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Laboratory Evaluation of Welder's Exposure and Efficiency of Air Duct Ventilation for Welding Work in a Confined Space

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Abstract: CO_2 arc welding in a confined space was simulated in a laboratory by manipulating a welding robot which worked in a small chamber to experimentally evaluate the welder's exposure to welding fumes, ozone and carbon monoxide (CO). The effects of the welding arc on the air temperature rise and oxygen (O_2) concentration in the chamber were also investigated. The measuring points for these items were located in the presumed breathing zone of a welder in a confined space. The time averaged concentrations of welding fumes, ozone and CO during the arcing time were 83.55 mg/m^3, 0.203 ppm and 0.006%, respectively, at a welding current of 120A–200A. These results suggest serious exposure of a welder who operates in a confined space. Air temperature in the chamber rose remarkably due to the arc heat and the increase in the welding current. No clear decrease in the O_2 concentration in the chamber was recognized during this welding operation. A model of air duct ventilation was constructed in the small chamber to investigate the strategy of effective ventilation for hazardous welding contaminants in a confined space. With this model we examined ventilation efficiency with a flow rate of 1.08–1.80 m^3/min (ventilation rate for 0.40–0.67 air exchanges per minute) in the chamber, and proved that the exposure level was not drastically reduced during arcing time by this air duct ventilation, but the residual contaminants were rapidly exhausted after the welding operation.

Key words: Welding, Confined space, Fumes, Ozone, Air duct ventilation

Introduction

CO_2 arc welding has been used extensively in various manufacturing industries, including shipyards, automobile factories, machines, bridge building and other construction, because CO_2 arc welding is suitable for joining impure mild steels. Although CO_2 arc welding has the advantage of a cheap shielding gas compared with the argon gas used in metal inert gas shielded arc welding (MIG welding), it generates several airborne contaminants such as welding fumes, ozone and carbon monoxide (CO) from the arc and pollutes working environment air.

It is known that such contaminants cause some respiratory illnesses of which pneumoconiosis has been one of the most serious occupational diseases in Japan[1, 2] and welder's lung caused by inhalation of the welding fumes, mainly composed of iron oxide[3–5], is now the most frequent form of pneumoconiosis in Japan.

In the welding shops in shipyards and in the bridge building industry, many structural components, such as box girders, are manufactured and assembled. Most of the welding processes are carried out inside the structural components having in confined spaces where the welding work area is surrounded on most sides by walls and there is insufficient space for the installation of a conventional exhaust hood. It is difficult to control contaminants from structural components

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efficiently with an ordinary local ventilating system[6], and to supply enough fresh air to the welder because general ventilation system[7] is not suitable for such a confined space. It is supposed that exposure to the contaminants is very serious for welders who operate in confined spaces. In addition, the possibility of heat stroke and anoxia caused by CO_2 impregnation and oxygen (O_2) consumption due to structural metal oxidation in a confined space is also worrying[8, 9].

In this study the authors set out to estimate an actual welder's exposure in a confined space by using a welding robot which works in a chamber. We then examined the applicability of air duct ventilation designed for this chamber. Because of its compactness, air duct ventilation has been commonly used for contaminant control in enclosed spaces, such as tunnels or galleries where an ordinary local ventilation system cannot be used.

Materials and Methods

Actual CO_2 arc welding work was simulated by robotic welding which permitted arbitrary operations with sufficient repeatability and precision. The cubic chamber was made to envelope the welding robot and a base metal of welding material, and was assumed to be the confined space for welding work. The efficiency of air duct ventilation was evaluated by monitoring the concentrations of welding fumes, ozone and CO in the chamber. In addition, air temperature and the O_2 concentration in the chamber during and after welding were measured in order to estimate the welder's thermal condition and the oxygen deficiency to be worried about in welding work.

