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Abstract

In the present study, the fumes generated from manual metal arc (MMA) and submerged metal arc (SMA) welding of low temperature service steel, and the chromium and nickel percentages in these fumes, were measured at various horizontal distances and vertical heights from the arc in order to obtain a three dimensional distribution. The MMA welding fume concentrations were significantly higher than the SMA welding fume concentrations. The highest fume concentration on the horizontal was shown in the fumes collected directly above the arc. The fume concentration vertically was highest at 50 cm height and reduced by half at 150 cm height. The fume concentration at 250 cm height was scarcely different from that at 150 cm height. The distribution of the chromium concentration vertically was analogous to the fume concentration, and a statistically significant difference in the chromium percentages was not found at the different heights. The nickel concentrations were not statistically significant within the welding processes, but the nickel percentages in the SMA welding fumes were statistically higher than in the MMA welding fumes. The highest nickel concentration on the horizontal was found in the fumes collected directly above the arc. The highest nickel concentration vertically showed in the fume samples collected at 50 cm height, but the greater the height the larger the nickel percentage in the fumes.

KEYWORDS: chromium and nickel alloy, manual are (MMA) welding, submerged metal arc (SMA) welding, three dimensional disribution, welding fume

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The Three Dimensional Distribution of Chromium and Nickel Alloy Welding Fumes

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In the present study, the fumes generated from manual metal arc (MMA) and submerged metal arc (SMA) welding of low temperature service steel, and the chromium and nickel percentages in these fumes, were measured at various horizontal distances and vertical heights from the arc in order to obtain a three dimensional distribution. The MMA welding fume concentrations were significantly higher than the SMA welding fume concentrations. The highest fume concentration on the horizontal was shown in the fumes collected directly above the arc. The fume concentration vertically was highest at 50 cm height and reduced by half at 150 cm height. The fume concentration at 250 cm height was scarcely different from that at 150 cm height. The distribution of the chromium concentration vertically was analogouse to the fume concentration, and a statistically significant difference in the chromium percentages was not found at the different heights. The nickel concentrations were not statistically significant within the welding processes, but the nickel percentages in the SMA welding fumes were statistically higher than in the MMA welding fumes. The highest nickel concentration on the horizontal was found in the fumes collected directly above the arc. The highest nickel concentration vertically showed in the fume samples collected at 50 cm height, but the greater the height the larger the nickel percentage in the fumes.

Key words : **chromium and nickel alloy, manual metal arc (MMA) welding, submerged metal arc (SMA) welding, three dimensional disribution, welding fume**

During the last decade, the use of low temperature service steel such as stainless steel and nickel steel has rapidly increased, resulting in a corresponding increase in the occurrence of chromium and nickel compounds in industrial metal aerosols. Both chromium and nickel are known to have various detelerious effects on the human organism (1-3). Chromium and nickel alloy for temperature service steel contains from 10 to 26 % chromium and from 0.5 to 27 % nickel. Also, the welding electrodes used for low temperature service steel generally contain a large amount of chromium and nickel; as much as or more than the parent metal.

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Exposure to stainless steel welding fumes has resulted in clearly elevated chromium and nickel concentrations in urine (4–12) and lung tissue (13, 14). Stainless steel welding fumes have been shown to induce occupational asthma (15), and mutation in bacteria and culture cells (16–20). There are several studies concerning the characteristics of stainless steel welding fumes from manual metal arc and inert gas welding techniques (6, 8, 18, 21–24). Many workers — such as crane-drivers, transport workers, gas welders, finishing workers, and assembly operators — work in shipbuilding factories where a large amount of welding fumes are generated. They are exposed to chromium and nickel from welding fumes just as arc welders are. It is presumed that the fume composition varies with collecting points, since the fume is not a simple substance. The amount of exposure to chromium and nickel is affected by their work locations (places and heights). In the present study, fume, chromium and nickel concentrations from manual metal arc (MMA) and submerged metal arc (SMA) welding of low temperature service steel, and chromium and nickel percentages in these fumes, were measured at various places on the horizontal and heights on the vertical, in order to obtain a three dimensional distribution.

