Particulate Fume Generation in Arc Welding Processes

Mechanisms of particulate emission along with emission rates and composition have been determined for a variety of arc welding processes.

BY R. F. HEILE AND D. C. HILL

ABSTRACT. A technical method has been developed that allows a determination of the fume formation rate and fume composition in arc welding processes. This method has been used to characterize particulate emissions in a number of processes: shielded metal arc (SMA), gas metal arc (GMA), flux cored arc (FCA), and gas tungsten arc (GTA) welding, and has permitted a ranking of these processes according to their relative "cleanliness." Of the continuous electrode processes studied, GMA welding with argon-based shielding gas produced the least fumes, while self-shielding FCA welding produced the most. The data indicate that the mechanism of fume formation is one of elemental vaporization-condensation and oxidation enhanced vaporization-condensation of the consumable constituents. A model relating this mechanism to process and process variables is advanced which would allow fume formation rates and composition to be predicted semi-quantitatively given a knowledge of the consumable composition, the volatility of the constituents, the transfer mode, the arc temperature and stability as determined by the welding parameters and shield gas, and the oxidizing potential of the shield gas. Based on the results, methods of fume control are indicated which can serve as a supplement to ventilation.

Introduction

Although numerous studies of the generation of smoke and fume in arc welding have been made (Ref. 1), the mechanism and character of the fume formation have not been extensively investigated or reported. It is now recognized that variations in sampling techniques, electrode compositions, and welding parameters all have a major impact on the results of fume experiments. As a result, care must be exercised in interpreting the existing literature. Recently, a proposed technique for measurement of fume generation in arc welding has been published (Ref. 2). Unfortunately, little statistical evidence for the accuracy and reproducibility of this technique was advanced.

The purposes of this study are to provide fume generation comparisons among different arc welding processes, to understand the mechanism of fume formation, and to supply the information necessary for choice of a welding process when ventilation considerations are important.

Method for Particulate Sampling

General

A critical aspect of particulate sampling is the technique itself. Various sampling techniques have been employed by other investigators (Ref. 1). Many of these techniques collect all of the evolved fume. In so doing, oftentimes unrealistic conditions are imposed on the particular welding process. We chose, instead, to use a modified stack sampling technique which would minimally disturb the welding process and at the same time allow a carefully controlled sample to be taken at a predetermined rate. This section briefly describes the technique and discusses the accuracy and reproducibility of the results.

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Experimental Technique

A schematic of the stack sampling system employed in this work is shown in Fig. 1. A duct was placed coaxially over a stationary welding torch. Welds were made on a rotating workpiece. The gas flow rate of the duct was set to allow collection of most of the fume, yet not so fast as to disturb the shielding gas. The duct velocity was measured using an inclined manometer. A probe, connected to a filter and a sampling pump, was inserted in the duct. The velocity in the probe was adjusted to optimize the duct velocity. By maintaining isokinetic sampling conditions, it is possible to relate the size of the sample collected to the total fume evolution without having to collect all of the fume.

This technique is applicable over a range of duct velocities, i.e., sampling rates for a constant sampling time. This is especially important in sampling emissions where the saturation time of the filter is short. Without control over the sampling rate in such situations, the results would be subject to transient effects related to short sampling times. This technique eliminates those problems.

The basic procedure followed for taking a sample was to establish isokinetic sampling conditions and then, before actually beginning the sample, to choose the welding parameters. Sampling was begun after the arc was struck and steady-state conditions established. The duration of the sampling period depended upon the fume generation rate and the filter capacity. The importance of the sampling period is discussed in greater detail in the section below.

Two types of filters were employed, glass fiber filters and triacetate filters. The glass fiber filters were used principally to determine the fume generation rates, and the triacetate filters were used to collect fume for chemical analysis. Typical sampling times were 2 minutes for the glass fiber filters and 30 seconds for the triacetate filters.

An optical viewing system attached to the welding station permitted a simple measurement of arc length.

Reproducibility and Variations

The purpose of sampling is, of course, to arrive at a fume formation rate (FFR) and a fume composition which can be assigned to a given welding process. It is obvious that the generation rate will depend upon voltage and current as well as the process and that the fume generation rate must be expressed as a function of these or related parameters. It is not so obvious how sensitive fume formation is to such things as work travel speed and variations in the plates on which the welds are made or, for that matter, to the sampling procedure itself.

In order to assess the accuracy of these experiments and to determine what parameters are needed to specify FFRs unambiguously, a two-fold investigation was undertaken. This included an investigation of the dependence of fume formation on voltage, current, work travel speed, and plate variations and an investigation of sources of error associated directly with the sampling technique.

