas that are reported from other studies (Ref. 14).

Results from Fillet Weld Tests

Mechanized fillet welds were made on T-joints using pulsed current with power source B to demonstrate that the welding parameters that generate low levels of fumes also produce acceptable welds. First, fillet welds were deposited using the welding conditions that produce minimum fume. These conditions were: 24 V at a wire feed speed of 260 in./min (mm/s) and 27 V at 410 in./min. The fillet welds made using these parameters had acceptable appearance and profiles. Acceptable welds were also made at 260 in./min and 23.5 V, and at 410 in./min and 26.5 V. These voltages (23.5 V at 260 in./min and 26.5 V at 410 in./min) were determined to be the lower bound of the useful voltage range because lower voltages resulted in unacceptable spatter. Increasing arc voltage above the initial settings by as much as 2 V (26 V at 260 in./min and 29 V at 410 in./min) produced a stable arc, smooth

Table 5 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source D, 0.045-in. Diameter (1.2-mm) ER70S-3 Electrode Wire and Argon 15% CO_2 Shielding Gas

WFS in./min (mm/s)	Average Voltage (volts)	Average Current (amps)	Fume Generation Rate Per Unit Time[1] (g/min)	Per Gram Of Wire[2] (mg/g)	Per Gram Of Deposit[3] (mg/g)
Pulsed Current					
500 (212)	25.6	290	0.271	2.59	2.73
500 (212)	28.7	300	0.148	1.42	1.49
500 (212)	29.2	295	0.180	1.72	1.81
500 (212)	29.6	308	0.198	1.90	1.99
500 (212)	31.9	325	0.313	3.00	3.02
Steady Current					
500 (212)	28.8	326	0.359	3.44	3.61
500 (212)	32.2	345	0.290	2.78	2.92
500 (212)	34.3	353	0.400	3.83	3.86
500 (212)	36.5	376	0.484	4.63	4.67
Pulsed Current					
600 (254)	29.9	334	0.181	1.44	1.52
600 (254)	32.6	340	0.202	1.61	1.69
600 (254)	33.4	365	0.391	3.12	3.14
Steady Current					
600 (254)	29.9	360	0.231	1.84	1.94
600 (254)	32.2	363	0.228	1.82	1.91
600 (254)	34.3	381	0.261	2.08	2.19
600 (254)	36.4	400	0.463	3.69	3.72

1) fume generated per unit time in grams per minute (g/min).
2) fume generated in milligrams of fume per gram of filler wire melted (mg/g) and;
3) in milligrams of fume per gram of weld metal deposited.

Table 6 — Fume Generation Rate for Pulsed Current Using Power Source B, 0.045-in. (1.2-mm) Diameter ER70S-3 Electrode Wire and Argon 15% CO_2 Shielding Gas at Different Contact Tip-to-Work Distances

WFS in./min (mm/s)	Average Voltage (V)	Contact-Tip-To-Work Distance in. (mm)	Fume Generation Rate (g/min)
260 (110)	24.0	0.5 (12)	0.154
260 (110)	24.0	0.5 (12)	0.150
260 (110)	24.0	0.63 (16)	0.177
260 (110)	24.0	0.63 (16)	0.144
260 (110)	24.0	0.75 (19)	0.147
260 (110)	24.0	0.88 (22)	0.114
260 (110)	24.0	0.88 (22)	0.136
260 (110)	24.0	1.0 (25.4)	0.130
260 (110)	24.0	1.0 (25.4)	0.160

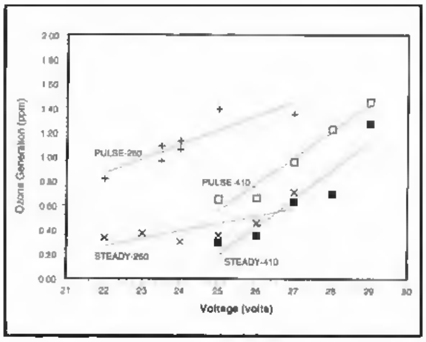

Fig. 18 — Ozone generation rate for pulsed and steady current at 260 in./min wire feed speed with power source B, ER70S-3 wire and Ar/15% CO_2 gas.

spray transfer and acceptable weld profiles. More fume was deposited on the plates when the voltage exceeded 25 V at 260 in./min and 28 V at 410 in./min. Figures 4 and 5 show the increase in fume generation rate that occurs with increased voltage at these conditions.

