Fume Formation Rates in Gas Metal Arc Welding

A new fume chamber design improves the accuracy of fume generation data

BY B. J. QUIMBY AND G. D. ULRICH

ABSTRACT. An improved fume chamber was constructed, and fume rates were measured with unprecedented precision for both steady- and pulsed-current welding of mild steel using 92% argon/8% CO_2 shielding gas. Comprehensive fume maps were constructed depicting fume rates over a wide range of currents and voltages. Fume generation was generally lower under pulsed-current conditions. Theoretical arguments explaining this difference are presented.

Introduction

Public agencies concerned with occupational safety and industrial hygiene have recently pressed for more stringent limits on metal-containing particles in factory air. In many cases, these particles originate as fume generated in welding arcs. Those opposed to stricter limits argue that such will require hundreds of millions of dollars to be spent in capital, maintenance and operation of ventilation equipment while yielding negligible gains in worker health. Proponents of stiffer standards maintain that medical fees, liability suits and lifestyle limitations attributed to welding fume are likely to cost much more.

Tougher proposed standards were recently challenged in U.S. courts and rejected. Nevertheless, many observers expect tighter limits will eventually be imposed. Meanwhile, fumes generated in the welding of stainless steel and other alloys have come under increased scrutiny, and even tighter controls have been proposed for them. Although improved ventilation is the most common way to clean shop air, other approaches show promise. Some researchers claim, for example, that fume can be reduced 60 to 90% by using power supplies that deliver pulsed rather than steady current (Refs. 1, 2).

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Accurate fume-generation data and a comprehensive fume formation model are necessary for more sophisticated fume control strategies. This paper includes precise fume generation data for GMAW of mild steel using one shielding gas under steady- and pulsed-current conditions. A physical model introduced by Gray, Hewitt and Dare (Ref. 4) is employed and amplified to explain our observations.

Although fume formation has been studied by many scientists, results are difficult to reconcile from one researcher to another. Limited accuracy of some results is one problem, but interpretation and correlation are complicated because of the multitude of variables involved. Many types of welding exist with and without fluxes using a wide range of possible shielding gases. Numerous different electrode and work materials or combinations are possible. Much of the prior work has been directed toward the solution of immediate problems in the workplace. Often, fume generation studies involve so many variables results are almost impossible to use for theoretical purposes. Our research was designed to produce precise results for narrow conditions. Although limited to GMAW of mild steel with a single shielding gas, our fume typography is typical of profiles one should expect with other electrodes and shielding gases. It is hoped that similar results for such systems will become available in the future.

Castner (Ref. 3) has provided what may be the most comprehensive study of a single system using the standard AWS fume chamber. Although a comparison of steady- and pulsed-current fume rates was the main focus of his study, much can be gained from examining the steady-current data alone. Sets of data obtained at fixed wire feed rate (essentially constant current) and increasing voltage were reported for a number of different wire feed speeds. Selected results are illustrated in Fig. 1.

KEY WORDS

Fumes
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Environment
Health
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Mild Steel
A36

Curves in Fig. 1 were fitted to data using a least-squares analysis. This is appropriate if a function is smooth. On the other hand, Gray, Hewitt and Dare (Ref. 4), who studied fume evolution in GMAW of stainless steel, reported behavior that is discontinuous. Their measured rates, illustrated in Fig. 2, rise through short-circuit to globular transfer, then drop in the spray mode and rise again in streaming transfer. Data from other researchers and common experience tend to confirm this discontinuous change in fume rate, dependent on transfer mode.

An interesting fume profile emerges if the cusped, rising/falling typography of the Grey, Hewitt and Dare report is employed to fit Castner's data. This is illustrated in Fig. 3 where two basic assumptions were applied. First was that of continuity. That is, fume rates must vary with current (from frame to frame of Figs. 1 and 3) in a continuous way. Second, the effect of transfer mode as suggested by Grey, Hewitt and Dare must be reflected. Figure 3 represents our intuitive fit of the data based on these assumptions. The solid curves are ours. Lighter curves represent the original least-squares set from Fig. 1.

The assumption that there must be a continuous progression through Figs. 3A, B, C, D and E requires a significant departure from some of the data points, especially in C and D. Various problems with the AWS standard fume chamber, such as filter blanking and deposition of particles on plate and chamber walls (mentioned by Castner), could explain such deviations. In fact, comparison of two experiments with different power sources but at conditions almost identical (Figs. 7 and 8 in Ref. 3) reveals discrepancies as large as a factor of two at some conditions. Fortunately, Castner's measurements cover a broad range of currents and voltages, encouraging one to interpolate and smooth the data. Figure 3F, a combination of the solid curves from 3A through E, summarizes our speculated intuitive fit of these results.

Examination of Fig. 3F suggests that fume generation rate might be presented effectively by a three-dimensional plot. In fact, an earlier publication by Willingham and Hilton (Ref. 5) shows fume data (Fig. 4) in a quasi-three-dimensional format. Figure 5 is our three-dimensional model of data taken from Fig. 3F. Fume rate is plotted on the vertical axis vs. a horizontal plane defined by voltage and current. Here, one sees the topography of a rising “foothill” interrupted by a depression or “valley” running parallel to the current axis.

The valley in Fig. 5 represents spray transfer conditions. The “ridge” at the left corresponds to globular conditions; the rising mountain at the right, to streaming transfer. Fume rates rise with voltage as one moves from short circuit (low voltage) to globular transfer (the ridge), then drops into the valley during a shift toward spray mode and finally rises again with the onset of streaming (high voltage) transfer. This figure illustrates the connection between fume generation rate and welding mode that some experienced welders might claim is obvious.

The profile of Fig. 5 is consistent with data from researchers who have plotted fume rate in two dimensions — as a function of either current or voltage, with the other variable being held constant. It agrees with results reported by Willingham and Hilton for a current-voltage path defined by the “feel” of an experienced welder. Two-dimensional graphs can be obtained by cutting the three-dimensional model (Fig. 5) with vertical planes — one parallel to either the current or voltage axis or one along the voltage-current path chosen by an experienced welder.