Figure 1 shows a schematic diagram of the experimental system for the present study. The cubic chamber was 1.4 m × 1.4 m × 1.4 m (capacity of 2.7 m^3) in size. This chamber was composed of a grounded steel workbench and an aluminum enclosure (⑤). Inside the chamber, CO_2 arc welding was done with a welding robot which consisted of a manipulator (③), a controller (②) and a power supplier (①) of AC 200/220 V rated voltage (ARCMAN-RON, KOBE STEEL, LTD., Japan). The base metal of 270 mm × 270 mm × 12 mm in size (④), rolled steel for general structure of JIS G3101 SS400 rating, was placed on the center of the workbench. Bead on-plate welding in the horizontal position was done on it.

Arcing time, welding speed and CO_2 shielding gas flow rate were set at 6 minutes, 30 cm/min and 20 *l*/min, respectively. The welding consumable was solid wire (JIS 3312) 1.2 mm in diameter. The wire extension and the torch angle were kept at 15 mm and 0°, respectively.

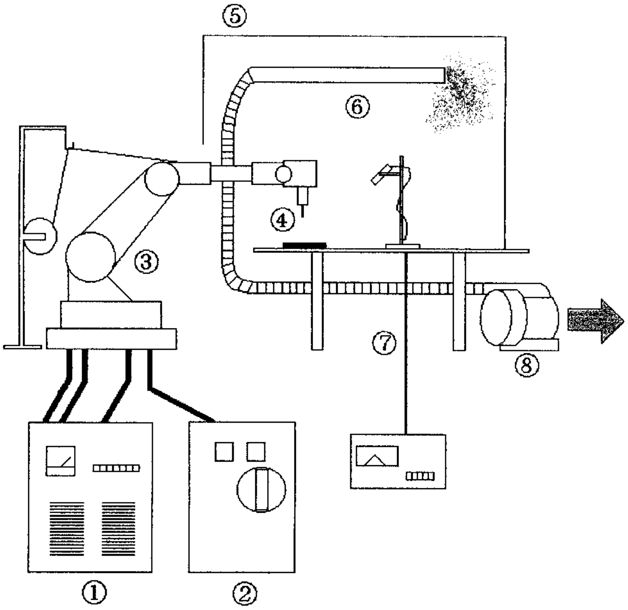

Fig. 1. Schematic diagram of the experimental apparatus.
① welding power source, ② control panel, ③ manipulator, ④ base metal, ⑤ enclosure of the chamber, ⑥ air duct, ⑦ contaminants monitor and thermometer, ⑧ blower.

The measuring positions for airborne fumes, ozone, CO, O_2 concentrations and air temperature in the chamber were located near the presumed breathing zone of the welder, at a point 60 cm above the base metal.

The fume concentration was measured with a portable laser dust monitor (DUSTMATE Model LD-1, SIBATA SCIENTIFIC TECHNOLOGY LTD., Japan) and a low-volume air sampler at a flow rate of 20 *l*/min fitted with a multi-stage particle size classifier. This air sampler has permeation characteristics conforming to the governmental regulation for "Standard for the Measurement of Working Environment 2-2".

The ozone concentration was measured with a toxic gas monitor to detect the ozone absorption of emitted UV-rays (Model EG-2001F, EBARA CO. LTD., Japan).

The CO concentration was measured with a potentiostatic electrolysis gas monitor (Model CO-85FL, RIKEN KEIKI CO. LTD., Japan).

The O_2 concentration and the air temperature in the chamber were measured with a portable oxygen alarm (Model OX51, YOKOGAWA CO. LTD., Japan) and an anemometer equipped with a thermistor thermometer (Model ISA-6-3P, SIBATA SCIENTIFIC TECHNOLOGY LTD., Japan), respectively.

The concentrations of airborne contaminants and the air temperature in the chamber during and after welding were monitored for 30 minutes in each case. The first 6 minutes was arcing time in which welding was carried out, and the next 24 minutes was an arc OFF period.

