Evaluation of the hazard of light emitted during arc welding

（アーク溶接時に放射される光の有害性の評価）

Hitoshi NAKASHIMA

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by Hitoshi NAKASHIMA

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Chapter I

Grand Introduction

1.1 Introduction

Light is one of the indispensable elements for mankind to live. However, light is also hazardous, such as playing a central role in the mechanism of the destruction of the ozone layer and the occurrence mechanism of global warming. In addition, light directly affects the human body. Ultraviolet radiation (UVR) is the cause of such as keratoconjunctivitis, dermatitis, cataract and skin cancer, and blue light causes photoretinopathy. Although these light sources are various, the arc emitted during arc welding is well known as an artificial light source that generates strong ultraviolet radiation and blue light at the same time.

Arc welding, a fundamental technology of the manufacturing and construction industries, is widely used in the production of various industrial products, such as vehicles, large metal structures, electrical products and household products. Thus, arc welding plays an extremely vital role in many industrial fields. However, many hazards, such as fumes (powder dust), poisonous gases, spatter (sparks), electrical shocks and hazardous optical radiation, are emitted during arc welding. These hazardous emissions can affect the health of workers and cause disastrous occupational accidents. In Japan, there are presumably over one million people involved in arc welding, with as many as 300,000 professional arc welders and an additional number of people who perform arc welding as part of their work. Furthermore, at workplaces where arc welding is performed, workers engaged in tasks other than welding may suffer health effects from the hazardous emissions from the arc welding.

In these circumstances, measures to protect workers from the health disorders due to fumes, poisonous gases and electrical shock from arc welding have been enforced by the Ordinance on Prevention of Hazards due to Dust and the Ordinance on Industrial Safety and Health, both of which have been enacted by the Japanese government. On the other hand,

health disorders due to spatter have been countered by measures that compel welders to wear personal eye protectors[1)], personal face protectors for welding[2)], protective leather gloves for welders[3)] and protective footwear[4)] specified by the Japanese Standards Association (JIS). These countermeasures have reduced the number of incidences of health disorders and disastrous occupational accidents caused by fumes, poisonous gases, electrical shock and spatter. JIS has enacted standards for protectors that shield light[5)] and personal face protectors for welding as measures against the health disorders caused by hazardous optical radiation, and the Department of Labor (presently the Ministry of Health, Labor and Welfare) issued a notification on the usage of protectors for shielding light (Notification No. 773: Usage of Protectors for Light Shield) in 1981. Nevertheless, at welding sites, there are still numerous incidences of eye injuries. Thus, it is safe to say that the effect of current countermeasures against hazardous optical radiation is limited and insufficient.

1.2 Hazards of light

Light is an essential element of human life, but it can be also hazardous. In fact, there are a number of light sources at manufacturing sites that can be injurious. However, the hazards of light are not well known, even by safety and health experts. For any risks associated with hazardous optical radiation, it is desirable to have correspondingly appropriate assessments of the hazards.

Electromagnetic waves having a wavelength ranging from 1 nm to 1 mm are defined as “light”[6)]. This light is roughly classified according to the wavelength as UVR, visible radiation or infrared radiation. Although UVR and infrared radiation are invisible, they exhibit physical properties that are similar to those of visible radiation. Moreover, because these three different types of radiation often occur concurrently, they are collectively called “optical radiation.” In cases where the intensity of this radiation can be injurious, it is called

"hazardous optical radiation." Table 1.1 shows seven optical categories of radiation classified by the International Commission on Illumination (CIE)[7] and the main adverse effects of each category on biological tissue.

Table 1.1 Seven spectral bands of the optical spectrum classified by CIE, where the most crucial adverse effects on biological tissue are limited to two or three spectral bands

Type of optical radiation	CIE band	Adverse effect
UVR	UV-C 100–280 nm	Keratoconjunctivitis, erythema, skin cancer
	UV-B 280–315 nm	Keratoconjunctivitis, erythema, skin cancer, cataracts
	UV-A 315–400 nm	Skin cancer, cataracts, thermal skin burns
Visible radiation	Visible radiation about (400–780 nm)	Retinal burns, thermal skin burns
	Blue light about (400–500 nm)	Retinal injuries
Infrared radiation	IR-A 780–1,400 nm	Corneal burns, retinal burns, thermal skin burns
	IR-B 1,400–3,000 nm	Corneal burns, cataracts, thermal skin burns
	IR-C 3,000–1 mm	Corneal burns, cataracts, thermal skin burns

Generally, the hazards of light are evaluated in accordance with the recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH)[8]. In this case, the term equivalent to "permissible amount" is "threshold limit value (TLV)." In this study, the TLVs is a time weighted average. The weighted average exposure time is an 8-hour workday and 40-hour workweek. Most workers are free from any adverse effects on their health, even if they are repetitively exposed to such working conditions.

Incidentally, the hazards from infrared radiation are generally very weak, so it is assumed that they will not cause any health disorders. In view of this, this study excludes infrared radiation, and focuses on UVR and visible radiation (blue light).

The action of optical radiation on biological tissue can be classified into two categories: photochemical action and thermal action. The photochemical action specifically means that a molecule in a biological body absorbs a particle (photon) of optical radiation, is excited, and initiates a chemical action. One of the characteristics of the photochemical action is its high accumulativeness. In particular, UVR can caused direct and indirect (free radicals such as reactive oxygen species) DNA damage. Although a living body has a recovery mechanism against DNA damage, there is a limit to the repair rate of DNA. Damage to DNA beyond the limits accumulates and causes aging and canceration. Due to this characteristic, therefore, even if the level of optical radiation is low, and health disorders could be caused by long-term exposure to the photochemical action. On the other hand, the thermal action specifically means that the temperature increases when the biological tissue absorbs the energy from the optical radiation. Because the heat generated by the absorption of optical radiation energy within the tissue diffuses circumferentially and momentarily, the accumulativeness of the thermal action is low. Therefore, unlike health disorders caused by photochemical action, those due to thermal action are caused by being exposed to optical radiation at a certain intensity. Generally, in photochemical action, optical radiation with a short wavelength is intense, and each photon has a large energy. On the other hand, thermal action does not depend on the wavelength of the light. For this reason, health disorders due to the photochemical action of UVR and blue light are a concern.

The adverse effects of UVR and blue light on the human body differ. As shown in Figure 1.1, as to the adverse effects on human eyes, for example, because UVR is mostly absorbed into the surface of the eyes (1% or less of UVR reaches the retina), UVR primarily

damages the cornea and conjunctiva. In contrast, blue light is transmitted through the lens, and adversely affects the retina. This study provides insight into the hazards of UVR and blue light.

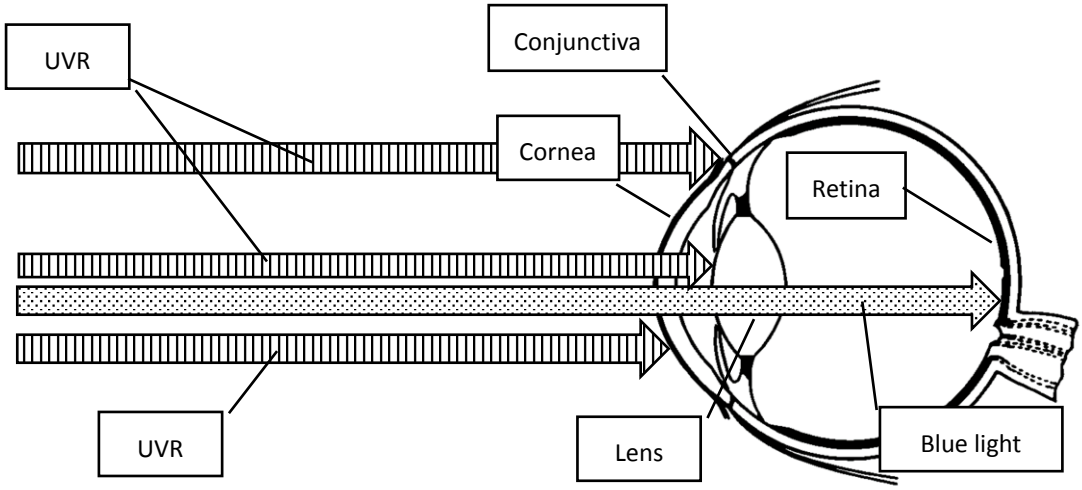

Figure 1.1. Areas of the human eye adversely affected by UVR (purple arrows) and blue light (blue arrow)

1.2.1 Ultraviolet radiation (UVR)

Light with a wavelength of approximately 400 nm, which is the lower limit of visible light, appears purple to human eyes. Based on this, the radiation shorter in wavelength than visible light but longer in wavelength than approximately 1 nm is called UVR. UVR having a wavelength of 190 nm or shorter is called “vacuum ultraviolet,” is strongly absorbed by oxygen molecules, and consequently is not transmitted through the air. Accordingly, people are not exposed to this type of UVR except in very special cases, a low-pressure mercury lamp, a xenon lamp and excimer lasers etc., which makes it unnecessary to consider the exposure to such UVR under normal conditions.

The depth that UVR reaches when entering the human body depends on its wavelength, with longer wavelengths passing deeper into the body. In the case of the eyes, for example,

UVR with a wavelength of 280 nm or shorter, is mostly absorbed by the cornea, and does not reach deeper areas of the eye. However, UVR with a wavelength of 300 nm or longer is partly transmitted through the cornea to the lens, where it is absorbed.

UVR strongly affects biological tissue, and, for this reason, causes various health disorders[9-13]. Moreover, UVR is strongly absorbed by proteins and water. Consequently, if UVR enters biological tissue, it is mostly absorbed into the surface of the tissue. This limits the health disorders due to UVR to surface tissue. Acute health effects from exposure to UVR include keratoconjunctivitis and erythema, and delayed health effects include cataracts and skin cancer. As the symptoms of acute health effects, keratoconjunctivitis is accompanied by photophobia (light sensitivity.), nociception (pain), epiphora (excessive watering of the eye), decreased visual acuity, foreign-body sensation (gritty sensation), conjunctiva, etc. If the symptoms are severe, opening the eyes may be difficult. These symptoms appear in a few hours after exposure to UVR, but resolve in a single day or so. In the case of erythema (redness), blistering and other symptoms appear a few hours after exposure to UVR, but resolve in a few days or so. However, if the symptoms are severe, the skin exfoliates after a few days.

The major sources of health-damaging UVR include the sun[9,12], arc welding[10,11], plasma cutting arc, low-pressure mercury lamps (e.g., sterilization lamps)[13], and high-pressure discharge lamps used as industrial ultraviolet lamps.

The hazard level of the acute health effects (e.g., keratoconjunctivitis and erythema) caused by UVR can be expressed by the effective irradiance (E_{eff}, mW/cm^2) calculated using Equation (1) under the evaluation standards of ACGIH:

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

where E_λ is the spectral irradiance mW/(cm^2·nm) of the wavelength λ, and S(λ) is the relative spectral effectiveness at wavelength λ (Figure 1.2). Δλ is the bandwidth (nm).

