Fume Generation and Content of Total Chromium and Hexavalent Chromium in Flux-cored Arc Welding

CHUNG SIK YOON¹, NAM WON PAIK²* and JEONG HAN KIM³

¹Department of Occupational Health, Catholic University of Daegu, Kyongsan-si, Kyongbuk 712-702; ²Institute of Health & Environment, School of Public Health, Seoul National University, Chongro-Ku, Seoul 110-799; ³Korea Institute of Industrial Technology, Ibjang-myun, Chonan-si, Chungnam 330–820, Korea

Received 13 September 2002; in final form 14 April 2003

This study was performed to investigate the fume generation rates (FGRs) and the concentrations of total chromium and hexavalent chromium when stainless steel was welded using flux-cored arc welding (FCAW) with CO₂ gas. FGRs and concentrations of total chromium and hexavalent chromium were quantified using a method recommended by the American Welding Society, inductively coupled plasma-atomic emission spectroscopy (NIOSH Method 7300) and ion chromatography (modified NIOSH Method 7604), respectively. The amount of total fume generated was significantly related to the level of input power. The ranges of FGR were 189–344, 389–698 and 682–1157 mg/min at low, optimal and high input power, respectively. It was found that the FGRs increased with input power by an exponent of 1.19, and increased with current by an exponent of 1.75. The ranges of total chromium fume generation rate (FGRCr) were 3.83–8.27, 12.75–37.25 and 38.79–76.46 mg/min at low, optimal and high input power, respectively. The ranges of hexavalent chromium fume generation rate (FGRCr₆+) were 0.46–2.89, 0.76–6.28 and 1.70–11.21 mg/min at low, optimal and high input power, respectively. Thus, hexavalent chromium, which is known to be a carcinogen, generated 1.9 (1.0–2.7) times and 3.7 (2.4–5.0) times as the input power increased from low to optimal and low to high, respectively. The ranges of hexavalent chromium fume generation rate (FGRCr₆+) were 0.46–2.89, 0.76–6.28 and 1.70–11.21 mg/min at low, optimal and high input power, respectively. As a function of input power, the concentration of total chromium in the fume increased from 1.57–2.65 to 5.45–8.13% while the concentration of hexavalent chromium ranged from 0.15 to 1.08%. The soluble fraction of hexavalent chromium produced by FCAW was ~80–90% of total hexavalent chromium. The concentration of total chromium and the solubility of hexavalent chromium were similar to those reported from other studies of shielded metal arc welding fumes, and the concentration of hexavalent chromium was similar to that obtained for metal inert gas-welding fumes.

Keywords: fume generation rates; chromium; hexavalent chromium; welding; flux-cored arc welding; alkaline extraction; ion chromatography

INTRODUCTION

Various hazardous agents, such as fumes, gases, vapors, heat, noise and radiation, are produced during welding operations. The agents of greatest concern in industrial hygiene are fumes, and specifically, hexavalent chromium, which is a human carcinogen (ACGIH, 2002; IARC, 1987). Although numerous epidemiological studies have indicated that increased numbers of lung cancer cases were found in workers performing stainless steel welding (NIOSH, 1988), direct evidence linking welding fume exposure to the incidence of cancer has not yet been demonstrated (Dennis et al., 2002).

One study indicated that the concentration and solubility of hexavalent chromium depended on the type of welding (Ulfvarson, 1981). Several studies showed that the total chromium concentration in welding fumes was higher in gas metal arc welding (GMAW) than in shielded metal arc welding (SMAW) but hexavalent chromium concentrations were higher in SMAW than in GMAW. Most chromium species
in GMAW exist as insoluble trivalent or elemental chromium. Concentrations of total chromium in GMAW fumes were reported as 15.8% (Kimura et al., 1979), 8.3% (Ulfvarson, 1981), 9.8% (Stern, 1981), 15.50% (Hewitt and Gray, 1983), 10.51% (Pedersen et al., 1987) and 8–25% (Voitkevich, 1995). Concentrations of hexavalent chromium in GMAW fumes were 0.32–0.54% (Pedersen et al., 1987) and 0.2–1% (Voitkevich, 1995). Total chromium concentrations in SMAW fumes were 4.9% (Kimura et al., 1979), 4% (Ulfvarson, 1981), 3.8% (Stern, 1981), 5.86% (Hewitt and Gray, 1983), 4.2% (Pedersen et al., 1987) and 0.5–7% (Voitkevich, 1995). It was found that a large proportion (60–90%) of the chromium was soluble hexavalent chromium in SMAW fumes (Pedersen et al., 1987; Voitkevich, 1995).

