# Fume Generation Rates for Stainless Steel, Nickel and Aluminum Alloys

*Pulsed welding current can reduce GMAW fume generation for stainless steels, nickel and aluminum alloys*

**BY H. R. CASTNER**

ABSTRACT. This paper describes a study of the effects of pulsed welding current on fume produced during gas metal arc welding (GMAW) of stainless steel, nickel, and aluminum alloys. This is an extension of earlier studies of mild steel electrode wire. Reduction of welding fume is important because steady current GMAW of stainless steels and nickel alloys may produce fume that exceeds recommended worker exposure limits for some of the fume constituents. Fume generation from aluminum alloy ER5356 was studied because steady current welding with this alloy produces much higher fume generation rates than ER4043 alloy electrode wire.

This work shows that pulsed current can reduce GMAW fume generation rates for ER308L, ER310, and ER312 stainless steel, ERNiCr-3 nickel alloy, and ER5356 aluminum-magnesium alloy electrode wires. The minimum fume generation rates that were measured for pulsed current using the stainless steel electrodes were between 25 and 50% of the fume generated using steady current at the same wire feed speeds. Minimum fume generation rates for ERNiCr-3 electrode wire using pulsed welding current were between 50 and 85% of those for steady current at the same wire feed speeds. Pulsed current dramatically reduced the fume generation rate for ER5356 aluminum-magnesium alloy electrode wire compared to that for steady current. The fume generation rates measured for the ER5356 electrode with steady current range from about 3 to over 6 g/min. The fume generation rates for pulsed current welding with ER5356 electrode wire were between 0.5 and 1.0 g/min. There was no significant difference in fume generation rates between pulsed and steady current for the 0.045-in. (1.2-mm) diameter ER4043 electrode wire tested. The minimum fume generation rate was very low for this electrode with both types of current. Analysis of fume composition from ER308L stainless steel shows that pulsed current does not significantly alter the composition of fume compared to that produced with steady current.

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## Introduction

While welding processes and procedures are normally chosen on the basis of their quality and productivity, it is becoming more important to use processes with low fume generation rates because of lower permissible exposure limits for some constituents in welding fume. Gas metal arc welding (GMAW) usually generates less welding fume than shielded metal arc welding (SMAW) or flux cored arc welding (FCAW) processes (Ref. 1).

**KEY WORDS**

Fume Generation Rate
Fume Composition
Optimum Voltage
Steady Current GMAW
Pulsed Current GMAW
Stainless Steel
Nickel Alloys
Aluminum Alloys
Pulse Parameters
Welding Procedures

The relatively low fume generation rate of GMAW still may result in fumes that exceed recommended worker exposure limits for some situations, including the following: welding of stainless steels, nickel alloys, and aluminum-magnesium alloys, as well as, welding in confined spaces or in high-production operations. In these situations, the ability to reduce the fume generation rate of GMAW would be an advantage.

The work described in this report compares fume generation rates for pulsed current GMAW with those for steady current using the following welding wires: ER308L, ER310, and ER312 austenitic stainless steels, ERNiCr-3 nickel alloy, and ER4043 and ER5356 aluminum alloys. This work is an extension of previous work (Ref. 2) on mild steel welding wire. The present work covers a wider range of materials and welding conditions than were reported earlier. The previous work (Ref. 2) discusses the mechanisms of welding fume formation and shows that pulsed welding current can reduce GMAW fume generation rates compared to steady welding current. The ability of pulsed current to reduce GMAW fume generation rates has also been reported in other literature (Refs. 3–5). However, these references contain little data on actual fume generation rates.

## Experimental Procedure

### Fume Generation Rate Test Procedure

Total airborne fume generation rates were measured using the U.S. standard procedure, ANSI/AWS F1.2 *Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes* (Ref. 6). Fume

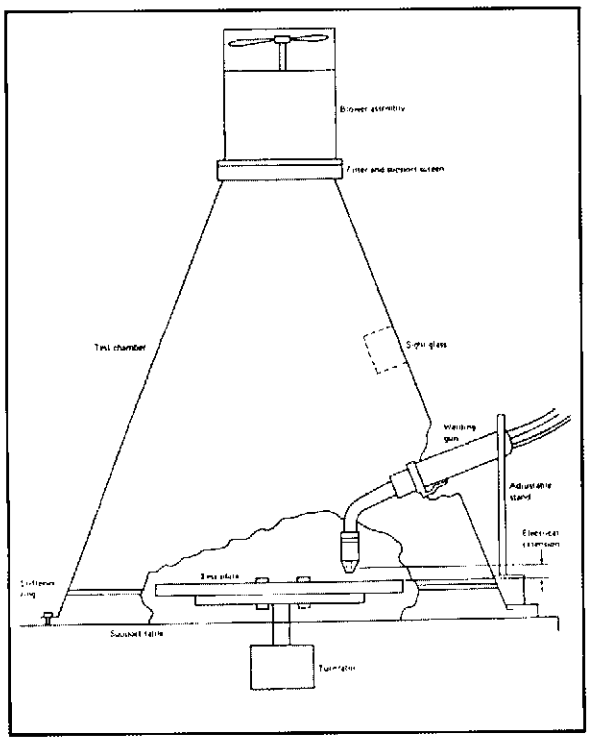


*Fig. 1 — Fume generation rate measurement chamber (ANSI/AWS F1.2).*

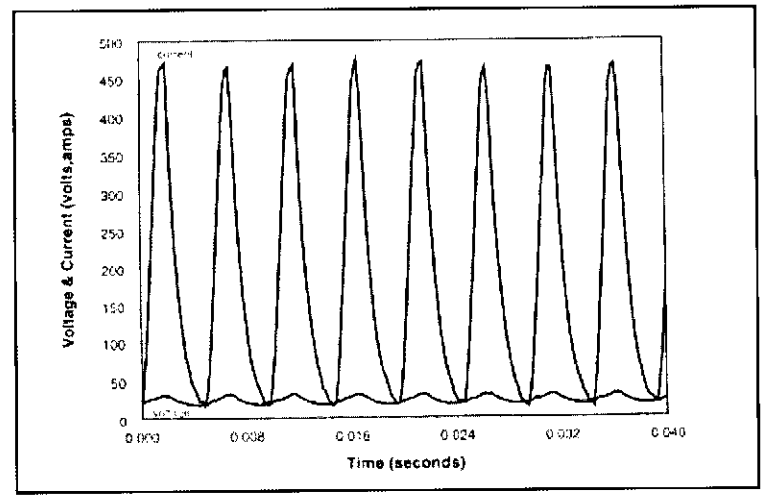


*Fig. 2 — Voltage and current waveform for power source B at 260 in./min (110 mm/s) wire feed speed and 23.5 average volts with ER308L electrode wire and argon-2% $O_2$ gas.*