Although there is some evidence of a variation in fume formation for different plates, the effect can be minimized, as far as relative measurements are concerned, by collecting a given series of weld data on the same plate. In absolute terms, the variation is a source of error on the order of a percent or two. Such an error is insignificant when compared to other sources yet to be discussed.

Work travel speed can also be omitted in the specification of FFRs. Increasing the travel speed by a factor of two produces a 5% decrease in the formation rate. Small variations in work travel speed from nominal values have, therefore, no significant effect. The observed variation is also not great enough to warrant specifying travel speed when stating the fume formation rates.

Depending on the shielding gas, voltage and current are by far the most important factors among the welding parameters. For argon-based shielding gas, a 1 to 5% variation in voltage for a fixed current can produce changes in the FFR of as much as 20%. By way of contrast, the sensitivity of the FFR to changes in the voltage and current is far less for CO₂ shielding gases. In terms of reproducibility of the results, one must exercise great care in maintaining the voltage and current settings when welding with the argon-based shielding gases. In this regard, the ability to measure the arc length is exceedingly useful.

From the above information, it was expected that the FFRs would be reproducible to within 10%, yet statistical fluctuations of as high as 40% were observed. The large standard deviations that resulted tended to reduce the statistically meaningful information which could be extracted from the data. As a result, the sampling method was explored as the source of the problem. The sensitivity of the fume formation rate to the fume collection rate was examined. Different fume collection rates produced statistically consistent FFRs as long as isokinetic sampling conditions were maintained. However, an investigation of the sensitivity of the FFR to the sampling period revealed that the problem resided in variations in the stopping power of the filters. This data is presented in Figs. 2 and 3. In Fig. 2, ten welds were made at a constant sampling rate. All conditions were held constant except for the sampling period which was increased by 10 seconds for each successive weld. In principle, all the points should be on a straight line passing through the origin. The slope of this line is proportional to the FFR. Instead of a straight line, a wide scatter was observed as Fig. 2 demonstrates.
In addition to the data, there are four lines drawn in Fig. 2. The outer lines represent the worst case slopes for all the data points. There is a factor of six between them. The inner lines are the worst case slopes for the data where the sampling period was greater than or equal to one minute. The longer sampling period tends to reduce the variations in the filters. In this case, the slopes are within 40% of one another. It should be remembered that these are worst case slopes. The accuracy can be further improved by making a least squares fit and limiting the sampling periods to one minute or greater. This results in an overall statistical accuracy of approximately 20% for the absolute measurements of the FFRs quoted in this report.

The behavior of individual pieces of filter paper was also examined as a function of time. The same piece of filter paper was successively exposed for constant time increments and weighed after each increment. These results are plotted in Fig. 3. In this case, the points lie on a straight line, as expected, although there appears to be a nonlinearity during the initial few seconds of sampling. This does not present a problem since the information can be drawn from the linear portion of the curve. Equally important is that over typical sampling periods of one or two minutes, no saturation of the filter was observed. In fact, no saturation was observed even with sampling periods as long as four minutes for many welding processes.

To summarize, therefore, absolute measurements of the FFRs are subject to large variations. Voltage and current must be precisely determined and maintained. Plate variations and work travel speed, although factors, do not result in significant variations. Differences from filter to filter account for the largest and least controllable variation. As a result, FFRs can be conveniently determined within no more than 20%. Greater accuracies are possible but are not required for the purpose of the comparisons made in this article.

**Particulate Data by Process**

**General**

Firm limits exist for both the time weighted and excursion levels of solid materials dispersed in air. These limits are rather arbitrary, although some toxicological data exist to support them. They are deficient in that they fail to recognize that variations in crystallographic structure, particle size, and chemical activity are important in influencing the interaction of such materials with the human system. We have studied fume generation in several arc welding processes: shielded metal arc (SMA), flux cored arc (FCA), gas metal arc (GMA), and gas tungsten arc (GTA) welding. Fume generation is measured in two ways: g of fume/min of arc time and mg of fume/g of metal deposited. These formalisms (g/min and mg/g) express the relative "cleanliness" of a process on real time and real completion rate bases.

FFR measurements were made on 200 × 250 mm fiberglass filters using the techniques described in the previous section. Samples for compositional analysis were made on trichloroethylene filters and analyzed using atomic absorption spectrophotometry and x-ray fluorescence techniques. A limited amount of size distribution data has been taken.

**SMA Welding**

Only electrodes for the welding of ferrous materials were studied. These electrodes include those of the cellular type, rutile type, rutile-iron powder type, and low hydrogen type. Both dcp and dcsp were studied wherever possible. A constant current type power supply was used. Results are briefly summarized in Table 1.

The FFR data (mg/g) is plotted against current in Fig. 4 for 6/32 in. electrodes. Data reduced from Refs. 2, 3, and 4 are also included. Note that the data fall into three bands. The lowest FFRs are associated with rutile and rutile-iron powder type electrodes. Higher hydrogen rates are found for low hydrogen type electrodes, probably due to the presence of CaF₂ in the flux. Cellulosic electrodes have the highest rates.