If pulsing the current extends the length and breadth of the valley, a dramatic reduction in fume could be explained as a shift from globular or steaming (high fume) conditions at steady current to spray (low fume) transfer under pulsed conditions.

Experimental Procedure

This research was designed to document the three-dimensional fume profile with a precision and reproducibility unapproached in past studies. Most standard welding fume chamber designs are inflexible, erratic and imprecise, plagued by variable purge-air rates, short welding times, filter blanking, plate overheating and loss of fume through deposition on chamber walls. A thorough review of past fume chambers and their problems can be found in Ref. 6.

Another consideration, in this laboratory, was our role in a New England Welding Research Consortium project to study the physiological effects of inhaled fume. We needed a device that could not only yield accurate, reliable fume rates but could also deliver fume-laden air to laboratory animals for long periods at a steady state.

The fume chamber designed and constructed to address these constraints is illustrated in Fig. 6. This cutaway sketch shows a rotating pipe workpiece on which a weld bead is deposited automatically with an indexed gas metal arc (GMA) welding gun. The pipe is enclosed by a chamber maintained under slight pressure. Compressed air is metered and added at a rate that simulates air flow in

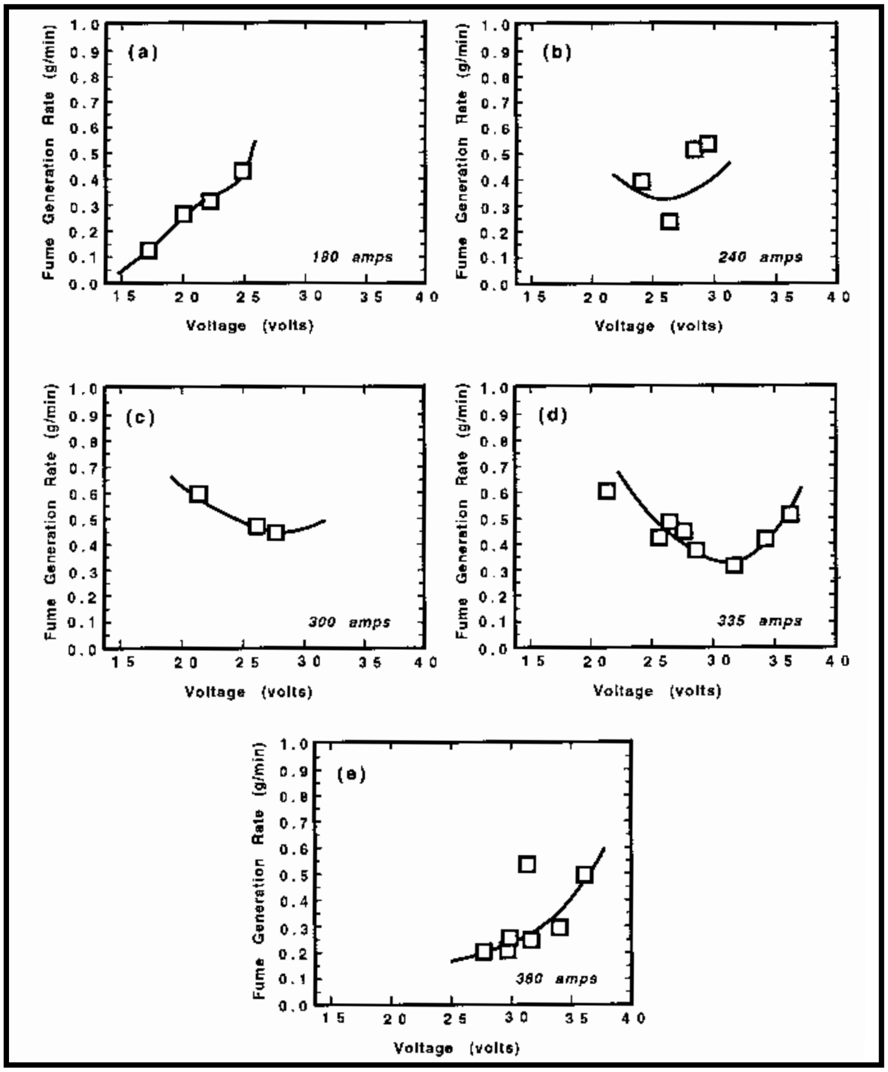

Fig. 1 — Selected fume formation rates for GMAW of carbon steel at steady current with 85% argon/15% CO_2 shielding gas (Ref. 3).

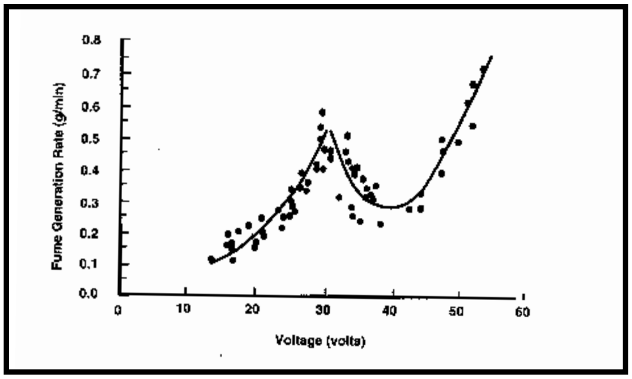

Fig. 2 — Fume generation data reported by Gray, Hewitt and Dare (Ref. 4).

