Materials Transactions, Vol. 47, No. 7 (2006) pp. 1859 to 1863

EXPRESS REGULAR ARTICLE

Fume Generation Behaviors in Short Circuit Mode during Gas Metal Arc Welding and Flux Cored Arc Welding

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Fume generation mechanisms in gas metal arc welding (GMAW) and flux cored arc welding (FCAW) have been widely investigated. The experimental approach using the different contents of chromium and nickel in electrodes and base metal was proposed in this study, in order to quantitatively measure the amount of fume generated from the electrode and the base metal respectively. The experiments were conducted by using a stainless steel electrode and a mild steel electrode, and chromium (Cr) and nickel (Ni) contents of the fume were calibrated by using the different electrodes. The welding fume was generated mainly from the wire electrode. In addition, the relationship between the welding parameters and fume generation rate (FGR) was investigated. FGR increased with welding current; however, weights of fume per unit electrode length showed a reverse trend compared with FGR per unit time. [doi:10.2320/matertrans.47.1859]

(Received February 13, 2006; Accepted June 8, 2006; Published July 15, 2006)

Keywords: *welding fume, fume generation rate, gas metal arc welding, flux cored arc welding*

1. Introduction

Arc welding process is one of the productive welding processes most commonly used throughout the manufacturing industries. It is presumed that more than a million tons of welding consumables are annually consumed all over the world, and five thousand tons of welding fumes, 0.5% of total consumed filler metal, are known to be generated and released into the atmosphere.[1] Welding fumes are generally produced in arc welding processes, specifically, using the consumable electrode and high-current such as gas metal arc welding (GMAW) and flux-cored arc welding (FCAW). Various kinds of heavy metal elements contained in welding fumes are well-known to cause respiratory diseases and critical diseases in the nervous system after being entered and accumulated in the worker's body through respiration.[2,3] For instance, many welders, who have been exposed to manganese fumes generated during welding, have been reported to suffer from Parkinson's disease.[4] Moreover, chromium and nickel generated from the welding of stainless steel are known as carcinogens causing septal perforation or lung-cancer.[5,6] NIOSH (National Institute for Occupational Safety and Health) in the U.S. has performed studies on noxiousness of welding fumes in terms of public health,[7] and OSHA (Occupational Safety and Health Administration) and ACGIH (American Conference of Governmental Industrial Hygienists) have suggested to strictly apply the permissible exposure limit regarding manganese, chromium and nickel to the U.S. government.[8] The Korean Ministry of Labor also noticed the permissible exposure limit of heavy metals to be applicable in the working environments,[9] and the Korean standard regarding the personal protective equipment is under revision to satisfy the requirements of international standards.

It is known that welding fumes are formed into particles and clusters in the ambient air after the metal vapor generated on the tip of the welding consumable is oxidized, quickly cooled and condensed.[10] Gray, *et al.* reported that fume generation rate depends on the vapor pressure of elements contained in welding consumables and base metals.[11] A number of researches have been performed to identify the fume generation mechanism with a mathematical model of various welding variables.[12,13] Several studies, in addition, have tried to investigate the correlation between Fume Generation Rate (FGR) and welding variables by precise evaluation of FGRs.[14,15] These studies were, nevertheless, insufficient to fully identify the fume generation mechanism affected by various welding variables and external environmental conditions.

Irving suggested the schematic sketch of welding fume generated in GMAW, as shown in Fig. 1.[16] Energy is concentrated on the electrode tip more than on the base metal. It is assumed that welding fume is mainly generated in the vicinity of the anode where welding wire melts and evaporates. This is a mere hypothesis in evidence with the results from observation using the measuring equipment such as high-speed camera. In order to clarify the fume generation mechanism quantitatively, Voitkevich investigated the range of FGRs from rod, covering of welding electrode and base metal in shielded metal arc welding (SMAW),[17] but few studies on the GMAW or FCAW have been reported to date.