Variations in rates accompanying polarity changes are best understood by variations in arc voltages due to the polarity change.

No chemical analyses were performed on SMA welding fume. It is expected that the principal difference between fume from rutile, rutile-iron powder electrodes, and from low hydrogen electrodes will be the presence of CaF₂.

**FCA Welding**

Three types of flux cored electrodes were studied: CO₂ shielded,
Table 2 — Fume Sampling in FCA Welding

<table>
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<tr>
<th>Electrode</th>
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<td>CO₂</td>
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<td>32</td>
<td>Ar-2% CO₂</td>
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Fig. 6 — Particle size distribution by weight percent in FCA welding

Fig. 7 — Comparison of FFRs in GMA welding using argon-based shielding gases

silica-base (E70T-5); CO₂ shielded, rutile-base (E70T-1); self-shielded, fluorospar-base (E70T-4). A constant potential type power supply was used. The results of the fume generation studies are shown in Table 2.

Figure 5 shows a combined plot of mg/g versus current for the data. There is an appreciable difference in FFR between self-shielded, fluorospar-base and CO₂ shielded, rutile-base electrodes. A similar difference is noted between CO₂ shielded, silica-base and CO₂ shielded, rutile-base electrodes. These differences are primarily due to variations in arc stability and CaF₂ content.

Table 3 shows the comparative and absolute variations in fume composition for the three types of electrodes. Note that the rather large variation in fume composition results from differences in the flux compositions.

Variations in welding parameters did not seem to have a significant effect on FFR. Voltage increases did not produce FFR increases in any way comparable with those found in SMA welding.

Particle size distribution data were taken using an inertial separation system. The results of two of the studies with the self-shielded, fluorospar-base electrode are shown in Fig. 6. The plot shows the cumulative weight percent of fume due to particles larger than any diameter. The weight distribution is log-normal. The mean particle size by weight calculated from this data is 0.12 μm.

GMA Welding

Particulate data were gathered in GMA welding with a variety of wire compositions, wire sizes, and shielding gases over a broad range of welding conditions. General considerations on reproducibility and technique were discussed in previous sections of this article. This section covers additional work on ferrous materials and aluminum alloys.

Ferrous Materials

Effect of Shielding Gas on FFR. Treating first the effect of shielding gas, reference is made to Figs. 7 and 8. Figure 7 shows the FFR plotted against current for argon-base shielding gases. The wire diameter was 0.045 in. and the welding voltage was 28 V. Note the presence of a well defined minimum in the 250-300 A range for each of the shielding gases. Figure 8 plots FFR versus current for CO₂ and Ar-25% CO₂. For these gases FFR is a monotonic function of current. Note that significant, reproducible departures from the Ar-25% CO₂ curve occur at 300 and 400 A.

A comparison of these figures reveals that considerably more fume is produced when welding with CO₂ shielding compared with argon-based shielding. The explanation of this effect involves consideration of the oxidizing nature of the shield gas and of the mode of metal transfer.

The dependence of the FFR on the oxidation potential of the shield gas was examined by measuring the FFR as a function of the oxygen content of an argon-based shielding gas. These results are shown in Fig. 9 for oxidizing additions of up to 40%. Note that the FFR is approximately equal to (%O₂)⁻¹. Since oxygen is present as atomic oxygen in the arc to a certain extent, it is possible that the dependence would be greater than (%O₂)⁻¹. Thus the exponent 1/4 is reasonable.

Effect of Welding Parameters and Wire Size on FFR. The existence of the minimum in FFR noted above for argon-based shielding gases was explored further as a function of welding parameters. Figure 10 shows constant current plots as a function of arc voltage for FFR (g/min). In all cases, arc length increased for increasing arc voltage. Note that the minimum FFR occurs at 28 V, 250 A. If mg/g is used as a criterion instead, a similar observation is made, Fig. 11. The minimum correlates with the transition from globular to spray transfer. This minimum is thought to result from the establishment of a stable spray arc at a minimum voltage.

Similar plots for CO₂ shielding gas are shown in Figs. 12 and 13. Note the absence of any minima. This observation reinforces the hypothesis that the transfer mode affects the FFR.

Figure 14 shows the effect of wire diameter on FFR in Ar-5% O₂.

Fume Composition and Particle Size Distributions. Fume composition was measured for a number of welding conditions. Data may be found in Table 4. For the most part, as measured by weight percent, the composition of the fume is constant. The most significant exception to this is that the fume silicon contents generated in argon shielding gas are significantly less than those produced with oxygen bearing argon-based gases and substantially less than CO₂.

