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Original Article

Hazard of ultraviolet radiation emitted in gas tungsten arc welding of aluminum alloys

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Abstract: Ultraviolet radiation (UVR) emitted during arc welding frequently causes keratoconjunctivitis and erythema. The extent of the hazard of UVR varies depending on the welding method and conditions. Therefore, it is important to identify the levels of UVR that are present under various conditions. In this study, we experimentally evaluated the hazard of UVR emitted in gas tungsten arc welding (GTAW) of aluminum alloys. The degree of hazard of UVR is measured by the effective irradiance defined in the American Conference of Governmental Industrial Hygienists guidelines. The effective irradiances measured in this study are in the range 0.10–0.91 mW/cm^2 at a distance of 500 mm from the welding arc. The maximum allowable exposure times corresponding to these levels are only 3.3–33 s/day. This demonstrates that unprotected exposure to UVR emitted by GTAW of aluminum alloys is quite hazardous in practice. In addition, we found the following properties of the hazard of UVR. (1) It is more hazardous at higher welding currents than at lower welding currents. (2) It is more hazardous when magnesium is included in the welding materials than when it is not. (3) The hazard depends on the direction of emission from the arc.

Key words: Hazard, Ultraviolet radiation, Effective irradiance, Gas metal arc welding, Aluminum alloy

Introduction

The light emitted in arc welding contains strong ultraviolet radiation (UVR). In the absence of a barrier, this radiation is emitted into the surrounding environment, ensuring that extremely large numbers of workers at workplaces where arc welding is performed are exposed to UVR. This includes not only expert arc-welding professionals—whose numbers are estimated at some 350,000 in Japan—but also welders who do not specialize in arc welding but perform it occasionally, as well as workers engaged in tasks other than arc welding[1)]. UVR consists of electromagnetic waves with wavelengths in the range from approximately 1 to 400 nm[2)]. However, a precise border between ultraviolet radiation and visible light cannot be defined, because visual sensation at wavelengths shorter than 400 nm is noted for very bright sources. The borders necessarily vary with the application[3)]. Although UVR is not visible to the human eye, its physical properties are similar to those of visible light. The International Commission on Illumination has subdivided UVR into three wavelength regimes: UV-A (wavelengths in the range 315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm)[3)]. Focusing our attention on the interaction of UVR with the human eye, one finds that UV-C is absorbed by the cornea and does not reach the interior of the eye. UV-B and UV-A are absorbed mostly by the

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cornea and the lens, and only trace amounts (<1%) reach the retina. The portion of the UV spectrum consisting of wavelengths below approximately 190 nm is known as vacuum UVR; because this radiation is strongly absorbed by oxygen molecules, it is not transmitted through air. Because humans are thus not exposed to vacuum UVR—except in extremely rare circumstances—there is little cause for concern regarding its hazard.

UVR interacts strongly with living organisms and is known to cause a variety of problems4, 5). Moreover, UVR is strongly absorbed by proteins and by water; thus, when UVR is incident on a living organism, the majority of the radiation is absorbed at the surface. Thus, damage to living organisms due to UVR is confined to surface regions; well-known examples of acute health effects include keratoconjunctivitis and erythema, while delayed health effects include cataracts and skin cancer. In practice, acute health effects due to UVR occur frequently at workplaces where arc welding is performed1, 6). The Japan Welding Engineering Society surveyed incidences of UV keratoconjunctivitis among workers at workplaces involving arc welding—including both workers who performed arc welding and workers who did not1). The results of the survey indicated that as many as 86% of workers reported past experience with UV keratoconjunctivitis, while 45% reported ongoing experience with this ailment, with one or more recurrences per month. Moreover, the majority of arc welders experienced UV keratoconjunctivitis despite wearing welding face shields. Possible causes for this include (a) cases in which workers fail to put on their face shields before striking the arc, ensuring exposure to UVR; and (b) cases in which workers are exposed to UVR by other workers performing arc welding at the same workplaces. Therefore, these findings demonstrate the need to introduce protective measures at workplaces involving arc welding to protect workers from UVR. As a basis for designing such measures, it would be desirable to acquire a quantitative understanding of the hazard of UVR emitted during arc welding.

The intensity of the UVR emitted during arc welding may be expected to vary depending on the welding conditions. In particular, it is said that workers experience greater degrees of sunburn (erythema) during the arc welding of aluminum alloys than in the arc welding of steel materials, suggesting that the intensity of UVR is greater in this case.