In this study, FGRs were evaluated by performing bead-on-plate welding with mild steel and stainless steel filler metals placed upon stainless steel base metal in order to investigate the fume generation behaviors in short circuit

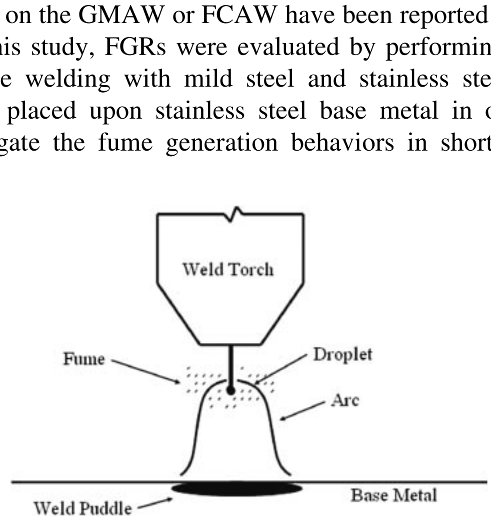

Fig. 1 Schematic sketch of fume generation mechanism.

Table 1 Chemical composition of base metal and filler metal.

Type	AWS code	Symbol	Content (mass%)					
			Cr	Ni	Mn	Si	P	Fe
Filler metal	ER308L	SS (Solid)	20.604	10.203	0.901	0.320	0.013	bal.
	E308LT-1	SS (FCW)	20.360	9.985	0.846	0.242	0.072	bal.
	ER70S-G	MS (Solid)	0.014	0.013	1.968	0.310	0.021	bal.
	E71T-1	MS (FCW)	0.011	0.010	1.054	0.512	0.013	bal.
Base metal	S 30400	—	19.397	9.018	0.871	0.242	0.011	bal.

Table 2 Experimental conditions in GMAW and FCAW.

Parameters	Range
Welding current, A	150–240
Welding voltage, V	25
Travel speed, mm/sec	6
Torch angle, Nozzle diameter; deg., mm	90, 17
CTWD, mm	17
Type and flow-rate of shielding gas, ℓ/min	CO_2, 20
Temperature and humidity; Celsius, %	26, 70

Fig. 2 Photo of fume collection chamber.

mode during GMAW and FCAW using the filler metals, which have diverse contents of chromium and nickel. The fume generation behaviors regarding the welding parameters are investigated through quantitative evaluation on the FGRs from the base metal and the filler metal respectively.

2. Experiment

The welding materials used in the experiments are shown in Table 1. The diameters of all filler metals were 1.2 mm. The filler metals for mild steel welding were a solid wire (AWS ER70S-G) and a flux-cored wire (AWS E71T-1) while the others for stainless steel welding were a solid wire (AWS ER 308L) and a flux-cored wire (AWS E308L). A stainless steel (S 30400) plate with the dimension of 260 mm × 260 mm × 12 mm was used as the base metal. In this study, ER308L is symbolized as SS (Solid wire), E308LT-1 as SS (FCW), ER70S-G as MS (Solid wire), and E71T-1 as MS (FCW) as shown in Table 1. While the base metal and the stainless steel filler metals contained about 20% chromium and 10% nickel, the mild steel filler metals contained less than 0.014% of chromium and nickel. The welding conditions for this study are listed in Table 2. The range of welding current was varied in typical short circuit mode with CO_2 shielding gas, and the rest of the welding conditions remained constant.

The photo of a welding fume collecting chamber and a schematic layout of fume collection equipment are presented in Figs. 2 and 3. The dimension of the fume collecting chamber and the procedure of measurement were followed by JIS Z 3930.[18] The welding fume collector was designed to automatically collect welding fumes during GMAW and

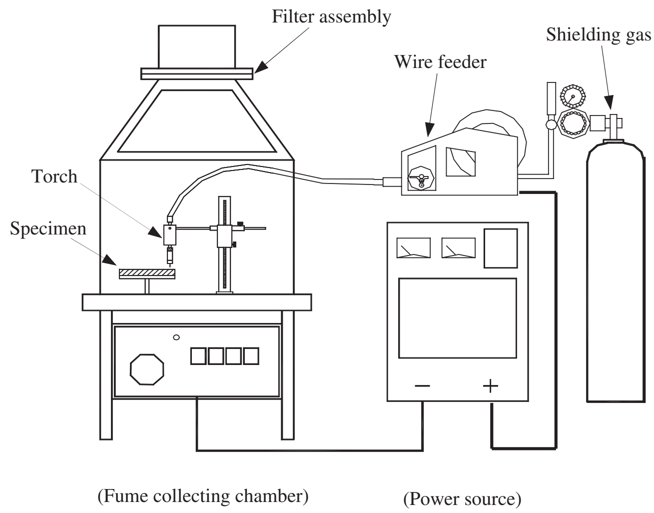

Fig. 3 Layout of fume collection equipment.