Particle size analysis of the fume produced using argon-based shielding gases and CO₂ shielding gases was attempted. However, when argon-based shielding was used, no fume could be collected on the upper
stages of the sorter. Electron micrographs revealed fume particle sizes on the order of 0.005 to 0.1 microns. These particle sizes are much smaller than for any other welding process and explains the null result with the sorter. A visual comparison of particle sizes is presented in Fig. 15.

The particle size distribution measurements for CO₂ shielding gas were made at 300 A, 34 V. The results are plotted in Fig. 16. An extrapolated mean particle diameter of 0.03 micron, considerably smaller than for FCA welding, is determined from this data.

Aluminum Alloys

FFRs and fume compositions were determined for 1100 and 5356 alloys welded in argon. Typical FFRs (g/min) and fume compositions are given in Table 5.

It is interesting to note the decrease in FFR with increasing current. This observation is similar to that observed in GMA spray arc welding of steel over a certain range of current and voltage. A precise understanding of this effect is lacking at this time.

GTA Welding

Fume formation in GTA welding of steel using 3 mm and 5 mm thoriated tungsten electrodes with argon shielding gas was studied. The FFRs for all currents between 50 and 450 A were essentially zero.

Discussion of Results and Probable Mechanisms

In addition to supplying comparative data among different arc welding processes, it was believed that the FFRs and the composition of the welding fume could help to identify the mechanism of fume formation.

Consider first free elemental vaporization as a source of fume. The partial pressures of Mn, Si, and Fe above molten steel with the composition of the E70S-2 electrode are plotted as a function of temperature in Fig. 17. Two things are apparent. Free vaporization can account for the increase in fume with arc temperature, but based on this mechanism alone there should be but negligible silicon in the fume compared with Mn and Fe. Since this is not the case, other mechanisms must contribute.

The notable difference in fume composition between weldments made in argon-based gases and CO₂ is the silicon content of the fume. The same difference, although somewhat smaller in magnitude, exists between fume produced with Ar-2%O₂ and Ar-5%O₂. This suggests that oxidation may be important in producing fume containing silicon. The supporting data, drawn from Table 4, are indicated below:

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<tr>
<th>Shield gas</th>
<th>Current (A)</th>
<th>Arg-2%O₂</th>
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<th>Ar-25%CO₂</th>
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Table 3 — Fume Composition in FCA Welding

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Table 4 — Fume Formation Composition in GMA Welding of Ferrous Materials

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<td>14</td>
<td>43</td>
<td>33</td>
<td>10</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>20</td>
<td>140</td>
<td>7</td>
<td>14</td>
<td>43</td>
<td>33</td>
<td>10</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>20</td>
<td>140</td>
<td>7</td>
<td>14</td>
<td>43</td>
<td>33</td>
<td>10</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>20</td>
<td>140</td>
<td>7</td>
<td>14</td>
<td>43</td>
<td>33</td>
<td>10</td>
<td>20</td>
<td>60</td>
</tr>
</tbody>
</table>

(36) E70T-1, rutile base flux, CO₂ gas shielding; E70T-4, fluoropel base flux, no gas shielding; E70T-5, silica base flux, CO₂ gas shielding.

(37) Tabulated data, drawn from Table 4, are indicated below:
Much work has been done studying the properties of SiO. Silicon monoxide is a gas at all temperatures of interest, 1500-3000 K. It is often formed when insufficient oxygen is available to form continuous SiO₂ layers over silicon-bearing liquids. It has a high vapor pressure. The reaction of interest is:

\[ \text{Si} + \frac{1}{2} \text{O}_2 \rightarrow \text{SiO} \quad \text{or} \quad \text{Si} + \text{CO}_2 \rightarrow \text{CO} + \text{SiO} \]  

The standard free energy of each of these reactions may be calculated from thermodynamic data (Refs. 5, 6). Consider Equation (1) for the E70S-2 electrode composition, \( a_{\text{Si}} = 3.35 \times 10^{-5} \); the partial pressure of SiO (\( P_{\text{SiO}} \)) as a function of temperature is:

\[
P_{\text{SiO}} \text{ (atm) for Temp, (K)} = 0.25^\frac{P_{\text{O}}}{3000}
\]

Obviously, since the reaction is controlled by \( (P_{\text{O}})_{\text{Si}} \), the ratio of \( P_{\text{SiO}} \) at any temperature in equilibrium with Ar-5\%O₂ to that in equilibrium with Ar-2\%O₂ is \((5/2)^{1/2} = 1.58\). If equilibrium thermodynamics can tell us anything about the relative fume formation, then we should measure this increase in silicon in our fume samples. The actual ratios, at each set of welding currents, for silicon emission from Table 4 are:

<table>
<thead>
<tr>
<th>Current, (A)</th>
<th>( \text{Si (5%O}_2 )</th>
<th>( \text{Si (2%O}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2.6</td>
<td>13.5</td>
</tr>
<tr>
<td>200</td>
<td>2.2</td>
<td>20</td>
</tr>
<tr>
<td>250</td>
<td>10.0</td>
<td>23.5</td>
</tr>
<tr>
<td>300</td>
<td>5.7</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Interpretation of these results is uncertain because of possible variations in arc behavior; however, it is apparent that the generation of silicon-bearing fume is dependent on oxidation potential. If we now perform the calculations for Equation (2) and assume that the stoichiometry of the reaction as written applies, we find:

\[
\text{K} = \frac{P_{\text{CO}}}{P_{\text{SiO}}} = 3.35 \times 10^{-5}
\]

Thus, we would expect significant increases in the rate of silicon emission, when CO₂ is present in the shielding gas, as great as an order of magnitude. It is not reasonable to compare data taken in Ar-2\%O₂, Ar-5\%O₂, and CO₂ except under conditions of globular transfer. The only data points are at 150 A, and caution must be used because the arc length varies significantly. Data from Table 4 show:

\[
\text{Si}_{\text{CO}_2}/\text{Si}(5\%\text{O}_2)/\text{Si}(2\%\text{O}_2) = 7.9/2.6/1.0
\]

Further comparisons are not justified. If we solve Equation (2) with \( P_{\text{CO}} = .25 \), for Ar-25\%CO₂ we obtain:

\[
\text{Temp, (K)} \quad P_{\text{SiO}} \text{ (atm)}
\]

2000 0.123
2500 0.165
3000 0.216

Silicon emission should now be roughly the same as it is for Ar-2\%O₂ and Ar-5\%O₂ in the temperature range 2000-2500 K. The data of Table 4 agree with these calculations.

What then of vaporization of FeO and MnO as contributors to fume generation? The calculations for FeO are tabulated below, for three partial pressures of oxygen:

\[
\text{Temp, (K)} \quad P_{\text{FeO}} \text{ (atm)}
\]

2000 0.001 0.006 0.007
2500 0.004 0.007 0.007
3000 0.006 0.009 0.010

The calculations in CO₂ yield:

\[
\text{Temp, (K)} \quad P_{\text{CO}} \text{ (atm)} = 0.25
\]

2000 0.003 0.007
2500 0.004 0.115
3000 0.000 0.008

Changing from Ar-5\%O₂ to CO₂ does not alter the FeO contribution significantly. The same is true for changing from Ar-2\%O₂ to Ar-25\%CO₂. The data agree with these calculations. For the temperature and ranges of Mn activity of interest, no significant amounts of MnO form.

Based on the above, it can be understood why fume generation is significantly less in the GMA welding process when argon-based shielding gases are employed than when CO₂ is used, and why there is a suppression of the silicon content of the fume. Both of these factors support the hypothesis that fume generation is the sum of elemental vaporization and oxide vaporization. It is felt that the Mn component comes strictly from elemental vaporization, the Si component from SiO formation, and the Fe component from elemental plus FeO vaporization. FFRs with argon-based shielding gas are lower because there is no enhanced vaporization due to oxide species as the data drawn from Table 4 indicate:

Table 5 — Fume Formation Rate and Composition in GMA Welding of Aluminum Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Diam</th>
<th>Current</th>
<th>Voltage</th>
<th>FFR (g/min)</th>
<th>Fume composition %Al %Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>5356</td>
<td>.045</td>
<td>150</td>
<td>24</td>
<td>1.10</td>
<td>45 5</td>
</tr>
<tr>
<td>5356</td>
<td>.045</td>
<td>200</td>
<td>25</td>
<td>.95</td>
<td>46 6</td>
</tr>
<tr>
<td>5356</td>
<td>.045</td>
<td>250</td>
<td>27</td>
<td>.85</td>
<td>47 8</td>
</tr>
<tr>
<td>5356</td>
<td>.045</td>
<td>300</td>
<td>28</td>
<td>.70</td>
<td>50 11</td>
</tr>
<tr>
<td>1100</td>
<td>.035</td>
<td>130</td>
<td>23</td>
<td>.60</td>
<td>50 0</td>
</tr>
<tr>
<td>1100</td>
<td>.035</td>
<td>210</td>
<td>26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8 — Comparison of FFRs in GMA welding using shield gases containing more than 25% CO₂.

Fig. 9 — The effect of oxidizing potential on the FFR in GMA welding.

The mechanism of fume formation appears to be, therefore, one of ele-
mental vaporization, condensation, and oxidation enhanced vaporization.