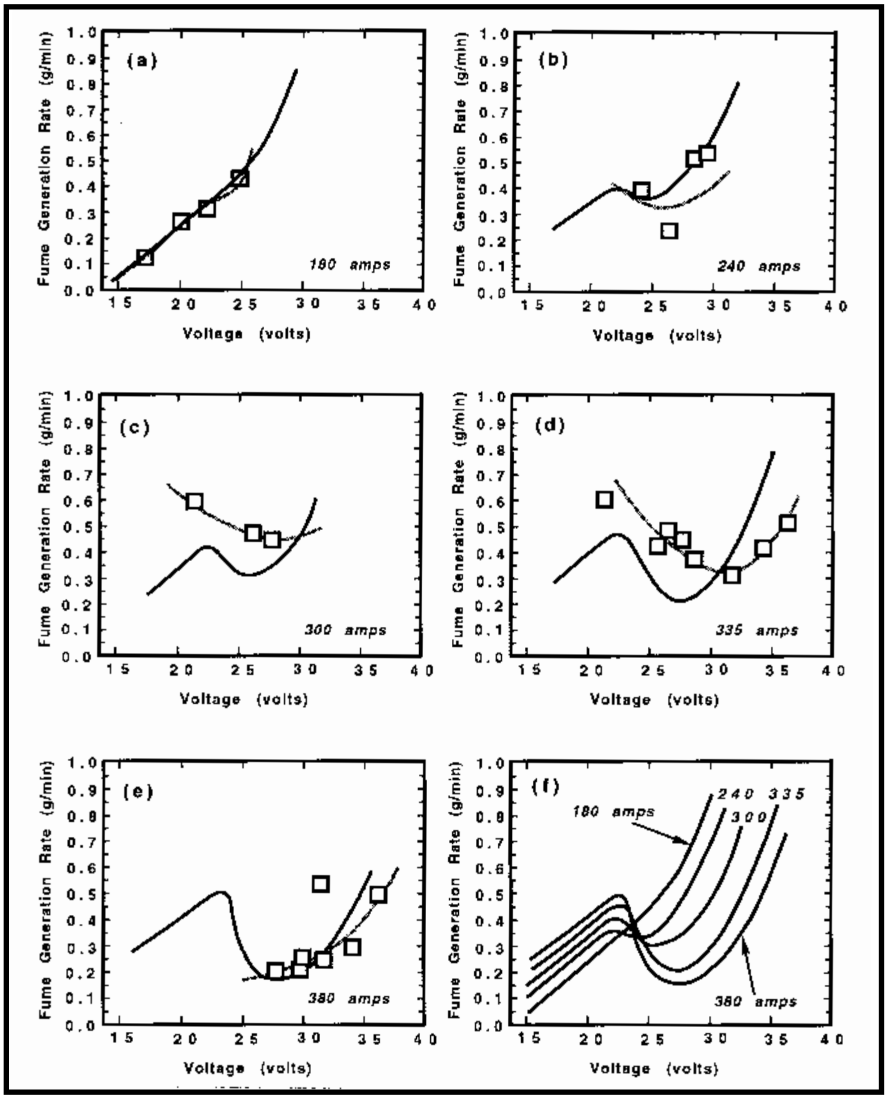

Fig. 3 — Intuitive fit of Castner data from Fig. 1. Continuity from frame to frame and curve shapes consistent with Gray, Hewitt and Dare were assumed. Lighter curves are from Fig. 1. Dark curves are ours. F is a composite of A through E.

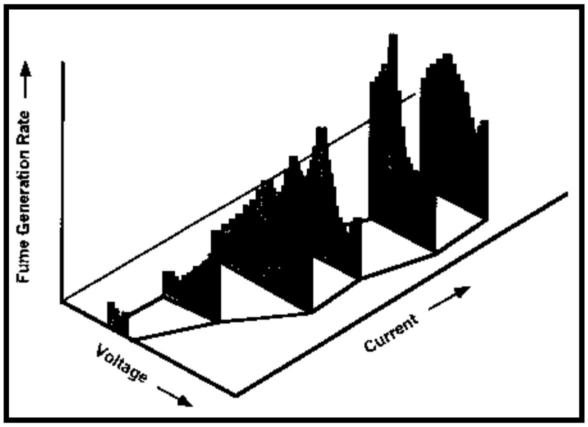

Fig. 4 — Quasi-three-dimensional graph of fume rate vs. current and voltage (Ref. 5).

a shop setting. Positive airflow eliminates changes in the purge rate as fume builds up on the filter. (In designs dependent on vacuum draw, airflow changes with time.)

The cylindrical workpiece allows longer periods of steady-state operation, and it can be cooled internally by either air or water. This avoids an increase of workpiece temperature with time characteristic of rotating disc designs. Photographs of our chamber are shown in Figs. 7 and 8. To confirm that results from this device are compatible with accepted standards, tests were conducted using 100% CO_2 shielding gas at the two conditions specified in the American Welding Society standard fume test (Ref. 7). Measured fume rates were well within ± 10% of specified values as required.

Nine variables were held constant and three were changed. Those parameters held constant are listed below along with justifications for holding them so. More extensive explanations and a thorough review of prior research can be found in Ref. 6.

Constant Parameters

Workpiece and Electrode Material

Prior research confirms that virtually all GMAW fume comes from the electrode rather than the work unless the workpiece is coated with oil, paint or some other substance. Since carbon steel (A36) is the most common metal welded today, it was chosen for this study. Carbon steel electrode welding wire ER70S-3 was used. Each pipe was cleaned with a sanding wheel on an electric grinder before use as recommended by the AWS procedure (Ref. 7).

Wire Type

Flux-cored welding wire generates much more fume than solid wire because of flux evolution, and each flux behaves differently. To keep parameters manageable, only solid-core wire was used.

Wire Diameter

Electrode diameter has a modest effect on fume rate because of differences in voltage, current and (possibly) welding mode. A wire diameter of 1.2 mm (0.045 in.) is specified in the AWS standard. It is also the median common standard in most GMAW and was used in all experiments here.

Polarity

Other researchers have found that polarity can affect fume rate, but since most GMAW is done with a positively charged electrode, such was used here.