FCAW. A monitoring device was employed to observe in real time whether welding and fume collecting were normal or not. A 600 A SCR welding power source and DCEP (DC Electrode Positive) were used for the experiment. To analyze the chemical content of welding fumes, JIS Z 3920 was used.[19]

A high speed video camera with capture speed of 3,000 frames per second was employed for observation of the fume generation behavior. The bandpass and ND filter were

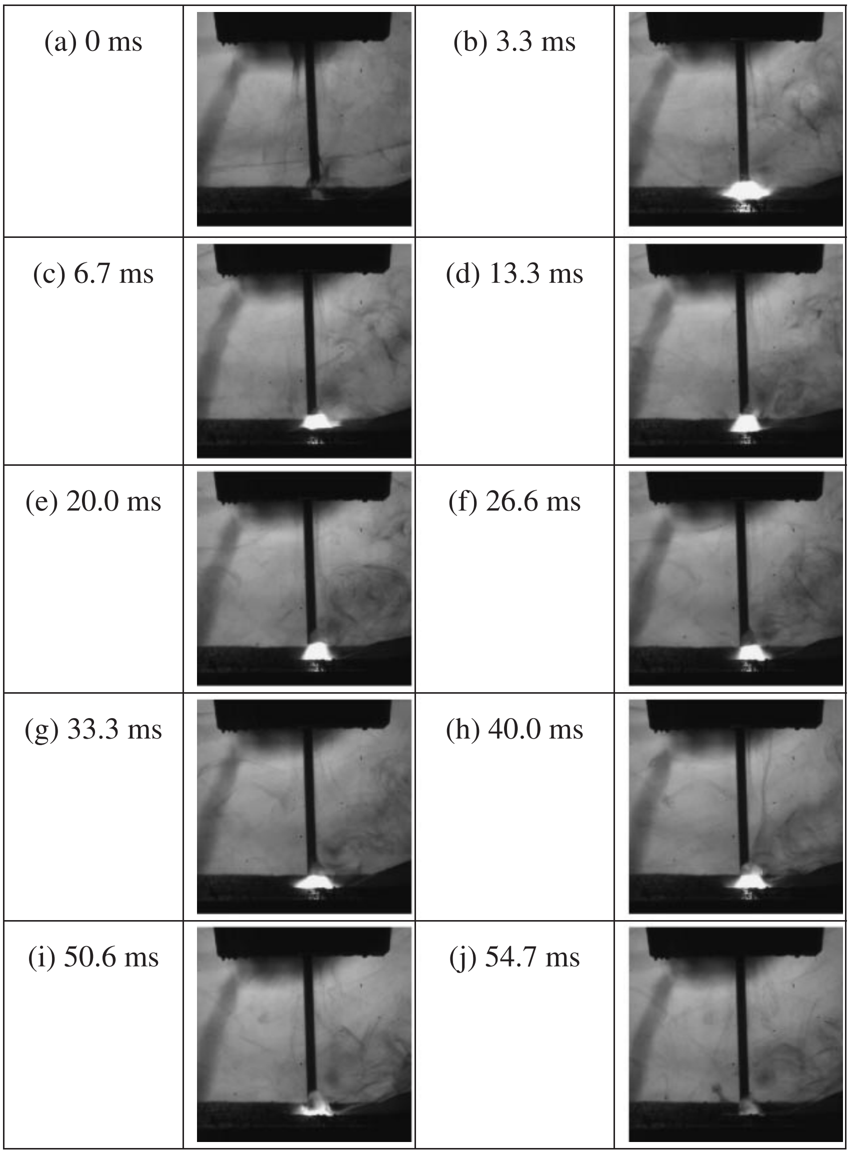

Fig. 4 Sequential images of welding fume generation by high speed camera in gas metal arc welding (welding current: 240 A, welding voltage: 25 V, frame rate: 3,000 fps).

utilized to obtain clear images, and also a halogen lamp was used for back lightening.

