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Welding Fume and Others from Welding Processes

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Abstract : A number of health hazards are generated in welding processes. In this paper, the characteristics of fumes and some other hazardous agents in welding are reviewed. Fumes in welding are generated by complex mechanism like physical ejection of particles, oxidation-enhanced vaporization, vaporization-condensation-oxidation, and spatter contribution. Fume generation rates could be described as a power function in a given process. Most of fume constituents was originated from consumables rather than base metal. The mass distribution for the welding fumes is unimodal and very small to penetrate respiratory system. So, almost fractions of fumes are classified into the respirable particulate mass. Total chromium contents in FCAW were similar to those from SMAW whereas hexavalent chromium concentrations in fume were similar to those produced from MIG welding fume. Hexavalent chromium was mostly soluble which was similar to the characteristic solubility of fume hexavalent chromium from SMAW.

Keywords : welding fume, chromium, particle size, health hazard, fume generation

Introduction

Various hazardous agents, such as fumes, gases, vapors, heat, noise, and radiation, are produced during welding operations. Among these, welding fumes and some components are the greatest concerns in welding processes. The major sources of fumes are the electrode metal and the flux metal. The base metal contributes little compared to the electrode metal.

Some components of fumes are very toxic. For example, hexavalent chromium is a great concern in industrial hygiene, which is a human carcinogen[1,2]. Although numerous epidemiological studies indicated that excess cases of lung cancer were found in workers performing stainless steel welding[3], direct evidence linking welding fume exposure to the incidence of cancer has not yet been demonstrated[4]. Also, manganese, nickel as well as cadmium, zinc which may be originated from protective coating of the base metal are all health concern components.

The type and quantity of fumes produced depend, to a great extent, upon the welding process being used. Within each process fume generation can vary widely, depending primarily upon the type of electrode and current[5].

Gases can be generated by several sources, including shielding gas, flux decomposing gas, and gases produced in reactions of the arc and/or the ultraviolet with atmospheric element or the contaminants.

In Korea, arc welding, Shielded Metal Arc Welding (SMAW) as well as Gas Metal Arc Welding (GMAW) (including Flux Cored Arc Welding (FCAW), on mild steel and/or stainless steel is often used.

In this paper, characteristics of fumes and some other hazardous agents in welding processes are reviewed.

Methods

Mechanism of fume generation was referenced from Hewitt and Hirst (1993)'s study[6]. They studied the systemic approach to control fume generation and reviewed the theoretical consideration for fume generation mechanism.

Fume generation rates were based on our previous research[7]. In our previous study, a fume collection chamber for welding operations was constructed. This chamber was validated for no loss of fume during welding and sampling[8]. Six different products

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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.

Size distribution of fumes was mainly referenced from Hewitt (1995)'s study[9]. SMAW and GMAW both on mild steel and stainless steel were done in a test chamber. Fumes were sampled using micro-orifice uniform deposit (cascade) impactor (MOUDI). Nonlinear least squares analytical method was used to fit smooth curve to the mass fraction distribution histograms of fumes. The mass distributions for all consumables were unimodal and well described by a lognormal distribution (GM and GSD).

Chromium and hexavalent chromium characteristics are referenced from our previous study[7]. To determine total chromium and hexavalent chromium, collected welding fume in test chamber were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) (NIOSH Method 7300)[10], and ion chromatography (IC) (modified NIOSH Method 7604)[11].

Table 1. General hazards in welding processes

Hazards	Welding types			
	SMAW GTAW GMAW FCAW	Oxyfuel	SAW (Submerged Arc Welding)	PAW (Plasma Arc Welding)
Shock	⊙		⊙	⊙
Fire	⊙	⊙	⊙	⊙
Burn	⊙	⊙	⊙	⊙
Heat	⊙	⊙	⊙	⊙
Fumes/Gas	⊙	⊙	(⊙)	⊙
Radiation	⊙	⊙	(⊙)	⊙
Noise	⊙			⊙