The TLV at 270 nm, which is the integral of the effective irradiance for 8 h per day, is 3 mJ/cm^2. Therefore, the maximum exposure time: t_{max} (s) per day against the effective irradiance when the unprotected skin or eye is irradiated with UVR is obtained using Equation (2):

$$t_{max} = \frac{3}{E_{eff}} . \cdots\cdots (2)$$

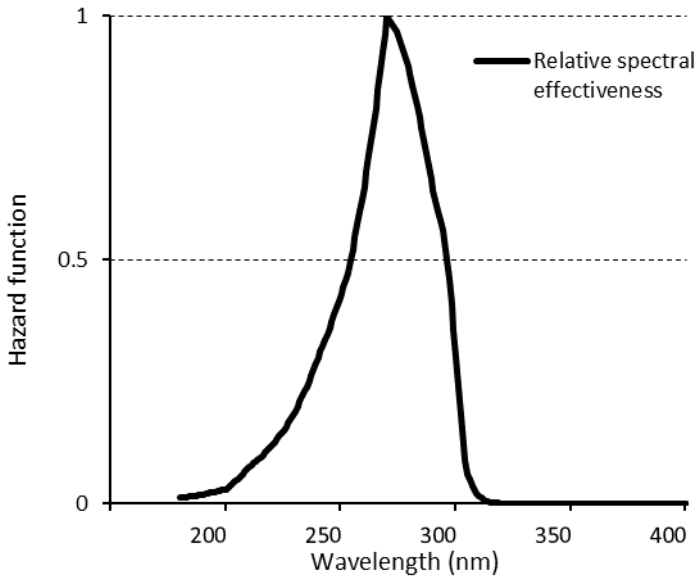

Figure 1.2. Relative spectral effectiveness showing hazard level according to light wavelength

1.2.2 Blue light (Visible radiation)

Because the response of photoreceptors in the eye to visible radiation is not precisely the same between individuals, the wavelength range of visible radiation has not yet been precisely defined. Generally, however, the lower limit of the wavelength range is from 360 to 400 nm and the upper limit is from 760 to 830 nm[6)]. Of all the visible radiation, the short-wavelength components (from approximately. 400 nm to approximately. 500 nm) appear

blue to humans. Thus, the visible radiation having such short wavelengths is generally referred to as blue light.

Of all the parts of the eye, the retina is the most susceptible to the effects of visible radiation. The internal structure of the eyeball from the cornea to the retina is transparent to visible radiation. The visible radiation enters the eyeball and reaches the retina with little attenuation. As shown in Figure 1.3, visible radiation converges at a specific portion of the retina due to refraction as it passes through the cornea and lens. This area of convergence is the most likely place for retinal damage to occur.

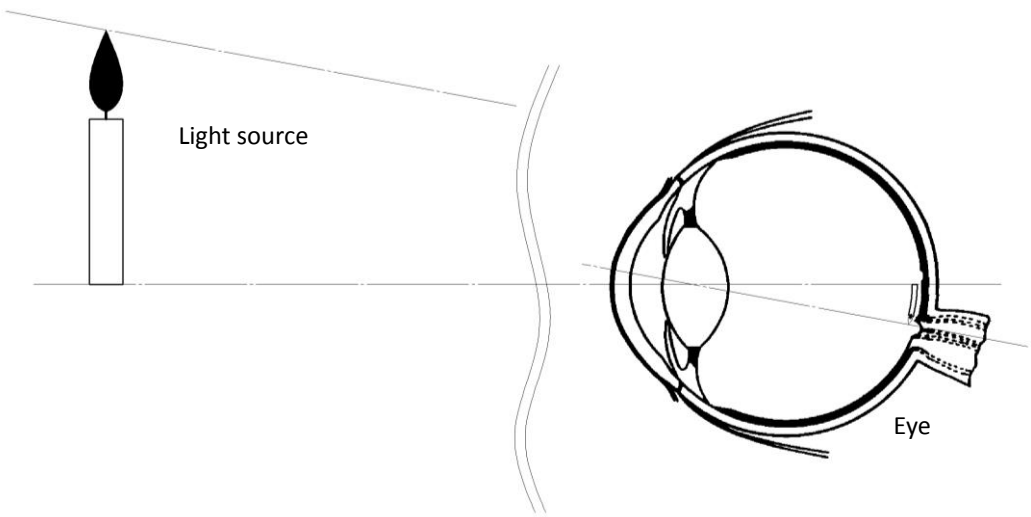

Figure 1.3. Schematic diagram of the absorption of visible radiation into the eye

Among visible radiation, blue light causes photochemical retinal disorders due to photochemical action. These disorders are observed as a change in the retina, such as edema or a hole, and are accompanied by symptoms, such as decreased visual acuity, blurred or foggy vision and scotoma (a blind spot or area of the visual field with reduced sensitivity). These symptoms appear immediately or within a single day after exposure, and then gradually resolve, but can remain for a few weeks to a few months, and, in some cases, become permanent. The retinal disorders can be severe enough to adversely affect activities

of daily living (ADL).

The major sources of health-damaging blue light are the sun and welding arcs. The hazard of a retinal disorder due to blue light is expressed by the effective blue-light radiance (L_B, W/cm^2·sr) of the light source, which is defined by Equation (3):

$$L_B = \sum_{305}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta\lambda, \cdots\cdots(3)$$

where L_λ is the spectral radiance W/(cm^2·sr·nm) of the wavelength λ, and B(λ) is the blue-light hazard function; that is, the function of the hazard level according to the wavelength, which is stipulated by ACGIH. Figure 1.4 shows the blue-light hazard function, where Δλ is the bandwidth (nm).

According to the guidelines set forth by ACGIH regarding the hazards of blue light, if the exposure time to blue light per day is shorter than 10^4 s (approximately 2.8 h) per a day, the value of the integral of the effective blue-light radiance should not exceed 100 J/cm^2·sr. Therefore, when the effective radiance of blue light is constant over time, the maximum acceptable exposure duration in one day, t_{max} (s), based on the effective blue-light radiance can be obtained using Equation (4):

$$t_{max} = \frac{100}{L_B}. \cdots\cdots(4)$$

ACGIH has also stipulated that, when the exposure time per day exceeds 10^4 s, the effective blue-light radiance should not exceed 0.01 W/cm^2·sr.

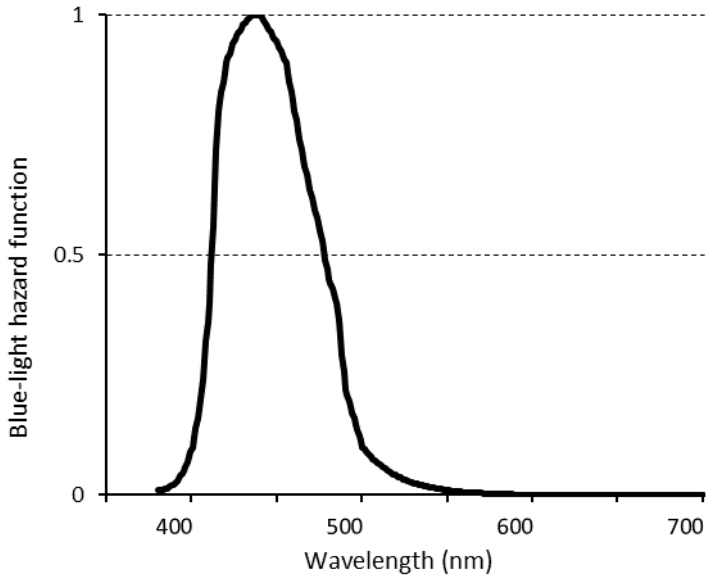

Figure 1.4. Blue-light hazard function showing hazard level according to light wavelength

1.3 Hazardous optical radiation emitted by arc welding

The most important source of optical radiation from industrial applications is the welding arc of arc welding. Arc welding is notorious for generating intense hazardous optical radiation. Because the welding arc is emitted into the surrounding environment in the absence of a barrier, it is presumed that many workers are exposed to the hazardous optical radiation in places where arc welding is performed. In Japan, there are at least 300,000 professional arc welders. There are also the workers who assist the professional welders, those who perform arc welding as part of their work and those who engaged in work other than arc welding around the arc welding operation. In total, over one million people are engaged in arc welding. Many of them are presumed to work in environments that put them at risk for exposure to welding arcs.

1.3.1 Outline of arc welding

Arc welding is one of typical means used for joining metallic materials. A continuous arc is generated between a base metal (the metal to be welded) and an electrode, and the base

metal and a filler metal (the metal to be added during the welding) are molten and mixed by the heat generated by arc. Arc welding, a fundamental technology of the manufacturing and construction industries, is widely used in the production of various industrial products, such as vehicles, large metal structures, electrical products and household products.

The arc is a type of discharge phenomenon within a gas, and it emits an intense light at a high temperature. Arcs visible in daily life include the sparks emitted from pantographs of Shinkansen bullet trains and those from a live outlet when an electrical cord is removed. The center temperature of the arc generated during arc welding depends on the welding method and conditions, but can be more than 13000 K[14)]. This extreme temperature, which is far above the boiling points of steel and aluminum, partially vaporizes the metal.

The metal, which is heated by the arc and directly exposed to the atmosphere, degrades in quality due to oxidation, nitriding, etc. Various arc welding methods have been developed to prevent this degradation in quality. One method performs with blowing shielding gas around the portion being welding to protect and cool the melted metals. This method is known as gas-shielded metal arc welding and use a different shielding gas which include argon (Ar) gas, helium gas, carbon dioxide (CO_2) gas, and Ar-CO_2 mixed gas. Gas shielded metal arc welding produces a high-quality weld and is easily adaptive to automatization. Thus, it is frequently applied in manufacturing. In gas shielded metal arc welding, gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are commonly applied. In view of this, this research investigates the arc generated during GMAW and GTAW.

GMAW is an arc welding process using an arc between a continuous filler metal electrode (welding wire) and a molten pool and is a semi-automatic welding process in which the welding wire is automatically supplied to the portion being welded. Further, GMAW has high working efficiency, it is currently the most used welding process to be performed. Figure 1.5 shows the state of GMAW operation.

GTAW is an arc welding process using an arc between a tungsten electrode (non-consumable) and a molten pool. In this method, a welding operator holds a welding torch with one hand and holds a filler rod with the other hand to perform the welding operation. welds, GTAW is used for high-quality welding and welding of thin plates. Figure 1.6 shows the state of GTAW operation.

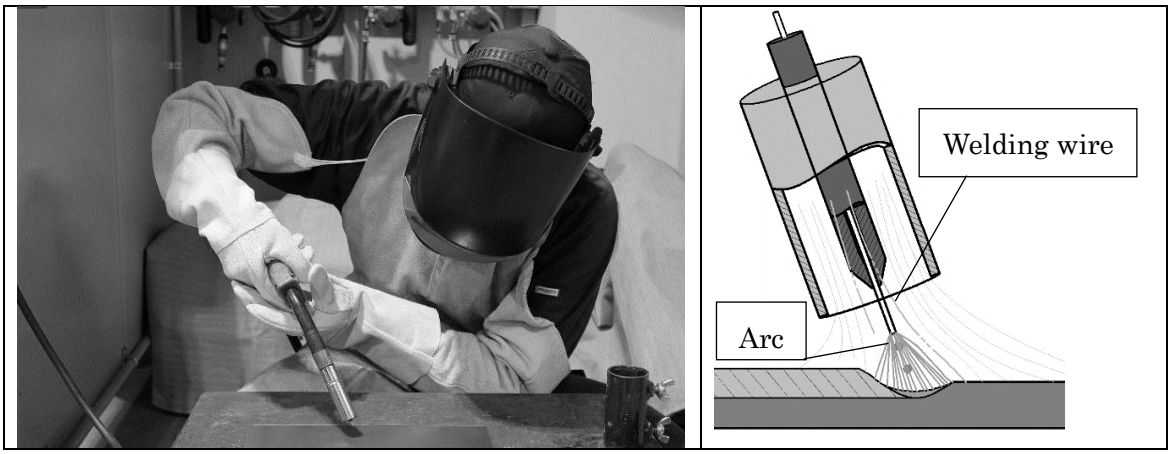

Figure 1.5. Work scenery of GMAW. A welding wire is automatically supplied during the arc.