The reason why hexavalent chromium concentrations are lower in metal inert gas (MIG) welding, which is one type of GMAW, is that there are low levels or even an absence of alkaline oxides, such as potassium and sodium compounds, and there is no oxygen that is able to oxidize various chromium valences to hexavalent chromium (Gray et al., 1983; Palmer, 1983). The lack of oxygen and alkaline oxide in MIG fume also contributes to the insolubility of chromium (Koponen et al., 1981). In contrast, the oxidation of chromium in slag and the reaction between chromium and alkaline oxide in shielding material contribute to the solubility of chromium in SMAW.

We often use operational definitions of solubility for the measurement of soluble metals in workplace air samples because there has been some debate over the definition of solubility. Solubility of metal and metalloids, including chromium in fume, depends on the extraction media, time, temperature and volume (Hewitt and Gray, 1983; Fairfax and Boltzer, 1994). Soluble hexavalent chromium usually refers to the water-soluble fraction, whereas insoluble hexavalent chromium often refers to the portion that is actually soluble in sodium hydroxide/sodium carbonate solution (Thomsen and Stern, 1979; NIOSH, 1994b). The water-soluble fraction is usually hexavalent (WHO, 1988). In 2001, the International Organization for Standardization (ISO) promulgated ISO 15202-2 as a final draft international standard, which includes a sample preparation procedure for soluble metals and metalloids (Ashley, 2001; ISO, 2001). Flux-cored arc welding (FCAW) has been growing in popularity as an alternative to SMAW because of its productivity and quality. Here, too, however, the release of chromium and hexavalent chromium fumes during FCAW on stainless steel is a major concern for occupational health.

Although there are guidelines suggested by the manufacturing company on welding conditions (shielding gas, voltage and current) specific to the welding filler material, welding operators often apply currents and voltages higher than those suggested in the guidelines to enhance productivity. The fume generation rate (FGR) and the fume composition are influenced by various welding factors, especially voltage and current (AWS, 1987; Voitkevich, 1995). This study was performed for the range of conditions used by welders rather than those recommended by the manufacturers of welding consumables, and thus provides a more realistic assessment of likely workplace emissions.

The purpose of this study was to evaluate the FGRs, concentrations and generation rates of total chromium and hexavalent chromium produced in CO2 FCAW, as a function of both current and voltage.

**MATERIALS AND METHODS**

**Fume chamber and welding operation**

A fume collection chamber for welding operations was constructed for this study (Fig. 1). The cross sectional area of the chamber was square in shape and measured 700 × 700 mm. The upper third of the chamber was tapered towards an opening (254 × 203 mm) at which a filter holder was set up, with an extraction fan located behind it. The copper baseplate was placed on a power-driven turntable that was mounted inside the welding chamber. The welding torch was placed inside the welding chamber and its angle and contact tip were controllable. This chamber was validated for no loss of fume during welding and sampling (KIIT, 1999).

It was possible to control the welding time, wire feeding rate, welding speed, torch angle and contact tube to work piece distance. Stainless steel (18% Cr, 8% Ni) base metal was mounted on the turntable and a 1.2 mm flux-cored wire was fed into the welding torch. The currents and voltage were monitored using an Arc Monitoring System V4.1 (OIS Engineering Ltd, UK). For a given welding condition, both the current and voltage were fairly constant.