was generated by welding on flat test plates rotated under a stationary welding gun inside the fume chamber shown in Fig. 1. Fume was captured by drawing it through a fiberglass filter with a fan. The filters were weighed, exposed to fume in the chamber and re-weighed. The quantity of fume generated during welding was determined by subtracting the initial weight of the filter from the weight after exposure to the fume. ANSI/AWS F1.2 includes a standard procedure for calibration of the fume chamber. This procedure was used at the beginning of tests and at regular intervals during testing. Calibration assures consistency of the data and allows this data to be compared with those of other researchers. Reference 2 gives additional details of the fume generation rate test method and calibration procedure.

**Welding Equipment and Materials Used for Tests**

Fume generation rate tests were conducted with the following 0.045-in. (1.2-mm) diameter electrode wires and shielding gases: ER308L, ER310, and ER312 electrode wires and 98% argon-2% $O_2$ shielding gas; ERNiCr-3 electrode wire and 75% argon-25% helium shielding gas; ER4043 electrode wire and argon shielding gas: and ER5356 electrode wire and argon shielding gas.

Typical chemical compositions of the electrode wires are shown in Table 1.

Welds using ER308L, ER310, ER312, and ERNiCr-3 electrode wires were made on 0.5-in. (12.7-mm) thick A36 plate. Typical composition for the A36 plate used is 0.2 C, 0.6 Mn, 0.015 S, 0.02 P and 0.25 Si. The surface of each plate was ground to remove mill scale prior to welding. The use of mild steel plate is acceptable for measurement of fume generation rates with stainless steel and nickel alloy electrode wires because the base metal has very little influence on the generation of welding fume (Ref. 7).

Fume generation rate tests for ER4043 and ER5356 aluminum alloy electrode wires were made on 0.375-in. (10-mm) thick 6061-T6 aluminum alloy plate. A nominal composition for this plate is 0.040–0.080 Si, 0.7 max Fe, 0.15–0.40 Cu, 0.15 max Mn, 0.8–1.2 Mg, 0.04–0.35 Cr, 0.25 max Zn, 0.15 max Ti, and balance aluminum.

Fume generation rates were measured using two commercial welding power sources. The power sources were identified by letters B and D during tests.

Power source B was a constant voltage inverter, with a 100% duty cycle rating of 350 A at 34 V.

Power source D was a constant voltage/constant current inverter, with a 100% duty cycle rating of 450 A at 38 V.

Fume generation rates were measured using steady current and pulsed current for each of the electrode wires tested with both power sources (B and D). These power sources are representative of present commercial practice, and their pulse waveforms are indicative of many available in the industry. Typical voltage and current pulse waveforms for these power sources using ER308L electrode wire and 98% argon-2% $O_2$ shielding gas are shown in Figs. 2 and 3. The purpose of

**Table 1 — Typical Compositions for Electrode Wires (wt-%)**

| | C | Mn | S | P | Si | Cr | Ni | Mo | Cu | Fe | Mg | Ti | Cb | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ER 308L | 0.02 | 1.8 | 0.010 | 0.020 | 0.45 | 20.6 | 10.0 | — | — | Bal | — | — | — | — |
| ER 310 | 0.08 | 1.7 | 0.010 | 0.012 | 0.50 | 25.0 | 20.0 | — | — | Bal | — | — | — | — |
| ER 312 | 0.08 | 1.6 | 0.010 | 0.013 | 0.40 | 29.0 | 9.0 | — | — | Bal | — | — | — | — |
| ERNiCr-3 | 0.02 | 3.0 | 0.007 | — | 0.20 | 20.0 | 72.0 | — | 0.04 | 1.0 | — | 0.60 | 2.5 | — |
| ER 4043 | — | — | — | — | 5.20 | — | — | — | 0.15 | — | — | 0.10 | — | Bal. |
| ER 5356 | — | 0.12 | — | — | 0.20 | 0.12 | — | — | 0.05 | — | 5.0 | 0.13 | — | Bal. |

this study is neither to compare performance of the two power sources nor to suggest that these power sources have advantages over others that were not tested.

#### Measurement of Fume Generation Rates

Fume generation rates were measured with both power sources and for both steady current and pulsed current GMAW. Wire feed speeds ranged from 180 to 600 in./min (76 to 254 mm/s), depending on the electrode wire being tested. These wire feed speeds were selected to include short circuit, globular and spray modes of metal transfer. During these tests, fume generation rates were measured over a range of average welding voltages for each power source, electrode wire, wire feed speed, and type of current to show the effects of voltage on fume generation rate. Welding voltage affects arc stability as well as arc length. Therefore, welding voltage also affects fume generation rates (Refs. 1, 2, 7). Voltage was measured between the welding gun and the workpiece. Welding gun angles were constant for all tests. The gun was positioned at a zero-deg work angle and ten-deg drag travel angle. The contact tube-to-work distance was 0.75 in. (19 mm) for all tests, except for tests with aluminum electrode wires at 180 in./min (76 mm/s) wire feed speed that were performed at a contact tube-to-work distance of 0.5 in. (12.7 mm). Travel speed was 14 in./min (6 mm/s), shielding gas flow rate was 40 $ft^3/h$, (19 L/min) and the inside diameter of the gas nozzle was 0.75 in. (19 mm) for all tests.

At least two tests were conducted for each wire feed speed and voltage. Fume generation rates were recorded in grams of welding fume per minute (g/min). A minimum of 0.2 g of fume was collected in the filter for each test condition to provide sufficient fume for accurate weight measurement. This meant that most of the test welds were 60 s long, although some of the tests at high fume generation rates were shorter. Tests at 500 and 600 in./min wire feed speeds required only 30 s. The ER5356 test welds generated such large quantities of fume that they were conducted for only 10 or 15 s. Some of the low fume generation rate tests required 120 s to generate sufficient fume to permit a proper test.