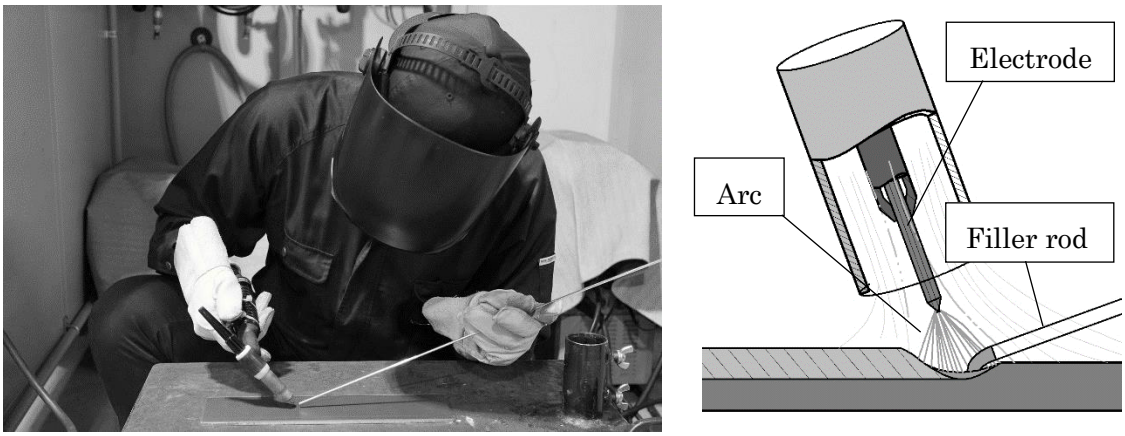

Figure 1.6. Work scenery of GTAW. A filler rod is inserted into a molten pool which is a localization liquid pool of molten metal in prior to its solidification as weld metal, and an inert gas is used as the shielding gas.

1.3.2 Welding arc

Figure 1.7 shows the wavelength distributions of the arc generated during GMAW of mild steel. As shown in this figure, the arcs generated during arc welding concurrently emit light in three wavelength regions of UVR, visible radiation and infrared radiation to the surrounding environment. Among them is the UV-C wavelength region, which does not exist in the natural environment. Figures 1.8 and 1.9 exemplify the distributions of arcs generated during GMAW of aluminum alloys and magnesium alloys, respectively. The arc generated during arc welding substantially differs according to the welding material. In general, in the case of GMAW of aluminum alloys and magnesium alloys, UVR and blue light account for higher percentages, respectively, compared with GMAW of mild steel. Moreover, the strength and wavelength distributions vary according to the conditions, such as welding method, shielding gas, welding current, welding voltage and arc length[15-23].

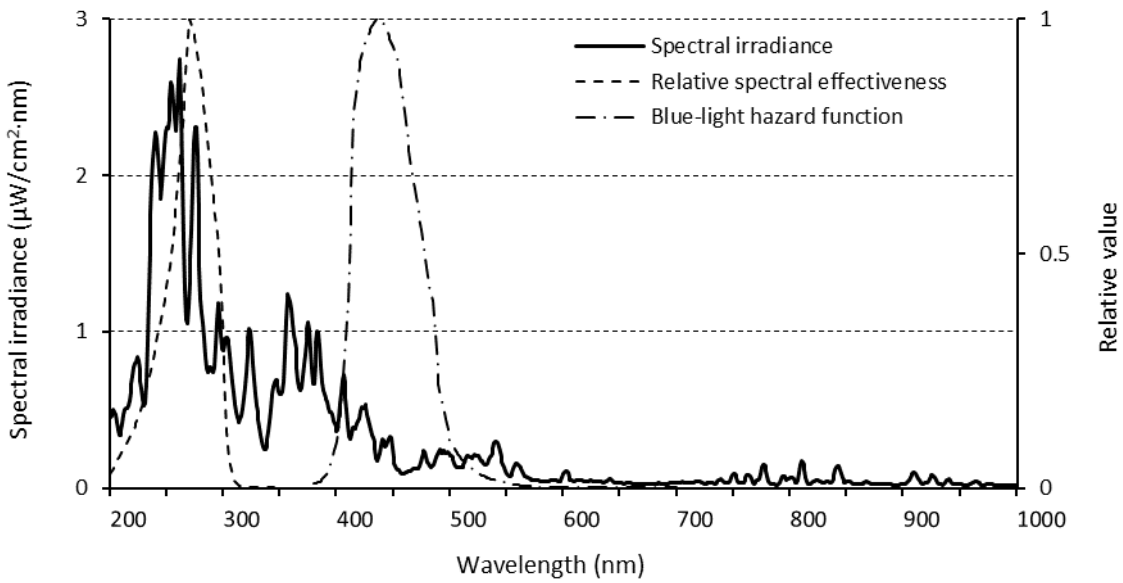

Figure 1.7 Spectral irradiance of arcs in GMAW of mild steel

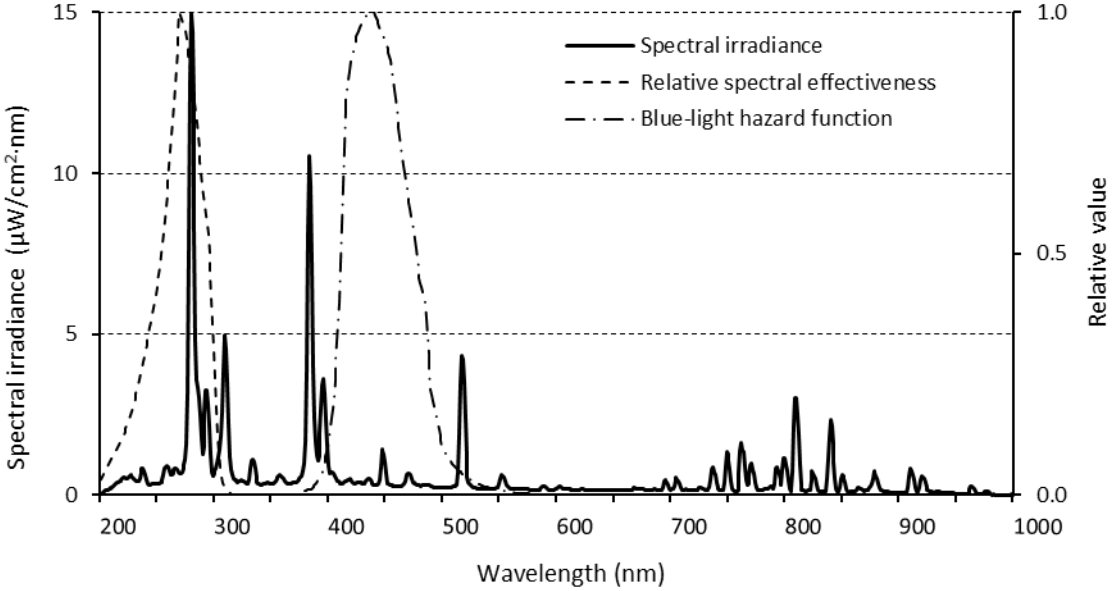

Figure 1.8 Spectral irradiance of arcs in GMAW of aluminum alloys

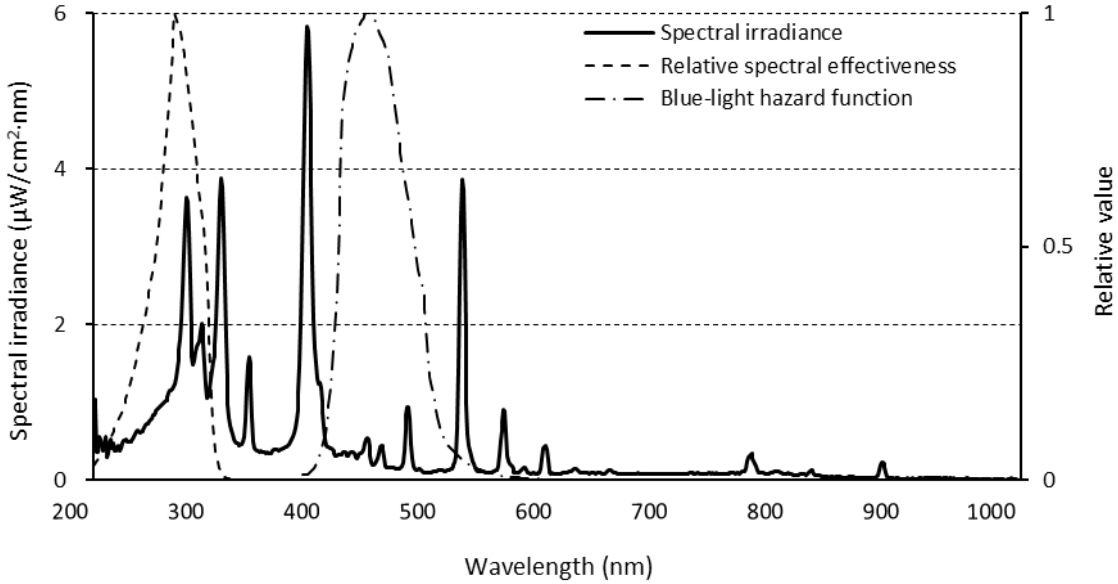

Figure 1.9 Spectral irradiance of arcs in GMAW of magnesium alloys

1.3.3 Health disorders caused by welding arc

Among the acute health effects of UVR during arc welding, the most common are keratoconjunctivitis and erythema. Although the number of incidences of kerato-conjunctivitis in the surrounding environment of an actual welding operation is presumably

very large, there is a paucity of relevant literature on the topic. According to an investigation by Emmett et al.[11], as many as 92% of all welders have experienced keratoconjunctivitis, and 40% of them have been affected by erythema on the neck.

According to a questionnaire investigation by the Japan Welding Engineering Society [10], welders complain of the following eye-disorder symptoms due to the arc generated by arc welding: foreign-body sensation (gritty sensation), eye pain, epiphora and photophobia. These subjective symptoms have different incubation periods. Welders are exposed to the arc during arc welding, but the symptoms appear after the welding work and overnight. However, the symptoms are transient, and normally disappear by the time the workers wake up the next morning. These transient subjective symptoms suggest that the disorder is keratoconjunctivitis due to UVR. As many as 86% of all welders have experienced such an eye disorder. Approximately 45% of the welders who have experienced such an eye disorder have experienced the same disorder once or more per month (as of the time when the investigation was made). Most welders (88%) use protectors for shielding light, these shading numbers and transmittance are shown in Table 1.2, and yet, many of them have experienced such an eye disorder. Therefore, it is considered that the 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 workplace.

There are reported cases of retinal damage caused by blue light emitted during arc welding. These cases involve workers who stared at the arc without wearing appropriate protective gear[24-32]. Blue light damages the eyes, which can adversely affect ADL. This damage is observed as a change in the retina, such as edema or a hole, and is accompanied by symptoms including decreased visual acuity, blurred vision and scotoma. These symptoms appear immediately or within a day after exposure, and then gradually resolve

over several weeks to several months. There are cases of complete recovery, but there are many cases where scotoma and decreased visual acuity become permanent.

Table 1.2 Light shielding ability value of filter (%)

Shading number	UVR transmittance (MAX)		Visible light transmittance		
	313 nm	365 nm	Max	Standard	Min
8	0.0003	0.013	0.16	0.100	0.061
9	0.0003	0.0045	0.061	0.037	0.023
10	0.0003	0.0016	0.023	0.0139	0.0085
11	0.0003	0.0006	0.0085	0.0052	0.0032
12	0.0002	0.0002	0.0032	0.0019	0.0012

1.4 Objective of this research

Hazardous emissions from arc welding have various adverse effects on welders and those working around the welding site. Various measures have been taken to counter this problem, but the countermeasures against welding arc are insufficient. From the perspective of improving the workplace environment for arc welding operations and the industrial health of workers, preventive measures against exposure to arcs emitted during arc welding are desired.