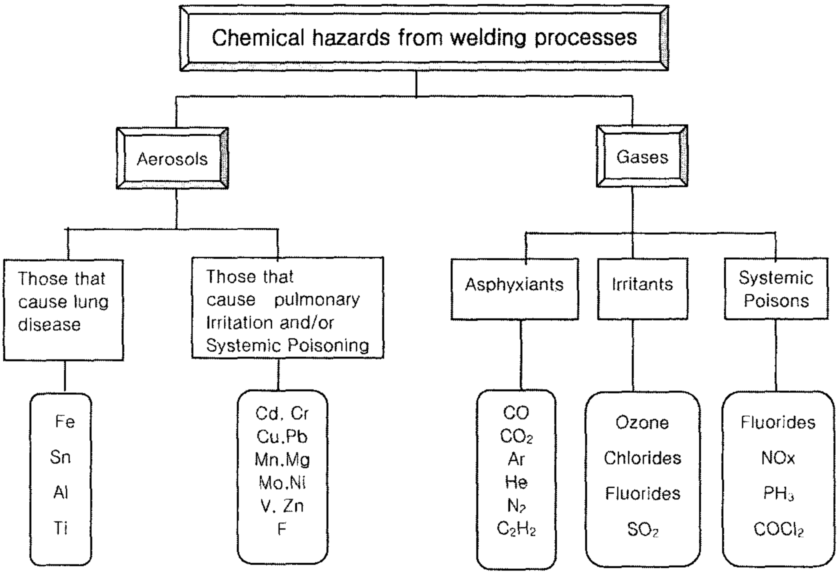

Fig. 1. Chemical hazards in welding processes.

Results

General Hazards in Welding

The potential hazards in welding may be different for each welding processes and situation but general hazards are summarized as Table 1[12]. Among these hazards, Fumes/gases, noise, radiation is major concern in industrial hygiene part.

Mechanism of chemical production, sources, disposition, and exposure profiles in welding processes are very complicated by welding processes, but possible agents are described as Fig. 1.

Mechanisms of Fume Generations[6]

A. Physical ejection of particles

Particles are ejected from molten metals by physical bursting and turbulent mixing of the molten metal, which increase the surface area available for vaporization. Direct transfer of elements to the fume in this way may be expected to occur more in FCAW, when flux is a fine power. So, direct transfer of fine particles may be more important in FCAW than using solid wires.

B. Oxidation-enhanced vaporization

Though the effect of oxidation-enhanced vaporization on fume formation is little in comparison to that of vaporization-condensation mechanism, Oxidizing gases, particularly oxygen was proved to increase the fume formation rates.

This was explained by that molten metal, such as molten iron, was more likely to form relatively volatile oxides with oxidizing gas such as oxygen and carbon dioxide.

The presence of slag formers, arc stabilizers and other flux components in FCAW make it more likely to occur oxidation-enhanced vaporization process.

C. Vaporization-Condensation-Oxidation

This mechanism was well known to industrial hygienists. Evaporation of metals in the arc zone may contribute highly portion of fume concentrations. Droplets of molten metal of the electrodes and/or metals from weld pool evaporated, and likely to be accompanied by subsequent oxidation, and condensation by oxidizing gas in the gas shield and in the general atmosphere.

D. Spatter contribution to fume formation

Spatter is generated from the unstable arc and turbulent weldpool. The formation and ejection of spatter into the air increases the surface area of molten metal which can easily vaporize and increase the potential for oxidation. Generally, In MAG welding, including CO_2 welding, arc is unstable in comparison to MIG welding. So, Spatter tends to be more produced in MAG welding.

Fume Generation Rates

Fume generation rates (FGR) are influenced by the welding process, current, voltage, type of electrode, diameter of electrode, electrode polarity, and base metal. It has been reported that fume generation rates are most affected by the current in a given welding process[5,13-15].