Aluminum and its alloys exhibit excellent properties—including light-weight, high strength-to-weight ratio, corrosion resistance, workability, and appearance—and are widely used as raw materials for structural products and components in a wide variety of fields, including railway vehicles, automobiles, ships, aerospace instruments, and chemical instruments. Arc welding is used extensively in portions of the production processes for these aluminum products. The two primary welding methods for aluminum alloys are gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). GMAW is a semi-automatic process in which the wire is supplied automatically; in this case the shielding gas is taken to be an inert gas, such as argon, helium, or a mixture of these gases. GTAW is a welding method involving a non-consumable tungsten electrode; in this method, a filler rod is inserted into a molten pool, and an inert gas is used as the shielding gas. GMAW is primarily used for base metals of thickness 3 mm or greater, while GTAW is used for beams of lesser thickness.

Several previous studies have measured the UVR emitted during arc welding of aluminum alloys and assessed its hazard with respect to acute health effects5, 7–10). The measurements made by these studies involved only a small, restricted set of welding conditions and measurement positions. However, the arc welding that takes place at actual workplaces occurs under a variety of welding conditions, and the situations in which workers are exposed to the resulting UVR are highly varied as well. In recognition of these realities at workplaces, it is important to investigate the hazard of the UVR emitted by arc welding of aluminum alloys under a wide range of conditions.

In previous work, the authors studied GMAW of aluminum alloys. Experiments involving the GMAW of aluminum alloys were conducted; the resulting UVR was measured and its hazard with respect to acute health effects was assessed11) in accordance with American Conference of Governmental Industrial Hygienists (ACGIH) guidelines12). The results of these studies confirmed that UVR is highly hazardous, with the degree of its hazard depending on the welding current, the combination of base metals and welding wire, and the direction in which UVR is emitted from the arc.

In the present work, we conducted investigation of the hazard of UVR emitted during GTAW of aluminum alloys. In particular, we studied the impact of (i) the type of base metal, the type of filler rod, and the magnitude of the welding current, (ii) the direction in which UVR is emitted from the arc, and (iii) the type of electrode.

Methods

According to the ACGIH guidelines12), the degree of hazard of UVR as a cause of acute health effects is measured by the effective irradiance. The effective irradiance is defined by equation (1):

$$E_{eff} = \sum_{180}^{400} E_{\lambda} \cdot S(\lambda) \cdot \Delta\lambda \quad \text{..................(1)}$$

In this equation, E_{eff} is the effective irradiance (units of W/cm^2), E_λ is the spectral irradiance at wavelength λ (units of W/(cm^2·nm)), S (λ) is the relative spectral effectiveness at wavelength λ, and Δλ is the wavelength bandwidth (units of nm).

For measurements of UVR, we used the X1$_3$ Hazard Lightmeter and a XD-45-HUV UV-Hazard Detector Head (both from Gigahertz-Optik). These measurement apparatuses were designed for measuring the effective irradiance. As shown in Fig. 1[13)], the relative spectral responsivity of the detector head agrees well with the relative spectral effectiveness around 270 nm. Some discrepancy between the relative spectral responsivity and the relative spectral effectiveness is visible from 310 to 320 nm; however, because the relative spectral effectiveness in this wavelength regime is small (0.015–0.0010), we expect the impact of this discrepancy to be small and believe it to cause no difficulties in practice. Thus, we conclude that this detector head is well-suited to measurements of effective irradiance. In actual experiments, the measured value displayed by the apparatus is the effective radiant exposure (units of J/m^2). Dividing this value by the measurement time yields the effective irradiance. The measurement apparatus was calibrated by the manufacturer and was used within the one-year interval of validity of this calibration.

The position of the welding torch was fixed to produce the arc in the same position, and the base metal was affixed to a movable table, allowing it to be subject to direct motion to enable the welding. The distance between the arc and the detector head was set to 500 mm to mimic actual distances to welders. The measurement time was set to 40 s. To exclude the time required for the arc to stabilize immediately after welding begins and the time required for the movable table to accelerate, measurements did not begin until 5 s after the start of welding.

In this study, no local exhaust ventilation system was used during measurement of UVR, because local exhaust ventilation is usually not used in the welding workplace. Local exhaust ventilation may disturb the airflow around the arc, and cause welding defects.

