

Original

Hazard of ultraviolet radiation emitted in gas metal arc welding of mild steel

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Abstract: Objectives: Ultraviolet radiation (UVR) emitted during arc welding frequently causes keratoconjunctivitis and erythema in the workplace. The degree of hazard from UVR exposure depends on the welding method and conditions. Therefore, it is important to identify the UVR levels present under various conditions. **Methods:** We experimentally evaluated the UVR levels emitted in gas metal arc welding (GMAW) of mild steel. We used both a pulsed welding current and a non-pulsed welding current. The shielding gases were 80% Ar + 20% CO₂ and 100% CO₂. The effective irradiance defined in the American Conference of Governmental Industrial Hygienists guidelines was used to quantify the UVR hazard. **Results:** The effective irradiance measured in this study was in the range of 0.51-12.9 mW/cm² at a distance of 500 mm from the arc. The maximum allowable exposure times at these levels are only 0.23-5.9 s/day. **Conclusions:** The following conclusions were made regarding the degree of hazard from UVR exposure during the GMAW of mild steel: (1) It is more hazardous at higher welding currents than at lower welding currents. (2) At higher welding currents, it is more hazardous when 80% Ar + 20% CO₂ is used as a shielding gas than when 100% CO₂ is used. (3) It is more hazardous for pulsed welding currents than for non-pulsed welding currents. (4) It appears to be very hazardous when metal transfer is the spray type. This study demonstrates that unprotected exposure to UVR emitted by the GMAW of mild steel is quite hazardous.
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Key words: Effective irradiance, Gas metal arc welding, Hazard, Mild steel, Ultraviolet radiation

Introduction

The light emitted during arc welding contains intense ultraviolet radiation (UVR). In the absence of a barrier, this radiation is emitted into the surrounding environment, and as a result, extremely large number 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 350,000 in Japan, but also welders who perform arc welding occasionally and workers engaged in tasks other than arc welding¹. UVR refers to electromagnetic waves in the range of 1-400 nm². However, a precise border between UVR and visible light cannot be defined because visual sensations from very bright sources are experienced at wavelengths below 400 nm. Therefore, the borders necessarily vary from situation to situation³. UVR below approximately 190 nm is known as vacuum UVR because it is strongly absorbed by oxygen molecules and therefore cannot propagate through air.

UVR is emitted during arc welding over its entire wavelength range excluding vacuum UVR, although the wavelength distribution of UV differs depending on the welding conditions^{4,5}. UVR from the arc welding of steel consists mostly of a large number of spectral lines of iron scattered over this wavelength range.

UVR is known to cause a variety of problems^{6,7}. For example, because it is strongly absorbed by proteins and water, UVR incident on a living organism is primarily absorbed at the surface, causing damage confined to surface regions. Well-known examples of acute health effects in-

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clude keratoconjunctivitis and erythema, whereas delayed health effects include cataracts and skin cancer. In practice, such acute health effects because of UVR occur frequently at workplaces where arc welding is performed¹⁾. The Japan Welding Engineering Society surveyed incidences of UV keratoconjunctivitis among 1667 workers at 47 workplaces where arc welding is performed; the survey included workers who performed arc welding as well as workers who did not¹⁾. The results indicated that as many as 86% of the workers reported past experience with symptoms of UV keratoconjunctivitis, including foreign body sensation, ophthalmalgia, lacrimation, and photophobia, whereas 45% reported ongoing experience with this ailment with one or more recurrences per month even though the majority of arc welders who experienced UV keratoconjunctivitis wore welding face shields. Possible causes for this include (a) cases in which workers mistakenly put on their face shields after starting the arc instead of immediately before thus exposing themselves to UVR and (b) cases in which workers were exposed to UVR by co-workers performing arc welding nearby. In addition, in a survey by Emmett *et al.*⁷⁾, 92% of welders had suffered one or more flash burns (keratoconjunctivitis), and 40% were afflicted with erythema in the neck.

These findings demonstrate the need to introduce protective measures at workplaces that use arc welding to protect all workers from UVR. As the basis for designing such measures, it is desirable to obtain a quantitative understanding of the hazard of UVR emitted during arc welding. In an actual work site, arc welding is performed under a variety of conditions, and the degree of hazard of the emitted UVR is thought to differ for each condition. Therefore, it is necessary to examine the hazards of the UVR emitted during arc welding under various conditions.