Six different types of 1.2 mm diameter flux-cored wires, all of which were specifically made for stainless steel welding applications, were tested under three welding conditions: low, optimal and high input power. The optimal condition was adopted from the value recommended by the wire manufacturers; the low and high conditions were the lower and higher ends of the usual operating range. A summary of the welding conditions used is given in Table 1.

**Sampling for fume, total chromium and hexavalent chromium**

To determine the FGR, welding was carried out for a period of 30 s and sampling was conducted for 60 s. Air was drawn through a glassfiber filter (pore size 0.6 µm, 254 × 203 mm, EMP 2000, Whatman, USA)
at a flow rate of 2.3–2.8 m³/min at the top of the welding chamber. After sampling, the pre-dried (105°C, >1 h) and weighed filter was redried and reweighed to the nearest 0.01 mg in a weighing room (AWS, 1992).

To collect samples for total chromium, welding was carried out for 60 s and sampling was performed using glassfiber filters. To measure hexavalent chromium, welding was performed at the same conditions as those used to measure FGR and sampling was conducted using PVC filters (pore size 5 µm, diameter 37 mm, Gelman Sciences, USA). Six samples, three for total hexavalent chromium and three for soluble hexavalent chromium, were collected at 20 cm above the welding arc using vacuum pumps (Model DOA-V152-AA, Waters, USA) and orifices (nominal flow, 2.0 l/min).

Because hexavalent chromium is reduced to trivalent chromium at room temperature, the PVC filter, after sampling, was transferred into a centrifuge tube (10 ml) with Teflon forceps and stored in a refrigerator until analysis.

**Analysis**

The FGR and total fume were determined using the AWS method and NIOSH Method 0500, respectively.

---

**Table 1. Welding conditions and materials**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of welding</td>
<td>Flux-cored arc welding</td>
</tr>
<tr>
<td>Welding time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>CO₂ (20 l/min)</td>
</tr>
<tr>
<td>Nominal current and voltage</td>
<td>Low input power: 120 A, 22 V</td>
</tr>
<tr>
<td></td>
<td>Optimal input power: 180 A, 25 V</td>
</tr>
<tr>
<td></td>
<td>High input power: 230 A, 30 V</td>
</tr>
<tr>
<td>Current characteristics</td>
<td>Direct current electrode positive</td>
</tr>
<tr>
<td>Welding machine</td>
<td>Dyna Auto super (Japan)</td>
</tr>
<tr>
<td>Electrode(wire)</td>
<td>C (SB 308L, AWS A5.22 E 308LT-1, KS D3612, Alloy Rod Korea, Korea)</td>
</tr>
<tr>
<td></td>
<td>S (CROMA CORE DW 329AP, AWS A5.22 E2209T0-4, Elga, Sweden)</td>
</tr>
<tr>
<td></td>
<td>T (AVESTA FCW 2205H, AWS A5.22 E 2209 T0-4, ABESTA AB, Sweden)</td>
</tr>
<tr>
<td></td>
<td>U (Esab OK Tubrod 14.30, AWS A5.22 E 308LT-1, USA)</td>
</tr>
<tr>
<td></td>
<td>V (WEL FCW, 329J2L, Nippon Welding Rod Co., Japan)</td>
</tr>
<tr>
<td></td>
<td>W (SB 308 Xtra, AWS A5.22 E 308LT-1, KS D3612, Alloy Rod Korea, Korea)</td>
</tr>
<tr>
<td>Base metal</td>
<td>SUS 304 (260 × 260 × 10 mm)</td>
</tr>
<tr>
<td>Base metal travel speed</td>
<td>6 mm/s</td>
</tr>
<tr>
<td>Contact tube to work piece distance</td>
<td>14 mm for low input power, 16 mm for optimal input power, 18 mm for high input power</td>
</tr>
<tr>
<td>Torch angle</td>
<td>90°</td>
</tr>
</tbody>
</table>
The PVC filter samples were stored in a desiccator and weighed immediately after being taken out; the procedure was repeated three times. For the determination of several metals, including chromium, part of the scraped fume was weighed and pretreated by microwave oven using a modification of NIOSH Method 7300 and analyzed using inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Hexavalent chromium in fume was determined using a modification of NIOSH Method 7604 (Yoon et al., 1999). Yoon and co-workers reported that the alkaline extraction on a hot plate, the recommended digestion method in NIOSH Method 7604, reduced hexavalent chromium to trivalent chromium to some degree and suggested a more reliable extraction method as follows:

- After weighing the PVC filter, a 5 ml alkaline extraction solution (2% NaOH/3% Na₂CO₃) was added to the centrifuge tube containing the PVC filter.
- The solution was purged with high-purity (>99.995%) nitrogen gas for 5 min to remove dissolved oxygen.
- For better extraction, the tube containing the solution was capped and sonicated for 45 min at room temperature.
- Extracted solution and rinsed water were transferred to a larger graduated centrifuge tube, and nitrogen-purged distilled water was added for a total volume of 25 ml.
- For filtering with a syringe filter (Acrodisc LC PVDF, pore size 0.45 µm, Gelman Sciences, USA), the hexavalent chromium in the extraction solution was separated and quantified using ion chromatography (IC), as recommended by NIOSH Method 7604. For the soluble hexavalent chromium, distilled water was used instead of alkaline solution.

For this study, the FGRs for total chromium (FGRCr) and hexavalent chromium (FGRCr₆⁺) were determined. The concentration of hexavalent chromium in total chromium and the soluble fraction of hexavalent chromium were also calculated.

### RESULTS

**Generation rates of fumes, total chromium, and hexavalent chromium**

Generation rates of total fumes, total chromium and hexavalent chromium from six types of flux-cored wires are summarized in Table 2. At low, optimal and high levels of input power, the ranges of FGR were 189–344, 389–698 and 682–1157 mg/min, respectively. The ranges of FGRCr were 3.83–8.27, 12.75–37.25 and 38.79–76.46 mg/min, respectively.