In this study, contaminant control by mean of air duct ventilation was also examined. A straight polyvinyl chloride air duct[10] 90 cm long and with a 41 mm inside diameter (⑥ in Fig. 1) was installed horizontally in the upper part of the chamber. The distance between the air duct and the top of the workbench was 85 cm. This air duct was connected to a blower with a 500/750 W output (⑧, RING BLOW type VFC406P, FUJI ELECTRIC CO. LTD., Japan) by a polyvinyl chloride flexible duct of about 200 cm in length and with a 41 mm inside diameter.

The air duct was ventilated at a flow rate of 1.08 m^3/min–1.80 m^3/min, i.e., a ventilation rate of 0.40–0.67 air changes per minute. This flow rate range employed was limited by the performance of the blower which was available for this study. The flow rate could be altered by adjusting the voltage applied to the blower. The efficiency of ventilation was evaluated from the decrease in the level of airborne contaminants in the chamber. The concentrations of contaminants were expressed as time averaged values in the three different stages.

Results

Estimation of welder's exposure in a confined space

Table 1 shows the O_2 monitoring results. The O_2 concentrations during and after welding in the chamber were expressed as time averaged values for 30 minutes in the three stages. The first stage (0–6 min) is a 6 minutes arcing time. The second stage (6–30 min) is an arc OFF period for the next 24 minutes. The 0–30 min stage corresponds to the entire monitoring time. As shown in Table 1, the O_2 concentrations did not change from about 21% during and after welding at any welding current. Shielding gas impregnation of the chamber in the 6 minute arcing was not seen in this experiment, but repetition of the welding was still thought to cause the CO_2 accumulation and impregnation of the chamber. Welding was then repeated seven times with minimum intervals at a welding current of 200 A, and it was found that the O_2 concentration in the chamber decreased from 20.9% to 18.9%.

Table 1. The time averaged O_2 concentration during and after welding operation

Welding current (A)	Average O_2 concentration (%)		
	0–6 min	6–30 min	0–30 min
120	20.84	20.92	20.90
160	20.92	20.99	20.97
200	21.02	21.11	21.09
260	20.39	20.10	20.16
300	21.25	21.22	21.23

Air temperature in the chamber was monitored for a corresponding period of 30 minutes at different welding currents of 120 A, 160 A, 200 A, 260 A and 300 A. As shown in Fig. 2A, the air temperature rose immediately after the arc was ignited and reached the maximum in about 8 minutes. The decrease in air temperature was relatively slow. The degree of air temperature rise increased with the increase of welding current. The maximum air temperature rise was 14°C at a welding current of 300 A.

The concentrations of welding fumes, ozone and CO in the chamber were also monitored for the period of 30 minutes at different welding currents of 120 A, 160 A, 200 A, 260 A and 300 A. Figure 2B shows the welding fume concentrations during and after welding operation. The maximum instantaneous concentration of approximately 290 mg/m^3 was found in the first 30 seconds after the arc was ignited with a welding current of 120 A. The maximum average concentration for the 6 minute welding operation was 83.55 mg/m^3 at the same welding current. No clear correlation between fume generation and the welding current was found. Although the fume concentration was reduced rapidly after the arc was put out, it was more than 9 mg/m^3 for the next 24 minutes. The time averaged concentration during the entire monitoring time (stage 0–30 min) at a welding current of 120 A was 24.15 mg/m^3.

Figure 2C shows the results of ozone monitoring during and after welding. The generation of ozone was also remarkable at the beginning of each welding operation. The maximum instantaneous concentration of 0.4 ppm was found in the first 30 seconds after the arc was ignited with a welding current of 200 A. The maximum average concentration during the arcing time of 6 minutes was 0.203 ppm at the same welding current. Within 2–9 minutes after the arc was put out, ozone in the chamber had almost dissipated to an undetectable concentration. The average concentration during the next 24 minutes and entire monitoring time at a welding current of 200 A were 0.005 ppm and 0.036 ppm, respectively.