Arc welding of metallic materials is conducted primarily on mild steel, aluminum alloys, and stainless steel alloys. Gas metal arc welding (GMAW), which uses a continuously fed consumable electrode and a shielding gas, is most often used for mild steel. GMAW is conducted while covering the welding point and the arc by the shielding gas. The shielding gas prevents a decrease in welding quality, such as the formation of an oxide or nitride because of exposure of the weld metal to air. The GMAW electrode is a coiled consumable wire that is automatically supplied throughout the welding. A few previous studies have measured the UVR emitted during arc welding processes, such as the GMAW of mild steel, and assessed their acute health effects^{4,5,8)}. However, in these studies, detailed information on the actual welding was not provided. Therefore, the available data about the level of UVR emitted by GMAW is unreliable and insufficient. In particular, the effects of specific conditions have not been examined systematically. One of the authors of this paper performed GMAW using 100% CO₂

in experiments and examined in detail the UVR emitted under these conditions⁹⁾. It was clearly found that the UVR hazard tends to increase with welding current and is dependent on the type of welding wire.

In this study, we conducted a survey of the UVR hazard present during the GMAW of mild steel with a shielding gas of 80% Ar + 20% CO₂ or 100% CO₂. The UVR emitted during GMAW performed with the recently popular digital inverter-type pulsed arc welding machine was measured, and its acute health effects were assessed in accordance with the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines¹⁰⁾. In particular, we studied the influence of (i) the type of shielding gas and the magnitude of the welding current, and (ii) using pulsed vs. non-pulsed welding current.

Methods

According to the ACGIH guidelines, the degree of UVR hazard as a cause of acute health effects is measured by the effective irradiance. The effective irradiance is defined by

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

where E_{eff} is the effective irradiance (mW/cm²), E_{λ} is the spectral irradiance at wavelength λ (mW/(cm² · nm)), $S(\lambda)$ is the relative spectral effectiveness at wavelength λ , and $\Delta\lambda$ is the bandwidth (nm).

For the UVR measurements, we used an X1₃ hazard lightmeter and an XD-45-HUV UV-hazard detector head (both from Gigahertz-Optik), which are designed for measuring effective irradiance. The relative spectral responsivity of the detector head agrees well with the relative spectral effectiveness around 270 nm¹¹⁾. 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 consider the influence of this discrepancy to be too small to cause issues in practice. Thus, we conclude that this detector head is well suited to measure the effective irradiance. In actual experiments, the value measured by the devices is the effective radiant exposure (J/m²). Dividing this value by the measurement time yields the effective irradiance. The measurement device was calibrated by the manufacturer and used within the one-year validity of the calibration.

The position of the welding torch was fixed to produce arcs in the same position, and the base metal was fixed on a movable table, which moved the metal for welding. The distance between the arc and the detector head was set to 500 mm to mimic the actual distances to welders. In addition, the detector head was positioned at an angle of 40°

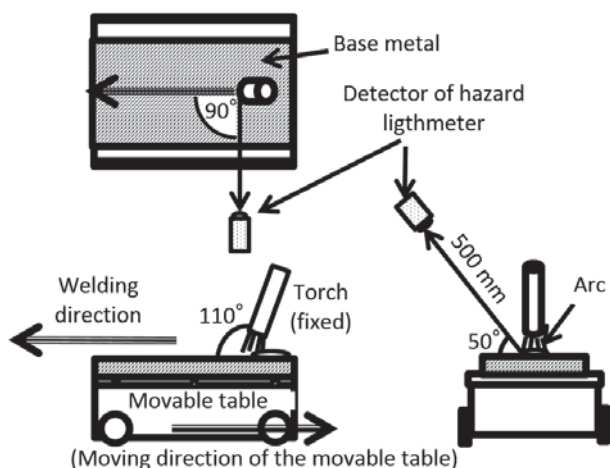


Fig. 1. Experimental setup for measuring effective irradiance (schematic diagram)

from the surface of the base metal and at an angle of 90° from the welding direction. Fig. 1 displays a schematic diagram of our experimental setup for measuring effective irradiance. 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 the measurement of UVR because local exhaust ventilation is usually not used in welding workplaces (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 then averaged. Furthermore, following the ACGIH guidelines, we divided 3 mJ/cm² by our measured values of effective irradiance to determine the maximum daily exposure time allowable at that irradiance (equation (2)).

$$t_{\max} = \frac{3 \text{ mJ/cm}^2}{E_{\text{eff}}} \dots\dots\dots(2)$$

In this equation, t_{\max} is the maximum daily exposure time (s) and E_{eff} is the effective irradiance.