#### Fume Composition Measurements

Fume samples were collected from ER308L welds for chemical analysis of the fume composition. Fume was collected using methods described in ANSI/AWS F1.2 (Ref. 6) and analyzed by two techniques. Hexavalent chromium oxide was measured using the wet chemistry method described by Moreton (Ref. 8). Other elements were measured using X-ray fluorescence spectrometry.

Power source D and welding parameters producing the minimum fume generation rate for the selected wire feed speed were used to produce these samples. Sample No. 1 was produced with steady current at a wire feed speed of 260 in./min (110 mm/s) and 26 average volts. Sample No. 2 was produced at the same wire feed speed and average voltage using pulsed current. Sample No. 3 was produced with steady current at 410 in./min (174 mm/s) and 32 average volts. Sample No. 4 was made with pulsed current at 410 pm and 30 average volts.

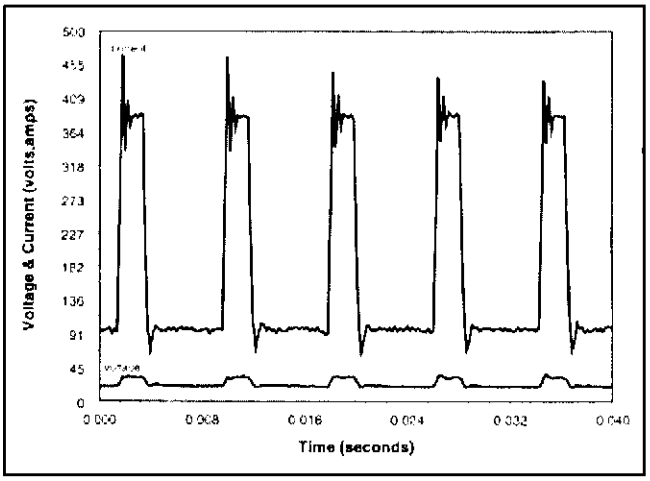


*Fig. 3 — Voltage and current waveform for power source D at 260 in./min wire feed speed and 27 average volts with ER308L electrode wire and argon-2% $O_2$ gas.*

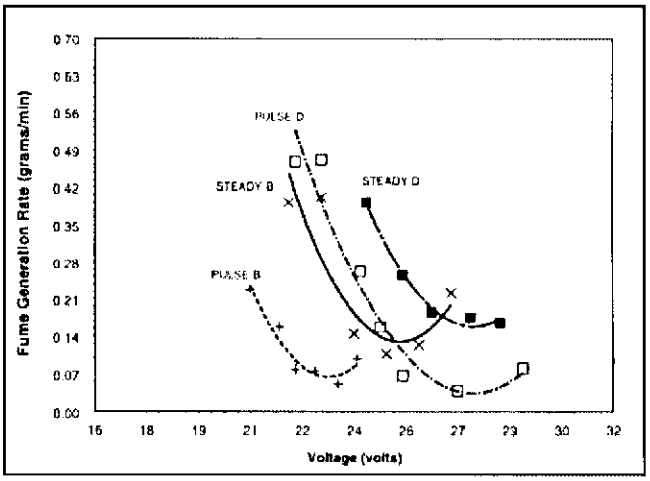


*Fig. 4 — Fume generation rate for pulsed and steady current at 260 in./min wire feed speed with power sources B and D, ER308L electrode wire and argon-2% $O_2$ gas.*

## Experimental Results

The results of fume generation rate tests in grams per minute (g/min) are presented graphically in Figs. 4–9. Each figure compares fume generation rates for steady and pulsed current as functions of voltage. Least squares curve fitting algorithms were used to obtain a best fit of the data points to first-order through fourth-order polynomial equations. Tables 2–6 contain fume generation rate data from selected tests.

#### Fume Generation Rate Test Results for Stainless Steel

Figure 4 shows that fume generation rates using pulsed current are lower than for steady current using both power sources at a wire feed speed of 260 in./min (110 mm/s). The electrode was 0.045-in. (1.2-mm) diameter ER308L solid wires, and the shielding gas was 98% Ar-2% $O_2$. The data used to plot the graphs in Fig. 4 are shown in Tables 2 and 3. The data for both power sources are similar, although the data points for power source B are displaced by 3 or 4 V from those for power source D. This difference in operating parameters is due to the control methods and preprogrammed pulse parameters selected by the power source manufacturers. Both power sources produced stable arcs and satisfactory welds.

The minimum fume generation rates for ER308L solid wire with pulsed current are between 25 and 50% of those for steady current. These percentages were determined by comparing minimum fume generation rates for pulsed current and steady current. The steady current fume generation rate for power source B was 0.107 g/min compared to 0.052 g/min with pulsed current. The steady current fume generation of 0.174 g/min

**Table 2 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source D, 0.045-in.-Diameter ER308-L Electrode Wire and Argon-2%$O_2$ Shielding Gas**