Figure 2D shows the results of CO monitoring in the chamber. The maximum instantaneous concentration of 0.013% (130 ppm) was also found in the first 30 seconds

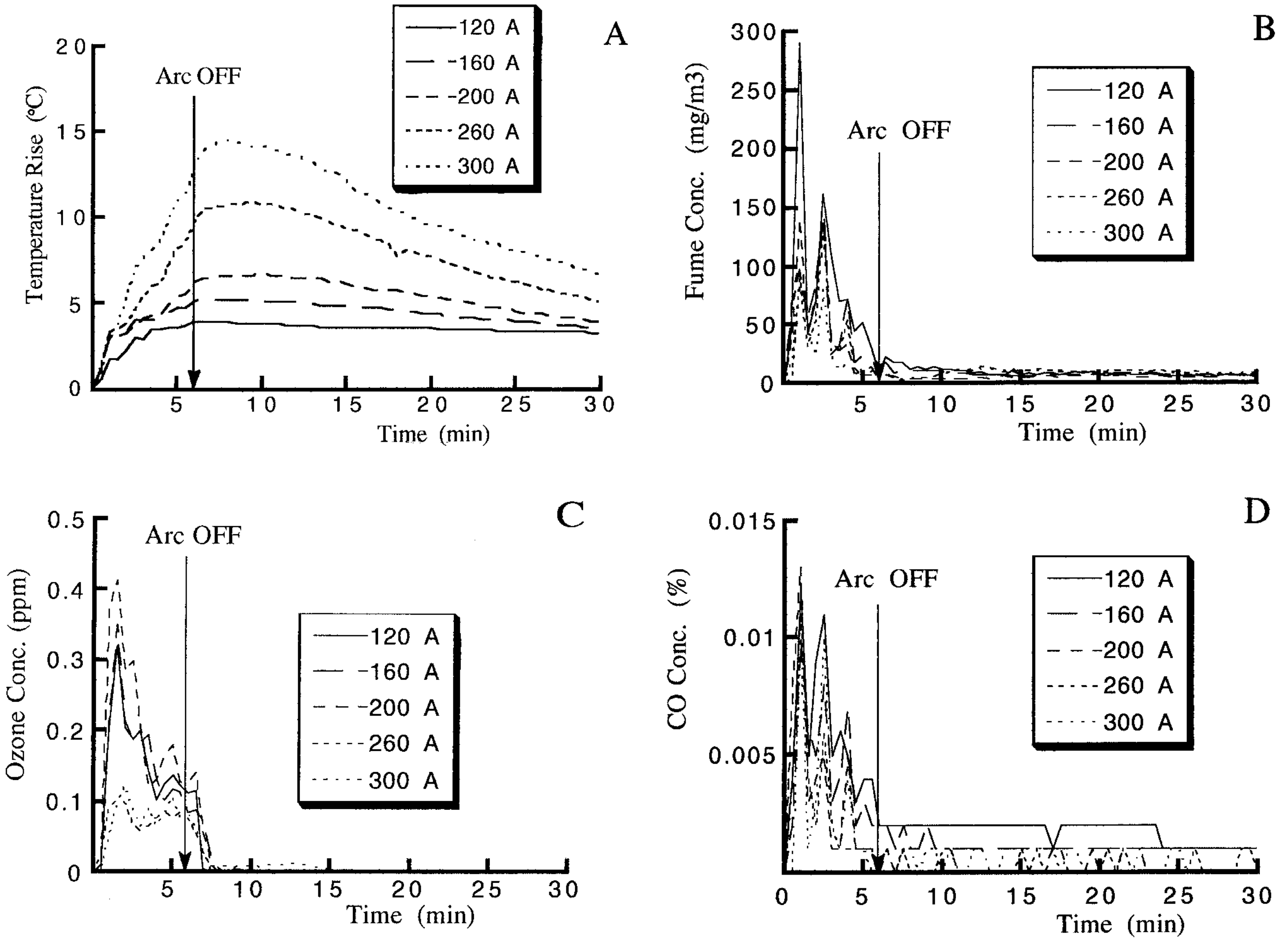

Fig. 2. Emission of airborne contaminants and temperature rise due to the welding operation in the chamber without air duct ventilation. A: Air temperature, B: Welding fume, C: Ozone, D: CO.