| Type of wire | Voltage (V) | Current (A) | Input power (kJ/min) | FGRCr mean (Sr) (mg/min) | FGRCr₆⁺ mean (Sr) (mg/min) | Concentration in fume (%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total chromium</td>
<td>Hexavalent chromium</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>22.1</td>
<td>125.0</td>
<td>165.6</td>
<td>312.1 (0.03)</td>
<td>8.27 (0.06)</td>
<td>2.65 (0.08)</td>
</tr>
<tr>
<td></td>
<td>24.8</td>
<td>143.5</td>
<td>213.3</td>
<td>426.3 (0.04)</td>
<td>1.31 (0.11)</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>24.3</td>
<td>178.0</td>
<td>259.5</td>
<td>504.2 (0.16)</td>
<td>36.86 (0.25)</td>
<td>7.31 (0.20)</td>
</tr>
<tr>
<td></td>
<td>30.5</td>
<td>228.0</td>
<td>417.2</td>
<td>848.3 (0.02)</td>
<td>59.49 (0.07)</td>
<td>7.01 (0.13)</td>
</tr>
<tr>
<td>S</td>
<td>22.1</td>
<td>123.0</td>
<td>163.3</td>
<td>278.8 (0.04)</td>
<td>4.37 (0.18)</td>
<td>1.57 (0.07)</td>
</tr>
<tr>
<td></td>
<td>25.3</td>
<td>178.0</td>
<td>270.2</td>
<td>499.9 (0.01)</td>
<td>37.25 (0.29)</td>
<td>7.45 (0.10)</td>
</tr>
<tr>
<td></td>
<td>30.1</td>
<td>226.8</td>
<td>409.2</td>
<td>786.8 (0.01)</td>
<td>63.29 (0.44)</td>
<td>8.04 (0.09)</td>
</tr>
<tr>
<td>T</td>
<td>22.3</td>
<td>122.0</td>
<td>163.2</td>
<td>343.8 (&lt;0.01)</td>
<td>5.56 (0.07)</td>
<td>1.62 (0.08)</td>
</tr>
<tr>
<td></td>
<td>25.1</td>
<td>186.3</td>
<td>280.2</td>
<td>697.7 (0.03)</td>
<td>19.71 (0.57)</td>
<td>2.82 (0.12)</td>
</tr>
<tr>
<td></td>
<td>29.9</td>
<td>236.5</td>
<td>423.3</td>
<td>1156.7 (0.03)</td>
<td>76.46 (0.37)</td>
<td>6.61 (0.07)</td>
</tr>
<tr>
<td>U</td>
<td>22.2</td>
<td>120.7</td>
<td>160.7</td>
<td>188.7 (0.01)</td>
<td>3.83 (0.24)</td>
<td>2.03 (0.08)</td>
</tr>
<tr>
<td></td>
<td>25.1</td>
<td>185.7</td>
<td>279.6</td>
<td>388.6 (0.03)</td>
<td>31.61 (0.53)</td>
<td>8.13 (0.07)</td>
</tr>
<tr>
<td></td>
<td>29.9</td>
<td>232.0</td>
<td>415.5</td>
<td>681.6 (0.03)</td>
<td>38.79 (0.36)</td>
<td>5.69 (0.09)</td>
</tr>
<tr>
<td>V</td>
<td>22.1</td>
<td>116.0</td>
<td>154.0</td>
<td>310.5 (0.05)</td>
<td>8.00 (0.44)</td>
<td>2.58 (0.11)</td>
</tr>
<tr>
<td></td>
<td>25.1</td>
<td>182.3</td>
<td>273.9</td>
<td>649.0 (0.01)</td>
<td>27.43 (0.26)</td>
<td>4.23 (0.07)</td>
</tr>
<tr>
<td></td>
<td>29.9</td>
<td>228.8</td>
<td>410.0</td>
<td>1073.5 (0.03)</td>
<td>68.14 (0.18)</td>
<td>6.22 (0.09)</td>
</tr>
<tr>
<td>W</td>
<td>22.3</td>
<td>122.0</td>
<td>163.0</td>
<td>242.6 (0.01)</td>
<td>5.90 (0.44)</td>
<td>2.43 (0.07)</td>
</tr>
<tr>
<td></td>
<td>24.8</td>
<td>182.0</td>
<td>271.2</td>
<td>495.2 (&lt;0.01)</td>
<td>12.75 (0.22)</td>
<td>2.57 (0.03)</td>
</tr>
<tr>
<td></td>
<td>29.8</td>
<td>231.5</td>
<td>413.2</td>
<td>807.6 (0.04)</td>
<td>44.03 (0.16)</td>
<td>5.45 (0.21)</td>
</tr>
</tbody>
</table>

Note: number of samples in each cell, n = 3.

*aCoefficient of variations or relative standard deviation.
*Not measured.
respectively; and the ranges of FGR Cr6+ were 0.46–2.89, 0.76–6.28 and 1.70–11.21 mg/min, respectively.

There was a variation in FGR by type of wire. This may be explained by the fact that the metal concentrations and flux compositions of the wires are likely to differ substantially between manufacturers (AWS, 1987). For example, the FGR from product ‘T’ was about twice as high as that from product ‘U’ at a similar level of input power (344 versus 189, 698 versus 389, 1157 versus 682 mg/min, respectively, for each level of input power).

Concentration of total chromium in fume

The total chromium concentration in fume increased with current as well as with input power, although there was some variation by type of wire as shown in Fig. 2. The total chromium concentrations of the fumes at low, optimal and high input power were 2.12 ± 0.74, 5.52 ± 3.00 and 6.55 ± 1.88%, respectively.

Concentration of hexavalent chromium in fume

The concentration of hexavalent chromium ranged from 0.15 to 1.08% of total fume. It should be noted that hexavalent chromium, which is known to be a carcinogen, generated 1.9 (1.0–2.7) and 3.7(2.4–5.0) times the initial concentrations as the input power increased from low to optimal, and then low to high, respectively. Although more hexavalent chromium was released with increased input power, the percentage ratio of hexavalent chromium to total chromium seemed to decrease with input power as shown in Fig. 3. The concentration of total chromium increased more steeply than hexavalent chromium with input power. Thus, the percentage ratio of hexavalent chromium to total chromium decreased. While the percentage ratio at a low level of input power was 8–60%, it decreased to <20% at high input power.