Additional support for the vaporization-condensation-oxidation mechanism (V-C-O) is also found in the data presented in Table 5 covering GMA welding of aluminum alloys. Because of inert shielding, the mechanism for fume generation is simply vaporization and condensation of elemental material. Aluminum 5356 generates more fume because of the additional contribution of Mg. Note that the Mg content of the 5356 fume (Mg/Al = 1/8) is enriched over that of the wire (Mg/Al = 1/16). This results from the fact that Mg has a considerably higher vapor pressure in the range of 2000-3000 K and its activity coefficient in molten aluminum is 0.5. In making a comparison of the above data, note that finer wires produce less fume at comparable currents and arc lengths.

The above discussion applies equally well to fume generation in FCA and SMA welding. In these processes, the fume results from the V-C-O of elemental and lower oxide species, and the V-C of oxide and fluoride flux species. As might be expected, the composition of the fume is strongly dependent on flux composition since significant quantities of low melting point flux components are contained in the fume.

The V-C-O mechanism advanced to this point is essentially a simple one involving the vapor pressures and latent heats of vaporization of the constituents present in the form of the consumables and with the oxide. Thus, the higher FFR for C0 shielding gas if one is used. To first order, these factors determine the amount of a particular constituent appearing in the fume. Obviously, rate controlling steps in the diffusion of various reactants and products will affect the FFR and composition of the fume as well. A more complete model requires consideration of these rate controlling factors and the dynamic nature of the metal transfer process including such factors as residence time of the molten droplet at a particular temperature, degree of surface exposed for participation in the vaporization process, and the efficiency of energy absorption by the surface. These contributions will be considered in turn.

For instance, as observed previously, the higher FFR for C0 compared with argon-based shield gases is believed to be caused by the greater contribution of oxide species resulting from the increased oxidizing potential of the CO2 shielding gas. Additionally, the inability to achieve rapid drop detachment when using CO2 may further augment the oxide enhancement. With CO2, the molten drop of metal spends a significant fraction of the total transfer time attached to and wandering about the wire tip. This instability can produce turbulent effects resulting in contamination which, coupled with the long detachment times, can further enhance the vaporization due to oxide species over and above the natural oxidizing potential of the shield gas. The rapid drop detachment obtained in the spray mode using argon-based shield gases does not permit this condition to occur. This fact and the lower oxidizing potential of the argon-based shield gases are sufficient to account for the differences in the mean FFRs.

The second experiment involved the welding of Mg bearing Al plate using the GMA process. Two wire types were employed, type 5356 containing Mg and type 1100 containing no Mg. Referring back to Table 5, Mg was found in the fume when the 5356 wires were used, but no Mg was found when the 1100 wires were used even though Mg was present in the plate in both cases. The conclusion to be drawn, therefore, is that the vaporization of elemental and oxide species is occurring at the wire tip and in the welding arc, but not in the weld puddle to any comparable degree. This is totally consistent with known temperature distributions of the arc.

A feeling for just how the fume evolution is affected by the welding conditions and shielding gas can now be gained by a more critical examination of the behavior of the fume data in CO2 and argon-based shielding gases exhibited in Figs. 10 and 12.

The CO2 results are presented in Fig. 12. Two features are apparent. For a given voltage, there is a monotonic increase of fume with current;
and for a given current, there is a gradual monotonic increase of fume with voltage. This behavior can be modeled in the following manner. The transfer mode for CO\textsubscript{2} is always globular. As current is increased, there is less of a change in the size of the drops as there is in the number of drops transferring across the arc. Two things must be considered: the length of time a drop can participate in the vaporization process, either appended on the tip or in flight; and the total amount of surface available. Since the drop size does not change all that much, the surface increases with current at approximately the same rate as the participation time decreases. The decrease in time is due primarily to more rapid detachment of the drops. This reduced residence time, especially in the vicinity of the wire tip, leads to a net increase in the fume formation rate. However, there are more drops and hence more surface which leads to a net increase. Since the surface is increasing at about the same rate as the residence time is decreasing, these two effects about balance each other.

The observed monotonic increase of the fume with current is due to the increased energy (i.e., temperature of the arc) available in the arc for the V-C-O process.

The observed gradual increase in the FFR with voltage demonstrates the importance of transfer time. For a constant current the melt-off rate is approximately the same over a range of voltages. Since the voltage affects neither the number nor the size of the drops to any great degree, the implication is that the increased arc length and hence increased transfer time is the cause of the higher fume formation rates. A similar, but more complicated, behavior is observed for argon-based shielding gases. The greater complexity is due primarily to the existence of a transition region which alters the dynamics of the transfer.