Ozone Generation Rate Test Results

Figure 18 shows ozone generation rates for pulsed and steady current using power source B with ER70S-3 wire and 85% Ar-15% CO_2 shielding gas at wire feed speeds of 260 and 410 in./min. This figure shows that ozone generation rates increase linearly with voltage for both pulsed and steady current at both wire feed speeds. The figure also shows that pulsed current produces higher levels of ozone than steady current. Increased ozone generation for pulsed current is also reported by other investigators (Ref. 12). Since pulsed current lowers fume generation rate, more ultraviolet radiation from the arc can react with oxygen in the atmosphere surrounding the arc to create ozone. This data also agrees with published information on ozone generation with other arc welding processes. Processes like SMAW that produce high fume levels tend to produce less ozone than GMAW (Ref. 14).

Discussion of Results

Steady current fume generation rates from the present study are typically between 0.2 and 0.8 g/min, which agrees with data in the literature (Refs. 5, 6, 12,14). Fume generation rates for steady current were found to increase with wire feed speed (welding current) and pass through a minimum value for a particular voltage at any given wire feed speed. The fume generation rates for pulsed current follow the same trends as steady current. They generally increase with wire feed speed (average welding current) and pass through a minimum value at a given voltage for each wire feed speed.

The data show that pulsed welding current can reduce fume generation rates compared to steady current. Pulsed current produced lower fume generation rates compared to steady current at each of the wire feed speeds (weld deposition rates) tested. This means that pulsed current converts a lower percentage of the electrode wire to fume. Therefore, a lower percentage of fume is generated per gram of electrode wire consumed and per gram of weld deposit. Compared to steady current, pulsed current reduced the minimum fume generation rate by as much as 50% with power sources A, B and C at a wire feed speed of 260 in./min. The reduction in minimum fume generation rate with pulsed current was approximately 15% at wire feed speeds of 180 and 410 in./min. Minimum fume generation rate for pulsed current at a wire feed speed of 500 in./min was significantly lower than for steady current only for power source D.

It is concluded that the lower fume generation rate of pulsed current is due to the ability of pulsed current to transfer metal droplets through the arc with a minimum of energy. This minimizes heating and vaporization of the metal droplets compared to that during steady current welding. This conclusion agrees with other studies that found (for steady current) a stable arc and droplet spray transfer uses the minimum energy to transfer molten metal droplets through the arc. Hilton and Plumridge (Ref. 9) found that fume generation rate decreased dramatically at the transition from globular to stable spray transfer for steady current GMAW using argon shielding gases. Ma and Apps (Ref. 10) found very low fume generation rates associated with droplet spray transfer which occurred in a narrow range of current between globular transfer and streaming spray. In addition, measurements in the present study show that the average pulsed welding current is lower than the average steady welding current at each of the wire feed speeds tested. This indicates that pulsed current transfers droplets of filler metal at lower average energy than steady current for the same wire feed speed.