Materials and Methods

Welding processes and materials. Welding fumes were generated either by the MMA welding process using flux-coated electrodes (NI 9, NIA 37 M, NIC 50), or by the welding process using nickel alloy wire (NF 196) and flux (NF 10). The materials and the welding conditions tested are shown in Table 1. The principal metal content,

Table 1 Meterials tested and welding conditions

Welding process	Material tested	Size (mm)	Welding arc current and polarity		Welding velocity (cm/min)
			Amp (A)	Polarity	
Manual metal arc (MMA) welding	NI 9 (Nittetsu Welding Co., Ltd.)	4.0	180	AC	5
	NIA 37 M (Nittetsu Welding Co., Ltd.)	4.0	180	AC	5
	NIC 50 (Kobe Steel Co., Ltd.)	4.0	120	AC	5
Submerged metal arc (SMA) Welding	NF 10 & NF 196 (Nittetsu Welding Co., Ltd.)	2.0	280	AC	20

Note : Mild steel (SS-41) plates of 10 mm thick were used for the parent material.

Tabel 2 Chemical composition of welding fumes from low temperature service steel, collected at 50 cm height straight above the arc

Type of electrode	Manual metal arc welding						Submerged metal arc welding	
	NI 9		NIA 37 M		NIC 50		NF 10 & NF 196	
Fume amount used for chemical analysis	28.4 mg	100.00 %	31.2 mg	100.00 %	19.0 mg	100.00 %	29.3 mg	100.00 %
Cr	1.91	6.75	0.75	2.40	1.04	5.47	Trace	Trace
Mn	1.63	5.74	3.13	10.00	0.50	2.63	1.59	5.43
Ni	0.22	0.77	0.06	0.19	0.05	0.26	0.07	0.24
Si	0.65	2.29	0.33	1.06	1.40	7.37	1.70	5.80
Mo	0.16	0.56	0.04	0.13	0.08	0.42	0.05	0.17
Ca	1.49	4.93	1.71	5.48	0.70	3.68	0.57	1.95
Mg	0.60	2.11	1.71	5.48	2.15	11.32	0.82	2.80

excluding iron, in the core wires of the electrodes and the nickel alloy wire used were the following: Cr 12.2%/Ni 68.1%/Mo 7.7%/Mn 3.0% for NI 9, Cr 8.8%/Ni 39.3%/Mn 2.3% for NIA 37 M, Cr 13.1%/Ni 49.3%/Mo 1.7%/Mn 2.6% for NIC 50, and Ni 7.1%/Mo 19.5%/Mn 2.3% for NF 196. In order to measure chromium and nickel concentration in the air generated from the tested electrodes, 10 mm thick mild steel (SS-41) plates that include neither chromium nor nickel were used for parent metal.

Welding fume sampling. The welding fume samples were collected either on cellulose nitrate membrane filters (Toyo Filter Paper Co., TM-100) for analyzing chemical contents, or on glass fiber filters (Toyo Filter Paper Co., GB-100 R) for measuring fumes, chromium, and nickel concentrations, connected to a high volume sampler (Kimoto Electron Co.). The filter holder was faced towards the arc and flow rate averaged 1,055 l/min and

Table 3 Means and standard devlations of welding fume, chromium and nickel concentrations in the air, and their percentages, for three samples at each collecting point.

Collecting place	M ± S. D. of concentration and content		NI 9 (MMA)			NF 10 & NF 196 (SMA)		
			50 cm	150 cm	250 cm	50 cm	150 cm	250 cm
Straight above the arc (A)	Fume	(mg/m³)	253.87 ± 28.62	68.37 ± 6.66	64.53 ± 7.18	118.23 ± 6.14	12.77 ± 1.45	6.60 ± 0.44
	Cr	(mg/m³)	12.57 ± 1.19	3.07 ± 0.31	2.77 ± 0.25	–	–	–
		(%)	4.96 ± 0.13	4.59 ± 0.36	4.29 ± 0.09	–	–	–
	Ni	(mg/m³)	1.34 ± 0.45	0.16 ± 0.03	0.16 ± 0.03	0.79 ± 0.02	0.21 ± 0.02	0.08 ± 0.06
		(%)	0.54 ± 0.22	0.24 ± 0.04	0.25 ± 0.02	0.61 ± 0.14	1.65 ± 0.03	1.33 ± 0.98
Front at 50 cm horizontal distance from the arc (B)	Fume	(mg/m³)	4.67 ± 0.74	6.87 ± 0.67	11.90 ± 1.30	1.93 ± 0.35	5.33 ± 0.21	2.90 ± 0.20
	Cr	(mg/m³)	ND	ND	0.08 ± 0.03	–	–	–
		(%)	–	–	0.57 ± 0.49	–	–	–
	Ni	(mg/m³)	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.05 ± 0.01
		(%)	0.22 ± 0.03	0.15 ± 0.14	0.19 ± 0.03	0.35 ± 0.02	0.19 ± 0.01	1.84 ± 0.11
Backside at 50 cm horizontal distance from the arc (C)	Fume	(mg/m³)	5.70 ± 0.30	5.10 ± 0.40	10.70 ± 1.60	2.07 ± 0.21	4.47 ± 0.15	2.27 ± 0.25
	Cr	(mg/m³)	ND	ND	ND	–	–	–
		(%)	–	–	–	–	–	–
	Ni	(mg/m³)	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	ND	0.04 ± 0.01	0.04 ± 0.01
		(%)	0.18 ± 0.01	0.02 ± 0.02	0.18 ± 0.07	–	0.82 ± 0.11	1.61 ± 0.12
Left side at 50 cm horizontal distanc from the arc (D)	Fume	(mg/m³)	26.90 ± 1.70	15.80 ± 0.70	4.07 ± 0.51	1.23 ± 0.25	1.67 ± 0.20	3.77 ± 0.25
	Cr	(mg/m³)	ND	ND	ND	–	–	
		(%)	–	–	–	–	–	–
	Ni	(mg/m³)	0.04 ± 0.00	0.03 ± 0.00	0.01 ± 0.00	ND	0.03 ± 0.01	0.03 ± 0.00
		(%)	0.15 ± 0.01	0.19 ± 0.01	0.25 ± 0.03	–	1.99 ± 0.12	0.80 ± 0.05