The basic behavior of the argon data is illustrated in Fig. 10. Two minima in the FFRs are observed. For a given constant current, there is a minimum FFR with voltage; and for a given constant voltage, there is a minimum FFR with current. The absolute minimum occurs at approximately 28 V and 250 A. Above 250 A the fume formation rate is a monotonically increasing function with current as with CO\textsubscript{2}. Although the mode of transfer is spray, the functional dependence is not too much different from that for CO\textsubscript{2}. As the current is raised, it is the number of spray droplets, not their size, which increases. In other words, total surface area is increasing. The time of transfer decreases correspondingly since arc length does not change substantially with current. As with CO\textsubscript{2}, the increase in fume with current in this region can be accounted for by the increased arc temperature and by the increased surface area to the extent that the additional area is not compensated for by the decreased transfer time.

Below the transition current, it is an entirely different picture. Drop volume decreases rapidly with current in the region prior to the transition. Likewise, the rate of transfer increases, i.e., transfer time of a particular drop decreases. Because of the square/cube law governing surface to volume ratios, the rate of increase of surface area does not match the decrease in transfer time. For example, a factor of 2 decrease in drop diameter results in a factor of 8 decrease in volume and a factor of 4 decrease in surface. Assuming that over the same change in current the amount of metal transferred has increased by 25%, then 20 drops would have to transfer in the same time as one drop transferred previously. The total surface of the 10 drops is 2-1/2 times the original surface; but because of the decrease in the transfer time, it can participate in the V-C-O process for only 1/10 the time. This would account for the minimum in the FFR with current which occurs through the transition region.

The change in transfer mode typified by the volume change also results in other effects which tend to further reduce the overall fume. Prime among these is the fact that the drop spends far less time at the tip of the wire and gives rise to less turbulence. Hence there is less of a chance of contamination resulting in enhancement of the FFR through vaporization of oxide species.

The observed increase in the FFR with voltage is much greater with argon in the spray transition region than it is with CO\textsubscript{2}. A number of factors are in operation. One, the argon arc length is much more sensitive to voltage than the CO\textsubscript{2} arc length. Therefore, a given voltage change corresponds to a greater change in the interaction time for argon. The voltage sensitivity is enhanced by the fact that the time of flight accounts for

![Fig. 14 — Effect of wire diameter on the FFR in GMA welding with argon-5% O\textsubscript{2} shielding gas](image)

![Fig. 15 — Electron micrographs of fume particle sizes obtained in GMA welding with (a) CO\textsubscript{2} and (b) AR-2% O\textsubscript{2} shielding gases. X 50,000 reduced 9%](image)
almost all of the interaction time with argon, but only a fraction of the time with Co. The drop size also plays a role. For argon in the spray transition region the drops are small and totally confined to the arc column. The surface to volume ratio is large and the whole surface can participate in the V-Co process. The larger Co drops cannot respond as readily. Increasing the arc voltage adds more power to the arc column. The observed rate of increase in the fume with voltage for argon is approximately 0.16 mg per joule of additional energy, (attained by increasing the arc voltage). This increase is the same regardless of the current. The inverse of the latent heat of vaporization for iron is also about 0.16 mg per joule. The similarity of these numbers is indicative of the high degree of energy transfer from the arc column to the metal droplets in the argon-based arc for the reasons expressed above. The rate of increase for Co is about half of that for argon indicating a much less efficient transfer. So, although the mean FFR is less for argon, the rate of increase of the FFR is greater.

It is felt that a reasonable understanding has been gained about the roles of current and voltage in the fume formation process. The one puzzle is the minimum in fume formation with voltage which appears in the argon data. There are a number of mechanisms which could be in operation here, but it is not clear at the present time exactly what is occurring.

The particle size distribution data for Co and argon-based GMA welding is consistent with the observed FFR behavior discussed above. The mean particle size for Co is at least an order of magnitude greater than for argon, indicating that the particles have more time to nucleate and grow with Co. This supports the position that the V-C-O process is dominant at the wire tip with Co and dominant in the arc column with argon. Fume particles for argon are swept out before they can become nucleation centers for further growth. Conditions in the vicinity of the wire tip with Co are more conducive to the attainment of greater particle sizes.

To summarize, the basic features of the fume formation process are the following. The mechanism is one of vaporization, condensation, and oxidation. Welding current determines the base levels of fume evolution by establishing the operating temperature at which the V-C-O process occurs. Voltage affects the fume evolution by affecting the spatial range over which the energy is available. Shielding gas determines the dynamics of transfer process which can act to promote or inhibit the V-C-O process and controls the oxidation potential of the arc. Welding process affects the fume evolution by affecting the arc dynamics and by affecting the nature of the consumable.

**Application of Results to Fume Control and Ventilation**

The preceding sections of this article have outlined the data and probable mechanisms for the generation of particulates and gases in various welding processes. The purpose of this section is to offer ways of determining whether a fumes and gas problem exists and if it does what reasonable solutions are available either in the form of the choice of a welding process, modification of a welding process, and/or ventilation requirements.