The use of pulsed current does not guarantee a lower fume generation rate for all welding conditions. Welding parameters must be correctly controlled if pulsed current is used to reduce fume levels. Figures 4 –11 show that either in-

Table 7 — Fume Composition for Steady Current and Pulsed Current Using ER70S-3 Welding Wire and Argon 15% CO_2 Shielding Gas

Sample	Pulsed Current	Wire Feed Speed in./min (mm/s)	Voltage (V)	% Iron	% Silicon	% Manganese	% Cu
1	Yes	260 (110)	24	64.3	1.4	5.7	<0.1
2	Yes	260 (110)	26	65.2	1.3	7.8	0.1
3	No	410 (174)	30	66.5	1.1	6.3	0.3
4	Yes	410 (174)	28	61.6	1.6	6.9	0.2
Typical ER70S-3 Fume Composition (Source: Reference 14)		—	—	65.7	1.2	5.3	0.11

creasing or reducing arc voltage from the optimum average voltage will increase the fume generation rate even with pulsed current. Welding voltage must not be so low that it produces an unstable arc or significant levels of spatter. Unnecessarily high arc voltages also should be avoided because they will increase the fume generation rate. It is recommended that arc voltage be controlled within ±2 V of the optimum valve to ensure that pulsed current is generating fume at a rate less than steady current.

The reductions in fume generation rates for pulsed current are not unique to one type of welding power source or to one set of pulse parameters. However, the welding power source must have sufficient capacity to maintain a suitable pulse waveform at the required average welding current and voltage. Only one of the power sources tested during this work reduced fume generation rate compared to steady current at a wire feed speed of 500 in./min.

There was no significant reduction in fume generation rate between pulsed and steady current for power sources A, B and C at this wire feed speed. Figure 15 shows that the pulse waveform at 500 in./min for power source B is not the regular rectangular waveform that is typical of lower wire feed speeds. This was also true for power sources A and C since the average welding current approaches the maximum output rating of these power sources at this wire feed speed.

The data indicate that under some conditions fume generation rate is influenced by pulse parameters. While power sources A, B and C all produced lower minimum fume generation rates than steady current, Fig. 4 shows slight differences between the three sets of data. These differences in fume generation rates are attributed to the differences in preprogrammed pulse parameters used by each of the three power sources as shown in Figs. 12–15. Power source B has the narrowest pulse width and highest frequency, and power source A has the widest pulse width and lowest frequency for most of the conditions tested. The data do not show that one set of pulse parameters produced the minimum fume generation rate under all conditions. For example, Fig. 5 shows little difference between the three sets of pulse parameters. These data do suggest that some pulse parameters may be more nearly optimum at one wire feed speed than another. Additional work is needed to investigate the relationship between fume generation rate and pulse parameters in order to achieve the absolute minimum fume generation rate for a given electrode wire, wire diameter, wire feed speed, welding voltage, and shielding gas composition.

The ANSI/AWS F1.2 test method used during this study is judged to be capable of comparing total airborne fume generation rates under the conditions tested. Tests were performed to demonstrate that the filters used for this test method are suitable to capture the fume generated using pulsed welding current. Other researchers have reported that the particle size of fume produced from pulsed current GMAW is smaller than the particle size from steady current (Refs. 10, 13). Measurement of fume particle size was not part of the present study. The reader is referred to other studies of fume particle size distributions and the effects of particle size on the health hazard to workers (Ref. 15).

Conclusions

Fume generation rate tests with pulsed and steady current GMAW lead to the following conclusions:

Using pulsed welding current offers the opportunity to reduce fume generation rates compared to steady current gas metal arc welding procedures.

Fillet welding trials demonstrate that the pulsed current welding parameters that produce minimum fume generation rates also produce acceptable welds.

Using pulsed current does not guarantee lower fume generation rates than steady current. There is a range of welding voltage that produces the minimum fume generation rate for each wire feed speed with both pulsed and steady current. Average arc voltage must be controlled within ±2 V of the optimum value to ensure that pulsed current is generating fume at a rate below that for steady current. Fume generation rate increases for voltages both above and below this optimum valve.

No significant difference was found in the chemical composition of fume from pulsed current compared to steady current. Fumes generated by both types of current are nearly identical mixtures of iron, manganese and silicon oxides.

Although total ozone production for GMAW of steel is relatively low, the same pulsed current conditions that reduce fume generation rates also increase ozone generation. Ozone generation increases with welding current and voltage for both pulsed and steady current.

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