For example, the ranges of FGR in Flux cored

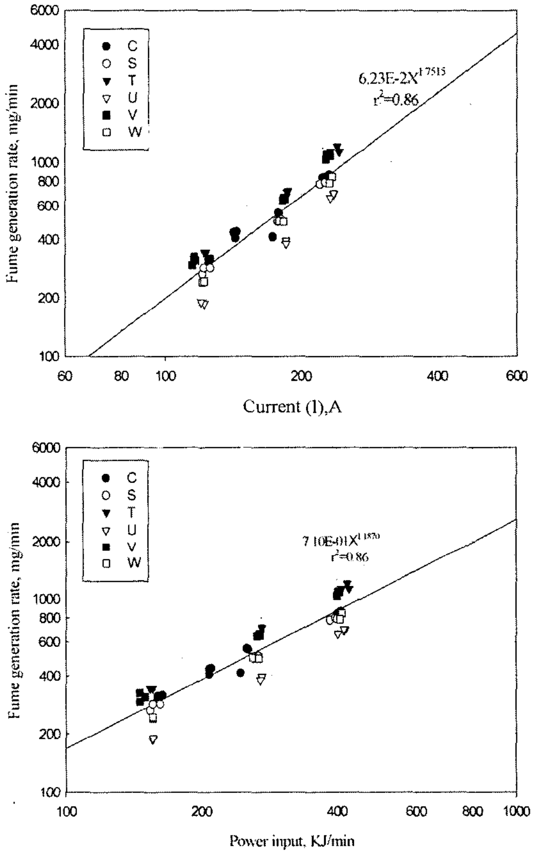

Fig. 2. Fume generation rate by type of flux-cored wire as a function of current and input power.

arc welding were 189-344, 389-698, and 682-1157 mg/min at low, optimal, and high levels of input power respectively[7].

Previous studies[5,14] suggested that the FGR could be related to welding current (I) as indicated in Equation (1) below.

$$FGR = kI^{l} \qquad (1)$$

The value of the power function coefficient (l) is reported in the range of 1.1-2.3 previously[5,14]. Yoon *et al.*[7] reported that the value of the power function coefficient (l) is 1.75 (1.59-1.93) and constructed the relationship between FGR and welding input power (current and voltage) as shown in Fig. 2.

Composition of Fume

The chemical composition of the fumes generally reflects the elemental composition of the electrode, base metal and flux. But the fume components may have different chemical forms[3]. Most of fume components (>85%) are originated from consumables rather than base metal (<15%)[15]. The electrode rod coating or wire flux is the source of such elements in fumes as sodium, potassium, calcium, magnesium, fluorine and titanium. While iron, manganese, chromium, nickel, and silicon can be introduced into fume from both base metal and weld electrode as well as from coating or flux. Table 2 summarized the content of metal components in fume by welding processes.

Metal contents of fume also are influenced by

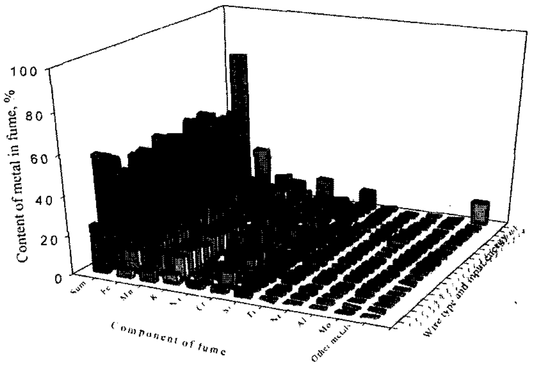

Fig. 3. Composition of metals in fumes generated from flux cored arc welding as a function of input power. (Product 'X' in x axis is a solid wire and have no flux in wire. -1, -2, -3 in x axis means the condition of input power as follows; C-1, S-1, T-1, U-1, V-1, W-1 : Low input power (156.0 ± 4.56 kJ/min) tested. C-2, S-2, T-2, U-2, V-2, W-2 : Middle input power (265.0 ± 8.17 kJ/min) tested. C-3, S-3, T-3, U-3, V-3, W-3 : High input power (406.3 ± 8.71 kJ/min) tested.

Table 2. Ranges of element content variation in welding fumes, generated when welding the most widely used types of steel with different welding consumables (%)

Element	Welding Method/Steel Types					
	SMAW/MS	FCAW/MS	GMAW/MS	SMAW/SS	FCAW/SS	GMAW/SS
Fe	20-40	35-45	45-50	5-20	8-10	28-50
Mn	5-15	5-15	10-15	2-12	8-25	1-20
Cr_{total}	0.01-0.05	0.1-0.3	0.1-0.3	0.5-7	2-5	8-25
Cr(VI)	-	-	-	0.5-5	1.5-4	0.2-1
Ni	-	-	-	0.1-5	0.1-6	2-7
Si	5-20	2-4	3-5	5-20	3-6	1-4
F	0-2* 14-18**	8-15	-	15-20	5-10	-
Ca	0.1-2* 8-15**	2-15	-	0.2-9	0.1-1	-
K	5-20	0-10	-	4-24	3-10	-
Na	3-15	0-10	-	2-15	3-10	-

SMAW: Shielded Metal Arc Welding, FCAW: Flux Cored Arc Welding, GMAW: Gas Metal Arc Welding, MS: Mild Steel, SS: Stainless Steel, *: Rutile Type, **: Lime Type input power. Fig. 3 shows the content variation of metal component by input power.