| Wire Feed Speed in./min (mm/s) | Average Voltage V | Average Current A | Fume Generation Rate Per Unit Times[a] (g/min) | Per Gram of[b] Wire (mg/g) |
|---|---|---|---|---|
| Pulsed Current | | | | |
| 180 (76) | 23.0 | 136 | 0.068 | 1.85 |
| 180 (76) | 25.6 | 146 | 0.040 | 1.09 |
| 180 (76) | 28.8 | 157 | 0.087 | 2.37 |
| Steady Current | | | | |
| 180 (76) | 22.5 | 152 | 0.237 | 6.46 |
| 180 (76) | 24.4 | 155 | 0.302 | 8.23 |
| 180 (76) | 27.5 | 156 | 0.224 | 6.11 |
| Pulsed Current | | | | |
| 260 (110) | 22.2 | 155 | 0.469 | 4.60 |
| 260 (110) | 23.0 | 160 | 0.473 | 4.64 |
| 260 (110) | 24.2 | 166 | 0.263 | 4.96 |
| 260 (110) | 24.8 | 171 | 0.157 | 2.96 |
| 260 (110) | 25.5 | 176 | 0.066 | 1.25 |
| 260 (110) | 27.2 | 185 | 0.039 | 1.06 |
| 260 (110) | 29.2 | 197 | 0.080 | 1.51 |
| Steady Current | | | | |
| 260 (110) | 24.4 | 183 | 0.392 | 7.40 |
| 260 (110) | 25.5 | 188 | 0.256 | 4.83 |
| 260 (110) | 26.4 | 193 | 0.186 | 1.52 |
| 260 (110) | 27.6 | 205 | 0.174 | 1.42 |
| 260 (110) | 28.5 | 213 | 0.165 | 3.11 |
| Steady Current | | | | |
| 410 (110) | 29.0 | — | 0.40 | — |
| 410 (110) | 30.0 | — | 0.80 | — |
| Pulsed Current | | | | |
| 410 (174) | 27.5 | 225 | 0.242 | 2.90 |
| 410 (174) | 29.2 | 242 | 0.127 | 1.52 |
| 410 (174) | 30.5 | 254 | 0.066 | 0.79 |
| Pulsed Current | | | | |
| 500 (212) | 30.1 | 250 | 0.197 | 1.93 |
| 500 (212) | 32.0 | 268 | 0.122 | 1.20 |
| 500 (212) | 33.1 | 300 | 0.137 | 1.34 |
| Steady Current | | | | |
| 500 (212) | 30.6 | 293 | 0.910 | 8.93 |
| 500 (212) | 32.5 | 322 | 0.492 | 4.83 |
| 500 (212) | 33.6 | 328 | 0.466 | 4.57 |
| Pulsed Current | | | | |
| 600 (254) | 31.3 | 294 | 0.249 | 2.04 |
| 600 (254) | 33.4 | 314 | 0.177 | 1.45 |
| 600 (254) | 35.8 | 348 | 0.323 | 2.64 |
| Steady Current | | | | |
| 600 (254) | 33.5 | 341 | 0.430 | 3.52 |
| 600 (254) | 34.5 | 358 | 0.492 | 4.02 |
| 600 (254) | 35.6 | 365 | 0.599 | 4.90 |

a Fume generated per unit time in grams per minute.
b Milligrams of fume generated per gram of welding wire melted.

decreased to 0.039 g/min with pulsed current for power source D.

Test data for power source D are presented in Table 2. Fume generation rates for steady current at 180 in./min range from 0.22 to 0.30 g/min for average welding voltages between 22.5 and 27.5 V, and the fume generation rates for pulsed current are between 0.04 and 0.09 g/min for average voltages from 23.0 to 28.8 V. The fume generation rates using pulsed current at 260 in./min are between 0.039 and 0.080 g/min at the optimum welding conditions of 25–29 average volts, compared to optimum conditions of 0.165–0.186 g/min with steady current. Pulsed welding conditions below 22 average volts at 180 in./min and below 24 average volts at 260 in./min produced higher fume generation rates than steady current because arc instabilities at these low average welding voltages result in a large amount of spatter. Pulsed welding current is not normally used at these low average welding voltages because of the high spatter and arc instability. The fume generation rates for pulsed current with power source D were 0.127 and 0.066 g/min for average voltages of 29.2 and 30.5 V at a wire feed speed of 410 in./min (174 mm/s). Fume generation rates for steady current at these voltages and this wire feed speed ranged from 0.40 to 0.80 g/min.

Data for power source B are shown in Table 3. The fume generation rates using power source B were between about 0.20 and 0.40 g/min for both pulsed current and steady current at 410 in./min. The average current was at the maximum output rating for power source B at this wire feed speed. Previous work (Ref. 2) showed that no fume reduction occurs when the rectangular pulse current waveform is lost at high output levels.

Figure 5 shows that the fume generation rates for wire feed speeds of 500 in./min (212 mm/s) and 600 in./min (254 mm/s) are between 25 and 50% of those for steady current when using power source D. The minimum fume generation rate using steady current at a wire feed speed of 500 in./min is 0.466 g/min at 33.6 V. The minimum fume generation rate for pulsed current at this wire feed speed is 0.122 g/min at 32.0 V. The minimum fume generation rate for steady current at 600 in./min is 0.430 g/min compared to 0.177 g/min with pulsed current.

Figure 6 compares fume generation rates for ER310 and ER312 solid wires with those measured for ER308L electrode wire. The figure shows that pulsed current reduced fume generation rates for ER310 and ER312 electrode wires. Similar results would be expected for other stainless steels provided the pulse parameters were suitable for the electrode wire used.

### Fume Generation Rates For ERNiCr-3 Nickel Alloy

Figure 7 and Table 4 show that power source D reduced fume generation rates for the 0.045-in.-diameter ERNiCr-3 electrode wire at wire feed speeds of 180, 260 and 410 in./min. The shielding gas used for these tests is 75% Ar-25% He because the preprogrammed pulse parameters were developed using this gas, and it is the recommended shielding gas for this alloy by both of the power source manufacturers. Figure 7 and Table 4 show that the fume generation rates for ERNiCr-3 solid electrode wire using pulsed welding current for power source D were approximately 50% of those for steady cur-

rent at wire feed speeds of 260 and 410 in./min. Pulsed current fume generation rates were about 85% of those for steady current at wire feed speeds of 180 and 500 in./min and about 70% of steady current rate at 600 in./min with this power source.

The data in Table 4 for ERNiCr-3 electrode wire show fume generation rates with power source D and steady current are above 0.10 g/min and increase with increasing wire feed speed and voltage. Pulsed current reduces the minimum fume generation rate to below 0.10 g/min for wire feed speeds of 180 in./min, and 260 in./min. Pulsed current produced low fume generation rates in spray metal transfer, which occurred at the following conditions: above 21 average volts at a wire feed speed of 180 in./min, above 23 average volts at 260 in./min wire feed speed, and above 27 average volts at a wire feed speed of 410 in./min. Except for the data taken at 180 in./min, steady welding current produced spray metal transfer only at the highest two voltages for each wire feed speed.

While the data are not shown, pulsed current reduced the minimum fume generation rate for ERNiCr-3 electrode wire by approximately 50% for power source B at wire feed speeds of 260 and 410 in./min.