ND : Not detectable, Cr < 0.01 mg/m³, Ni < 0.005 mg/m³.

Table 4 Means and standard deviations of measurements by factors (type of electrode, place, and height)

Factor	Fume	Cr		Ni	
	Concentration (mg/m³)	Concentration (mg/m³)	Content %	Concentration (mg/m³)	Content %
Type of electrode					
NI 9	39.87 ± 69.40 (36)			0.15 ± 0.38 (36)	0.23 ± 0.12 (36)
NF 10 & NF 196	13.60 ± 32.18 (36)			0.11 ± 0.22 (36)	0.90 ± 0.78 (36)
F-test	F = 4.245, p = 0.0431			F = 0.348, p = 0.5569	F = 26.822, p = 0.0000
Places (Horizontal)					
Straight up (A)	87.39 ± 86.38 (18)	6.13 ± 4.87 (9)	4.61 ± 0.35 (9)	0.46 ± 0.50 (18)	0.77 ± 0.65 (18)
Front (B)	5.60 ± 3.38 (18)	0.03 ± 0.04 (9)	0.19 ± 0.38 (9)	0.02 ± 0.02 (18)	0.43 ± 0.65 (18)
Backside (C)	5.05 ± 3.01 (18)	0.01 ± 0.00 (9)	0.00 ± 0.00 (9)	0.02 ± 0.01 (18)	0.50 ± 0.58 (18)
Left side (D)	8.91 ± 9.72 (18)	0.01 ± 0.00 (9)	0.00 ± 0.00 (9)	0.02 ± 0.01 (18)	0.56 ± 0.71 (18)
F-test	F = 15.567, p = 0.0000	F = 14.211, p = 0.0000	F = 708.253, p = 0.0000	F = 13.865, p = 0.0000	F = 0.892, p = 0.4501
Heights (Vertical)					
50 cm	51.83 ± 87.20 (24)	3.15 ± 5.70 (12)	1.24 ± 2.24 (12)	0.28 ± 0.50 (24)	0.21 ± 0.24 (24)
150 cm	15.05 ± 21.16 (24)	0.30 ± 1.34 (12)	1.15 ± 2.08 (12)	0.06 ± 0.08 (24)	0.68 ± 0.71 (24)
250 cm	13.34 ± 20.18 (24)	0.71 ± 1.24 (12)	1.22 ± 1.88 (12)	0.05 ± 0.05 (24)	0.81 ± 0.73 (24)
F-test	F = 4.024, p = 0.0222	F = 1.930, p = 0.1612	F = 0.006, p = 0.9938	F = 4.371, p = 0.0163	F = 6.431, p = 0.0027
Grand mean	26.74 ± 55.32 (72)	1.55 ± 3.46 (36)	1.20 ± 2.01 (36)	0.13 ± 0.31 (72)	0.57 ± 0.65 (72)

( ) : Number of samples.