Size Distribution of Fume

The particle size distribution of fumes greatly influences where deposition occurs in the respiratory system, and the deposition site determines the degree of hazard of the fumes. Welding fumes from the arc sources are very small but can be agglomerate, thus increasing particle size to several micrometers. Welding fume particles in the 1 um or smaller range penetrate deeply in the system, all the way to the alveoli. So, most of fumes in welding process can be classified into 'respirable particulate mass' according to American Conference of Government Industrial Hygienists(ACGIH)'s particle size selective sampling criteria[1].

Table 3. Mass median aerodynamic diameter (MMAD; Geometric Mean of the Mass Distribution) and geometric standard deviation for each type of fume

Consumable	MMAD (um)	GSD
SMAW-MS	0.59	1.80
SMAW-SS	0.46	1.55
GMAW-MS	0.24	1.65
GMAW-SS	0.25	1.55

Here, results of Hewitt (1995)'s study[9] were presented. He measured for fumes from SMAW and GMAW both on mild steel and stainless steel.

Mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) was reported as shown Table 3.

The element distribution histogram was shown in Fig. 4. The mass distribution for the welding wires (GMSW) was shifted to the smaller particle sizes compared to those for the welding rods (SMAW)

Chromium and Hexavalent Chromium in Fume

The total chromium concentration in fume increased with current as well as with input power, though ther was some variation by type of wire as shown in Table 4. 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.

The concentration of hexavalent chromium ranged from 0.15-1.08% of total fume (Table 4). It should

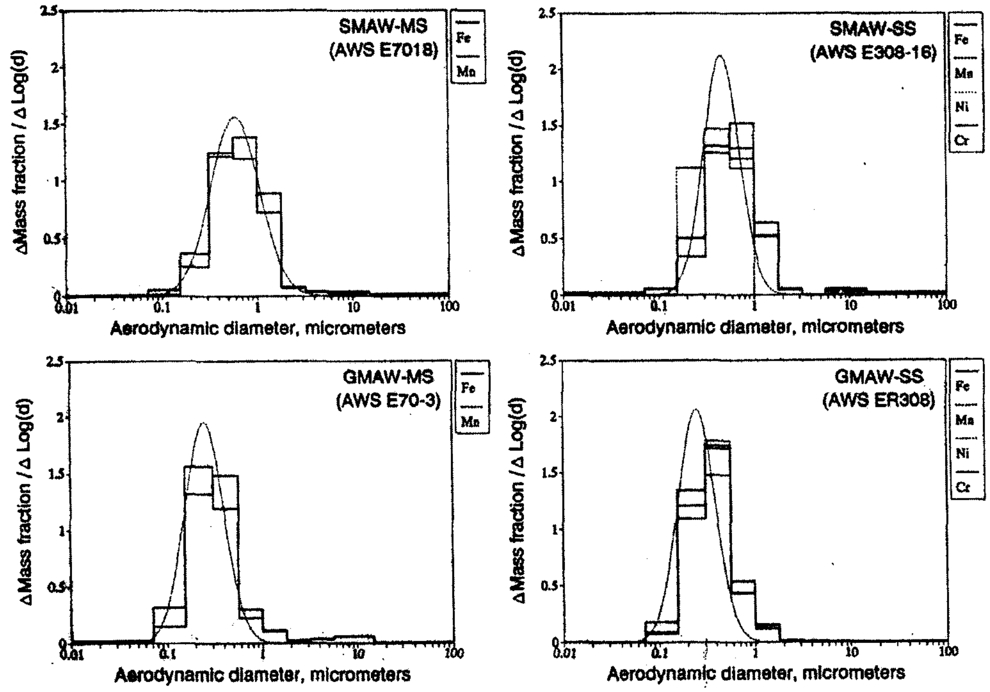

Fig. 4. Elemental mass distribution histograms for each welding rod and wire.