We measured the effective irradiance of the UVR emitted during three types of welding: 100% CO₂ welding using non-pulsed welding current, non-pulsed 80% Ar + 20% CO₂ welding, and pulsed 80% Ar + CO₂ welding.

The welding apparatus was a digital inverter-type pulsed arc welding machine (DP350, DAIHEN Welding and Mechatronics Systems Co., Ltd.), which has recently become popular. The inclination of the welding torch was fixed at 110°. The type of welding was bead-on-plate welding in which the base metal is melted while the welding wire is added. The welding was performed using flat position forehead welding. The base metal was rolled

SS400, which is a mild structural steel specified by the Japanese Industrial Standards (JIS)¹²⁾. The dimensions of the base material were 30 mm × 380 mm × 50 mm. For the welding wire, we used solid wire YGW12 of diameter 1.2 mm specified by JIS¹³⁾. The usable range of welding current for this wire was 80-350 A for flat position welding. The welding speed was 300 mm/min. The shielding gas was 80% Ar + 20% CO₂ or 100% CO₂, and the shielding gas flow rate was 15 l/min. The distance between the base metal and the contact tip was 17 mm, and the wire extension length before the start of welding was 12 mm. The welding parameters are listed in Table 1. Here the welding voltages were preset values corresponding to the welding current determined by the manufacturer of the welding equipment.

Influence of the type of shielding gas and the magnitude of the welding current

To investigate the influence of the type of shielding gas, we conducted bead-on-plate welding and measured the resulting UVR when using 80% Ar + 20% CO₂ or 100% CO₂ as the shielding gas and non-pulsed welding current. The range of the welding current was 100-350 A as shown in Table 1. Because it is less expensive, 100% CO₂ is used more commonly as shielding gas in the GMAW of mild steel in Japan, whereas mixed gas is usually used when manufacturing high-quality products efficiently.

Influence of pulsed current

To investigate the influence of pulsed current, we performed pulsed current GMAW with an 80% Ar + 20% CO₂ shielding gas and measured the resulting UVR. We then compared it with the results for non-pulsed 80% Ar + 20% CO₂ welding. Incidentally, the digital inverter-type pulsed arc welding machine provides excellent stability of the arc in the low current range, highly effective reduction of sputter, and is mainly used under 250 A. Therefore, the range of welding current used was 100-250 A as shown in Table 1. Pulsed current is now commonly used in the welding of thin plates of automobile bodies.

Results

Fig. 2 and 3 display the effective irradiance for various welding conditions in bead-on-plate welding. The effective irradiance measured in this study at a distance of 500 mm from the arc was in the range of 0.51-12.9 mW/cm². The allowable daily exposure times corresponding to these values are 0.23-5.9 s.

Fig. 2 shows that the effective irradiance in bead-on-plate welding of mild steel was influenced by the welding current and the shielding gas composition. The effective irradiance increased with increasing welding current for each type of shielding gas. For the case of non-pulsed

Table 1. Welding parameters of 100% CO₂, non-pulsed 80% Ar+20% CO₂ welding and pulsed 80% Ar+20% CO₂ welding

100% CO ₂	Welding current, A (Steady)	100	150	200	250	300	350
	Welding voltage, V	18.5	19.0	23.0	27.0	34.0	38.0
Non-pulsed 80%Ar+20%CO ₂	Welding current, A (Non-pulsed)	100	150	200	250	300	350
	Welding voltage, V	16.0	17.0	20.0	26.5	33.0	35.5
Pulsed 80%Ar+20%CO ₂	Welding current, A (Average)	100	150	200	250	-	-
	(Peak/Base)	(450/35.0)	(450/44.0)	(450/55.0)	(450/60.0)	-	-
	Time (Peak/Base), s	(1.4/7.5)	(1.4/4.0)	(1.6/2.8)	(1.8/1.9)	-	-
	Welding voltage, V	21.3	23.3	25.5	28.1	-	-