Measurements were repeated three times for each set of conditions and averaged to yield measured results. Furthermore, following ACGIH guidelines, we divided 3 mJ/cm^2 by our measured values of the effective irradiance to determine the maximum daily exposure time allowable at that irradiance [equation (2)].

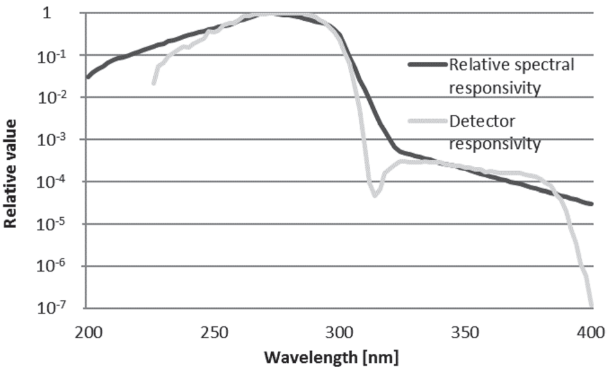

Fig. 1. Relative spectral responsivity of the hazard lightmeter and ACGIH relative spectral effectiveness.

Table 1. Welding conditions

Welding current, A	100	200
Welding speed (mm/min)	200	200
Size of base metal (mm)	2×300×75	5×300×75
Electrode diameter (mm)	2.4	3.2
Electrode extension (mm)	4	6
Filler rod diameter (mm)	2.4	4.0
Arc length (mm)	4	4
Nozzle diameter (mm)	16.1	17.2
Shield gas flow rate (l/min)	7	8

$$t_{max} = \frac{0.003\ J/cm^2}{E_{eff}} \quad \text{..................(2)}$$

In this equation, t_{max} is the maximum daily exposure time (units of s) and E_{eff} is the effective irradiance (units of W/cm^2).

The welding apparatus was a digital inverter-type pulsed arc welding machine (DA300P, Daihen Welding and Mechatronics Systems Co., Ltd.), a machine that has been used with increasing frequency in recent years. The inclination of the welding torch was fixed at 70°. Using flat position forehand welding, two types of welding were performed: bead-on-plate welding (in which the base metal is melted while a filler rod is added) and melt-run welding (in which only the base metal is melted and no filler rod is used). Pure argon was used as the shielding gas. Other conditions were chosen to match typical welding conditions at actual workplaces[14, 15)]. The primary welding conditions at welding currents of 100 and 200A are presented in Table 1.

Table 2. Chemical compositions of base metals (mass %)

Base metal (JIS designation)	Thickness (mm)	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Al
A1050P-H24	2	0.08	0.32	0.02	0.01	0.00		0.01	0.02	0.01	>99.50
	5	0.07	0.34	0.02	0.00	0.00		0.01	0.03	0.01	>99.50
A5083P-O	2	0.15	0.23	0.03	0.66	4.59	0.11	0.01	0.02		re
	5	0.15	0.30	0.04	0.58	4.35	0.11	0.02	0.02		re
A6061P-T6	2	0.61	0.43	0.28	0.02	1.01	0.23	0.01	0.05		re
	5	0.62	0.43	0.29	0.02	1.02	0.11	0.01	0.04		re

re: remainder

Impact of the type of base metal, the type of filler rod, and the magnitude of the welding current

To investigate the impact of the choice of base metal, we conducted melt-run welding—and measured the resulting UVR—using three base metals specified by the Japanese Industrial Standards (JIS): A1050P-H24, A5083P-O, and A6061P-T6[16]. Table 2 presents the composition of these base metals as specified by JIS. A1050P-H24 is essentially pure aluminum, while A5083P-O is an alloy including 4–5% magnesium and A6061P-T6 is an alloy including 1% magnesium as well as additional elements other than magnesium. Pure tungsten was used for the electrode. Welding was performed at a welding current of 200A. The detector head was positioned at an angle of 40° from the surface of the base metal and at an angle of 90° from the welding direction. In addition to the effective irradiance, we also measured the spectral irradiance of the UVR. The measurement apparatus was a multichannel spectrometer (HSU-100S, Asahi Spectra Co., Ltd.). The wavelength precision of the apparatus was ±1.2 nm. The distance from the arc was set to 2,600 mm, and the measurement time was set in the range of 130–235 ms by the automated adjustment functionality of the measurement apparatus. Figure 2 shows a schematic diagram of our experimental setup for measuring effective irradiance and spectral irradiance.