Table 4. Generation rates of fume (FGR), total chromium (FGR_{Cr}), hexavalent chromium (FGR_{Cr6+}) and concentrations in fume

Type of Wire	Voltage V	Current A	Input power KJ/min	FGR Mean (Sr*) mg/min	FGR $_{Cr}$ Mean (Sr) mg/min	FGR_{Cr6+} Mean (Sr) mg/min	Concentration in fume, %	
							Total chromium	Hexavalent chromium
C	22.1	125.0	165.6	312.1 (0.03)	8.27 (0.06)	1.31 (0.08)	2.65	0.42
	24.8	143.5	213.3	426.3 (0.04)	-**	1.31 (0.11)	-	0.31
	24.3	178.0	259.5	504.2 (0.16)	36.86 (0.25)	1.28 (0.20)	7.31	0.25
	30.5	228.0	417.2	848.3 (0.02)	59.49 (0.07)	3.16 (0.13)	7.01	0.37
S	22.1	123.0	163.3	278.8 (0.04)	4.37 (0.18)	2.60 (0.07)	1.57	0.93
	25.3	178.0	270.2	499.9 (0.01)	37.25 (0.29)	5.39 (0.12)	7.45	1.08
	30.1	226.8	409.2	786.8 (0.01)	63.29 (0.44)	6.97 (0.11)	8.04	0.89
T	22.3	122.0	163.2	343.8 (<0.01)	5.56 (0.07)	2.89 (0.12)	1.62	0.84
	25.1	186.3	280.2	697.7 (0.03)	19.71 (0.57)	6.28 (0.12)	2.82	0.90
	29.9	236.5	423.3	1156.7 (0.03)	76.46 (0.37)	11.21 (0.15)	6.61	0.97
U	22.2	120.7	160.7	188.7 (0.01)	3.83 (0.24)	0.95 (0.08)	2.03	0.50
	25.1	185.7	279.6	388.6 (0.03)	31.61 (0.53)	2.59 (0.03)	8.13	0.67
	29.9	232.0	415.5	681.6 (0.03)	38.79 (0.36)	4.73 (0.09)	5.69	0.69
V	22.1	116.0	154.0	310.5 (0.05)	8.00 (0.44)	1.34 (0.11)	2.58	0.43
	25.1	182.3	273.9	649.0 (0.01)	27.43 (0.26)	2.72 (0.07)	4.23	0.42
	29.9	228.8	410.0	1073.5 (0.03)	68.14 (0.18)	6.22 (0.09)	6.35	0.58
W	22.3	122.0	163.0	242.6 (0.01)	5.90 (0.44)	0.46 (0.01)	2.43	0.19
	24.8	182.0	271.2	495.2 (<0.01)	12.75 (0.22)	0.76 (0.03)	2.57	0.15
	29.8	231.5	413.2	807.6 (0.04)	44.03 (0.16)	1.70 (<0.01)	5.45	0.21

Note: Number of samples in each cell, n = 3
*: Coefficient of variations
**: Not measured.

be noted that hexavalent chromium, known as 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. Though more hexavalent chromium was released with increased input power, the percent ratio of hexavalent chromium to total chromium seemed to decrease with input power as shown in Fig. 6. The concentration of total chromium increased more steeply than hexavalent chromium with input power. Thus, the percent ratio of hexavalent chromium to total chromium decreased.

It has been reported that the concentration of hexavalent chromium from metal active gas (MAG) welding with a CO_2 shielding gas is lower than that from MIG welding, which uses helium or argon. It is explained that CO_2 gas destructs O_3 gas, which plays a role in developing hexavalent

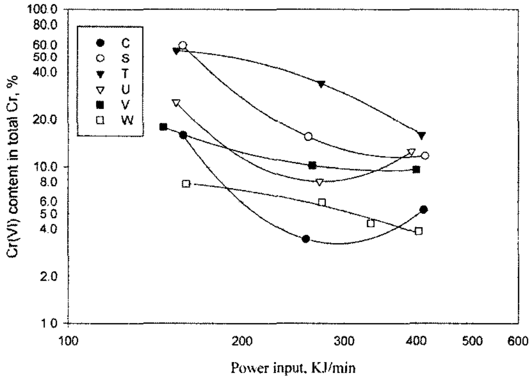

Fig. 5. Hexavalent chromium content in total chromium by input power.

chromium[16,17], and oxygen, the thermal decomposition product of CO_2 in hot welding arc, formulates a stable trivalent chromium compound (Cr_2O_3).