In particular, disorders of the eyes are serious and adversely affect ADL. Establishing effective preventive measures against eye disorders due to welding arc requires quantitative evaluation of welding arcs. Arc welding is performed using various materials by applying different welding methods and conditions, and there may be varying degrees of hazard level according to the respective welding arc that is emitted. For this reason, it is necessary to research the hazards of arcs emitted during arc welding under various conditions that mimic actual welding operations.

For UVR, previous studies have measured the UVR emitted during arc welding processes, such as mild steel and aluminum alloys, and assessed their acute health effects

by ACGIH guideline[18-22, 33-35]. In these studies, the effective irradiance of UVR emitted during gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) of aluminum alloys and GMAW of mild steel was measured. Dependence of effective irradiance on the welding current and adaptation of the inverse square law of distance were also verified. In arc welding, welding results, such as the shape of weld bead and the depth of fusion, have been dependent on welding materials (components of a base metal and a filler metal), the pulsed current, the shielding gas, and the type of electrodes. It is considered that these elements also have an effect on UVR, because there is a close relationship between the state of the arc and the welding result. However, the influence of these elements on the hazard from UVR has not yet been investigated. In addition, because the UVR emitted during arc welding is influenced by reflections from the surface of a base metal and the liquid surface of molten pool, and by absorption/scattering due to fumes, the effective irradiance of UVR is thought to be subjected to the angular dependence. However, it is considered to be insufficient because the angular dependency of the effective irradiance had only been investigated regarding the angle from the surface of the base material in GMAW of mild steel[33].

For blue light, a few studies have measured the blue light in arc welding of aluminum alloys [35-37], one of these has actually measured the effective radiance of blue light emitted during arc welding of mild steel[37]. And two studies have determined the effective blue-light radiance of mild steel and aluminum alloy[35,36]. In these studies, the effective blue-light irradiance (spectral irradiance weighted against the blue-light hazard function) was measured at a fixed distance from the arc. The effective blue-light radiance was then calculated from the effective blue-light irradiance by using the estimated size (area) of the arc. However, this method provided inaccurate results, because the arc has no definite

boundaries and consequently no definite size. Thus, no reliable data on the effective blue-light radiance for arc welding of aluminum alloys are available.

The author provides technical guidance on arc welding of mild steel, stainless steel and aluminum alloys at the Polytechnic University of Japan. Among them, people who suffer from keratconjunctivities or dermatitis often appear. In particular, at the time of GMAW of aluminum alloys, the occurrence frequency of keratconjunctivities and dermatitis is high, and the symptom is serious. Actually, in the ophthalmologic examination, abnormalities were found in the skin of the keratoconjunctiva and eyelid for workers tasked to GMAW of aluminum alloy[10)]. Therefore, the hazard of UVR emitted during GTAW and GMAW, which is a typical arc welding methods of aluminum alloys, were quantitatively evaluated. Next, in order to compare with the hazard of UVR emitted during arc welding of aluminum alloys, the hazardous of UVR emitted in GMAW of mild steel most frequently carried out in the country was quantitatively evaluated. Furthermore, since the hazard of UVR emitted during the arc welding of aluminum alloys were strongly influenced by magnesium contained in the aluminum alloy, the hazardous of UVR emitted during GTAW and GMAW of magnesium alloy were quantitative evaluated. In addition, the hazard of blue light emitted during GMAW of aluminum alloys were also quantitatively evaluated, because the arcs emitted by arc welding of aluminum alloys appeared strong emission in the wavelength range of blue light. The features of the three types of metallic materials used in this study are shown below.

Aluminum alloys exhibit excellent properties—light weight, high strength-to-weight ratio, corrosion resistance, workability, and good appearance—and are widely used as raw materials for structural products and components in a wide variety of fields, including manufacture of 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 GMAW and GTAW. GMAW is primarily used for base metals of thickness 3 mm or greater, while GTAW is used for beams of lesser thickness.

Mild steel is the most welded metal material so far. Among them, GMAW of mild steel is the most widely practiced and applied to various industrial products and building structures. Currently, mild steel is being converted to aluminum alloy and the like for the purpose of reducing environmental burden, but it is expected to be widely used in the future because of high cost and weldability.

Magnesium alloys are promising as structural materials because of their excellent specific strength and vibration damping properties. However, their flammability and difficulty in plastic forming have limited the application of these alloys. In recent years, flame-retardant magnesium alloys and their plastic working technology have been developed and are expected to be applied to structures in various fields such as railway vehicles. Moreover, with the development of production technique a welding wire made of flame-retardant magnesium alloy, welding of magnesium alloys is expected in the future.

The purpose of this thesis is to evaluate the hazard of light emitted to the surrounding environment during welding operation, the hazard level in relation to the acute health effects of UVR and blue light emitted during arc welding under suitable various conditions for actual welding operations quantitatively have been evaluated according to ACGIH recommendations. Among them, the hazard of UVR and blue light were examined for welding materials, welding methods and welding conditions, detailed corresponding to the latest welding technology. Experimental methods with high reliability and reproducibility were adopted for the investigation.

1.5 Composition of this thesis

This thesis is organized based on the background and a series of considerations as stated in the above. Chapters 2–5 describe the research into the hazards of UVR during arc welding, and Chapter 6 describes the research into the hazards of blue light during arc welding. Table 1.3 summarizes the relationships between the evaluation of hazardous optical radiation discussed in this thesis and the welding materials.

Table 1.3 Evaluation of hazardous optical radiation and welding materials

	Aluminum alloys	Mild steel	Magnesium alloys
UVR	Chapters 2 and 3	Chapter 4	Chapter 5
Blue light	Chapter 6	—	—

The content of each Chapter is summarized as follows:

Chapter II

In this chapter, I evaluated quantitatively the hazard of UVR emitted during GTAW of aluminum alloys. In particular, I 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.

Chapter III

In this chapter, I evaluated quantitatively the hazard of UVR emitted during GMAW of aluminum alloys. In particular, I studied the impact of (i) the type of base metal, the type of welding wire, and the magnitude of the welding current, (ii) the direction in which UVR is emitted from the arc, and (iii) the use of pulsed welding current.

Chapter IV

In this chapter, I evaluated quantitatively the hazard of UVR emitted during GMAW of mild steel. 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. steady welding current.

Chapter V

In this chapter, I evaluated quantitatively the hazard of UVR emitted during GTAW and GMAW of magnesium alloys. In particular, I studied the influence of (i) the magnitude of the welding current, (ii) the type of electrode and the type of shielding gas, and (iii) the type of welding methods.

Chapter VI

In this chapter, I evaluated quantitatively the hazard of blue light emitted in the GMAW of aluminum alloys. In particular, we studied the impact of (i) the magnitude of welding current, (ii) the use of pulsed welding current, (iii) the type of base metal and welding wire.

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Chapter II

Hazard of Ultraviolet Radiation Emitted in Gas Tungsten Arc Welding of Aluminum Alloys

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, I 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 (ACGIH). 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, I 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

2.1 Introduction

The light emitted in arc welding contains strong 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 300,000 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)]. UVR is not visible to the human eye. 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 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 such as low a pressure mercury lamp, a xenon lamp and excimer lasers etc.—there is little cause for concern regarding its hazard.

UVR interacts strongly with living organisms and is known to cause a variety of problems[4,5)]. 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 performed[1,6]. 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 not[1]. 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

GMAW and 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 which is a localized volume of molten metal in a weld prior to its solidification as weld metal, 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 effects[5,7-10]. 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 this chapter, I conducted investigation of the hazard of UVR emitted during GTAW of aluminum alloys. In particular, I 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.

2.2 Methods

According to the ACGIH guidelines[11], 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):

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

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, I 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 Figure 2.1[12)], 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 (in the range 0.015–0.0010), I expect the impact of this discrepancy to be small and believe it to cause no difficulties in practice. Thus, I 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 keep 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.

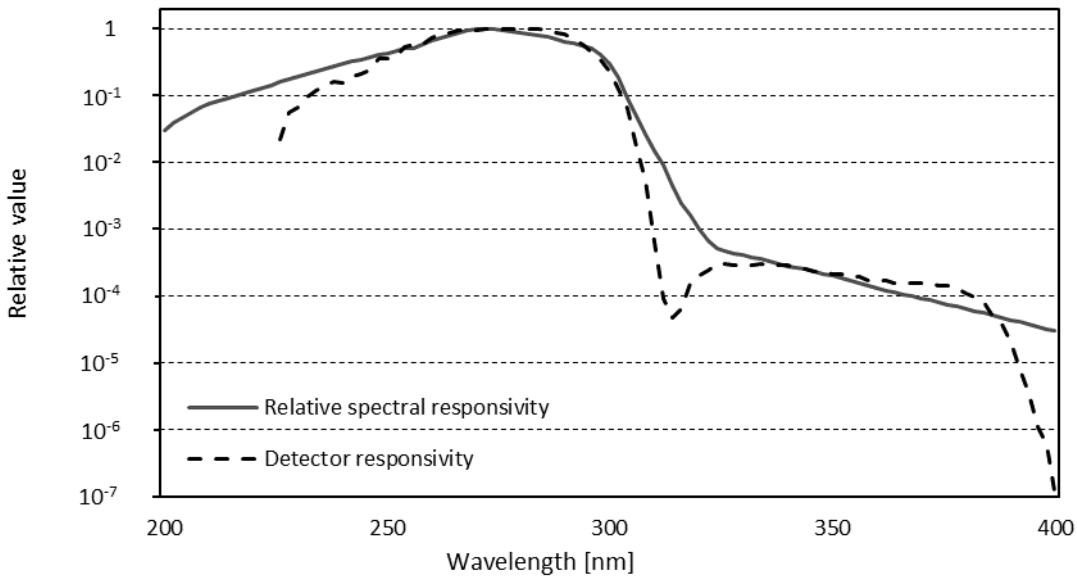


Figure 2.1 Relative spectral responsivity of the hazard lightmeter and ACGIH relative spectral effectiveness.

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, I 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)].

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

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.) that has been used with increasing frequency in recent years. The inclination of the welding torch was fixed at 110°. 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[13,14]. The primary welding conditions at welding currents of 100 and 200 A are presented in Table 2.1.

Table 2.1 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

2.2.1 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, I 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[15]. Table 2.2 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 200 A. 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 2600 mm, and the measurement time was set in the range of 130–235 ms by the automated adjustment functionality of the measurement apparatus. Further, these measured data not include the influence of light other than welding arc. This is because, immediately after the measurement of a welding arc, the measuring apparatus automatically measures the wavelength distribution of the light under the experimental environment without the welding arc, and removes the influence other than the welding arc. Figure 2.2 shows a schematic diagram of experimental setup for measuring effective irradiance and spectral irradiance.