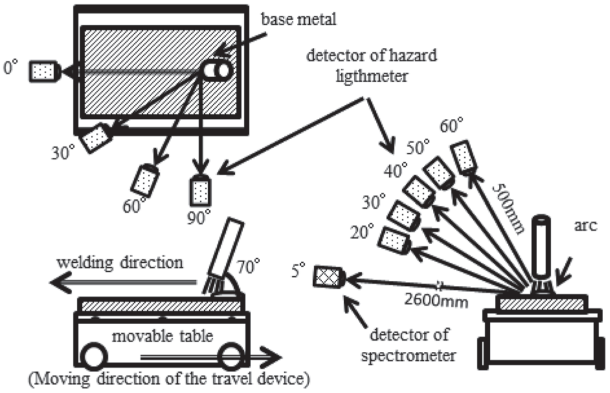

Fig. 2. Experimental setup for measuring effective irradiance and spectral irradiance (schematic diagram).

To investigate the impact of the combination of base metal and filler rod, we performed bead-on-plate welding using different types of base metal and filler rod and measured the UVR in each case. The base metals used were the same three base metals used for melt-run welding, as discussed above. For the filler rods, we used three types of filler rods specified by JIS: A1100BY, A4043BY, and A5183BY[17]. The JIS-specified composition of these materials is presented in Table 3. A1100BY is essentially pure aluminum, A4043BY is an alloy containing small quantities of magnesium and other non-magnesium elements, and A5183BY is an alloy containing 4–5% magnesium. To investigate the impact of the welding current, we used two values of the welding current: 100 and 200A. As shown in Fig. 2, the detector head was positioned at an angle of 40° from the surface of the base metal and at an angle of 90° from the welding direction. The distance from the arc was 500 mm. Table 4 presents the combinations of base metals and filler rods, and their symbols.

Dependence on the direction of emission from the arc

To investigate the dependence on the direction of emission from the arc, we conducted measurements of UVR while varying the angle from the horizontal surface of the base metal and the angle with respect to the welding direction. Figure 2 illustrates the position of the detector head. The angle with respect to the welding direction was first fixed at 90°, and the angle from the surface of the base metal was set to 20°, 30°, 40°, 50°, and 60°. Then the angle from the surface of the base metal was fixed at 40° and the angle with respect to the welding direction was set to 0°, 30°, 60°, and 90°. Melt-run welding was conducted using a welding current of 200A and a pure tungsten

Table 3. Chemical compositions of filler rods (mass %)

Element Filler rods (JIS designation)	Diameter (mm)	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Al
A1100BY	2.4	0.04	0.24	0.06	0.00			0.00			>99.50
	4.0	0.05	0.23	0.07	0.00			0.00			>99.50
A4043BY	2.4	5.14	0.14	0.01	0.00	0.01		0.00	0.02		re
	4.0	4.97	0.21	0.01	0.01	0.04		0.01	0.03		re
A5183BY	2.4	0.07	0.17	0.00	0.70	5.12	0.07	0.00	0.07		re
	4.0	0.07	0.17	0.00	0.70	5.12	0.07	0.00	0.07		re

re: remainder

Table 4. Combination of base metal and filler rod

Symbol	Base metal		Filler rod	
	JIS designation	Importance secondary element	JIS designation	Importance secondary element
P1	A1050P-H24	(None)	Not applicable	
P5	A5083P-O	Mg	Not applicable	
P6	A6061P-T6	Si	Not applicable	
P1F1	A1050P-H24	(None)	A1100BY	(None)
P5F5	A5083P-O	Mg	A5183BY	Mg
P1F5	A1050P-H24	(None)	A5183BY	Mg
P5F1	A5083P-O	Mg	A1100BY	(None)
P6F4	A6061P-T6	Si	A4043BY	Si

electrode. The base metal was A5083P-O. The distance between the detector head and the arc was 500 mm.

Impact of the type of electrode

To investigate the impact of the choice of electrodes, we performed welding using five different JIS-specified electrodes (YWP, YWCe-2, YWLa-2, WZ8, and YWTh-2)[18] and measured the resulting emission of UVR. Table 5 presents the composition of these electrodes as specified by JIS. YWP is a pure tungsten electrode, while the other electrodes contain oxides. We performed melt-run welding using a base metal of A5083P-O and a welding current of 200A. The detector head was positioned at an angle of 90° from the welding direction, at an angle of 40° from the surface of the base metal, and at a measurement distance of 500 mm.