As in the case of the SMAW, the composition of fumes generated from flux-cored arc welding 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 likely to be low and, thus, chromium concentration in fume is low. In shielded metal arc welding, alkaline oxides in shielded flux contribute to form hexavalent chromium and its concentration is higher than that from MIG welding[18].

Potassium and sodium contribute to chromium's solubility. Previous investigators[15,19] reported that in SMAW, hexavalent chromium is almost entirely in soluble form because potassium or sodium in flux reacts with chromium and formulates K_2CrO_4, $K_2Cr_2O_7$, Na_2CrO_4, and K_2NaCrF_6, which are all soluble forms. A previous study[20] reported that potassium and sodium in fume was about 16.7% when the same flux-cored wires were used 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[21].

Solubility of Fume Components

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[22,23]. Soluble hexavalent chromium usually refers to the water-soluble fraction (Table 5)[7] whereas insoluble hexavalent chromium often refers to the portion that is actually soluble in sodium hydroxide/sodium carbonate solution[10,24]. The water-soluble fraction is usually hexavalent[25]. In 2001, ISO (International Organization for Standardization) promulgated ISO 15202-2 as a final draft international standard, which includes a sample preparation procedure for soluble metals and metalloids[26,27].

The soluble fraction of the hexavalent chromium was 80-90% as presented in Table 5. Thus, it was found that most of the hexavalent chromium produced in flux-cored arc welding existed as a soluble form.

Table 5. Soluble fraction of hexavalent chromium by type of wire

Types of wire	Soluble fraction of Cr (VI) Mean (%) ± Sr
S	85.1 ± 9
T	80.1 ± 4
U	89.5 ± 3
V	86.1 ± 5
W	87.0 ± 7

Note: Number of samples in each cell, n = 3

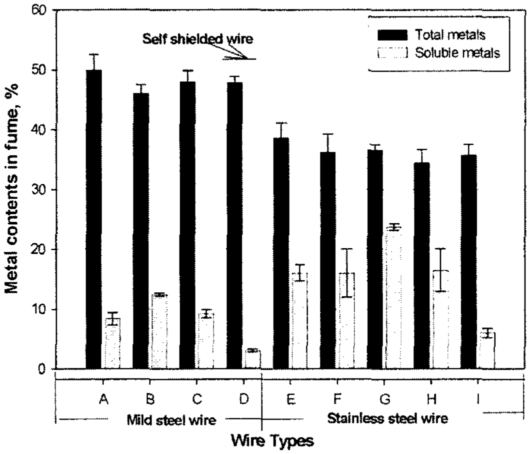

Fig. 6. Total metal and soluble metal contents in fume by wire types.

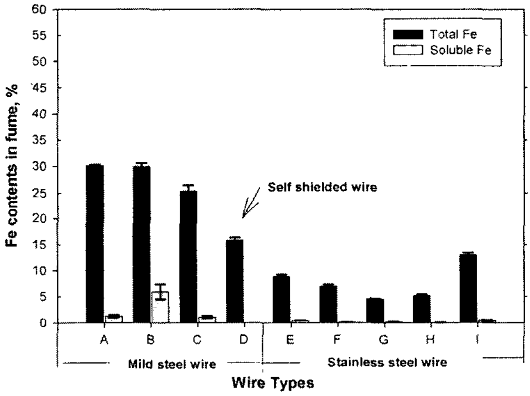

Fig. 7. Total iron and soluble iron contents in fume by wire types.

Previous study[7] studied the soluble fraction of FCAW fumes (Figs. 6-9) . The soluble contents of

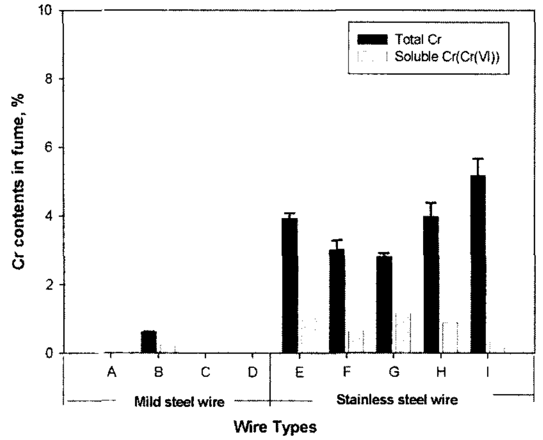

Fig. 8. Total chromium and soluble chromium contents in fume by wire types.