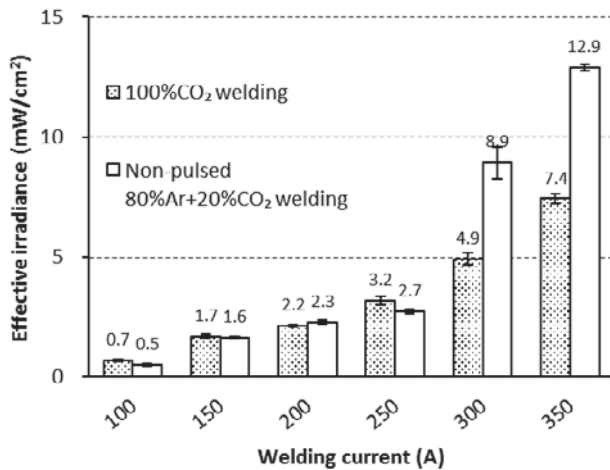


Fig. 2. Effective irradiance for 100% CO₂ welding and non-pulsed 80%Ar+20%CO₂ welding. Measurements were repeated three times for each set of conditions and then averaged. Error bars represent the standard deviation.

80% Ar + 20% CO₂ welding, the effective irradiance measured with welding currents of 100-350 A was in the range of 0.51-12.9 mW/cm². The increase in effective irradiance between current intervals is very large, starting from 250 A. For 100% CO₂ welding, the effective irradiance measured with welding currents of 100-350 A was in the range of 0.69-7.4 mW/cm². The effective irradiances measured with non-pulsed 80% Ar + 20% CO₂ welding and 100% CO₂ welding at 250 A or less were approximately equal. However, at 300 A and higher, the effective irradiance for non-pulsed 80% Ar + 20% CO₂ welding increased beyond that for 100% CO₂ welding.

As shown in Fig. 3, the effective irradiance of UVR emitted during mild steel arc welding was strongly influenced by the pulsed current. The effective irradiance measured for pulsed 80% Ar + 20% CO₂ welding with welding currents of 100-250 A was in the range of 3.4-

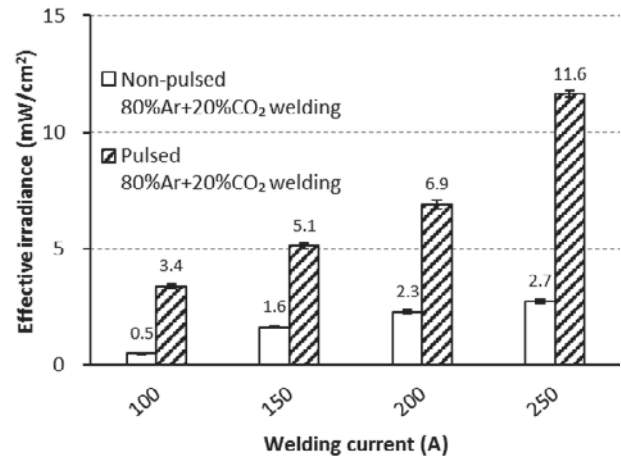


Fig. 3. Effective irradiance for non-pulsed and pulsed 80% Ar+20% CO₂ welding. Measurements were repeated three times for each set of conditions and then averaged. Error bars represent the standard deviation.

11.6 mW/cm². The effective irradiance increased with increasing welding current. In addition, the effective irradiance of UVR occurring during pulsed 80% Ar + 20% CO₂ welding was very high in comparison with that during non-pulsed 80% Ar + 20% CO₂ welding.

Discussion

The effective irradiance observed at a distance of 500 mm from the arc was in the range of 0.51-12.9 mW/cm². At these irradiances, the allowable daily exposure times are just 0.23-5.9 s, which are extremely short times. These results indicate that exposure to the UVR emitted by the GMAW of mild steel is quite hazardous. It is thought that workers are often exposed to UVR when the arc is started¹⁾. Although the exposure is brief for each start of an arc, this may occur often because workers usually start an arc many times in a day. Therefore, the actual

total exposure time may easily exceed the allowable daily exposure times determined in this study. Thus, we conclude that if workers engage in the GMAW of mild steel without adequate protection, they are exposed to hazardous quantities of UVR for short periods of time.