3. Results and Discussion

3.1 The observation of fume generating behavior

The photos of one cycle to observe the fume generation phenomena at the short-circuit mode in GMAW are indicated in Fig. 4. The arc is regenerated in (a) subsequent to short-circuiting, and the volume of molten metal is gradually increased on the tip of the welding wire, which can clearly be observed in (f). The welding fumes were observed in the whole process of short-circuiting and arcing. However, more welding fume was clearly observed in (b)–(i) where the molten metal is growing on the electrode tip rather than (a) and (j) in short-circuiting. The electrode tip is overheated by the arc during the arcing period, which induces the evaporation of metals, and the arc heat disappears during the short-circuiting period. Therefore, it seemed that the welding fume in GMAW is mainly generated on the surface of the molten metal growing in the arcing rather than the short circuiting period. Nevertheless, it is not clear whether the fumes from the filler metal rather than the base metal are abundant or not in the photographing analysis. The quantitative analysis to identify where the fumes mainly generate is necessary.

3.2 Fume generation behavior by the evaluation of chromium and nickel fume generation rates

The chromium FGRs generated from the conditions of Figs. 3(a) and (b) are shown in Fig. 5. Figures 5(a), (b) and (c) represent the whole chromium FGR, the chromium FGR from filler metal and one from base metal, respectively. In the case of (c), the entire chromium fume should be generated in the base metal since the mild steel welding wire contains little chromium. The chromium FGR in the filler metal was calculated by subtracting (c) from (a) in Fig. 5 and plotted as Fig. 5(b). The whole chromium FGR is not linearly increased with the welding current. The wire feeding rate equal to the wire melting rate increases with the welding current. Hence,

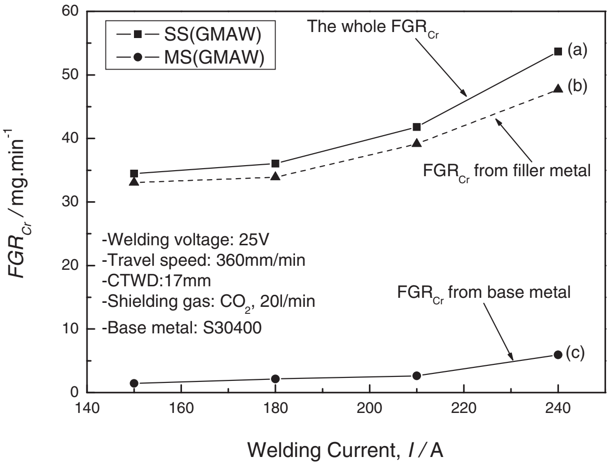

Fig. 5 Elemental FGRs of chromium generated in GMAW.

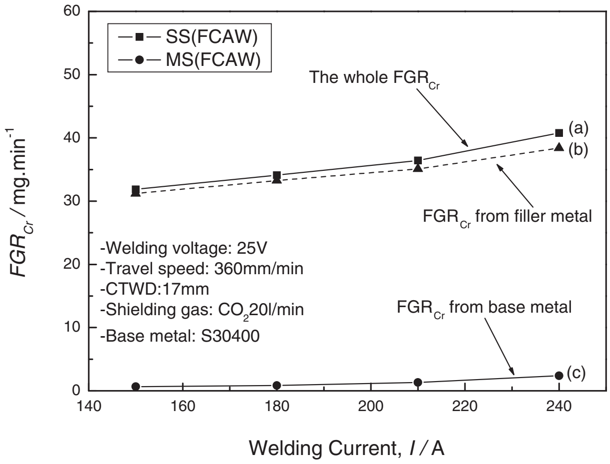

Fig. 7 Elemental FGRs of chromium generated in FCAW.