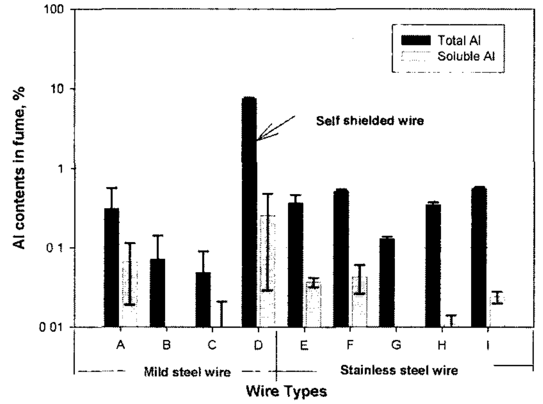

Fig. 9. Total aluminum and soluble aluminum contents in fume by wire types.

all metals were higher in stainless welding fume than in non-stainless welding fumes (15.7% vs 8.3%). The reason that soluble fractions are higher in stainless welding fumes is because there are high levels of potassium and sodium, which contribute other metals to be solubles. Hexavalent chromium, A known human carcinogen, can easily be soluble by combining with potassium and sodium. Total chromium content in FCAW stainless welding fumes was 3.8 (2.8-5.2)% and soluble content was 0.8 (0.4-1.2)%.

Gases from Welding Processes

Gases for welding processes are used to protect arc from atmospheric environment and welding part. They include argon, helium, carbon dioxide, and varying mixtures of these gases. Oxygen is sometimes used in the mixture as well.

Fumes are more generated when carbon dioxide or its mixture is used as shielding gas than helium or argon gas is used.

Some hazardous gases are formed from the arc, either by UV radiation, decomposition of the flux or by reaction with the shielding gas. Carbon monoxide is formed as a decomposition product of the flux and/or by reaction of the carbon dioxide gas. Nitrogen oxides and Ozone are formed by UV irradiation of the atmosphere. Fluorides are mainly formed from flux.

Conclusions

Characteristics of fumes and some other hazardous agents in welding are reviewed

- Fumes in welding were generated by complex mechanism; physical ejection of particles, oxidation-enhanced vaporization, vaporization -condensation-oxidation, and spatter contribution.
- A power function relationship between FGR and welding input power was described as $\mathrm{FGR} = kI^{l}$
- Most of fume composition was originated from consumables rather than base metal.
- The mass distribution for the welding fumes is unimodal and aerosol size was very small to penetrate respiratory system.
- Fume total chromium concentrations in FCAW were similar to those from SMAW. hexavalent chromium concentrations in fume were similar to those produced from MIG welding fume.
- Hexavalent chromium was mostly soluble, which was similar to the characteristic solubility of fume hexavalent chromium from SMAW.

References

1. American Conference of Governmental Industrial Hygienists (ACGIH) : Threshold limit values and physical agents and biological exposure indices. Cincinnati, OH, ACGIH, **22**, 74-76, 2004.
2. International Agency for Research on Cancer (IARC) : IARC Monographs on the evaluation of carcinogenic risks to humans(supplement 7). IARC,

ISBN 92 832 1411 0, 60, 165-168, 1987.