Nozzle-to-Work Distance

Prior research has shown that nozzle-to-work distance has a minor influence on fume rate. The "typical" setting of 19 mm (0.75 in.) was used for all our profiles except one. This one (steady-current, 174 mm/s [410 in./min] wire feed rate) was conducted with a nozzle-to-work dis-

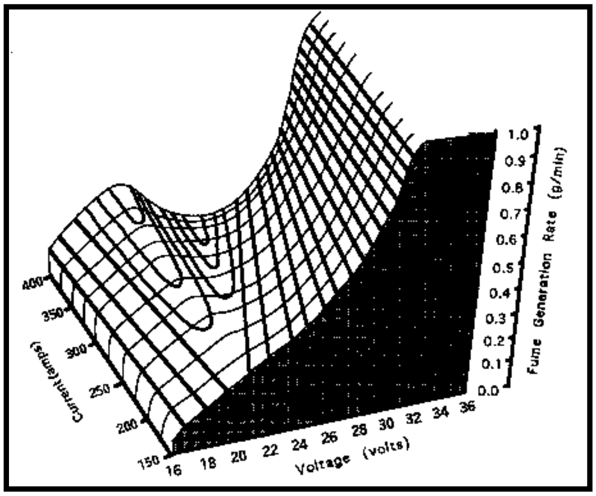

Fig. 5 — Three-dimensional visual model based on an intuitive fit of Castner's steady-current fume data (Ref. 3).

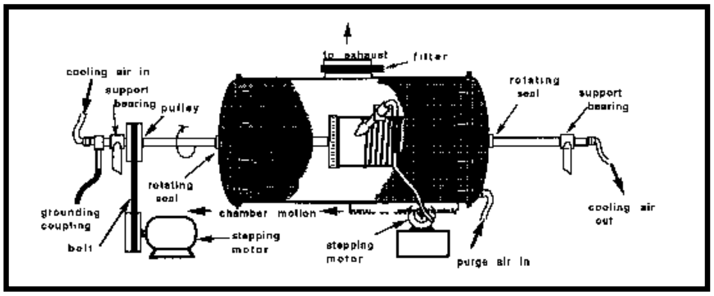

Fig. 6 — Cutaway sketch of the University of New Hampshire (UNH) fume chamber.

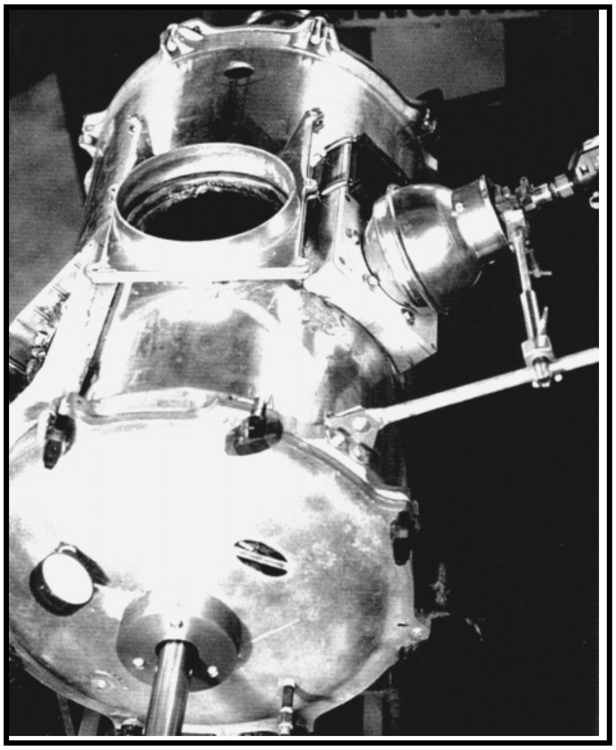

Fig. 7 — Photograph of the UNH fume chamber. Slide gate mounted at the top of the chamber is for filters and sampling. Torch and self-darkening lens are mounted at the one o'clock position.

tance of 12 mm (0.5 in.). Emission profiles were similar for both separation distances over the voltage operating range, but absolute fume rates ranged about 20% higher at 12 mm.

Electrode Angle

Others have found that variations in electrode angle have only a slight effect on fume rate (within reasonable operating limits). A 10-deg drag angle was used here as recommended by the AWS standard procedure (Ref. 7).

Welding Speed

Changing the torch travel speed by a factor of two reportedly increases fume rate by about 5% (Refs. 8, 9). A value of 6 mm/s (14 in./min) as recommended by AWS standard procedure (Ref. 7) was used throughout this study.

Shield Gas Composition

It is widely known the type and composition of shielding gas profoundly affects fume generation rate. The gas recommended for our power supply is 92% argon/8% CO_2, a common choice in industry. Therefore, this shielding gas mixture was chosen for all experiments (except calibration) conducted in this research.

Shield Gas Flow Rate

Others have found shielding gas flow rate to affect fume rate. Presumably, shielding gas rates must be high enough to protect the weld zone from oxygen in the air but low enough to minimize turbulent mixing. A value of 16.5 L/min (35 ft^3/h), in the midrange of values recommended by the manufacturer of our welding equipment, was used here.

Variable Parameters

In GMAW, three variables — voltage, current and wire feed speed — are interdependent. In this research, voltage and wire feed speed were dictated by the operator while current, which is approximately constant at a given wire feed speed, was controlled by the power supply.

Wire Feed Speed

Five different wire feed rates were chosen: 76, 102, 127, 148 and 174 mm/s (180, 240, 300, 350 and 410 in./min), similar to values selected by Castner (Ref. 3). These wire feed speeds encompass normal welding modes and represent common practice in GMAW of mild steel.

Voltage

Voltages ranged from 18 to 34 V in these experiments. (Not all voltages could be employed at all wire feed speeds. Excessive voltage at low wire rate melts through the workpiece. Low voltage and high wire feed rate creates a visibly unsatisfactory weld.)

Steady/Pulsed Current

Fume rates were measured under both steady- and pulsed-current conditions. At steady-current conditions, wire feed speed and voltage were set by the operator and current was controlled by the power supply. In pulsed-current experiments, wire feed speed, pulse width and frequency were set by the operator. The power supply controlled voltage and average current at steady levels during a weld. These parameters were read and recorded by the operator.