**Table 3 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source B, 0.045-in.-Diameter ER308-L Electrode Wire and Argon-2%$O_2$ Shielding Gas**

| Wire Feed Speed in./min (mm/s) | Average Voltage V | Average Current A | Fume Generation Rate Per Unit Time[a] (g/min) | Fume Generation Rate Per Gram of[b] Wire (mg/g) |
|---|---|---|---|---|
| Pulsed Current | | | | |
| 260 (110) | 20.8 | 172 | 0.228 | 4.27 |
| 260 (110) | 21.7 | 182 | 0.157 | 2.94 |
| 260 (110) | 22.2 | 187 | 0.078 | 1.48 |
| 260 (110) | 22.8 | 193 | 0.075 | 1.42 |
| 260 (110) | 23.5 | 197 | 0.052 | 0.98 |
| 260 (110) | 24.1 | 201 | 0.098 | 1.86 |
| Steady Current | | | | |
| 260 (110) | 22.0 | 20.5 | 0.392 | 7.38 |
| 260 (110) | 23.0 | 216 | 0.402 | 7.62 |
| 260 (110) | 24.0 | 225 | 0.145 | 2.75 |
| 260 (110) | 25.0 | 234 | 0.107 | 2.03 |
| 260 (110) | 26.0 | 242 | 0.124 | 2.35 |
| 260 (110) | 27.0 | 255 | 0.221 | 4.19 |
| Pulsed Current | | | | |
| 410 (174) | 26.5 | 283 | 0.199 | 2.39 |
| 410 (174) | 27.3 | 292 | 0.199 | 2.39 |
| 410 (174) | 27.7 | 300 | 0.281 | 3.38 |
| 410 (174) | 28.3 | 307 | 0.331 | 3.98 |
| 410 (174) | 29.8 | 369 | 0.342 | 4.11 |
| Steady Current | | | | |
| 410 (174) | 25.0 | 294 | 0.417 | 5.01 |
| 410 (174) | 26.0 | 307 | 0.333 | 4.00 |
| 410 (174) | 27.0 | 335 | 0.25 | 3.00 |
| 410 (174) | 28.0 | 351 | 0.295 | 3.54 |

a Fume generated per unit time in grams per minute.
b Milligrams of fume generated per gram of welding wire melted.

### Fume Generation Rate Test Results For ER4043 and ER5356 Aluminum Alloys

The data in Figure 8 and Table 5 were produced with power source D, 0.045-in. diameter ER4043 aluminum-silicon electrode wire and argon shielding gas at wire feed speeds of 180 and 260 in./min. Although the data points for pulsed current are slightly higher than for steady current at several average voltages, the minimum fume generation rates range from about 0.03 to 0.07 g/min for both wire feed speeds. While the data are not shown, the minimum fume generation rates for pulsed current are slightly lower than for steady current for power source B. Examination of all of the data from both power sources does not show a significant difference in fume generation rates between pulsed and steady current for the 0.045-in diameter ER4043 electrode wire.

The graphs in Fig. 9 show that pulsed current produces a large reduction in the fume generation rates with both power

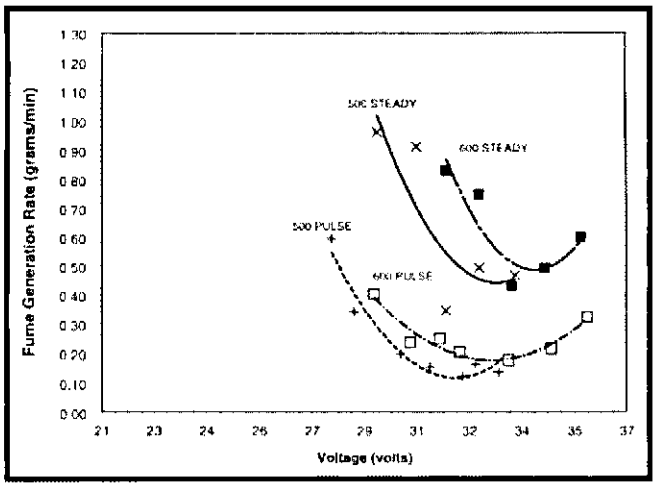


*Fig. 5 — Fume generation rate for pulsed and steady current at 500 and 600 in./min wire feed speed with power source D, ER308L electrode wire and argon-2% $O_2$ gas.*

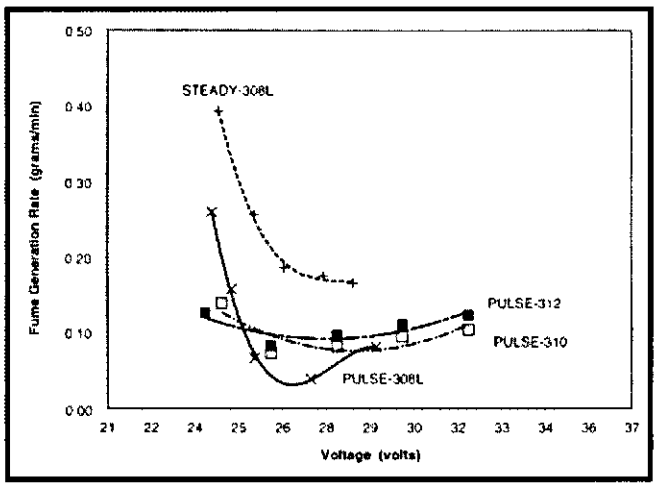


*Fig. 6 — Fume generation rate for pulsed and steady current at 260 in./min wire feed speed with power source D, ER308L, ER310, and ER312 electrode wires and argon-2% $O_2$ gas.*

**Table 4 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source D, 0.045-in.-Diameter ERNiCr-3 Wire and Argon-25% Helium Shielding Gas**