3. National Institute for Occupational Safety and Health (NIOSH) : Criteria for a recommended standard - welding, brazing, and thermal cutting. Cincinnati, OH: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 88-110, 54-84, 136-148, 1988.
4. Dennis, J.H., French, M.J., Hewitt, P.J., Mortazavi, S.B. and Redding, C.A.J. : Control of occupational exposure to hexavalent chromium and ozone in tubular wire arc-welding processes by replacement of potassium by lithium or by addition of zinc. *Ann. Occu. Hyg.*, **46**(1), 33-42, 2002.
5. American Industrial Hygiene Association (AIHA) : Chapter VIII Fume and gas generation in 'Welding health and safety resource manual'. Cincinnati, OH, American Industrial Hygiene Association, 5-35, 1984.
6. Hewitt, P.J. and Hirst, A.A. : A system approach to the control of welding fumes at source. *Ann. Occu. Hyg.*, **37**(3), 297-306, 1993.
7. Yoon, C.S., Paik, N.W. and Kim, J.H. : Fume generation and content of total chromium and hexavalent chromium in flux-cored arc welding. *Ann. Occu. Hyg., British Occupational Hygiene Society,* **47**(8), 671-680, 2003.
8. Korea Institute of Industrial Technology (KIIT) : The evaluation techniques of fume generation characteristics and feedability during Arc Welding (Korean), Seoul, KIIT, 34-70, 1999.
9. Hewitt, P. : The particle size distribution, density, and specific surface area of welding fumes from SMAW and GMAW mild and stainless steel consumables. *Am. Ind. Hyg. Assoc. J.*, **56**(2), 128-135, 1995.
10. National Institute for Occupational Safety and Health (NIOSH) : NIOSH Method 7300 Elements. In Eller PM, editor. NIOSH Manual of analytical methods. Cincinnati, OH: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 1990.
11. National Institute for Occupational Safety and Health (NIOSH) : NIOSH Method 7604 Chromium, Hexavalent. In Eller PM, editor. NIOSH Manual of analytical methods. Cincinnati, OH: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 1994.
12. American Welding Society (AWS) : Welding Health and Safety. Miami, Fl, American Welding Society, 12-30, 1992.
13. American Welding Society (AWS) : The welding environment (edited by Bland J). Miami, Fl, American Welding Society, ISBN 0 87171 103 6, 92-103, 1973.
14. American Welding Society (AWS) : Fumes and gases in the welding environment (edited by Speight FY and Campbell HC). Miami, Fl, American Welding Society, ISBN 0 87171 1745, 63-114, 1987.
15. Voitkevich, V. : Chapter 2. Welding fume properties. In welding fumes-formation, properties and biological effects. England, Abington Publishing, ISBN 1 85573 185 1, 18-77, 1995.
16. Hewitt, P.J. and Madden, M.G. : Welding process parameters and hexavalent chromium in MIG fume. *Ann. Occu. Hyg.*, **30**, 427-434, 1986.
17. Dennis, J.H., Mortazavi, S.B., French, M.J., Hewitt, P.J. and Redding, C.R. : The Effects of welding parameters on ultra-violet light emissions, ozone and Cr^{VI} formation in MIG welding. *Ann. Occu. Hyg.*, **41**(1), 95-104, 1997.
18. Orr, J.L. : Effects of welding on health VIII. Miami, Fl, American Welding Society, 1-23, 1993.
19. Koponen, M., Gustafsson, T., Kalliomäki, P. and Pyy, L. : Chromium and nickel aerosols in stainless steel manufacturing, grinding and welding. *Am. Ind. Hyg. Assoc. J.*, **42**, 596-601, 1981.
20. Yoon, C.S., Park, D.U. and Park, D.Y. : A study on the content variation of metals in welding fumes. *Korean Journal of Environmental Health Society,* **28**(2), 117-129, 2002.
21. Korean Welding Society (KWS) : Archives of welding and joining. Part 4. Welding and joining processes and instruments (Korean), Seoul, Korean Welding Society, 1998.
22. Fairfax, R. and Boltzer, M. : TLVs-Soluble and Insoluble metal compounds. *Appl. Occu. Environ. Hyg.*, **9**(10), 683-686, 1994.
23. Hewitt, P.J. and Gray, C.N. : Some difficulties in the assessment of electric arc welding fume. *Am. Ind. Hyg. Assoc. J.*, **44**(10), 727-732, 1983.
24. Thomsen, E. and Stern, R.M. : A simple analytical technique for the determination of hexavalent chromium in welding fumes and other complex matrices. *Scan. J. Work. Env. Health*, **5**, 386-403, 1979.
25. World Health Organization (WHO) : Environmental health criteria 61-Chromium. WHO, Geneva, ISBN 92 4 154261 6, 20-31, 1988.
26. Ashley, K. : International standard procedure for the extraction of metal compounds having soluble threshold limit values. *Appl. Occup. Environ. Hyg.*, **16**(9), 850-853, 2001.
27. International Organization for Standardization (ISO) : ISO 15202-2-2001, Workplace Air-Determination of metals and metalloids in airborne particulate matter by inductively coupled plasma atomic emission spectrometry-part 2: sample preparation. annex B: sample dissolution method for soluble metal and metalloid compounds. ISO, Geneva, Switzerland, 2001.