Table 5. Chemical compositions of electrodes (mass %)

Electrodes (JIS designation)	Chemical compositions			
	Oxide content		Impurities	Tungsten
YWP	-	-	–0.10	>99.00
YWCe-2	Ce_2O_3	1.8–2.2	–0.10	Remainder
YWLa-2	La_2O_3	1.8–2.2	–0.10	Remainder
WZ8	ZrO_2	0.7–0.9	–0.10	Remainder
YWTh-2	ThO_2	1.7–2.2	–0.10	Remainder

Results

The effective irradiances measured in this study at a distance of 500 mm from the arc were in the range 0.091–0.91 mW/cm^2. The allowable daily exposure times corresponding to these values are 3.30–33.0 s.

Figure 3 shows the effective irradiance for various welding materials in melt-run welding and in bead-on-plate welding. The effective irradiance for melt-run welding was highest when the base metal was the magnesium-rich P5; lower values were observed for P6 (which contains a small amount of magnesium), and still lower values were observed for P1 (which does not contain any magnesium). Figure 4 shows the spectral irradiance of UVR measured for the case of melt-run welding. For all choices of the base metal, UVR emission from aluminum was observed at many wavelengths. In the cases of P5 and P6, intense emission from magnesium was observed at a wavelength near 280 nm.

For the case of bead-on-plate welding, the effective irradiance was highest for the base-metal/filler-rod combi-

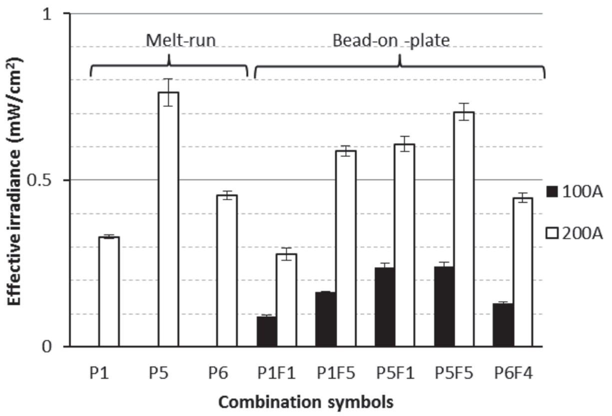

Fig. 3. Effective irradiance for different base metals and filler rods. Error bar represent the standard deviation.

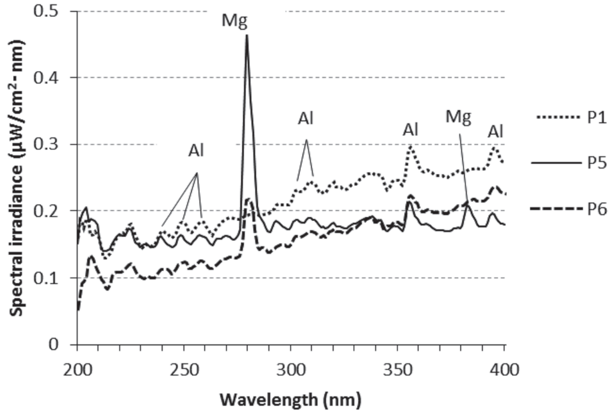

Fig. 4. Spectral irradiance for different base metals in melt-run welding.

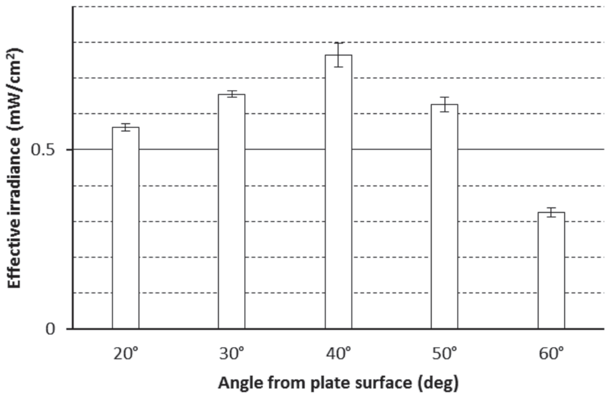

Fig. 5. Effective irradiance against angle from plate surface. Error bars represent the standard deviation.