| Wire Feed Speed in./min (mm/s) | Average Voltage V | Average Current A | Fume Generation Rate Per Unit[a] Time (g/min) | Fume Generation Rate Per Gram[b] of Wire (mg/g) |
|---|---|---|---|---|
| Pulsed Current | | | | |
| 180 (76) | 21.4 | 128 | 0.055 | 1.43 |
| 180 (76) | 22.4 | 149 | 0.064 | 1.66 |
| Steady Current | | | | |
| 180 (76) | 19.4 | 143 | 0.135 | 3.50 |
| 180 (76) | 20.4 | 155 | 0.112 | 2.90 |
| 180 (76) | 23.4 | 169 | 0.126 | 3.27 |
| Pulsed Current | | | | |
| 260 (110) | 25.0 | 174 | 0.073 | 1.31 |
| 260 (110) | 25.4 | 192 | 0.083 | 1.49 |
| Steady Current | | | | |
| 260 ((110) | 24.4 | 203 | 0.185 | 3.32 |
| 260 (110) | 28.7 | 276 | 0.291 | 2.72 |
| 260 (110) | 30.4 | 298 | 0.196 | 1.83 |
| Pulsed Current | | | | |
| 410 (174) | 27.3 | 243 | 0.248 | 2.82 |
| 410 (174) | 28.3 | 254 | 0.135 | 1.54 |
| 410 (174) | 29.4 | 274 | 0.081 | 0.92 |
| Steady Current | | | | |
| 410 (174) | 27.5 | 284 | 0.457 | 5.20 |
| 410 (174) | 28.6 | 287 | 0.283 | 3.22 |
| 410 (174) | 30.0 | 297 | 0.256 | 2.91 |
| Pulsed Current | | | | |
| 500 (212) | 28.4 | 268 | 0.234 | 2.18 |
| 500 (212) | 30.4 | 298 | 0.196 | 1.83 |
| 500 (212) | 31.8 | 318 | 0.244 | 2.28 |
| Steady Current | | | | |
| 500 (212) | 28.4 | 325 | 0.462 | 4.31 |
| 500 (212) | 30.5 | 338 | 0.205 | 1.91 |
| 500 (212) | 32.5 | 387 | 0.455 | 4.25 |
| Pulsed Current | | | | |
| 600 (254) | 30.7 | 309 | 0.260 | 2.02 |
| 600 (254) | 32.7 | 329 | 0.263 | 2.05 |
| 600 (254) | 33.5 | 360 | 0.310 | 2.41 |
| Steady Current | | | | |
| 600 (254) | 30.5 | 365 | 0.417 | 3.24 |
| 600 (254) | 31.5 | 377 | 0.375 | 2.92 |
| 600 (254) | 33.5 | 412 | 0.435 | 3.38 |

a Fume generated per unit time in grams per minute.
b Milligrams of fume generated per gram of welding wire melted.

sources for 0.045-in.-diameter ER5356 aluminum-magnesium alloy electrode wire compared to that for steady current. This figure also illustrates the much higher fume generation rates for steady welding current with the ER5356 aluminum-magnesium alloy electrode compared to that shown in Fig. 8 for ER4043 aluminum-silicon electrode wire. The fume generation rates in Fig. 9 for the ER5356 electrode with steady current range from 2.6 to 6.9 g/min. The fume generation rates for power source D with pulsed current at a wire feed speed of 260 in./min are below 1.0 g/min, and the minimum value is approximately 0.50 g/min. The data for power source B are listed in Table 6. This table also shows that fume generation rates with pulsed current at 180 in./min wire feed speed are between 0.43 and 0.61 g/min and range from 1.02 to 1.19 g/min at 260 in./min.

#### Fume Composition Measurements

Table 7 contains the chemical compositions of fumes generated with both pulsed and steady current using ER308L electrode wire. This table shows that these fumes are oxides of iron, manganese, chromium, nickel, and silicon. Hexavalent chromium content was less than 0.1% with both steady current and pulsed current. This chemical analysis of fume shows that there is no significant difference in the composition of fume generated with pulsed current compared to steady current. These fume compositions also agree with published compositions for GMAW fumes from austenitic stainless steel electrodes reported from other studies (Refs. 4, 9, 10).

## Discussion of Fume Data

This work shows that pulsed current can reduce GMAW fume generation rates for stainless steel, nickel alloy and aluminum-magnesium alloy electrode wires. These results indicate that pulsed current welding procedures can reduce fume generation rate and, potentially, worker exposure to welding fumes. Reduction of fume is particularly significant for stainless steels and nickel alloys, since these fumes contain oxides of nickel and chromium, which have very low recommended worker exposure limits.

The data show that the minimum fume generation rates for ER308L, ER310, and ER312 stainless steel electrodes with pulsed welding current were between 25 and 50% of the fume generation rates using steady current at equal wire feed speeds. Minimum fume generation rates for ERNiCr-3 nickel-alloy electrode wire using pulsed welding current were between 50 and 85% of those for steady current at equal wire feed speeds. Pulsed current dramatically reduced the fume generation rate for ER5356 aluminum-magnesium alloy electrode wire compared to that for steady current.

Chemical analysis of fume using ER308L electrode wire showed no significant difference in the composition of fume from pulsed current compared to steady current. Earlier work (Ref. 2) showed that pulsed current did not change the composition of mild steel fume. Breathing zone measurements under actual shop conditions are required to determine actual worker exposure to welding fumes because exposure can vary depending on ventilation, size of work space, welding position, welding parameters and other factors. The analysis of ER308L fume shows that pulse current does not alter fume composition significantly. Therefore, past experience with worker exposure sampling for steady current GMAW can be used to guide worker exposure sampling for pulsed current.

The mechanisms of fume generation and the effect of welding parameters on fume generation rates are discussed in a number of the references (Refs. 1–4, 7, 9,

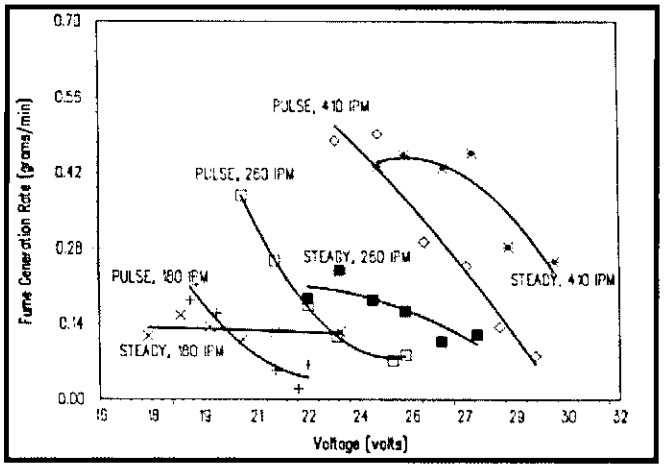


*Fig. 7 — Fume generation rate for pulsed and steady current at 180, 260 and 410 in./min wire feed speeds with power source D, ERNiCr-3 electrode wire and argon- 25% helium gas.*