The soluble fraction of the hexavalent chromium was 80–90% as presented in Table 3. Thus, it was found that most of the hexavalent chromium produced in FCAW exists as a soluble form.

DISCUSSION

Generation rates of fumes, total chromium, and hexavalent chromium

It has been reported that FGRs are most affected by the current in a given welding process (AWS, 1973, 1987; AIHA, 1984; Voitkevich, 1995). Previous studies (AIHA, 1984; AWS, 1987) suggested that the FGR could be related to welding current (I) as indicated in equation (1) below.

\[
FGR = kI^l
\]  

(1)

When the equation is applied to this study, the value of the power function coefficient (l) is 1.75 (1.59–1.93) (Fig. 4), which is within the range of 1.1–2.3 reported previously (AIHA, 1984; AWS, 1987). The overall mean correlation coefficient (r²) between the current and FGR in all types of wires was 0.86. However, the correlation coefficients by type of wire
ranged from 0.9903 to 0.9980 except for one \( r^2 = 0.9434 \) for type C) (Table 4).

In this study, we tried to compare the relationship between current and FGR to the melting rate of filler material. It was reported that the primary source of fume is filler material (wire) rather than the base metal (Voitkevich, 1995). Under steady state conditions (constant contact tip to work piece distance and wire extension length), the wire feeding speed (WFS) and melting rate (MR) are equal and are related to current by equation (2) (KWS, 1998).

\[
WFS = MR = aI + bL_e^2 \tag{2}
\]

where WFS is the wire feeding speed (kg/h), MR is the melting rate (kg/h), \( a \) is the proportion constant for positive or negative electrode heating (depends on polarity and composition of wire) \( [\text{kg/(h-A)}] \), \( b \) is the proportion constant of electric resistant heat \( [\text{kg/(h-A^2-mm)}] \), \( L_e \) is the extruding length of wire (from the end of contact tip to the wire end) (mm) and \( I \) is the current (A).

This equation can be approximated by equation (3) since \( aI \) is much smaller than \( bI^2 \). Thus, melting rate is said to be proportional to current squared as presented in equation (3).

\[
WFS = MR \propto I^2 \tag{3}
\]

A constant term can be introduced to the above equation as indicated in equation (4), which is similar to the FGR equation (equation 1).

\[
WFS = MR = k'I^2 \tag{4}
\]

where \( k' \) is the proportional coefficient.

Since \( I \) in equation (1) is 2, one would expect the FGR to correlate with MR. It means that the extent of total fume generation increases as the melting rate increases for a given welding condition.

The welding voltage also affects the melting rate; thus, input power rather can be used instead of current to describe the FGR. Electric resistant heat (= current \times voltage) increases according to extruding wire length \( (L_e) \), usually 10–15 mm for short-circuiting mode and 15–25 mm for droplet mode (KWS, 1998). Since the extruding wire length \( (L_e) \) is affected by voltage as well as current, as indicated in equation (2), wire-melting rate is also affected by the voltage and current. Thus, the input power can be used to designate the current and voltage at a given time (kJ/min was used for power unit here because FGR, FGR_{Cr} and FGR_{Cr6+} were designated per minute, although watts are generally used).

\[
\text{input power (J/min)} = I \text{ (amps)} \cdot V \text{ (volts)} \cdot 60
\]
Based on the theoretical consideration mentioned above, the relationship between FGR and the input power was computed and is presented in Fig. 4. As indicated in Table 2 and Fig. 4, it was also found that the fume generation rates increased with input power by an exponent of 1.19, whereas they increased with current by an exponent of 1.75.

As input power increases, the flux-cored wire and base metal melt rapidly and the flying distance of droplet to weld pool increases. These provide more opportunities for evaporation to occur. Therefore, evaporation has a major role in generating fumes as input power increases.