Sampling Procedure

Samples were collected on filters of

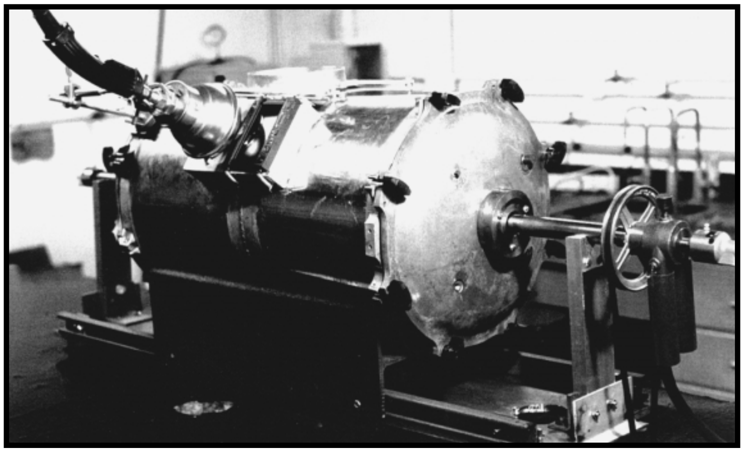

Fig. 8 — Photograph of UNH fume chamber, side view.

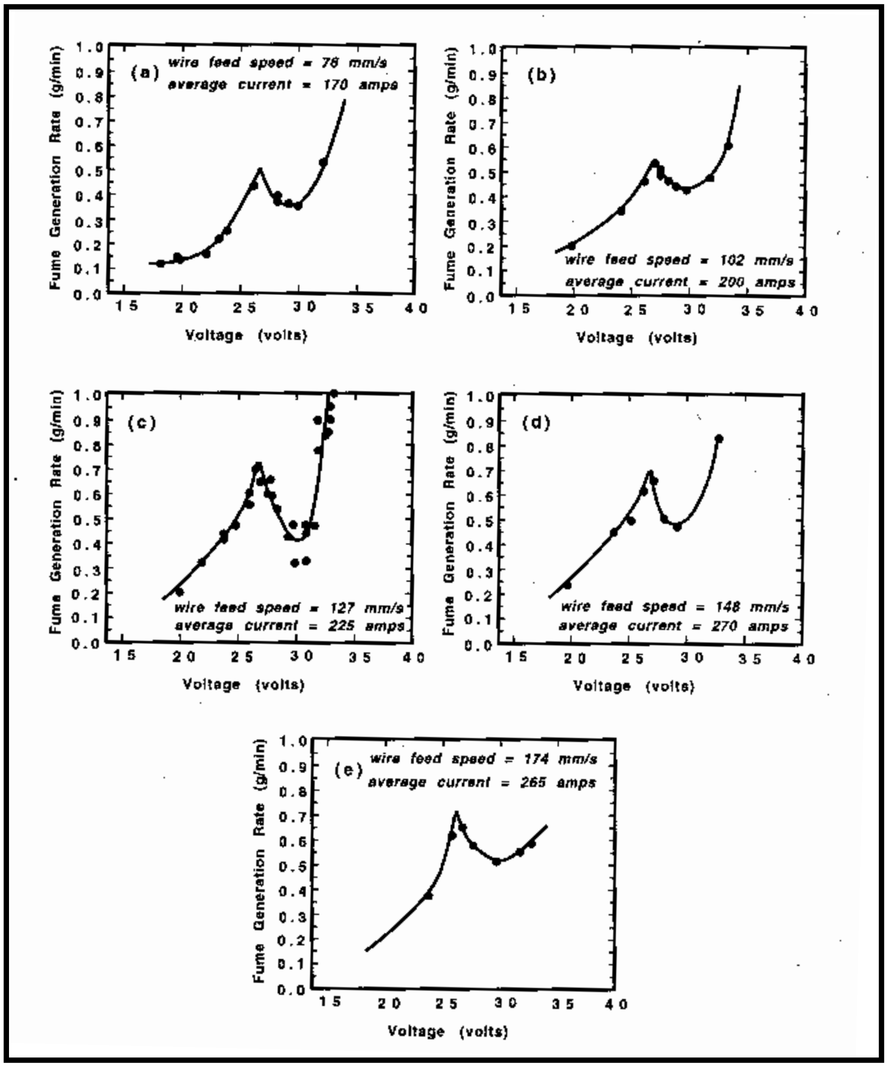

Fig. 9 — Fume formation rates for GMAW of carbon steel at steady current with 92% argon/8% CO_2 shield gas. Wire feed speeds and average currents vary from frame to frame as specified.

various types mounted at the chamber exhaust port. (Fume quantity was the major concern in this study. In a related project, particle size distributions were measured using an Electrical Aerosol Analyzer. Results of that work will be reported elsewhere.)

To create a data map, bead-on-pipe welding was conducted for 20 s at a fixed condition. Then, the chamber was purged by sweep-air for an additional 2 min to ensure complete collection of fume. The filter was removed and weighed. A new, preweighed, predried filter was installed, and the process was repeated at a different experimental condition.

Numerous experiments were conducted with welding durations of 30 and 60 s. Measured fume generation rates were independent of welding time. To prolong workpiece life, a duration of 20 s was used for most experiments.

Results

The equipment described above was used to define two separate fume profiles. Both apply to GMAW of mild steel with 92% argon/8% CO_2 shielding gas. One is for steady-current welding, the other for pulsed current. Type ER70-S mild steel electrode welding wire of 1.2-mm diameter was used to weld a continuous bead on a 10-in. Schedule 40 mild steel (A36) pipe.

Equipment was calibrated using the AWS standard procedure with mild steel and 100% CO_2 shielding gas. Calibration fume rates were in excellent agreement with AWS standard values. Reproducibility was checked several times during the collection of approximately 150 data points. Standard deviation was found to be within ± 5% for this system compared with values in the range of ±15 to 20 % typical of other recent studies.