One of the authors previously measured the UVR emitted during the GMAW of mild steel when using 100% CO₂ as a shielding gas⁹⁾ and obtained an effective irradiance of 0.028-0.785 mW/cm² at a distance of 1 m from welding currents of 120-500 A. If we assume that the effective irradiance decreases as the inverse square distance from the arc, the effective irradiance would be 0.106-3.14 mW/cm² at 0.5 m from the arc, which is roughly half the effective irradiance obtained in the present study for the same type of welding. This difference is considered to be because of differences in welding conditions such as the welding device, welding wire, and ventilation conditions.

In this study, no local exhaust ventilation system was used during the measurement of UVR because local exhaust ventilation is usually not used in the welding workplace. Local exhaust ventilation removes the welding fume, which strongly mitigates UVR by scatter and absorption. 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 as the inverse square distance from the arc, the allowable daily exposure times at a distance of 5 m from the arc will be in the range of 23-590 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 in which the emitted UVR is weak, we believe that prolonged exposure is hazardous. Thus, in cases where the GMAW of mild steel is performed, it is necessary to take precautions to ensure that surrounding workers are not exposed to the UVR emitted by the arc.

Influence of the type of shielding gas and the magnitude of the welding current

The effective irradiance measured in this study, regardless of the pulse current and the type of shielding gas, increased with increasing welding current (Fig. 2 and 3). This trend was also previously observed for the GMAW of mild steel using 100% CO₂⁹⁾ and 5% O₂ + 95% Ar⁶⁾ as the shield gas. More recently, we also observed the trend for the GMAW and the GTAW of aluminum^{14,15)} and magnesium alloys¹⁶⁾. Thus, the welding current is an important factor influencing the degree of hazard of the UVR emitted during the welding process; the UVR hazard can be understood to be a rapidly increasing function of the welding current.

The effective irradiance of the UVR generated during non-pulsed 80% Ar + 20% CO₂ welding was in the range of 0.51-12.9 mW/cm² and increased with increasing welding current. In particular, a significant difference in the

increase in effective irradiance for welding currents from 100 to 250 A and from 250 A upward was observed. To investigate the reason for this difference, we observed the arc during welding. As shown in Fig. 4, short-circuit transfer was observed at 100 A. In short-circuit transfer, the tip of the welding wire is short-circuited with the base metal (molten pool), and the molten metal is shifted to the base material¹⁷⁾. In addition, globular transfer was observed at 250 A. In globular transfer, the welding wire tip melted by the arc is transferred to the base metal in which the grain size grows larger than the wire diameter¹⁷⁾. As also shown in Fig. 4, it was not possible at 300 A to observe the droplets, which were blocked by the arc light. However, the wire tip was pointed, and because no change appeared in the shape of the wire tip with the passage of time, we assumed this was spray transfer. In spray transfer, the welding wire tip melted by the arc is transferred to the base material with a grain smaller than the wire diameter¹⁷⁾. These results were consistent with the research of Takeuchi *et al.*¹⁸⁾. The effective irradiance of the UVR emitted by non-pulsed 80% Ar + 20% CO₂ welding increased with increasing welding current from 100 to 250 A, and no change was seen in this increasing trend (Fig. 2). Therefore, the effect of changing the metal transfer mode from short-circuiting to globular on the effective irradiance was considered to be small. However, the effective irradiance increased rapidly between 250 A and 300 A. The metal transfer mode changed to spray transfer from globular transfer. The amount of metal vapor in the arc during spray transfer is large compared to that during globular transfer¹⁹⁾, and the properties of light emitted by the arc welding are affected by the amount of metal vapor blending into the arc²⁰⁾. Therefore, the cause of the rapid increase in the effective irradiance from 250 to 300 A is considered to be because of the change in the metal transfer mode (globular transfer to spray transfer).

The effective irradiance of the UVR emitted during 100% CO₂ welding was in the range of 0.69-7.4 mW/cm² and increased with increasing welding current. Takeuchi *et al.* reported that for 100% CO₂ welding, the transition from short-circuit transfer to globular transfer takes place at approximately 250 A¹⁸⁾. However, in the present study, no clear difference was seen in the effective irradiance vs. current trend between short-circuit transfer and globular transfer.