Table 2.2 Chemical compositions of base metals (mass %)

Element		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Al
Base metal	Thickness, mm										
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		remainder
	5	0.15	0.30	0.04	0.58	4.35	0.11	0.02	0.02		remainder
A6061P-T6	2	0.61	0.43	0.28	0.02	1.01	0.23	0.01	0.05		remainder
	5	0.62	0.43	0.29	0.02	1.02	0.11	0.01	0.04		remainder

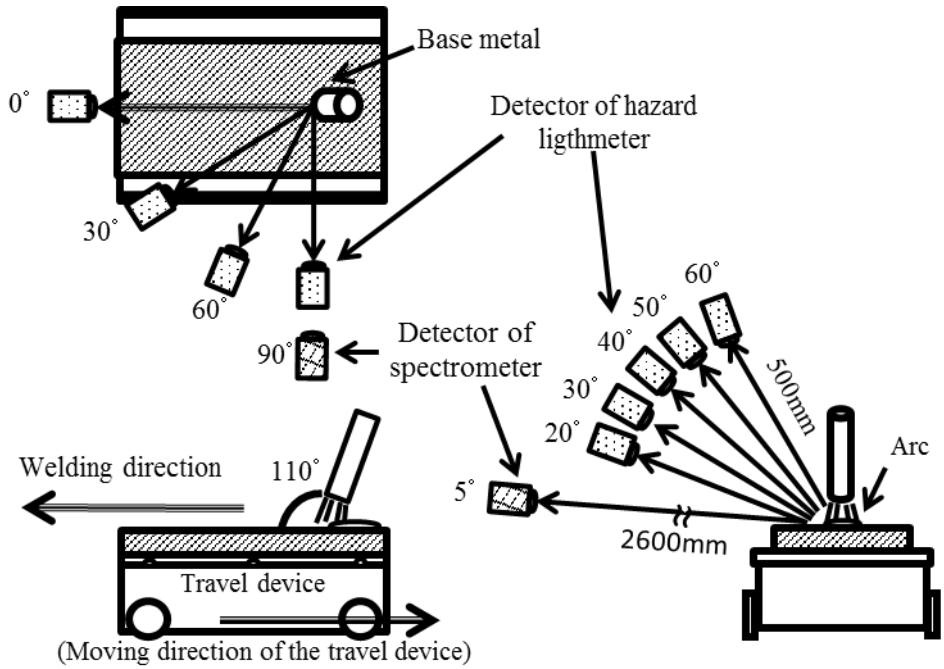


Figure 2.2 Experimental setup for measuring effective irradiance and spectral irradiance (schematic diagram).

To investigate the impact of the combination of base metal and filler rod, the bead-on-plate welding were performed 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. The bead-on-plate welding is a weld method applied to surface, as opposed to making a joint, to obtain desired properties or dimensions (Figure 2.3). For the filler rods, three types of filler rods were used specified by JIS: A1100BY, A4043BY, and A5183BY[16)]. The JIS-specified composition of these materials is presented in Table 2.3. 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, two values of the welding current were used: 100 and 200 A. As shown in Figure 2.2, 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 2.4 presents the combinations of base metals and filler rods, and their symbols.

Table 2.3 Chemical compositions of filler rods (mass %)

Element		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Al
Filler rods	Diameter, mm										
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		remainder
	4.0	4.97	0.21	0.01	0.01	0.04		0.01	0.03		remainder
A5183BY	2.4	0.07	0.17	0.00	0.70	5.12	0.07	0.00	0.07		remainder
	4.0	0.07	0.17	0.00	0.70	5.12	0.07	0.00	0.07		remainder

Table 2.4 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

2.2.2 Dependence on the direction of emission from the arc

To investigate the dependence on the direction of emission from the arc, I 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. As figure 2.2 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 200 A and a pure tungsten electrode. The base metal was A5083P-O. The distance between the detector head and the arc was 500 mm.

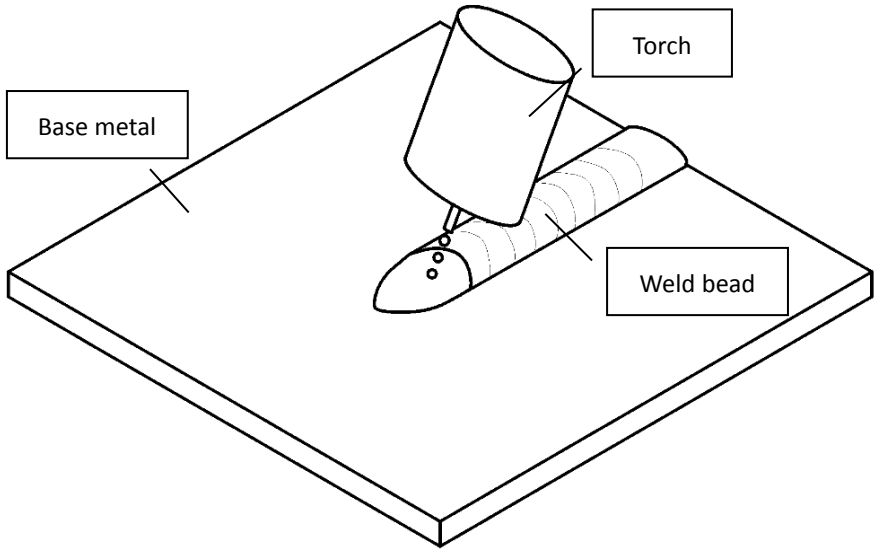


Figure 2.3 Bead-on-plate welding (simulated welding with no joint).

2.2.3 Impact of the type of electrode

To investigate the impact of the choice of electrodes, GTAW were performed using five different JIS-specified electrodes (YWP, YWCe-2, YWLa-2, WZ8, and YWTh-2)[17] and measured the resulting emission of UVR. Table 2.5 presents the composition of these electrodes as specified by JIS. YWP is a pure tungsten electrode, while the other electrodes contain oxides. Melt-run welding was performed using a base metal of A5083P-O and a welding current of 200 A. 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 2.5 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

2.3 Results

The effective irradiances measured in this study at a distance of 500 mm from the arc were in the range 0.09–0.91 mW/cm^2. The allowable daily exposure times corresponding to these values are 3.3–33 s.

Figure 2.4 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; lowest 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 2.5 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 various 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 combination 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 second 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 200 A than for a welding current of 100 A.

Figure 2.6 shows the effective irradiance for various angles from the horizontal surface of the base metal. The effective irradiance was greatest when the angle from the surface of the base metal is 40° and decreased for angles greater or less than this.

Figure 2.7 shows the results of measurements of the effective irradiance versus the angle of inclination with respect to the welding direction. There was no clear dependence of the effective irradiance on the angle of inclination.

Figure 2.8 shows the results of measurements of the effective irradiance for different electrodes. The effective irradiance for electrodes containing oxides was 10–20% larger than that for the pure tungsten electrode YWP.

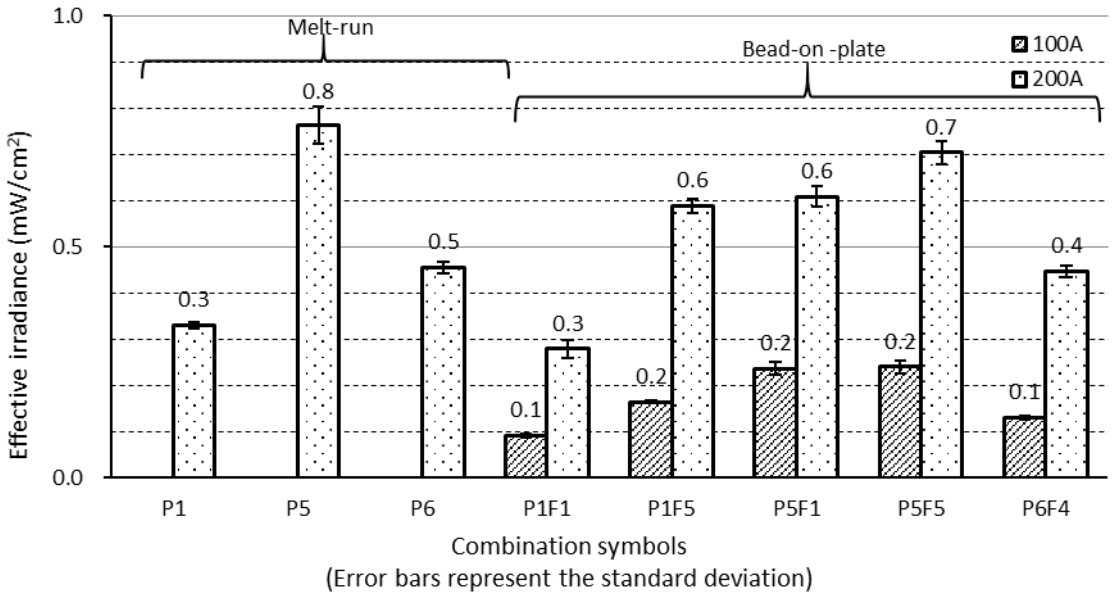


Figure 2.4 Effective irradiance for different base metals and filler rods. Error bar represent the standard deviation.

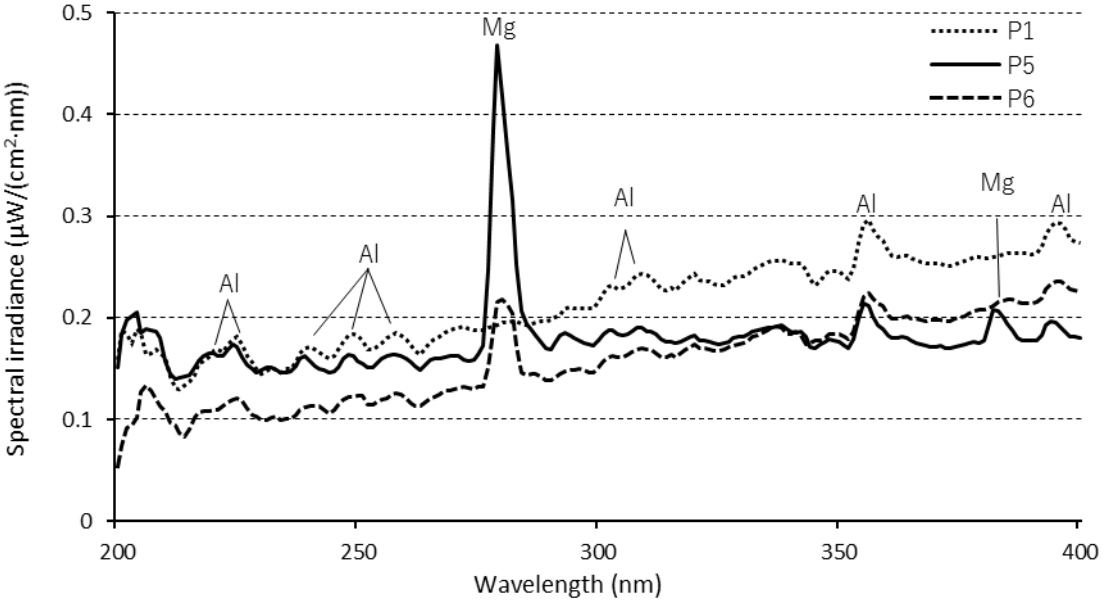


Figure 2.5 Spectral irradiance for different base metals in melt-run welding.