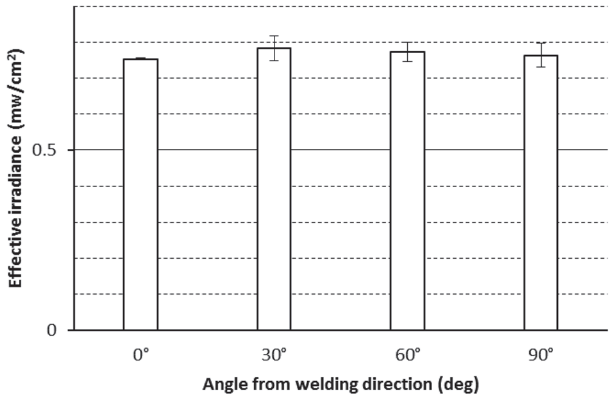

Fig. 6. Effective irradiance against angle with respect to welding direction. Error bars represent the standard deviation.

nation P5F5, a case in which both the base metal and the filler rod contain magnesium. The values observed for the combination P1F5—in which only the filler rod contains magnesium—do not differ significantly from the values observed for the combination P5F1, in which only the base metal contains magnesium. The lowest value was observed for the combination P1F1, which consists of pure aluminum; the next lowest value was observed for the combination P6F4, which contains small amounts of magnesium and silicon. A comparison of the P5 case—involving melt-run welding of base metal A5083 P-O—and the P5F5 case, in which bead-on-plate welding was conducted using filler rod A5183BY—reveals higher values of the effective irradiance for P5. Similarly, a comparison of P1 and P1F1 reveals higher values of the effective irradiance for the melt-run welding of P1. For all combinations of base metal and filler rods, the effective irradiance was higher for a welding current of 200A than for a welding current of 100A.

Figure 5 shows the effective irradiance for various angles from the horizontal surface of the base metal. The effective irradiance is greatest when the angle from the surface of the base metal is 40° and decreases for angles greater or less than this.

Figure 6 shows the results of measurements of the effective irradiance versus the angle of inclination with respect to the welding direction. We observe no clear dependence of the effective irradiance on the angle of inclination.

Figure 7 shows the results of measurements of the effective irradiance for different electrodes. The effective irradiance for electrodes containing oxides is 10–20% larger than that for the pure tungsten electrode YWP.

Discussion

The effective irradiances observed at distances of 500 mm from the arc were in the range 0.091–

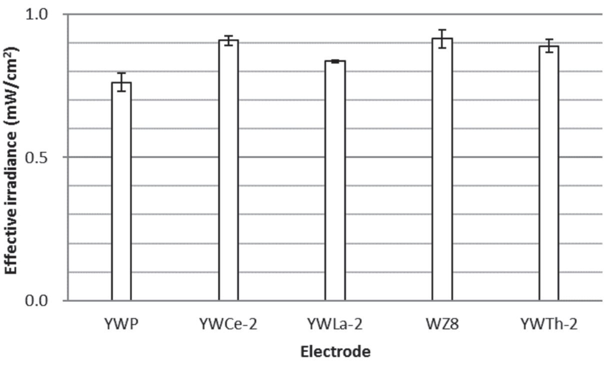

Fig. 7. Effective irradiance for different electrodes in melt-run welding. Error bars represent the standard deviation.

0.91 mW/cm^2. At these irradiances, the allowable daily exposure times are just 3.30–33.0 s, extremely small numbers for the accumulated exposure time over the course of a single day, meaning that exposure to UVR emitted by GTAW of aluminum alloys is quite hazardous. It is thought that workers are often exposed to UVR when striking the arc[1]. Although the exposure is brief for each strike of arc, this may occur many times because workers usually strike an arc many times in a day. So, the total exposure time may easily exceed the allowable daily exposure times obtained in this study. Thus, we conclude that if workers are engaged in the GTAW of aluminum alloys without adequate protection, they are exposed to hazardous quantities of UVR even if they are only welding for short periods of time.

In this study, no local exhaust ventilation system was used during measurement of UVR, because local exhaust ventilation is usually not used in the welding workplace. Local exhaust ventilation removes the welding fume, which strongly attenuates UVR by scatter and absorb. Therefore, if local exhaust ventilation had been used during the measurement, the effective irradiance would have been higher.

If we assume that the effective irradiance of UVR decreases with the distance from the arc according to the inverse-square law, the allowable daily exposure times at a distance of 5 m from the arc fall in the range 330–3300 s. Thus, even at a distance of 5 m from the arc, exposure to UVR is hazardous in cases in which the emitted UVR is intense; moreover, even in cases where the emitted UVR is weak, we believe that prolonged exposure is also hazardous. Thus, in cases where GTAW of aluminum alloys is performed, it is necessary to take precautions to ensure that surrounding workers are not exposed to the UVR emitted by the arc.