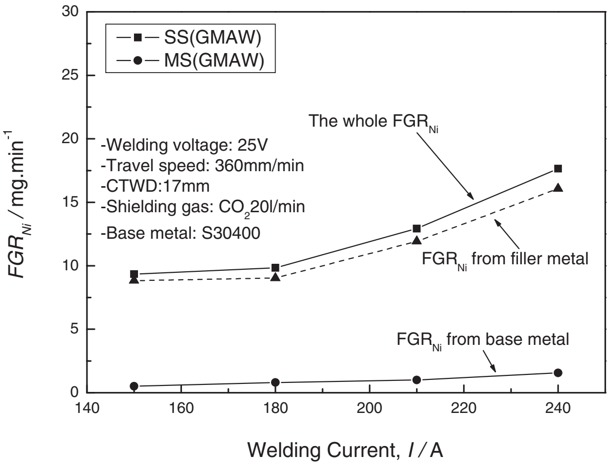

Fig. 6 Elemental FGRs of nickel generated in GMAW.

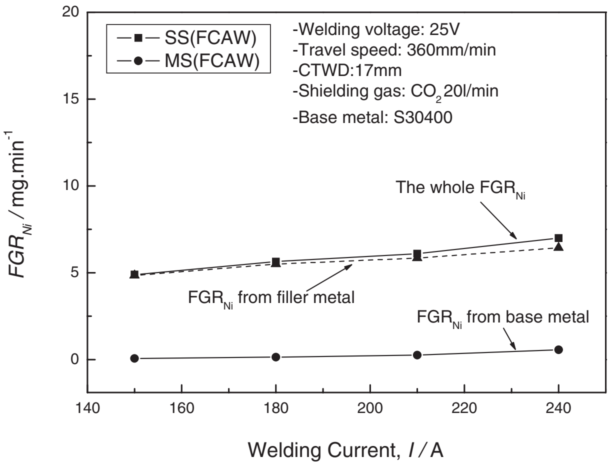

Fig. 8 Elemental FGRs of nickel generated in FCAW.

FGR increases with the increase in welding current. In addition, the surface overheating of molten metal on the electrode tip is accelerated with increasing arc temperature as welding current increases, and the surface area of molten pool formed on the base metal increases. Also, although the nickel contents in the welding materials are less than half the chromium contents, the nickel FGR has the same tendency as the chromium FGR, as shown in Fig. 6.

The chromium and nickel FGRs generated from FCAW are shown in Figs. 7 and 8. In FCAW, the chromium and nickel FGRs generated from the base metal are relatively small, compared with GMAW, and most chromium and nickel in fumes are expected to be generated from the filler metal. A flux-cored wire contains the fluxing ingredients influencing slag formation, arc stabilization, de-oxidation, and fusion metal protection during welding. The slag floating on the molten pool surface during welding prevents the molten metal from exposing the ambient air, which is a cause for the decreased FGR from the base metal in FCAW.

3.3 Fume generating behavior through the evaluation of chrome and nickel fumes generation rate per unit wire length

The FGR per unit wire length, which is an important index in developing welding consumables, is analyzed in this section. The chromium FGRs per unit time shown in Figure 5 are redrawn in Fig. 9 after it is converted into the chromium FGR per unit wire length, mg/m. The chromium FGRs per unit wire length from the whole and the filler metal are decreased while that from the base metal is increased with the increase in welding current. While welding voltage remains constant, the arc period is longer at low welding current than at the high one in the short circuit mode. Figure 10 shows wire feed rate, short circuit frequency, and duty of arc (DA) with the increase in welding current. DA is defined as the ratio of the arcing time to the whole welding time in one period for the short-circuiting transfer. That is, DA represents the period when the arc heat can affect the molten metal on the electrode tip. In case of increasing the welding current at the constant voltage, short circuit frequency increases as welding current increases, while DA decreases.

DA per wire feed rate (DA/WFR) for the case of Fig. 9(a) and itself are re-plotted in Fig. 11. The chromium FGR per unit wire length and DA/WFR have similar tendencies in spite of the discordance in 240 A of welding current. At high welding current, the FGR from the base metal is more dependent on the surface area and temperature of the molten pool than at low welding current.