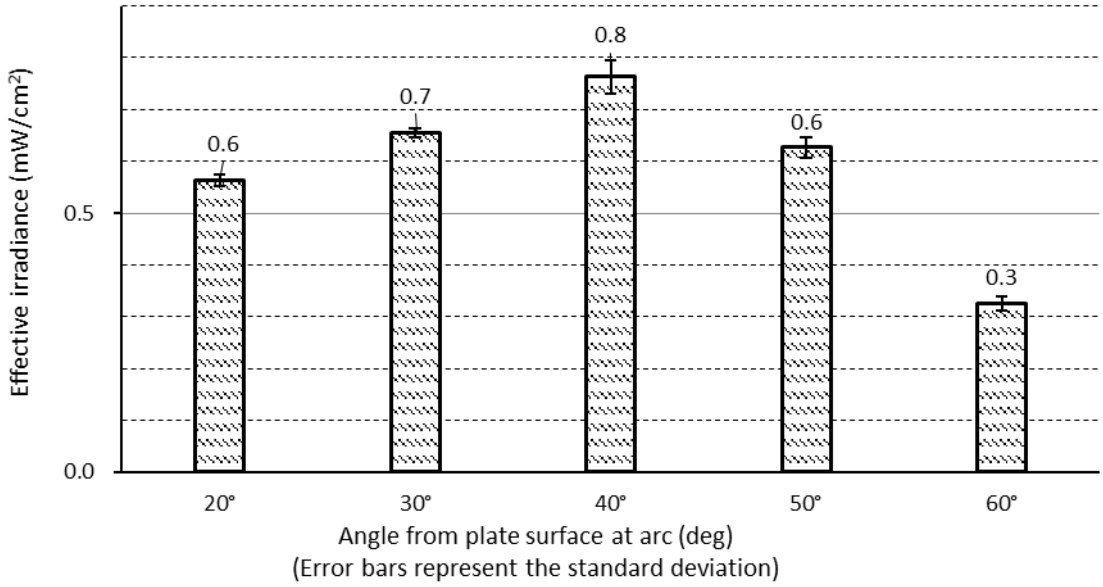


Figure 2.6 Effective irradiance against angle from plate surface. Error bars represent the standard deviation.

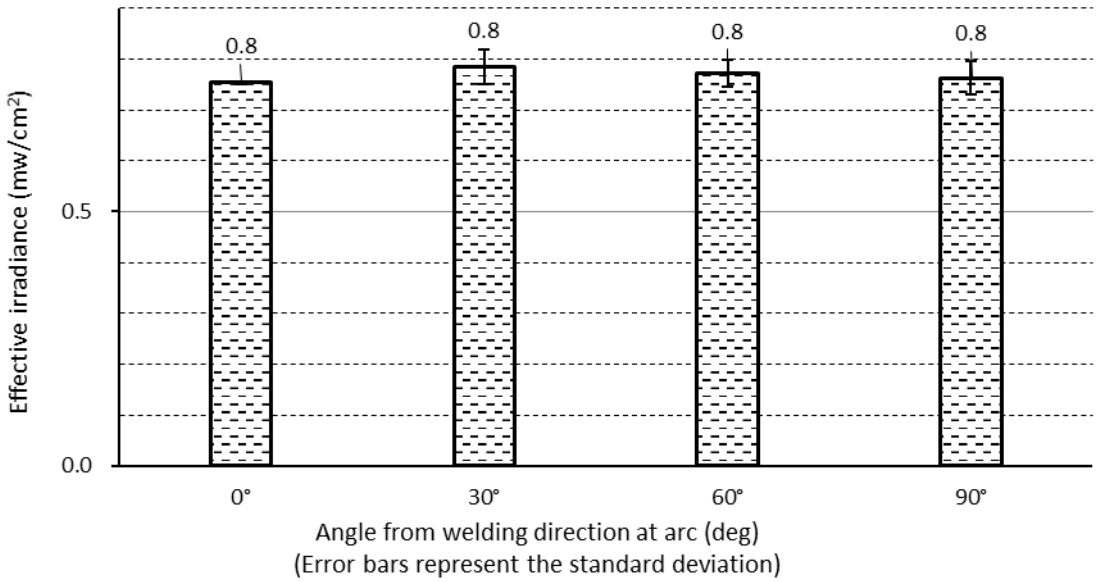


Figure 2.7 Effective irradiance against angle with respect to welding direction. Error bars represent the standard deviation.

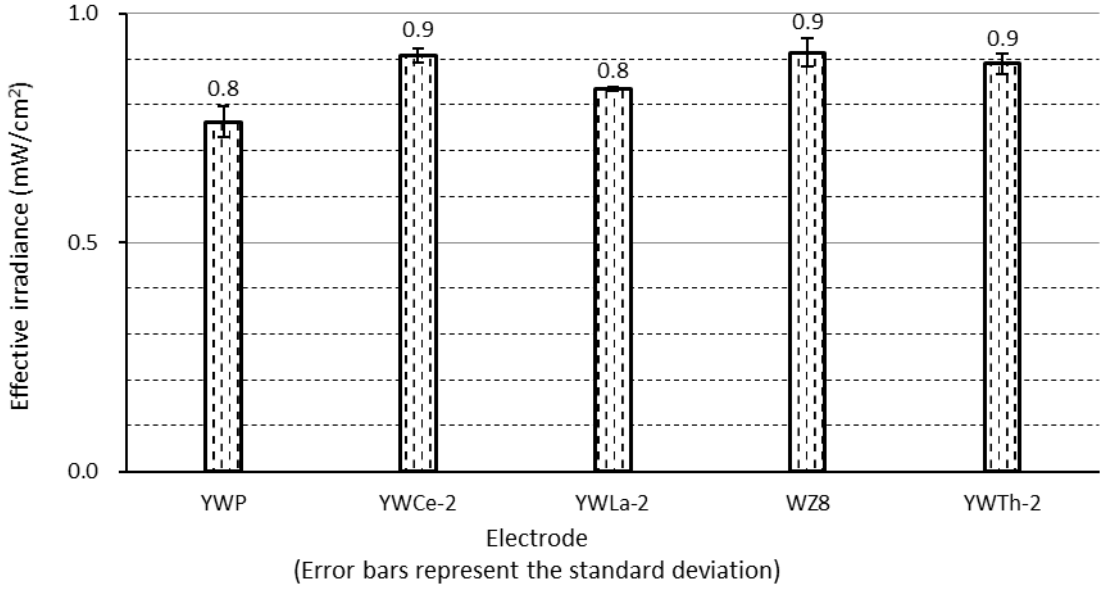


Figure 2.8 Effective irradiance for different electrodes in melt-run welding. Error bars represent the standard deviation

2.4 Discussion

The effective irradiances observed at distances of 500 mm from the arc were in the range 0.091–0.91 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, it is concluded 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.

Assuming 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, I sure 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.

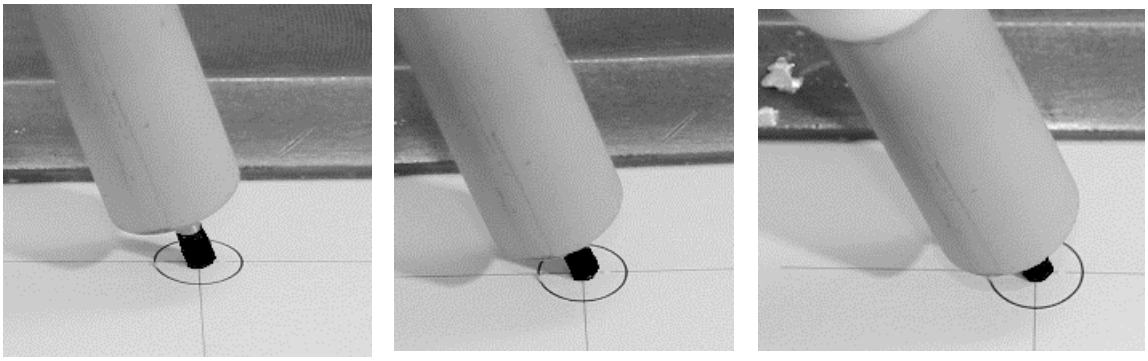
For the case of bead-on-plate welding, the effective irradiances measured for a welding current of 200 A were 2.6–3.6 times greater than those measured for a welding current of 100 A, with other conditions held fixed (Figure 2.4). Thus, the welding current is an important factor influencing the hazard 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 (Figure 2.4). 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 (Figure 2.5). 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. It is able to attribute this to the fact that the boiling point of magnesium (1090°C) is considerably lower than that of aluminum (2470°C), ensuring that magnesium is preferentially vaporized from the molten pool, giving rise to greater UVR. In addition, the relative spectral effectiveness[11)]—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, it is concluded 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 (Figure 2.6). I sure the reason for this to be as follows. Figure 2.9 shows the positional relation between the nozzle, the simulated arc column and the simulated molten pool, as observed from the detector. In the figure, a circle shows a simulated molten pool, and the black portion of the electrode (nozzle) tip displays a simulated arc column. The UVR associated with GTAW arises from the metal vapor produced from the surface of molten pool[18)]; 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.



40° 50° 60°

Figure 2.9 Angular relations of nozzle and molten pool observed from the detector

As shown in Figure 2.7, 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 sure to be caused by absorption or scattering of UVR by fumes (smoke emitted during welding) produced in GMAW[19]. 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 study[11] 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, it is expected that GMAW of aluminum alloys will be more hazardous than GTAW at actual workplaces, as was observed in research studies.

2.5 Conclusions

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.

2.6 References

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Chapter III

Study of Ultraviolet Radiation Emitted by Gas Metal Arc Welding of Aluminum Alloys

Abstract

The ultraviolet radiation (UVR) generated during arc welding is a well-known cause of photokeratoconjunctivitis and is also associated with dermatitis and skin cancer. Determining the ultraviolet radiation level of the various welding conditions is important for establishing protective measures for workers in the workplace.

In this study, the UVR emitted during gas metal arc welding (GMAW) of aluminum alloys with a digital inverter-type pulsed arc welding machine was measured. In the experiment, the base metal is moved, and the welding torch and the UVR detector are fixed to measure the effective irradiance of UVR. Measurements are carried out for 40 seconds and repeated three times. The distance between the detector and the arc is 500 mm.

The following results were obtained: (1) the effective irradiance of UVR is strongly influenced by the amount of magnesium contained in aluminum alloys, and magnesium in the welding wire contributes more to the emission of UVR than that in the base metal; (2) the effective irradiance is dependent on the angle of the welding direction and the angle from the base material and is the strongest near the face and cervix of the welding operator; and (3) the effective irradiance is significantly increased when using the pulsed current.

Key words: ultraviolet radiation, UVR, effective irradiance, GMAW, pulsed current, aluminum alloys

3.1 Introduction

About 15 years ago, a digital inverter-type pulsed arc welding machine (DP welding machine) was developed. This welding machine has facilitated gas metal arc welding (GMAW) of aluminum alloys, which are considered difficult to weld. In actual welding operation, even if the same welding current is used, UVR seems more intense in the GMAW of aluminum alloys as compared with shielded metal arc welding (SMAW) and CO_2 arc welding of mild steel. Because the opportunities for the GMAW of aluminum alloys are expected to increase in the future, welding workers and their surrounding workers will be exposed to strong UVR for longer times in the workplace, and the exposure on the human body has always been a concern. The effective irradiance during arc welding of aluminum alloys has been measured in past research[1-4]. However, in this past research, the effective irradiance was measured under conditions that were different from those of an actual welding operation. For example, the measurement time was as short as a few seconds and the measurement distance was 1 to 2 m, which is longer than that in actual welding operations. In addition, because the detector was moved along with the arm movements of the welding operators, the measured values varied. To solve these problems, in this research, the welding torch was fixed to make the arc remain in the same position, while the base metal was placed horizontally on a travel device that was moved along a horizontal line at a constant speed when the effective irradiance was being measured. The measurement distance was set to 500 mm, and the effective irradiance of the UVR was obtained not only by using the inverse square method but also by actual measurement.

The effective irradiance during the GMAW of aluminum alloys has been reported to possibly depend on the magnesium content[3]. However, it was not clarified whether the dependence was larger for the magnesium contained in the base metal or that in the welding wire. To answer this question, I prepared several combinations of base metal and welding

wire, measured the effective irradiance, and investigated the effects of magnesium.