after the arc was ignited at a welding current of 200 A. The maximum average concentration during arcing was 0.006% at a welding current of 120 A. No clear correlation between CO generation and the welding current was found. The CO concentration during the arc OFF period was reduced to a level below the Occupational Exposure Limit value of Japan (50 ppm)[11] and the ACGIH TLV-TWA (25 ppm)[12] at any welding current. The average concentration during the next 24 minutes and the entire monitoring time at a welding current of 120 A were 0.002% and 0.003%, respectively.

Efficiency of air duct ventilation for exhausting contaminants in the chamber

We tried to evaluate the efficiency of air duct ventilation by monitoring the concentrations of welding fumes, ozone and CO for 30 minutes in the chamber when ventilation was on and off. In the monitoring time, arcing time was the first 6 minutes, and the arc OFF period was the next 24 minutes. Welding was carried out under the same welding condition as in the previous section of this article.

The exhaustion flow rates for the air duct ventilation were 1.08, 1.71, 1.77 and 1.80 m^3/min which correspond to ventilation rates of 0.40, 0.63, 0.65 and 0.67 air changes per minute, respectively.

As shown in Table 2, the air duct ventilation was not effective for fume exhaustion during arcing since the concentration during the first 6 minutes still exceeded 55 mg/m^3 at any flow rate, and no remarkable decrease in the concentration was seen. On the other hand, by means of air duct ventilation, most residual fumes in the chamber were considerably removed, so that the concentration during the arc OFF period was reduced to 3.67–4.20 mg/m^3 which was below the ACGIH TLV-TWA of welding fumes (5 mg/m^3)[12]. The average concentration throughout the monitoring time

Table 2. The efficiency of air duct ventilation for contaminants exhaustion

Stage	Arc	Ventilation flow rate (m^3/min)	Ventilation rate (air exchanges/min)	Fume conc. (mg/m^3)*	Ozone conc. (ppm)*	CO conc. (%)*
0–6 min	ON	1.08	0.40	58.35	0.284	0.005
6–30 min	OFF			3.67	0.005	0.000
0–30 min	ON → OFF			14.61	0.061	0.001
0–6 min	ON	1.71	0.63	58.95	0.206	0.004
6–30 min	OFF			4.09	0.004	0.000
0–30 min	ON → OFF			15.06	0.045	0.001
0–6 min	ON	1.77	0.65	56.85	0.141	0.004
6–30 min	OFF			4.18	0.004	0.000
0–30 min	ON → OFF			14.71	0.031	0.001
0–6 min	ON	1.80	0.67	55.65	0.095	0.004
6–30 min	OFF			4.20	0.003	0.000
0–30 min	ON → OFF			14.49	0.021	0.001

*Time averaged concentration for each stage.

(stage 0–30 min) was reduced to approximately 15 mg/m^3 (about 63% of the level without ventilation) by the ventilation.

No clear decrease in the ozone concentration caused by the ventilation was observed with an exhaust flow rate of $\leqq$ 1.71 m^3/min. Ozone in the chamber was successfully removed by ventilation at a 1.80 m^3/min flow rate. During the welding operation, ventilation at a 1.80 m^3/min flow rate was able to decrease the ozone concentration to 0.095 ppm (46.8% of the level without ventilation) which was barely below the Occupational Exposure Limit of Japan (0.1 ppm)[11]. The ozone concentration was reduced to an undetectable level with and without the ventilation within 3 minutes after the arc was put out. The average concentrations throughout the monitoring time could be reduced to the level of 58% by the ventilation.