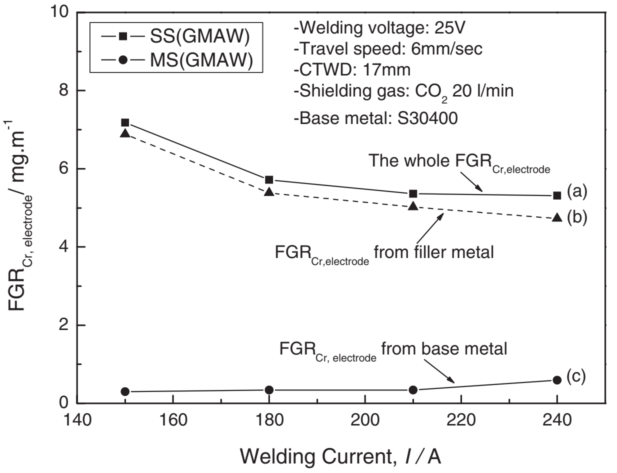

Fig. 9 Elemental FGRs of chromium per unit electrode length.

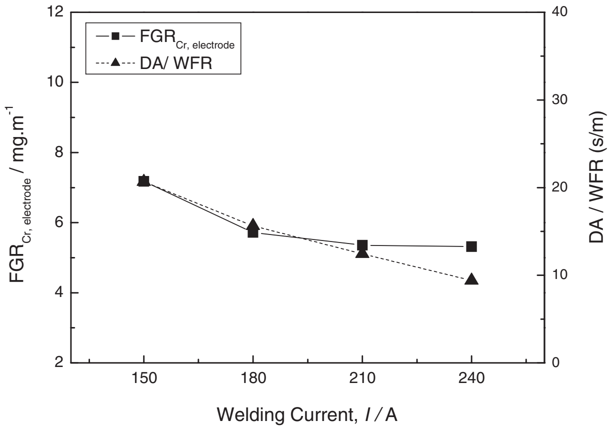

Fig. 11 Elemental FGRs of chromium per unit electrode length and the ratio between duty of arc and wire feed rate.

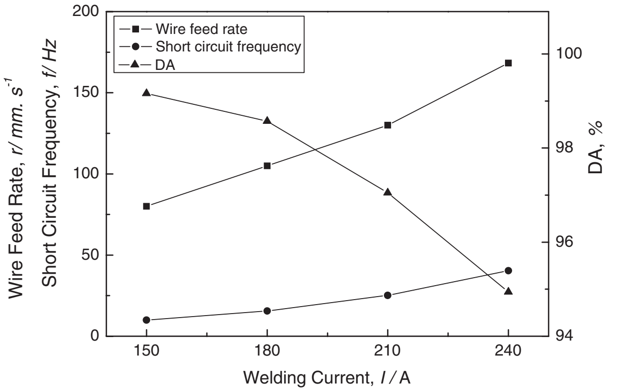

Fig. 10 Relationship among wire feed rate, short circuit frequency and duty of arc.

Therefore, it is recognized that FGR is proportional to the arc period, in accordance with the analysis of high-speed photographing in Section 3.1.

4. Conclusions

In this study, fume generation behaviors in short circuit mode during GMAW and FCAW were investigated by observing the behavior of chromium and nickel fumes generated during stainless steel welding, and the conclusive details are described below.

(1) By analyzing high-speed images, it was identified that the welding fume is mainly generated not in short circuiting but rather in arcing period in short circuit mode in GMAW.
(2) The experimental approach measuring the amounts of chromium and nickel in stainless steel GMAW and FCAW was suggested, which was able to evaluate the FGRs from filler and base metal, respectively.
(3) By the suggested method, it was found that most welding fumes were generated from the filler metal, and the FGRs per unit time from the filler and base metal were increased with the welding current.
(4) The FGR per unit wire length for the low welding current was higher than that for the high one in the short circuit mode of GMAW. This is because the duty of arc per wire feed rate (DA/WFR) is decreased with welding current.

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