Individual templates were developed by measuring fume rate vs. voltage at a fixed wire feed speed. Data for steady-current operation are illustrated in Fig. 9. Each frame is for a given constant wire feed speed (or current). These results were used to construct the three-dimensional typography shown in Fig. 10.

Pulsed-current results are presented in Fig. 11 for individual wire feed rates. A three-dimensional representation of these data is shown in Fig. 12. Pulsed-current operation introduces other parameters: pulse width, frequency and waveform. The representation in Fig. 12 is for data gathered at a constant pulse width of 2.5 ms with waveform parameters, as delivered by the Hobart Arc-Master 500 power supply. To generate each curve in Fig. 11, wire feed speed was set and frequency was increased (from about

100 to 250 Hz), raising power level. Voltage and average current were controlled automatically by the power supply and recorded by the operator.

The effect of using pulse width rather than frequency as a primary variable is illustrated in Fig. 13. Here, wire feed speed and frequency were held constant, and pulse width was varied from 2.0 to 4.0 ms. Current and voltage were controlled by the power supply to deliver constant power of 4600 W (from 2.1 to 2.7 ms). Then, power rose linearly from 4600 to 6400 W at 3.9 ms. (At a pulse width of 6.25 ms, one would have steady current. At this hypothetical extrapolated condition, we estimate the potential would have been approximately 34 V. This is useful as the basis for another point in Fig. 13, that is, a fume value of 1.1 g/min at 6.25 ms as obtained by extrapolating steady-current data from Fig. 9C to 34 V.)

Another useful correlation is illustrated in Fig. 14. This shows fume rate vs. frequency at the same wire feed speed as in Fig. 13, but here power was held constant by allowing frequency to change with pulse width. The upper curve is for a power level of 4600 W, which corresponds to the globular peak fume rate in Fig. 11C. The lower curve is for 5900 W, the spray valley minimum in Fig. 11C.

Filter Studies

In prior presentations (Ref. 10) and informal discussions, we have questioned the efficiency of the fiberglass filter used in the AWS standard test. This medium is not designed for filtration but for aircraft insulation. It is recommended in the AWS standard (Ref. 7) because that fume chamber depends on a blower to exhaust fume, and finer high-efficiency filters clog or "blank" before a test can be concluded. (Arguments that a second AWS filter shows no added fume pickup are inconclusive because ultra-fine dust that might escape the first filter pad would also pass through the second.)

To resolve doubts about the filter, we performed tests using both the AWS recommended medium- and high-efficiency (HEPA) filters. Each medium was tested separately. Further tests were made using a HEPA filter behind the AWS fiberglass pad.

Fume mass was basically the same at identical welding conditions independent of primary filter type. In fact, even in this positive-pressure system, blanking of a HEPA primary filter was serious enough to cause leakage of fume from the chamber seals, limiting test time. When the HEPA filter was used as a backup to the AWS pad, fume was visibly evident on the HEPA filter, but its weight was too small to register.

We conclude that even though some fume does pass through the AWS medium, it is too small in mass to affect results. Thus, the recommended fiberglass pad is suitable for measuring welding fume rate on a mass basis. Indeed, it was used for most of our experiments. If one is concerned about ultra-fine fume and particle number populations, on the other hand, this medium might be inappropriate.

Discussion

Design and construction of an improved fume chamber was one goal of this research. Its use to document three-dimensional fume maps for a single, common GMAW material and shield gas under steady- and pulsed-current conditions was another goal. The chamber illustrated in Figs. 6–8 was built and used to measure fume rates for solid mild steel (ER70S-3) electrode welding wire 1.2 mm in diameter, and a 92% argon/8% carbon dioxide shielding gas at steady- and pulsed-current conditions (pulse width of 2.5 ms).

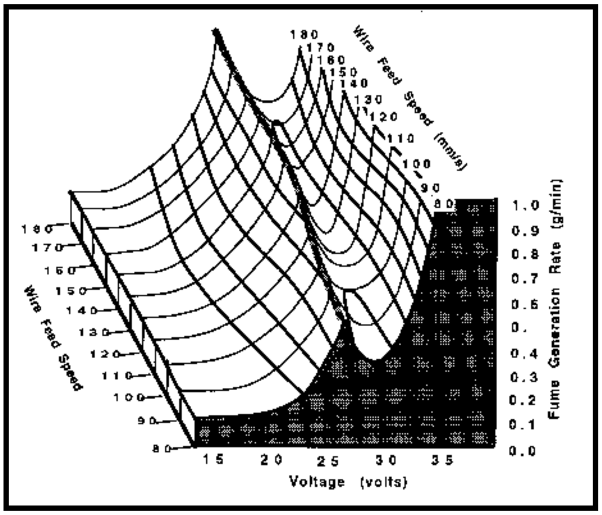

Fig. 10 — Three-dimensional representation of steady-current fume data from Fig. 9. (GMAW of carbon steel at steady current with 92% argon/8% CO_2 shielding gas.)