Other studies have also reported the angular dependence of the effective irradiance from the surface of a horizontally arranged base metal[5]. However, when the UVR exposure of operators working around the welding site is considered, the angle dependence from the base metal surface alone is not sufficient. In view of this, this research added studies of the angle dependence against the welding direction during flat position forehead welding.

In addition, no previous studies have measured the effective irradiance during pulsed gas metal arc welding (GMAW-P) by the pulsed current of the DP welding machine. Therefore, I made include this welding process in our study.

In summary, the hazard of the UVR emitted during the GMAW of aluminum alloys was investigated. In particular, I studied the impact of **(i)** the type of base metal, the type of welding wire, and the magnitude of the welding current, **(ii)** the direction in which the UVR is emitted from the arc, and **(iii)** the use of pulsed welding current.

3.2 Hazard assessment of the UVR

According to the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines[6], the degree of hazard of the UVR as a cause of acute health effects is measured by the effective irradiance. The effective irradiance is defined by equation (1):

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

In this equation, E_{eff} is the effective irradiance (mW/cm^2), E_{λ} is the spectral irradiance at wavelength λ (mW/ (cm^2· nm)), $S(\lambda)$ is the relative spectral effectiveness at wavelength λ, and Δλ is the wavelength bandwidth (nm).

ACGIH has set the threshold of E_{eff} at 270 nm to be limited to 3 mJ/cm^2. If the UVR is irradiated to the skin and eyes unprotected, in general, the maximum exposure time for the broadband UV source can be determined from equation (2).

$$t_{max} = \frac{3\ \mathrm{mJ/cm^2}}{E_{eff}} \quad \cdot\cdot\cdot\cdot\cdot (2)$$

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

3.3 Methods

For the UVR measurements, An X1$_3$ hazard lightmeter and an XD-45-HUV UV-hazard detector head (both from Gigahertz-Optik) were used. Both of these devices can measure the effective irradiance conforming to the ACGIH criteria. The detector head has three sensors. The measurement of effective irradiance was taken by two sensors: one for UV-CB (measurement wavelength range: 200–320 nm) and one for UV-A (measurement wavelength range: 320–400 nm). Table 3.1 shows the characteristics of these sensors. The sensitivity of these sensors was adjusted to coincide with the relative spectral effectiveness determined by ACGIH and the manufacturer. The measurement device was calibrated by the manufacturer and used within the one-year validity of the calibration. Figure 2.1 shows the relation between the relative spectral effectiveness and the sensitivity of the sensors[7)]. The sensitivity of these sensors almost matches the relative spectral effectiveness in the vicinity of 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 consider the influence of this discrepancy to be negligible. Thus, it was concluded that this detector head

is well suited to measure the effective irradiance.

Table 3.1 Characteristics of UV sensors

	Wavelength, nm	Measurement range, mW/cm^2	Max. resolution, mW/cm^2
UV-CB	200–320 nm	0.5×10^{-4}–1×10^{3} mW/cm^2	5.0×10^{-6} mW/cm^2
UV-A	320–400 nm	0.5×10^{-7}–1 mW/cm^2	5.0×10^{-6} mW/cm^2

In this study, in the measurement of the UVR, 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 linearly for welding. This setup enabled stable measurement. The distance between the arc and the detector head was set to 500 mm to simulate the 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 began and the time required for the movable table to accelerate, measurements did not begin until 5 s after the start of welding. Measurements were repeated three times for each set of conditions and then averaged. In this study, no local exhaust ventilation system was used during measurement of the 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).

The welding apparatus was a DP welding machine (DA300P, Daihen Welding and Mechatronics Systems Co., Ltd.), a machine that has been used with increasing frequency in recent years. 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 by flat position forehead welding. For the welding wire, we used solid wire of diameter 1.2 mm. The distance between the base metal and the contact tip was 20 mm, and the wire extension length before the start of welding was 15 mm. The welding speed was 300 mm/min. The

shielding gas was 100% Ar, and the shielding gas flow rate was 20 l/min. The inner diameter of the nozzle was 16.5 mm. In this experiment, the effective irradiance was measured during GMAW-P using the pulsed current. In a DP welding machine, the welding voltage and the pulse conditions (peak current, peak time, base current, base time) were set by the monistic setting of the welding current (average current). Table 3.2 shows the pulsed conditions used in this study. The relation of the welding current and the pulsed conditions are shown in equation (3).

$$I_{av} = \frac{I_p T_p + I_b T_b}{T_p + T_b} \quad \cdot \cdot \cdot \cdot \cdot (3)$$

In this equation, I_{av}: welding current (the average current), I_p: peak current, T_p: peak time, I_b: base current, T_b: base time.

Table 3.2 Parameters based on welding current in the DP350 welding machine

Welding current (Average current) (A)	100	150	200	250
Welding voltage (V)	19.0	21.5	24.0	26.0
Peak current (A)	330	330	340	370
Base current (A)	30	50	80	120
Peak time (ms)	0.8	0.8	0.8	1.0

3.3.1 Impact of the welding current and the combinations of base metal and welding wire

To investigate the influence of the welding current and the combinations of base metal and welding wire, the effective irradiance during bead-on-plate welding was measured. The welding currents used were 100, 150, 200 and 250 A. For the base metals, we used three types of base metals specified by the Japanese Industrial Standards (JIS): A1050P-H24,

A5083P-O, and A6063P-O[8,9]. Table 3.3 presents the composition of these base metals as specified by JIS. A1100P-O is essentially pure aluminum, A5083P-O is an alloy including 4–5% magnesium and A6063P-O is an alloy including 1% magnesium as well as additional elements other than magnesium. The dimensions of all base metal were 15 × 300 × 150 mm. For the welding wires, we used three types of welding wires specified by JIS: A1100WY, A4043WY, and A5183WY[10] The JIS-specified composition of these materials is presented in Table 3.4. A1100WY is essentially pure aluminum, A4043WY is an alloy containing small quantities of magnesium and other non-magnesium elements, and A5183WY is an alloy containing 4–5% magnesium. The diameter of welding wire was 1.2 mm. Table 3.5 lists the combinations of base metal and welding wire, and their abbreviated labels. As shown in Figure 3.1, the detector head was positioned at an angle of 20° 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.

In addition to the effective irradiance, the spectral irradiance of the UVR for combinations P5W5, P1W1 and P6W4 was also measured. The welding current was 250 A at that time. By analyzing the intensity of irradiance of each broadband UVR wavelength of the arc, we can identify the factors that affect the hazard 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 detector was positioned at an angle of 5° from the surface of the base metal and at an angle of 90° from the welding direction. The distance from the arc was set to 2000 mm, and the measurement time was set in the range of 395 ms by using the automated adjustment functionality of the measurement apparatus.

Table 3.3 Chemical compositions of base materials (mass%)

Alloy symbol (JIS designation)		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A1100-PO	min	-		0.05	-	-	-	-	-	99.00
	max	0.90		0.2	0.05			0.10	-	-
A5083-PO	min	-	-	-	0.40	4.0	0.05	-	-	remainder
	max	0.40	0.40	0.10	1.0	4.9	0.25	0.25	0.15	
A6063-PO	min	0.20	-	-	-	0.45	-	-	-	remainder
	max	0.6	0.35	0.10	0.10	0.90	0.10	0.10	0.10	

Table 3.4 Chemical compositions of welding solid wires (mass%)

Alloy symbol (JIS designation)		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A1100-WY	min	-		0.05	-	-	-	-	-	99.00
	max	0.90		0.2	0.05			0.10	-	-
A4043-WY	min	4.5	-	-	-	-	-	-	-	remainder
	max	6.0	0.8	0.30	0.05	0.05	-	0.10	0.20	
A5083-WY	min	-	-	-	0.50	4.3	0.05	-	-	remainder
	max	0.40	0.40	0.10	1.0	5.2	0.25	0.25	0.15	

Table 3.5 Combinations of base metal and welding solid wire

Combination label	Base metal	Welding wire
P1W1	A1100P-O	A1100WY
P1W5	A1100P-O	A5183WY
P5W1	A5083P-O	A1100WY
P5W5	A5083P-O	A5183WY
P6W4	A6063P-O	A4043WY

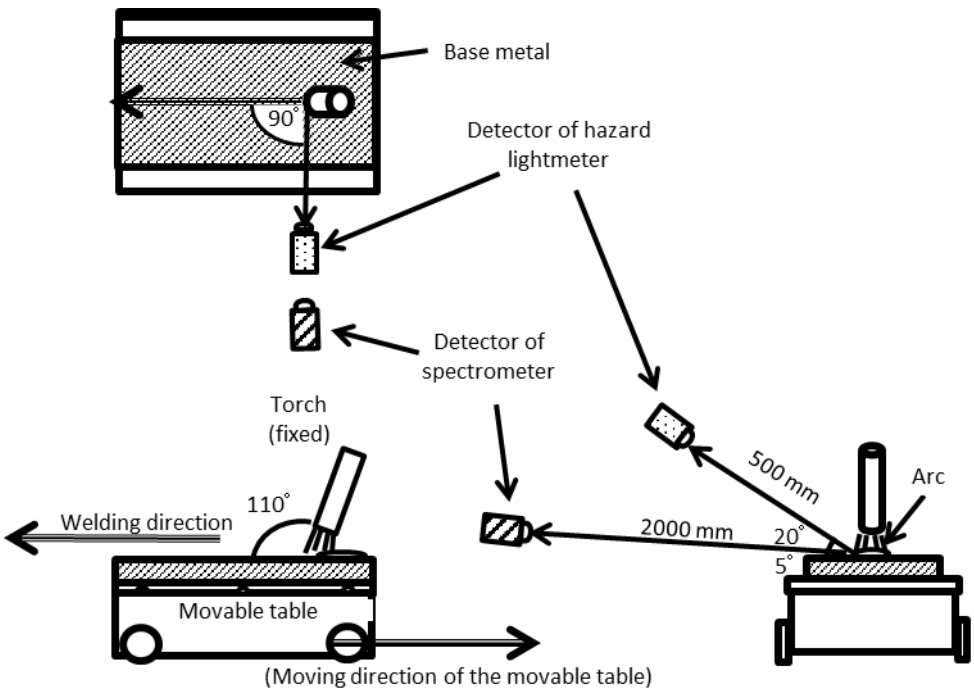


Figure 3.1 Setup for measuring influence of magnesium in welding materials (schematic diagram)

3.3.2 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 the UVR while varying the angle from the horizontal surface of the base metal and the angle in the welding direction. Figures 3.2 and 3.3 illustrate 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 50° and the angle with respect to the welding direction was set to 0°, 30°, 60°, and 90°. Bead-on-plate welding was conducted by using welding currents of 100, 150, 200 and 250A. The base metal was A5083P-O and the welding wire was A5183WY. The distance between the detector head and the arc was 500 mm.