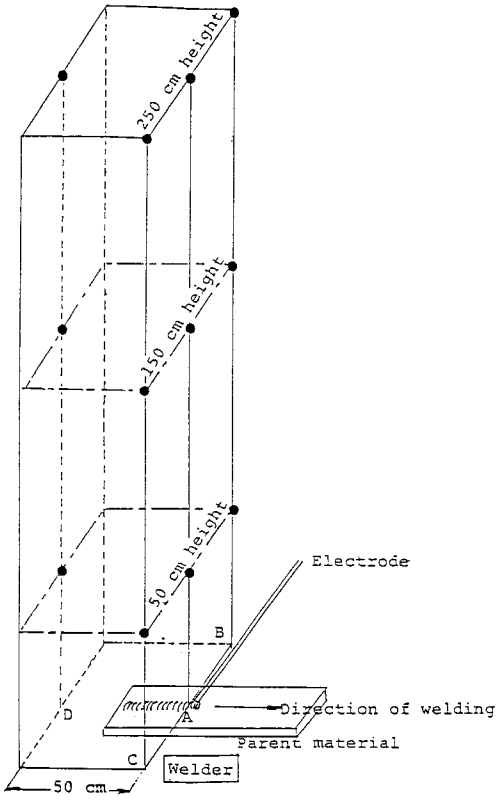

Fig. 1 Points where welding fumes were collected.
● : Collecting point, A : Straight above the arc, B : Front at 50 cm horizontal distance from the arc, C : Backside at 50 cm horizontal distance from the arc, D : Left side at 50 cm horizontal distance from the arc.

sampling duration ranged between 90 and 129 sec. In the first sampling for analyzing chemical contents (Table 2), the filter holder was placed at 50 cm height directly above the arc. From the starting poins, each welding fume was generated for 60 sec, and each welding fume sample was collected for 90 sec. In the later sampling (Tables 3 and 4), a welder welded for 90 sec and welding fume samples for measuring fume, chromium and nickel concentrations were collected for 120 sec at various collecting points as shown in Fig. 1. Three samples at each collecting point were obtained. The room temperature was 18 ± 5°C, relative humidity 55 ± 5%, and air movement 0.3 ± 0.1 m/sec in the opposite direction of welding.

Welding fume analysis. The welding fume concentrations were measured gravimetrically, by calculating the mass of the filter before and after sampling, expressing the results in milligrams per cubic meter. After welding fume samples collected on the filter were pretreated by the method shown in Fig. 2, they were analyzed by atomic absorption spectrophotometry (AAS) to determine the metal content: Cr, Mn, Si, Mo, Ca, Mg. All reagents used were G. R. quality from Nakarai Chemicals Ltd.. The AAS determinations were made with a Shimazu Model AA-640-01 Atomic Absorption Spectrophotomater with an air-acetylene flame according to manufacture's manual. The detection limit was 0.01 mg/m^3 in the air for chromium and 0.005mg/m^3 for nickel.

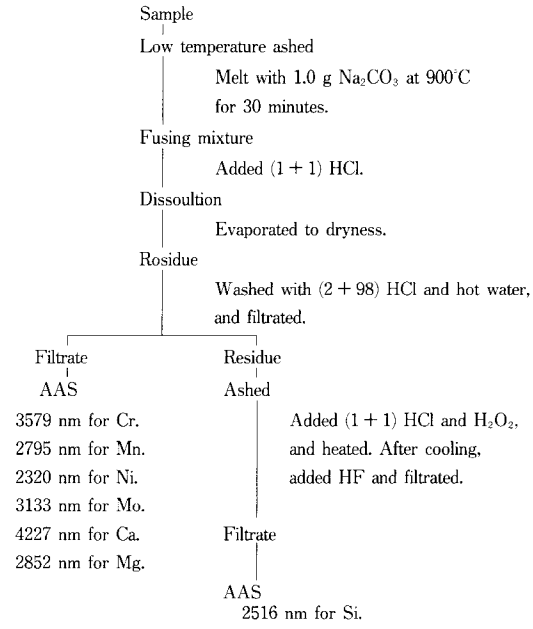

Fig. 2 Diagram of chemical analysis of welding fumes by the atomic Absorption Spectrophotometry (AAS).

Results

The chemical composition, excluding iron, of welding fumes collected at 50 cm height above the arc, is shown according to the welding process in Table 2. The remaining percent, from 70 to 80 % in each sample was iron. The following contents were high in the welding fumes: Cr, Mn,

and Ca in NI 9; Mn, Ca, and Mg in NIA 37 M ; Mg, Si, and Cr in NIC 50 ; Si and Mn in NF 10 & NF 196. Chromium and nickel, the principal metals of low temperature service steel, were 6.75 %, 0.77% for NI 9, 2.40 %, 0.19 % for NIA 37 M, 5.74 %, 0.26 % for NIC 50, respectively, in the welding fumes. The NF 196 wire did not contain chromium, and nickel showed 0.24 % in the WF 10 & NF 196 welding fumes.