The particulate FFR data, as presented earlier, have been given purposefully in two forms: mg/minute, and mg/gram. Each set of units has its utility depending on how it is to be used. The unit of mg/minute allows an absolute comparison of welding processes in terms of joint completion rates. In other words, for a fixed number of joints, this unit will provide a measure of the total amount of fume generated in the completion of those joints. The unit of mg/minute is oftentimes misleading for such a comparison since an increase in this number may actually correspond to a decrease in the total amount of evolved fume per gram of metal deposited. A comparison of Figs. 10 and 11 and Figs. 12 and 13 will illustrate this point for different deposition rates using argon-based and Co2 shielding gases. For the higher deposition rates, there is more fume evolved per minute; but the total amount of fume generated in the completion of the joint is less in most instances.

The unit of mg/minute is useful in determining ventilation requirements. In any real situation both units must be used to obtain a balance between the total amount of fume generated and the ability to dispose of it.

The importance of the correct choice of welding processes in terms of the level of evolved fume is illustrated in Fig. 18. This figure compares mean fume levels which can be anticipated. The difference between air operating cored wires and GMA/argon-based is substantial. An interesting feature which becomes apparent on a plot of this sort is that the difference between GMA/Co2 and GMA/argon-based is really quite small when compared with the difference between FCA/air operating and GMA/argon-based. If a substantial fume problem existed with GMA/Co2, it probably could not be solved by switching to GMA/argon-based even though GMA/argon-based exhibits the least amount of fume of any process. Substantial improvements could be made if GMA/argon-based could be used in place of one of the other welding processes.
processes. It must be remembered, however, that in spite of the fact that argon has no order of magnitude advantage over CO₂ in terms of gross fume levels, compositional differences in the fume between the two shielding gases can make the use of argon-based gases quite advantageous.

Because the mechanism of fume formation is one of vaporization, condensation, and oxidation, little can be done to affect the total fume levels. Fume level can be controlled to the extent that the volatility of the consumable can be controlled. The degree of flexibility which exists here does not result in significant changes. The controllability of fume composition is a little greater, especially in the GMA process. This can be accomplished by controlling the oxidizing potential of the shield gas or by varying minor but potentially hazardous components of the consumable. In a certain few instances where the controllable component is a significant fraction of the total fume, fume levels can also be controlled. Argon-based shielding gases are particularly advantageous in this regard since the oxygen content and hence the oxidizing potential can be controlled in a way which is not possible with CO₂. This has the advantage that particularly toxic constituents such as silica can be substantially reduced even though overall fume levels have not undergone a similar reduction.

An example of controlling fume composition by controlling wire composition was found in the welding of aluminum alloy. Substantial differences in the Mg content of the fume could be obtained by using non-Mg-bearing wires (see Table 5). In this instance, total fume levels were also reduced since the Mg component accounts for a significant fraction of the total fume.

In general, the best method of controlling particulate fume is to choose the cleanest welding process capable of doing the task and additionally providing adequate ventilation.

Summary and Conclusions

A technical method has been developed that allows quantitative determination of the fume formation rate and fume composition in arc welding processes. This method has been used to characterize particulate emissions in a number of arc welding processes: SMA, GMA, FCA, and GTA welding. In the simplest terms, processes can be identified by the number of mg of fume evolved during the deposition of one gram of metal. This characteristic number, mg of fume per g of metal deposited, is relatively constant over the range of applicable welding current as indicated in Fig. 18. Of the continuous electrode processes studied, GMA with argon-based shielding gas, scored 5, while FCA with selfshielded electrodes, scored 22.

Analysis of the composition of the fume generated by electric arc welding processes indicates that fume is produced by two mechanisms. The first is simply vaporization of the metal or compound from the vicinity of the arc and subsequent condensation of that species. Oxidation may follow. The second is enhanced vaporization due to the formation of a more volatile oxide on the surface of the molten electrode followed by condensation and, perhaps, further oxidation.

The degree to which each of these mechanisms participates in fume production and hence, the fume composition and rate of fume evolution, depends on the process and process variables. The degree of participation has been described in the model relating these mechanisms to the process and process variables. The first mechanism will always be active to some extent. The second can be minimized by lowering the oxidation potential of the shielding gas and by improving arc stability.

Based on the model it is possible to predict FFRs and fume compositions semi-quantitatively given a knowledge of the consumable composition, the volatility of the constituents, the transfer mode and arc temperature and stability as determined by the welding parameters and shield gas, and the oxidizing potential of the shield gas; however, such calculations are difficult. The model is much more easily applied to predicting the effect on the FFR and fume composition of selective changes in consumable composition for a particular process.

References

2. Ibid., Part III.
6. Frantzreb, J., unpublished research contributed to the American Welding Society Committee on Safety and Health, April, 1974.