On CO exhaustion, over the flow rate range in this experiment, no remarkable decrease in the concentration during the arcing time was found, but the residual CO concentration during the arc OFF period was reduced to a negligible figure by the ventilation. The average concentration throughout the monitoring time was reduced to a level of approximately 30% by the ventilation at a 1.80 m^3/min flow rate, which was below the ACGIH TLV-TWA (25 ppm).

Discussion

Impregnation with choke damp such as CO_2 in a confined space can often cause oxygen deficiency. In Japan, CO_2 for industrial use is mainly consumed in arc welding and mold casting. It is known that subjective symptoms of anoxia develop with an O_2 concentration of <16%, and the Industrial Safety and Health Law of Japan[8] requires employers to take measures for the prevention of welder's anoxia. We did a model experiment to examine the problem of oxygen deficiency when welding in a confined space, but failed to find an obvious decrease in the O_2 concentration during welding for 6 minutes. This might be due to the fact that the volume of CO_2 which was released during arcing was much smaller than the chamber capacity. In the case of this study, the CO_2 volume released during one welding operation corresponds to approximately 4% of the chamber capacity, ignoring thermal expansion but repetition of the welding operation might in some case causes accumulation and impregnation with CO_2 in a confined space, and the possibility of the occurrence of anoxia could not be entirely ruled out. In this study, the O_2 concentration in a small chamber decreased to 18.9% after successive welding operations for 42 minutes, and this was barely above the level required by the Ordinance on Prevention of Anoxia in Japan (18%). The degree of CO_2 impregnation should be affected by the chamber capacity and the shielding gas flow rate. To further study the oxygen deficiency problem in welding, it would be necessary to examine other examples of confined spaces and welding conditions.

A high temperature arc ought to be an enormous heat source in a confined space, and heat exhausting by a natural draft is scarcely possible in such a space. In the present study, a maximum air temperature rising of 14°C due to one welding operation in the chamber was confirmed experimentally. Repetition of the welding operation may increase the air temperature even further, and the amount of welder's heat stress can be imagined. According to the Ordinance on Industrial Safety and Health of Japan (chapter 5, article 607), air temperature, humidity and radiation heat in an indoor workshop should be measured in order to evaluate worker's heat stress precisely. As the amount of heat in a welding shop is not yet regulated legally in Japan, further studies will be necessary for the determination of welder's heat stress.

The results of contaminant monitoring in the present study suggest serious exposure of the welder in a confined space. The maximum instantaneous concentration of welding fumes exceeded 100–200 mg/m^3, and the welder's fume exposure during arcing time was found to be more than 10–20 times the ACGIH TLV-TWA in this study, but it seemed difficult to greatly reduce the exposure level by means of air duct ventilation in this experiment. The reason would be that the breathing zone of a welder is usually close to an arc point and ordinary welding work is carried out outside the effective capture zone of the air duct. The Japan Welding Engineering Society recommends that air velocity should be controlled to 0.3–0.5 m/sec at an arc point as the capture velocity for fume control[13)]. It would be almost impossible to reach this capture velocity at an arc point by air duct ventilation in normal use since this ventilation is inadequate for high volume exhausting.

Despite the insufficient ventilation during welding, as mentioned above, air duct ventilation effectively exhausted residual contaminants in a longer period after welding in a confined space. Welding generally involves other processes, such as grinding, gouging, torch-cutting and deburring which follow welding and are completed within the arc OFF period. An ordinary work cycle of a welder consists of welding and these various other processes. Contaminants once emitted in a confined space, where a sufficient air supply and exhaustion are ordinarily unavailable, would be hard to eliminate effectively by natural draft. As to this problem, it was proved by the present study that removal of airborne contaminants from the chamber was successfully achieved by air duct ventilation after the arc was put out, and average exposure during the entire work cycle of a welder should be reduced to some extent by air duct ventilation.

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