Two electrodes, NI 9 in the MMA welding process and NF 10 & NF 196 in the SMA welding process, were used in order to see a three dimensional distribution of the fume, the chromium, and the nickel concentrations, and the chromium and nickel percentages, in welding fume samples. These results are shown in Table 3.

NI 9. Samples taken in a line directly above the arc showed high fume concentrations of 253.87 mg/m^3 at 50 cm height, 68.37 mg/m^3 at 150 cm height, and 64.53 mg/m^3 at 250 cm height. Chromium was detected in the fume samples collected at 50 cm, 150 cm, and 250 cm height straight above the arc and at 250 cm height at the front. The chromium concentrations in the fume samples collected straight above the arc were 12.57 mg/m^3 at 50 cm height, 3.07 mg/m^3 at 150 cm height, and 2.77 mg/m^3 at 250 cm height, but the chromium percentages were 4.96 % at 50 cm height, 4.59 % at 150 cm height, and 4.29 % at 250 cm height straight above the arc. Nickel was detected in all fume samples generated from NI 9 and they showed from 0.01 to 1.34 mg/m^3 nickel concentrations and from 0.15 to 0.54 % nickel contents.

NF 10 & NF 196. The fume samples collected straight above the arc had higher concentrations than at the other places, and were 118.23 mg/m^3 at 50 cm height, 12.77 mg/m^3 at 150 cm height and 6.60 mg/m^3 at 250 cm height. Nickel was not detected in the fume samples collected at 50 cm height at the back and the left side, but it was detected in the fume samples at the other collecting points. The fume samples generated from NF 10 & NF 196 were from 0.01 to 0.79 mg/m^3 nickel concentrations and from 0.19 to 1.99 % nickel contents.

When chromium and nickel were not detected in the fume samples, means and standard deviations of those reasurements were obtained by substituting 0.01mg/m^3 for the chromium concentration, 0.002 % for the chromium percent, 0.005 mg/m^3 for the nickel concentration, and 0.001 % for the nickel percent. These results were examined by the analysis of variance for the effects of the welding processes, places on the horizontal, and heights on the vertical, and were shown in Table 4.

Welding processes. The fume concentrations were 39.87 mg/m^3 for NI 9 (MMA) and 13.60 mg/m^3 for NF 10 & NF 196 (SMA). Therefore, the fume concentration from MMA was higher than SMA. Nickel concentrations were 0.15 mg/m^3 for MMA and 0.11 mg/m^3 for SMA, and no statistically significant difference between the former and the latter was found. However, nickel percent was 0.23 % for MMA and 0.90 % for SMA, and a statistically significant difference between the former and the latter was found.

Places on the horizontal. The fume concentration straight above the arc showed 87.39 mg/m^3 and was significantly larger than the other places at the 0.1 % level. Chromium concentration and percentage straight above the arc were also significantly larger than at the other places. The nickel concentration straight above the arc was significantly larger than at the other places, but the nickel percent did not show a statistically significant difference among places.

Heights on the vertical. The fume concentration at 50 cm height showed 51.83 mg/m^3 and was significantly larger than at 150 cm and 250 cm height. Chromium concentration and percentage did not differ significantly among the fume samples collected at various heights. Nickel concentrations were 0.28 mg/m^3 at 50 cm height, 0.06 mg/m^3 at 150 cm height, and 0.05 mg/m^3 at 250 cm height, and significant differences among them were not found. Nickel percentages were 0.21 % in the fume samples collected at 50 cm height, 0.68 % at 150 cm height, and 0.81 % at

250 cm height. The greater the height the larger the nickel percentage in the fume samples.

Discussion

Effects of the High Volume Sampler on the Welding Arc and the Distribution of Welding Fumes

We could not avoid using a high volume sampler in order to collect a large enough fume sample for chemical analysis. We were apprehensive that strong air flow while collecting the fume samples might affect both the welding arc and the three dimensional distribution of welding fumes. The velocity at any poins in front (distance X) of the filter was calculated easily using the following equation (25):

$$Q = 60\ V\ (10\ X^2 + A),$$

where Q = air flow (= 1.055 m^3/min), V = velocity at point X (m/sec), X = centerline distance (= 0.5 m), A = area of the filter (= $0.253 \times 0.203\ m^3$)

Velocity obtained at a distance of 0.5 m was 0.69 cm/sec. Therefore, it is assumed that the air flow during the collection of fume samples, 1.055 m^3/min, did not affect either the welding arc or the three dimensional distribution of fumes at a distance of 0.5 m from the filter.