For the case of bead-on-plate welding, the effective irradiances measured for a welding current of 200A were 2.6–3.6 times greater than those measured for a welding current of 100A, with other conditions held fixed (Fig. 3). Thus, the welding current is an important factor influencing the hazard of the UVR emitted during the welding process; the hazard of the UVR may be understood to be a rapidly increasing function of the welding current.

For GTAW of aluminum alloys, the effective irradiance was high for welding materials containing magnesium (Fig. 3). For cases P5 and P6, which used base metals A5083P-O and A6061P-T6, strong emission arising from the presence of magnesium was observed in the vicinity of 280 nm, while emission from aluminum—the primary component of the base metals—was observed at wavelengths of 240–260 nm and 300–310 nm (Fig. 4). Despite the very low magnesium content of the base metal, its contribution to the spectral distribution of UVR was on the same order of magnitude as, or even greater than, the contribution of aluminum, as shown in the figure. We attribute this to the fact that the boiling point of magnesium (1,090°C) is considerably lower than that of aluminum (2,470°C), ensuring that magnesium is preferentially vaporized from the molten pool, giving rise to greater UVR. In addition, the relative spectral effectiveness[12]—a measure of the relative hazard of UVR at various wavelengths—was 0.88 at a wavelength of 280 nm, 0.3–0.65 for wavelengths in the range 240–260 nm, and 0.015–0.3 for wavelengths in the range 300–310 nm. Thus, the impact of aluminum on the effective irradiance is relatively small compared to that of magnesium. Consequently, we conclude that the hazard of the UVR emitted during GTAW of aluminum alloys is primarily determined by the emission from magnesium. Similar conclusions were obtained from the authors' previous study of GMAW of aluminum alloys[11].

The effective irradiance of the UVR emitted by GTAW is greatest when the angle from the surface of the base metal is 40°, and decreases for angles greater or less than this (Fig. 5). We believe the reason for this to be as follows. The UVR associated with GTAW arises from the metal vapor produced from the surface of molten pool[19]; when the angle from the surface of the base metal is small, the effective area of the molten pool is small, but this effective area increases as the angle increases, causing an increase in effective irradiance. On the other hand, when the angle is too large, the nozzle of the welding torch covers the molten pool, blocking UVR and reducing the effective irradiance. Thus, when a welder adopts typical configurations for performing GTAW welding, the UVR will be strongest near the welder's head and neck. Welders must take care to protect these areas thoroughly using welding face shields or other protective gear. In particular, during hot summer weather it is common for welders to neglect to equip themselves with protective gear for the neck region, necessitating heightened attention to the risk of exposure to UVR.

As shown in Fig. 6, changing the angle with respect to the welding direction yields essentially no change in the effective irradiance of the UVR emitted in GTAW. In the case of GMAW, a drop in effective irradiance was observed for directions closer to the welding direction; this was believed to be caused by absorption or scattering of UVR by fumes (smoke emitted during welding) produced in GMAW11). The absence of any dependence on the angle with respect to the welding direction in GTAW may be attributed to the fact that almost no fumes are produced during this welding process.

The effective irradiances measured for GMAW of aluminum alloys in this study at a distance of 500 mm from the arc were in the range 0.091–0.91 mW/cm^2, while those measured for GMAW of aluminum alloys in our previous study11) were in the range 0.33–10.0 mW/cm^2, which indicates that the UVR hazard of GTAW is approximately 1/10 that of GMAW. Both studies investigated the UVR emitted under welding conditions typically found at actual workplaces. Thus, we expect that GMAW of aluminum alloys will be more hazardous than GTAW at actual workplaces, as was observed in research studies.

Conclusion

GTAW of aluminum alloys leads to the emission of intense UVR. Exposure to this radiation is considered hazardous according to the ACGIH guidelines. The hazard of this UVR exhibits the following characteristics. (1) It is more hazardous at higher welding currents. (2) It is more hazardous when the welding materials include magnesium. (3) It is more hazardous for melt-run welding. (4) The hazard depends on the direction of emission from the arc. (5) Electrodes containing oxides yield stronger hazard than pure tungsten electrodes. (6) Under the welding conditions typically present at actual workplaces, the hazard of GTAW is approximately 1/10 that of GMAW.

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