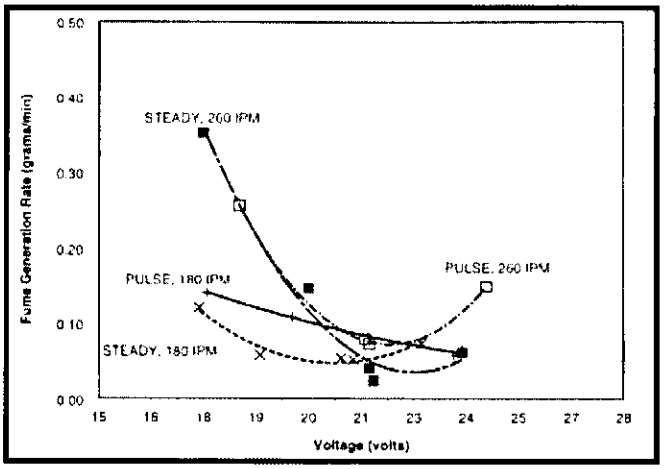


*Fig. 8 — Fume generation rate for pulsed and steady current at 180 and 260 in./min wire feed speeds with power source D, ER4043 electrode wire and argon gas*

10). These references agree that steady current GMA welding conditions that produce a stable arc, droplet spray transfer and low levels of spatter produce minimum fume. During spray transfer, the small droplets move across the arc quickly and are exposed to high arc temperatures for a minimum period of time. While droplet spray transfer can produce minimum fume, fume generation rate increases as welding current and arc voltage increase during spray transfer. Globular transfer produces some of the highest fume generation rates because the molten metal droplets are large and remain attached to the tip of the welding electrode wire for relatively long periods of time. Long exposure to the arc results in a large amount of metal vapor that is subsequently oxidized in the arc and by the air surrounding the arc. Globular transfer also produces high spatter levels. The vaporization and combustion of ejected spatter particles add to the generation of fume. The data show that the average pulsed welding current is lower than the average steady welding current at each of the wire feed speeds tested. In addition, pulsed current assists in producing small droplets that can be transferred through the arc at the lowest possible voltage without producing spatter. It can be noted that for many of the conditions tested, the minimum fume generation rate for pulsed current occurred at a lower voltage than for steady current. This is further evidence that pulsed current minimizes heating and vaporization of the metal droplets compared to steady current.

The use of pulsed current does not guarantee lower fume generation rate for all welding conditions. Welding parameters must be correctly controlled if pulsed current is used to reduce fume levels. The data show increased fume generation rates at average voltages both higher and lower than the voltage that produces the minimum fume. The high fume levels at these low average voltages result from arc instability and spatter due to intermittent short circuits that occur at the short arc length even for droplet spray transfer. Although the effects of low average voltages on fume generation were studied, in practice, pulsed current welding procedures normally do not include these low average voltages. The data indicate that unnecessarily high average voltages also should be avoided because they will increase fume generation rate. Minimum fume generation rate with pulsed current can be achieved at average arc voltages just above those that prevent intermittent short circuits and the accompanying spatter. These voltages also produce sound welds.

Reductions in fume generation rates were not found to be specific to one welding power source or to a single set

**Table 5 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source D, 0.045-in. (1.2-mm) Diameter ER4043 Electrode Wire and Argon Shielding Gas**

| Wire Feed Speed in./min (mm/s) | Average Voltage V | Average Current A | Fume Generation Rate Per Unit[a] Time (g/min) | Fume Generation Rate Per Unit[b] of Wire (mg/g) |
|---|---|---|---|---|
| Pulsed Current | | | | |
| 180 (76) | 17.7 | 104 | 0.14 | 10.44 |
| 180 (76) | 19.8 | 106 | 0.12 | 8.00 |
| 180 (76) | 23.8 | 111 | 0.06 | 4.22 |
| 180 (76) | 24.0 | 112 | 0.07 | 4.82 |
| Steady Current | | | | |
| 180 (76) | 17.5 | 118 | 0.12 | 8.96 |
| 180 (76) | 19.0 | 122 | 0.06 | 4.30 |
| 180 (76) | 21.0 | 123 | 0.05 | 4.00 |
| 180 (76) | 21.3 | 123 | 0.05 | 3.85 |
| 180 (76) | 23.0 | 125 | 0.07 | 5.41 |
| Pulsed Current | | | | |
| 260 (110) | 17.6 | 151 | 0.65 | 33.13 |
| 260 (110) | 18.5 | 156 | 0.26 | 13.13 |
| 260 (110) | 21.7 | 160 | 0.07 | 3.74 |
| 260 (110) | 21.6 | 160 | 0.08 | 4.05 |
| 260 (110) | 24.6 | 163 | 0.15 | 7.64 |
| Steady Current | | | | |
| 260 (110) | 17.6 | 146 | 0.35 | 18.05 |
| 260 (110) | 20.2 | 168 | 0.15 | 7.54 |
| 260 (110) | 21.7 | 174 | 0.04 | 2.10 |
| 260 (110) | 21.8 | 173 | 0.03 | 1.28 |
| 260 (110) | 24.0 | 174 | 0.06 | 3.13 |

a Fume generated per unit time in grams per minute.
b Milligrams of fume generated per gram of welding wire melted.

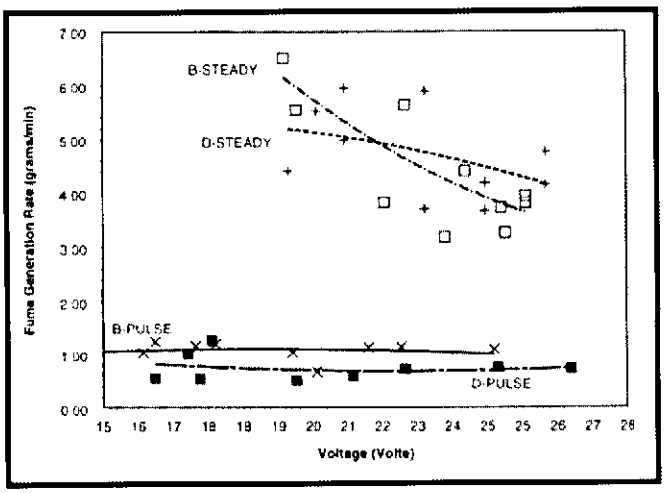


*Fig. 9 — Fume generation rate for pulsed and steady current at 260 in./min wire feed speed with power sources B and D, ER5356 electrode wire and argon gas.*

of pulse parameters. The welding power source must have sufficient capacity to maintain a suitable pulse waveform at the required average welding current and voltage. Although there are differences in the preprogrammed pulse parameters for the two power sources used in this study, both power sources produced similar fume generation rates for most of the conditions tested. Pulse parameters can have an influence on arc stability and droplet transfer, which affect fume generation. The fact that reductions in fume generation rates for the ERNiCr-3 nickel alloy electrode wire were not as great as those measured for austenitic stainless steel may indicate that the pulse parameters were not optimum for the nickel alloy electrode. Further development of pulsed parameters may reduce fume for this alloy.