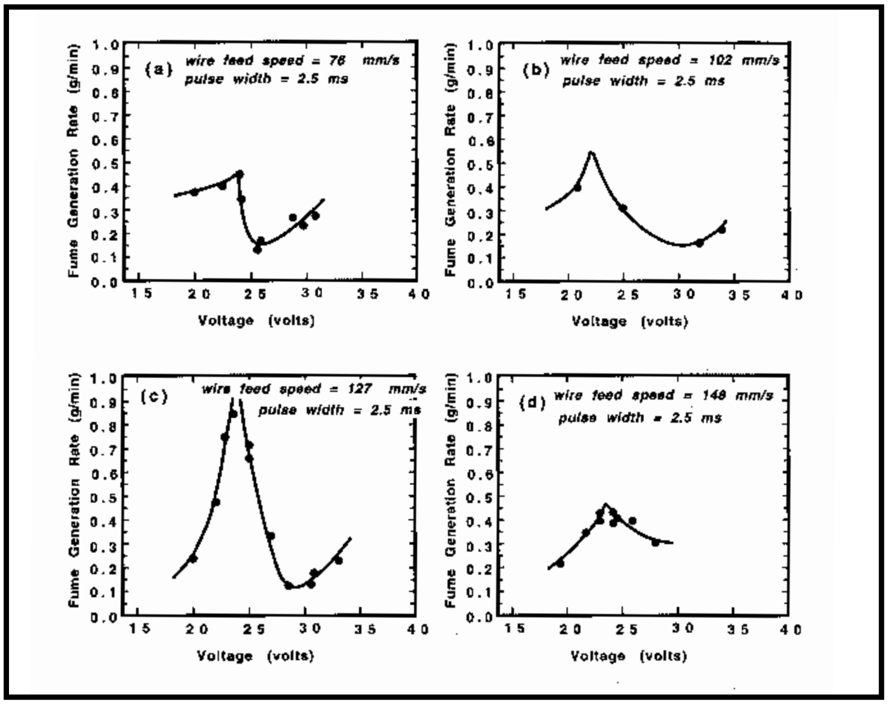

Fig. 11 — Fume formation rates for GMAW of carbon steel, pulsed current, with 92% argon/8% CO_2 shielding gas. Wire feed speeds vary from frame to frame as specified.

Results are illustrated in Figs. 10 and 12. Both maps display a typography similar to that foreshadowed in Fig. 5. That is, fume rate rises gradually as current, voltage and wire feed speed increase and the welding mode migrates from short-circuit to globular. Globular transfer creates peak fume rates, as illustrated in Figs. 10 and 12 by ridges running parallel to the wire-feed-speed axes. Voltage along this ridge is almost constant (26.5 V with steady current and 23.5 V with pulsed

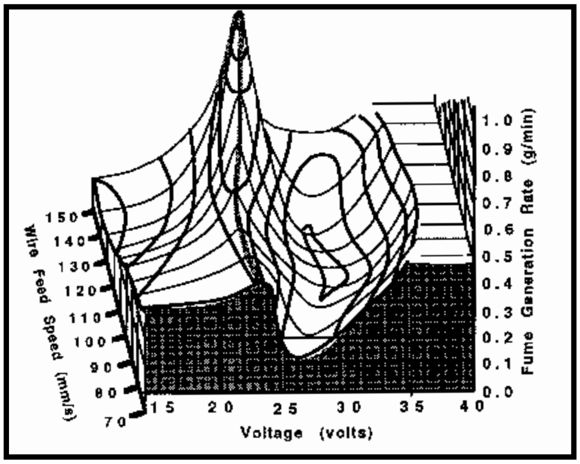

Fig. 12 — Three-dimensional representation of pulsed-current fume data from Fig. 11. (GMAW of carbon steel at pulsed-current with 92% argon /8% CO_2 shielding gas.)

current). At higher voltages, fume rates decline dramatically as the welding mode shifts toward spray transfer. At 127 mm/s wire feed speed with steady current, the peak-to-valley fume rate differs by a factor of two. At the same wire feed speed with pulsed current, the drop in going from globular to spray mode is even more dramatic, a factor of nine. At even higher voltages, fume rates rise again sharply and for both current types as transfer shifts from spray mode to streaming.

Several important points should be made in comparing Figs. 10 and 12. For example, fume rates in the spray valley are consistently lower with pulsed current, less than half those observed with steady current. Also, the voltage range for spray transfer (*i.e.*, the width of the valley) with pulsed current is about double that found with steady current. In general, claims that fume rates are lower with pulsed-current welding are confirmed by these data. There is one notable interesting exception. At a wire feed speed of 127 mm/s and at globular conditions, the maximum fume rate with pulsed current (the "peak" in Fig. 12) is higher than that with steady current.

The influence of other pulsed-current welding parameters is illustrated in Fig. 13. Here, one sees a fume rate of 0.65 g/min at "machine standard" conditions (160 Hz, 2.5 ms pulse width, a point just to the right of the globular peak in Fig. 11C). With an increase in pulse width to 3.5 ms, fume rate drops by a factor of three to 0.2 g/min, a level typical of spray transfer. Similar variations are evident from Fig. 14. Here, frequency was changed while the power supply automatically adjusted pulse width to maintain constant power. Again, we see dramatic variations in fume rate with frequency. (It should be noted that a family of typographies similar to Fig. 12 could be generated under pulsed-current conditions, one for each pulse width. Other variations are possible depending on the waveform delivered by the power supply.)

For a given welding situation, fume generation rate is essentially dictated by welding mode. According to our research, one should, if given a choice, operate under spray transfer conditions to minimize fume evolution in GMAW of carbon steel with solid electrodes. Fume can be cut further by a shift from steady to pulsed current if the latter is also tuned to the spray-mode minimum. Welding at globular and streaming conditions increases fume rate dramatically with both steady and pulsed current.

Modeling Considerations

How does one explain the dramatic difference in fume rate between globular and spray transfer conditions? A detailed answer to this question is the basis of work to be published later, but a brief discussion is appropriate here. Our explanation is based on the model introduced by Gray, Hewitt and Dare (Ref. 4). They list seven potential sources of fume. Of these, evaporation and explosive droplet detachment are relevant to this discussion. We assume that these two

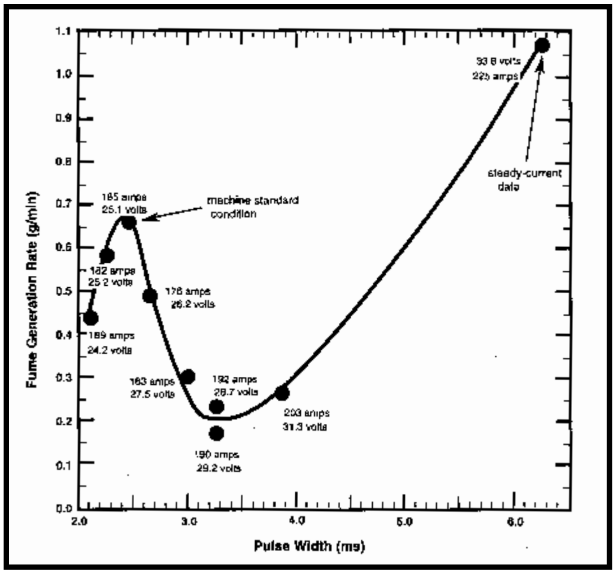

Fig. 13 — Fume formation rates vs. pulse width in pulsed-current GMAW of mild steel. Wire feed speed was fixed at 127 mm/s and pulse frequency at 160 Hz. Voltage and current were automatically controlled by the power supply at values shown. Extreme data point at 6.25 ms extrapolated from steady-current data of Fig. 9C.