Effects of Factors on Measurements

Core wires of the electrode and welding wires for low temperature service steel excluding iron contain a large amount of chromium and nickel. However, chromium and nickel were not rich in the welding fumes. Close agreement of the chromium and the nickel percentage between the welding fumes and the core wire was not obtained. And linear relation between the welding fumes and the core wires were not found. Furthermore, the relations between fume concentrations and percentages of chromium and nickel in the welding fumes were not linear, and they showed great variability at the collecting point.

Fume concentration. The fume concentration differs with welding process. Because MMA welding generates more welding fume than SMA, the MMA welding fume concentrations are significantly higher than the SMA welding fume concentrations. These finings concur with Kalliomäki *et al.* (6). The highest fume concentration was shown in the fume samples collected straight above the arc. The fumes dispersed evenly on all sides from the line straight above the arc. The fume concentration on the vertical was highest at 50 cm height and reduced by half at 150 cm height. The fume concentration at 250 cm height was scarcely different from that at 150 cm height. For this reason it is presumed that the temperature of an updraft which rises from the welding arc noticeably decreases between 50 cm and 150 cm height, and that most of the low specific gravity components in the fume float in the air.

Chromium. It has been reported that the chromium percentage in the welding fumes is dependent on the welding process, and that the chromium percentage in the MMA welding fumes is higher than in tungsten inert gas (TIG) and metal inert gas (MIG) welding fumes (6, 18). In this study, however, the chromium in the MMA welding fumes is not compared with the SMA welding fumes (NF 10 & NF 196), which do not contain chromium. Chromic oxide (Cr_2O_3) formed by heating chromium in the air reacts to potassium (K) and sodium (Na) scattered from the arc (26), and then produces K_2CrO_4 and Na_2CrO_4. Kimura *et al.* showed that 60 to 90 % of chromium in the welding fumes was hexavalent chromium, and that the alkaline content of the covering greatly affected the formation of hexavalent chromium and when the alkaline content ($K_2O + Na_2O$) in the covering was less than 1 %, hexavalent chromium in the welding fumes was greatly reduced (22). When the alkaline content in the covering is small, Cr_2O_3 will easily form spinel type compounds with metal oxide such MgO, FeO, NiO, MnO and form solid solutions with magnetite (Fe_3O_4). It is estimated that chromium is hard to scatter on the horizontal

and flows straight above the arc on the updraft, since the molecular weight of the spinel type compounds and the solid solution becomes greater than that of Cr_2O_3. Therefore, chromium can be measured in the fume samples collected straight above the arc, but it may not detectable at other places (C and D). The specific gravity of Cr_2O_3 is 5.21, which is nearly equal to 5.20, the specific gravity of Fe_3O_4(27), the largest component (28). It is estimated that the scattering pattern of chromium is analogous to Fe_3O_4. Chromium concentration on the horizontal consequently have a similar distribution to the fume concentrations. Also, chromium contents in the fume samples at each height are quite similar to each other.

Nickel. Nickel heated in the air changes to nickel monoxide (NiO) at 600°C and nickel trioxide (Ni_2O_3) at 400°C (27). Furthermore, nickel changes to nickel trioxide by reaction with ozone (O_3) which is generated during arc welding. It is reported that nickel trioxide is produced in metallurgical slags (4). Judging from these findings, most of the nickel in the welding fumes is estimated to change to nickel trioxide. The nickel concentration is not significantly different between the welding processes, but the nickel percentages in the SMA welding fumes are statistically higher than in the MMA welding fumes. The nickel concentration is high strainght above the arc (A), and the nickel percentage shows no statistically significant difference from other places (B, C, and D). For this reason, nickel trioxide disperses evenly on all sides because of its lower molecular weight than magnetite (Fe_3O_4). Vertically the highest nickel concentration shows in the fume samples collected at 50 cm height. Since the specific gravity of nickel trioxide is 4.83, less than the specific gravity of magnetite 5.20 (27), the greater the height the larger the nickel percentage in the fumes. Therefore, workers who work at higher worklocations than the welding arc are exposed to excessive nickel in the fume concentration, and it is dangerouse as well as for workers at lower levels.

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