Fume generation rates using steady welding current and the ER5356 electrode wire were ten times higher than those with the ER4043 wire at comparable wire feed speeds. This difference in fume generation rate between aluminum-magnesium and aluminum-silicon electrode wires is believed to be due to the difference in vapor pressure of magnesium compared to silicon (Ref. 7).

The vapor pressure of magnesium is much higher and increases with temperature much more rapidly than does the vapor pressure of aluminum or silicon. The boiling point of magnesium is less than half that for aluminum. Therefore, the ability of pulsed current to produce a stable arc and minimize heating of metal droplets appears to have a greater effect on the fume generation rate of aluminum-magnesium electrodes than it does for aluminum-silicon electrodes.

Table 6 shows that the average pulsed current is approximately 20% lower than steady current for comparable wire feed speeds with the ER5356 electrode wire. With pulsed current, stable spray transfer with virtually no spatter occurred at approximately 116 A and 21 V with pulsed current, but 150 A and 27.5 V were required to achieve the same conditions with steady current. The lower arc temperatures and shorter arc lengths for pulsed current welding should reduce the vaporization of magnesium and therefore fume generation.

Pulsed current did not significantly reduce fume compared to steady current for the 0.045-in. diameter ER4043 electrode wire tested. Steady current produced spray transfer and low fume levels for many of the test conditions for the ER4043 electrode. Average pulsed current was only about 5% lower than steady current for this electrode, not the nearly 20% reduction found for the ER5356 electrode. Pulsed current may have more of an effect on fume generation for larger diameter ER4043 electrode wires than was found for the 0.045-in. electrode tested.

Ozone generation was not measured during this study. However, ozone measurements during the previous study (Ref. 2) showed that pulsed current conditions

**Table 6 — Fume Generation Rate for Pulsed and Steady Welding Current Using Power Source B, 0.045-in.-Diameter ER5356 Aluminum Electrode Wire and Argon Shielding Gas**

| Wire Feed Speed in./min (mm/s) | Average Voltage V | Average Current A | Fume Generation Rate Per Unit[a] Time (g/min) | Fume Generation Rate Per Gram[b] of Wire (mg/g) |
|---|---|---|---|---|
| Pulsed Current | | | | |
| 180 (76) | 15.9 | 78 | 0.393 | 29.19 |
| 180 (76) | 16.4 | 80 | 0.45 | 33.42 |
| 180 (76) | 17.4 | 83 | 0.43 | 31.64 |
| 180 (76) | 17.6 | 85 | 0.573 | 42.71 |
| 180 (76) | 19.8 | 86 | 0.55 | 41.00 |
| 180 (76) | 24.4 | 88 | 0.61 | 44.94 |
| Pulsed Current | | | | |
| 260 (110) | 16.3 | 110 | 1.236 | 63.61 |
| 260 (110) | 17.3 | 115 | 1.156 | 58.49 |
| 260 (110) | 17.8 | 119 | 1.19 | 61.24 |
| 260 (110) | 19.7 | 124 | 1.02 | 52.65 |
| 260 (110) | 20.3 | 120 | 0.666 | 34.37 |
| 260 (110) | 22.4 | 121 | 1.13 | 58.31 |
| 260 (110) | 24.7 | 127 | 1.08 | 55.74 |
| Steady Current | | | | |
| 260 (110) | 22.0 | 130 | 3.82 | 196.52 |
| 260 (110) | 22.5 | 140 | 5.64 | 289.70 |
| 260 (110) | 23.5 | 150 | 3.18 | 163.40 |
| 260 (110) | 24.0 | 154 | 4.39 | 225.52 |
| 260 (110) | 24.9 | 156 | 3.73 | 191.9 |
| 260 (110) | 25.0 | 142 | 3.26 | 167.52 |
| 260 (110) | 25.5 | 158 | 3.81 | 195.91 |
| 260 (110) | 25.5 | 158 | 3.94 | 202.7 |

a Fume generated per unit time in grams per minute.
b Milligrams of fume generated per gram of welding wire melted.

**Table 7 — Composition of Welding Fume Generated Using ER308L Electrodes and Argon 2%$O_2$ Shielding Gas (Values are wt-%)**

| Sample Number | Current (A) | WFS in./min (mm/s) | Si | Fe | Mn | Ni | Total Cr | CR+6 |
|---|---|---|---|---|---|---|---|---|
| 1 | Steady | 260 (110) | 2.6 | 36.5 | 16.1 | 1.9 | 15.0 | <0.1 |
| 2 | Pulse | 260 (110) | 1.5 | 39.8 | 15.3 | 3.3 | 16.7 | <0.1 |
| 3 | Steady | 410 (174) | 2.8 | 37.8 | 12.2 | 2.9 | 15.6 | <0.1 |
| 4 | Pulse | 410 (174) | 3.8 | 36.4 | * | * | 15.5 | <0.1 |

*Data not available.

that reduce fume increase the generation of ozone. The reduction in fume allows more ultraviolet radiation from the arc to react with oxygen in the atmosphere surrounding the arc, thereby creating more ozone. Therefore, use of pulsed current to reduce fume generation rates of stainless steel, nickel alloys or ER5356 electrode wires may increase ozone generation. However, since fume generation rates for ER5356 with pulsed current are still above those for ER4043, ozone generation using pulsed current may be no higher than that presently achieved with steady current and ER4043 electrode wires.

## Conclusions

1) Use of the proper pulsed current welding procedures can reduce GMAW fume generation rates compared to steady welding current for ER308L, ER310, ER312, ERNiCr-3 and ER5356 alloy electrode wires.

2) Pulsed welding current was found to be very effective in reducing the rate of fume generation for ER5356 aluminum-magnesium electrodes to between 10 and 20% of those for steady current.

3) Pulsed welding current reduced the minimum fume generation rates for austenitic stainless steel electrode wires to a level that is between 25 and 50% of that using steady current.

4) Pulsed current reduced minimum fume generation rates to between 50 and 85% of those for steady welding current for ERNiCr-3 electrode wires.

5) Tests on ER308L stainless steel show that use of pulsed current reduces the volume of fume generated but does not alter fume composition.

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