The effective irradiance was approximately the same for non-pulsed 80% Ar + 20% CO₂ welding and 100% CO₂ welding at 250 A or less. However, a significant difference was observed at 300 A or higher. By observation of the arc during welding, the metal transfer mode of non-pulsed 80% Ar + 20% CO₂ welding was spray transfer and that of 100% CO₂ welding was globular transfer. Therefore, the effective irradiance is considered to depend on the metal transfer mode because of the differences in the shielding gas composition between them, and the ef-

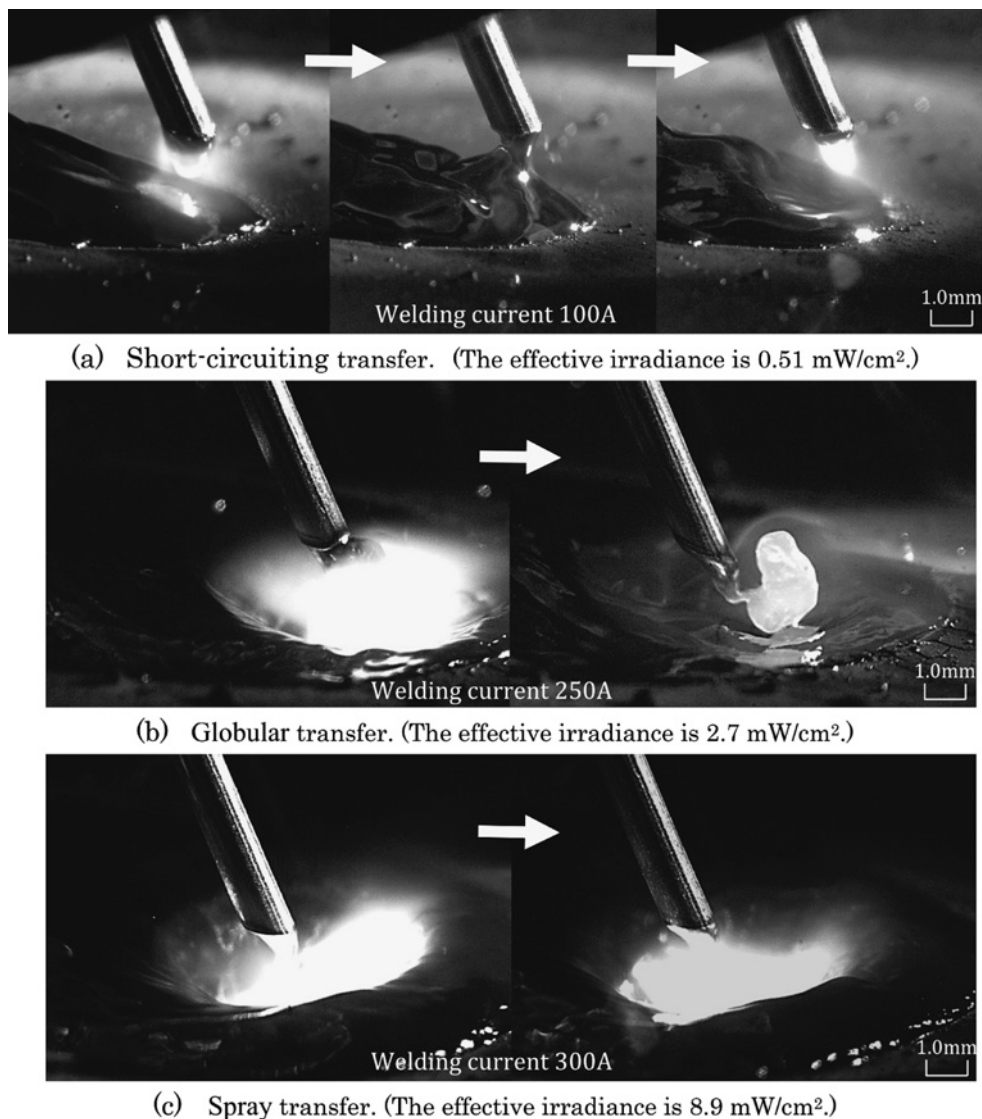


Fig. 4. The metal transfer for non-pulsed 80% Ar+20% CO₂ welding

ffective irradiance increases with the transition to spray transfer. As shown above, the UVR emitted during the GMAW of mild steel was very hazardous during spray transfer. The welding operator must recognize that welding under spray transfer conditions is extremely dangerous, so it is necessary to take adequate protective measures.