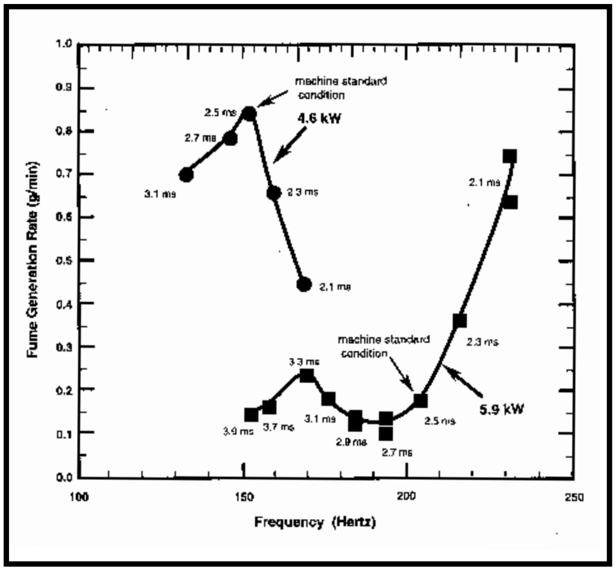

Fig. 14 — Fume formation rate vs. frequency in pulsed-current GMAW of mild steel. Wire feed speed was fixed at 127 mm/s. Voltage, current and pulse width were automatically controlled by the power supply to maintain power constant (4.6 kW in top curve and 5.9 kW in the bottom curve). High fume conditions correspond to globular transfer at this wire feed speed. Low fume corresponds to the spray valley minimum (see Fig. 11C).

mechanisms are both active during globular transfer. That is, as a droplet forms and grows at the tip of the electrode, its surface heats up and electrode metal evaporates to diffuse into the gas stream where it later oxidizes and condenses to form fume. Then, when a droplet detaches from the electrode, the area of the "neck" decreases to a point where enormous heat is released because of the rising resistance and high current. This generates metal vapors at explosive rates, ejecting micro-droplets into the gas phase. Some droplets, or "spatter," are too large to remain in the atmosphere, but smaller droplets, or "sputter," persist as fume. Thus, under globular conditions, evaporation and explosive detachment both contribute to the fume.

Why do fume rates drop during spray transfer? In spray mode, the arc spot is no longer focused at the bottom of the growing drop, but the arc moves around detaching droplets and up the side of the melting electrode. (See recent high-speed photographs of Jones, Eagar and Lang, Ref. 11, for illustration.) Thus, explosive ejection is no longer a major contributor to fume. In fact, there may be even less droplet superheating with the expanded arc contact area, creating even less evaporation than in the globular mode.

Why are fume rates generally lower with pulsed current? If the droplet detachment frequency matches pulse frequency, detachment can occur during the low background current phase of the cycle and there will be less explosive fume ejection. Also, it is likely that pulsing, by promoting early droplet detachment, results in even less superheating of molten electrode droplets and less metal evaporation.

Why is the spray valley wider with pulsed current than with steady current? Pulsing evidently promotes droplet detachment under spray conditions over a wider voltage range. This causes spray transfer under what might be globular conditions with steady current.

Why, under special conditions (the spike in Fig. 12), does pulsed-current globular transfer create more fume than steady-current globular? If droplet and current frequencies are quite different, detachment may occur not during the background current cycle but during peak current, which is considerably greater than the steady-current value at similar power levels. This high peak current passing through the detaching droplet neck will cause even more explosive fume expulsion than what occurs at steady-current globular conditions.

Summary

Welding fume will undoubtedly persist as a subject of litigation and legislative debate. Its role in workplace health and safety will command more scrutiny as time passes. This research was conducted to improve the accuracy of fume formation data and to correlate fume rate with welding mode.

Fume formation rates measured in the past have lacked precision. Heile and Hill's pioneering work (Ref. 9) reported a standard deviation of ± 20%, but some statistical variations were as great as ± 40%. Other researchers report standard deviations of ± 15% to 20% using established U.S. and European fume chamber designs.

The fume chamber of new design introduced in this paper was operated through a comprehensive range of steady- and pulsed-current conditions that produce acceptable welds. With more than 150 test results, many of them replicates, the standard deviation was ± 5%. Thus, excessively broad limits of accuracy need no longer be a hindrance to data interpretation.

Each electrode type/shielding gas combination has its unique fume profile. A different profile results if pulsed current is used. In fact, each pulse width exhibits its own fume typography.

Conclusions

A fume chamber of new design was used to measure fume generation rates for gas-shielded metal arc welding of mild steel under both steady- and pulsed-current conditions using a single common shield gas. A continuous three-dimensional typography is revealed when fume rate is plotted above a plane defined by wire feed speed and voltage. In general, fume rates rise as power is increased through the short circuit mode. Rates peak under globular transfer conditions and then drop dramatically as the mode shifts to spray transfer. Fumes increase again as the mode shifts to streaming transfer.

Profiles are similar for both steady- and pulsed-current welding, except the spray-transfer "valley" is wider and lower with pulsed current.

The fume chamber design used here is recommended for its high accuracy and flexibility. This particular chamber has been moved to another New England Welding Research Consortium location (the Harvard School of Public Health) where it is being used for MIT-Harvard projects involving stainless steel fume and the effects inhaled welding fumes of various kinds exert on animals.

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