There was evidence that the FGRCr increased more steeply than the FGR with current or input power. Fitting the data to a power function of current indicated that FGRCr is expressed as a function of $I^{3.57}$ ($r^2 = 0.81$) (Fig. 5), FGR is expressed as a function of $I^{1.75}$ ($r^2 = 0.86$) (Fig. 4) and FGRCr6+ is expressed as a function of $I^{2.00}$ ($r^2 = 0.42$) (Fig. 6). The magnitudes of the correlation coefficients indicate a strong dependence of FGR and FGRCr on current and a weak dependence of FGRCr6+ on current. When input power is used as an independent variable instead of current, the exponents of FGRCr and FGRCr6+ decreased from 3.57 to 2.43 and 2.00 to 1.39, respectively (Figs 5 and 6).

Table 4. Regression for FGR by current and input power

<table>
<thead>
<tr>
<th>Type of wire</th>
<th>Independent variable</th>
<th>Input power (kJ/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>FGR = 1.4817E–1X1.5870, $r^2 = 0.9434$</td>
<td>FGR = 1.2759E–0X1.0836, $r^2 = 0.9719$</td>
</tr>
<tr>
<td>S</td>
<td>FGR = 7.2308E–2X1.7128, $r^2 = 0.9934$</td>
<td>FGR = 9.1690E–1X1.1302, $r^2 = 0.9986$</td>
</tr>
<tr>
<td>T</td>
<td>FGR = 5.4393E–2X1.8165, $r^2 = 0.9933$</td>
<td>FGR = 7.5038E–1X1.2170, $r^2 = 0.9966$</td>
</tr>
<tr>
<td>U</td>
<td>FGR = 1.7517E–2X1.9907, $r^2 = 0.9916$</td>
<td>FGR = 2.3087E–1X1.3271, $r^2 = 0.9952$</td>
</tr>
<tr>
<td>V</td>
<td>FGR = 5.9884E–2X1.7951, $r^2 = 0.9903$</td>
<td>FGR = 6.5397E–1X1.2342, $r^2 = 0.9969$</td>
</tr>
<tr>
<td>W</td>
<td>FGR = 3.2342E–2X1.8574, $r^2 = 0.9980$</td>
<td>FGR = 4.5075E–1X1.2488, $r^2 = 0.9958$</td>
</tr>
<tr>
<td>Total</td>
<td>FGR = 6.2354E–2X1.7519, $r^2 = 0.8619$</td>
<td>FGR = 7.0994E–1X1.1870, $r^2 = 0.8647$</td>
</tr>
</tbody>
</table>

Total chromium and hexavalent chromium concentration in fume

Although numerous studies have reported the concentrations of total chromium and hexavalent chromium (Kimura et al., 1979; Stern, 1981; Ulfvarson, 1981; Hewitt and Gray, 1983; Pedersen et al., 1987; Voitkevich, 1995), most of these simply mentioned chromium concentrations for specific welding applications, without describing the effect of input power, i.e. the current and voltage.

This study indicated that the concentrations of chromium in fume were greatly influenced by the input power, and the influence varied according to the type of wire. The concentrations of chromium determined in this study were lower than those from GMAW but similar to those from SMAW because both SMAW and FCAW utilize a flux that is likely to behave in a similar way to some extent (Hewitt and Hirst, 1993). It was reported that concentrations of chromium, manganese and iron, i.e. metal core components in SMAW using stainless steel electrodes, increased with increasing voltage. However,
concentrations of potassium and fluoride, which originated from shield flux components, decreased with voltage in SMAW (Palmer, 1983). Although the reason is not explained, various factors, such as binding status, evaporation heat of each component, interaction of each component and transferring mode of electrode, may affect the composition of fume.

There is not a lot of work in the literature on the relationship between FGR and input power with respect to FCAW. Dennis et al. (1996) demonstrated that FGR increased with voltage (when voltage increased, the input power is also increased), while the concentration of hexavalent chromium remained relatively constant at a level of 0.2%. Stern (1981) reported that the concentration of hexavalent chromium was 1% when CO₂ shielding gas was used. Voitkevich (1995) reported that concentrations of total chromium and hexavalent chromium were 2–5 and 1.5–4%, respectively.