The influence of pulsed current on the UVR hazard

We examined the effects of pulsed current on the degree of the UVR hazard. As shown in Fig. 3, the effective irradiance of the UVR emitted during pulsed 80% Ar + 20% CO₂ welding increased with increasing current and was 3.0-6.7 times larger compared with that emitted during non-pulsed 80% Ar + 20% CO₂ welding at each welding current. The effective irradiance was observed in the vicinity of the arc and the metal transfer mode was spray

transfer for the entire current range. Example photographs of the welding under these conditions are shown in Fig. 5.

For non-pulsed 80% Ar + 20% CO₂ welding, the short-circuit or globular transfer modes were observed at 250 A or less (Fig. 4). The amount of metal vapor in the arc during spray transfer is large compared to that during short-circuit and globular transfer¹⁹⁾. In addition, the properties of the light emitted during the arc welding are affected by the amount of metal vapor blended into the arc²⁰⁾. Therefore, we believe that the effective irradiance of the UVR generated by spray transfer for a pulsed current is very large compared with that produced by the short-circuit and the globular transfer modes for a non-pulsed welding current.

These results confirm that the effective irradiance is strongly influenced by the pulsed current, and the degree of the effect increases with decreasing pulsed current. In

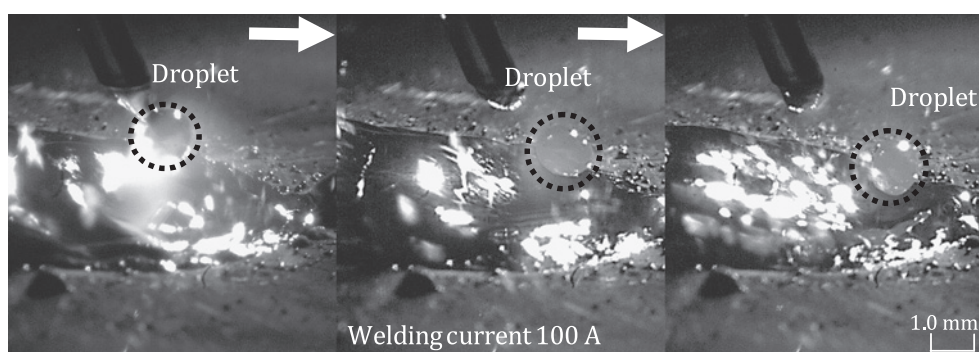


Fig. 5. The metal transfer for pulsed 80% Ar+20% CO₂ welding (spray transfer). (The effective irradiance is 3.4 mW/cm².)

recent years, the demand for mild steel thin plate welding has increased to reduce the weight of equipment that needs to be transported. We used a low welding current below 100 A in the welding of thin plate. In addition, a digital inverter-type pulsed arc welding machine was used to increase the working efficiency.

In this study, the effective irradiance of the UVR that occurred during pulsed 80% Ar + 20% CO₂ welding at 100 A was 1.2 times greater than the effective irradiance during non-pulsed 80% Ar + 20% CO₂ welding at 250 A. Therefore, welding operators need to recognize the very high hazard of the UVR when they are welding with pulsed current, and supervisors must take adequate protection measures for the peripheral workers who are not welding.

Conclusions

GMAW of mild steel leads to the emission of intense UVR. The exposure to this radiation is considered hazardous according to the ACGIH guidelines. This UVR hazard exhibits the following characteristics. (1) It is more hazardous at higher welding currents than at lower welding currents. (2) At higher welding currents, it is more hazardous when 80% Ar + 20% CO₂ is used as a shielding gas than when 100% CO₂ is used. (3) It is more hazardous for pulsed welding currents than for non-pulsed welding currents. (4) It appears to depend on the metal transfer; the hazard of the UVR emitted during spray transfer is the highest.

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