It has been reported that the concentration of hexavalent chromium from metal active gas (MAG) welding with a CO₂ shielding gas is lower than that from MIG welding, which uses helium or argon. The reason for this is that CO₂ destroys O₃ gas, which plays a role in developing hexavalent chromium (Hewitt and Madden, 1986; Dennis et al., 1997), and oxygen, the thermal decomposition product of CO₂ in hot welding arc, formulates a stable trivalent chromium compound (Cr₂O₃). Also, as the temperature increases, chromium is transitioned into spinel oxide (FeO·Cr₂O₃), which is hardly oxidized (Dennis et al., 1997).

The concentration of hexavalent chromium produced from FCAW in this study (0.15–1.08%) is similar to that from MIG welding (0.2–1%) (Pedersen et al., 1987; Voitkevich, 1995), whereas the concentration of total chromium from FCAW in this study (2–8%) is similar to that from SMAW (0.5–7%) (Kimura et al., 1979; Stern, 1981; Ulfvarson, 1981; Hewitt and Gray, 1983; Pedersen et al., 1987; Voitkevich, 1995). The reason for this is as follows.

![Fig. 5. Total chromium generation rate by type of flux-cored wire as a function of current and input power.](image-url)

![Fig. 6. Hexavalent chromium generation rate by type of flux-cored wire as a function of current and input power.](image-url)
As in the case of the SMAW, the composition of fumes generated from FCAW depends on the composition of the wire tube, inner flux and, to a minor extent, on the base metal. Since the content of total chromium in sheath or inner flux is low, total chromium concentration in filler material is also likely to be low and, thus, chromium concentration in fume is low. In SMAW, alkaline oxides in shielded flux contribute to form hexavalent chromium and its concentration is higher than that from MIG welding (Orr, 1993). Conversely, hexavalent chromium concentration in FCAW is lower than that in SMAW for two reasons. First, since most flux components are non-conductive and exist inside the tube, these components are less influenced by input power and there is little chance for them to react with alkaline oxide to form hexavalent chromium. In some cases, flux is transferred directly into the weld pool without being melted. This phenomenon was observed by high-speed camera (KWS, 1998). Second, as mentioned above, the CO₂ shielding gas destroys O₃ gas and forms the stable trivalent chromium.

Potassium and sodium contribute to chromium's solubility. Previous investigators reported that in SMAW, hexavalent chromium is almost entirely in soluble form because potassium or sodium in flux reacts with chromium and forms K₂CrO₄, K₂Cr₂O₇, Na₂CrO₄ and K₂NaCrF₆, which are all soluble forms (Koponen et al., 1981; Voitkevich, 1995). A previous study reported that potassium and sodium in fume was 16.7% when the same flux-cored wires were used (Yoon et al., 2002) and it seems that this has also contributed to chromium’s solubility in water. Potassium is used as an arc stabilizer or binder and sodium as an arc stabilizer (KWS, 1998).

CONCLUSIONS

- In stainless steel FCAW, FGR and FGR₆₇ increase with welding input power. The generation rate of hexavalent chromium, known as a carcinogen, also increases as the input power increases.
- A power function relationship between FGR and welding input power has been constructed.
- Observations on FGR₆₇ and FGR₆₇₅ provide a more complete understanding of the role of welding input power.
- Fume total chromium concentrations are similar to those from SMAW. Fume hexavalent chromium concentrations are similar to those produced from MIG welding fume. Fume hexavalent chromium is mostly soluble, which is similar to the characteristic solubility of fume hexavalent chromium from SMAW.

Acknowledgements—The authors would like to thank Dr Samuel Y. Paik, Senior Specialist of Abbott Laboratories in the USA, for his valuable reviewing and editing. This study was funded by the Korean Occupational Safety and Health Agency and the Catholic University of Daegu.

REFERENCES


KIIT. (1999) The evaluation techniques of fume generation characteristics and feedability during arc welding [in
Korean]. Seoul: Korea Institute of Industrial Technology. pp. 34–70.