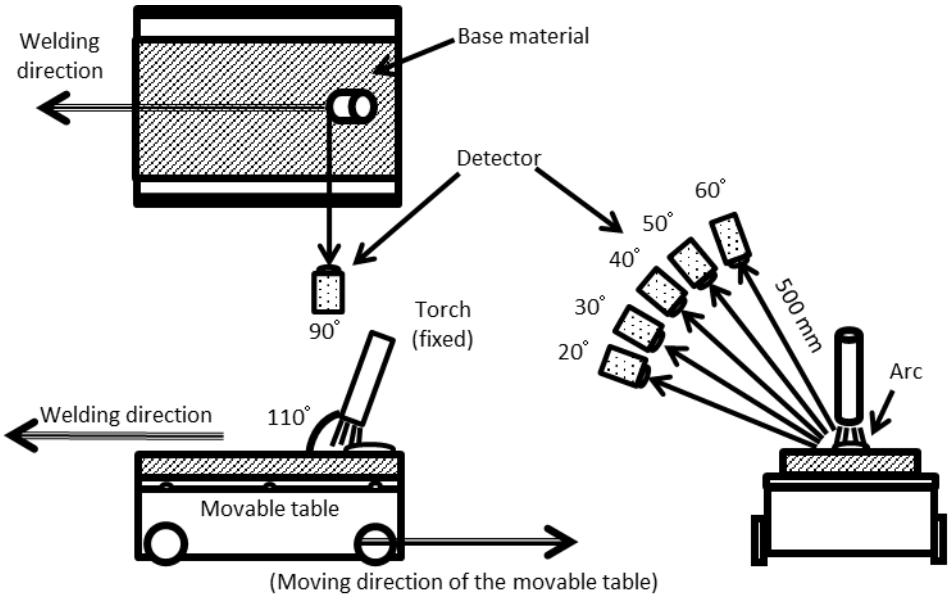


Figure 3.2 Setup for measuring angle dependence from the material surface (schematic diagram)

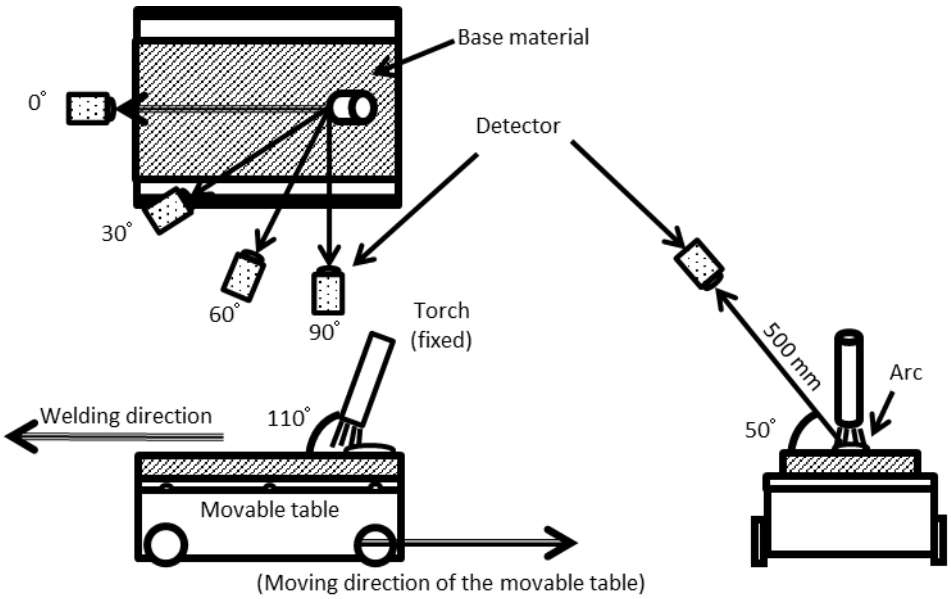


Figure 3.3 Setup for measuring angle dependence of the welding direction (schematic diagram)

3.3.3 Influence of the pulsed current

To investigate the influence of the pulsed current (GMAW-P) on the effective irradiance, the effective irradiance of the GMAW of the steady welding current (GMAW-S) was measured. Table 3.6 shows the welding parameters including current and voltage in GMAW-S. The bead-on-plate welding was performed using the base metal A5083P-O (t30×400×250 mm) and welding wire A5183-WY. As shown in Figure 3.3, the detector head was positioned at an angle of 50° 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 3.6 Welding parameters of GMAW-S

Welding current (A)	100	150	200	250
Welding voltage (V)	14.0	16.0	23.5	26.5

3.4 Results

The effective irradiances measured in this study at a distance of 500 mm from the arc were in the range of 0.30–10 mW/cm^2. The allowable daily exposure times corresponding to these values are 0.30–10 s.

Figure 3.4 shows the effective irradiance for different combinations of base metal and welding wire. In all combinations, the effective irradiance increases with increasing welding current. The effective irradiance is highest for the combination P5W5, in which both the base metal and the welding wire contained magnesium. The lowest value is observed for the combination P6W4, in which both the base metal and the welding wire contained small amounts of magnesium and silicon. The next lowest value is observed for the combination P1W1, in which both the base metal and the welding wire consisted of pure aluminum.

Figure 3.5 shows the effective irradiance for various angles from the horizontal surface of the base metal. The effective irradiance is highest when the angle from the surface of the

base metal is 50° and decreases for angles greater or less than this.

Figure 3.6 shows the effective irradiance and the angle of inclination with respect to the welding direction. The effective irradiance is highest when the angle from the welding direction is 60°, and lowest when the angle is 30°.

Figure 3.7 shows the effective irradiance of the UVR emitted during GMAW. The aluminum alloys are strongly influenced by the pulsed current. The effective irradiance measured for GMAW-P using the pulsed current is 3.3–9.7 mW/cm^2 in the welding current range of 100–250 A. On the other hand, the effective irradiance measured for GMAW-S using the steady current is 3.1–10.0 mW/cm^2 in the welding current range of 150–250 A.

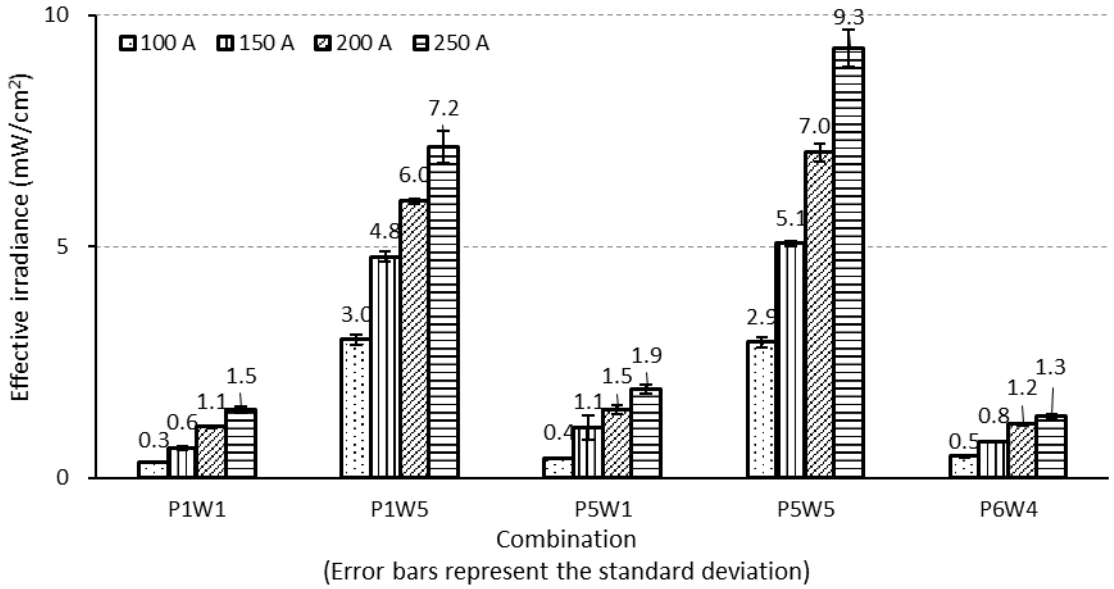


Figure 3.4 Relation of effective irradiance and combinations of wire and base metal

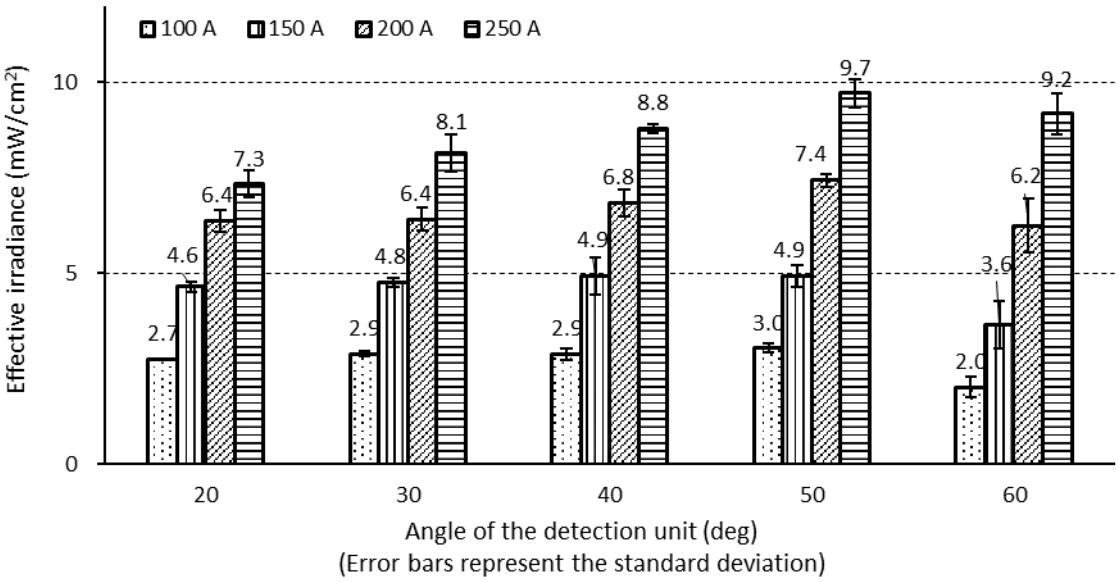


Figure 3.5 Relation of effective irradiance at 500 mm and horizontal angle from base metal surface at arc

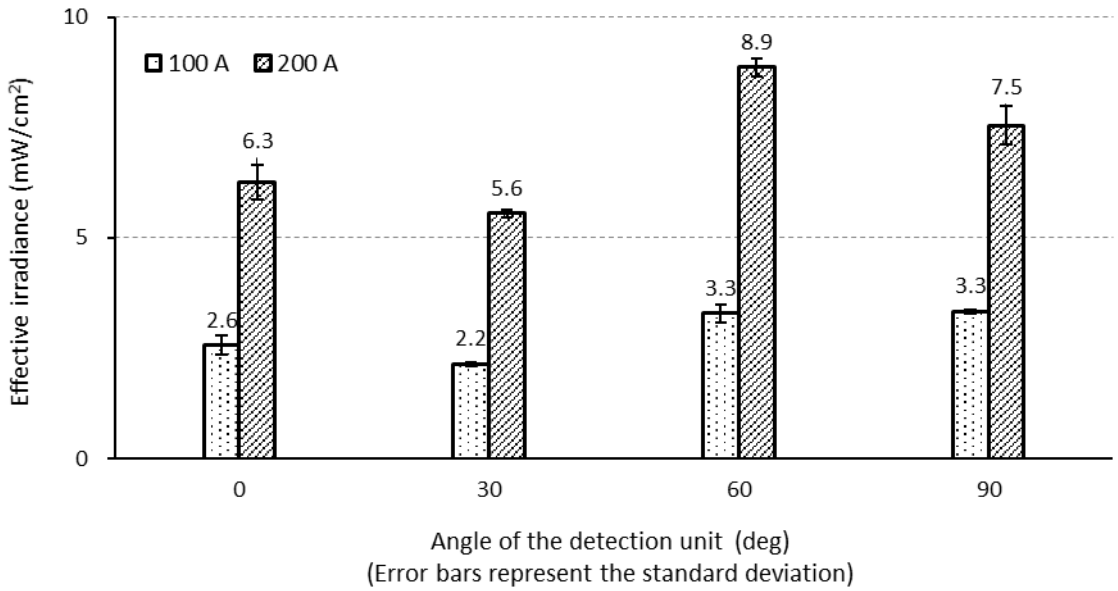


Figure 3.6 Relation of effective irradiance at 500 mm and angle from welding direction at arc

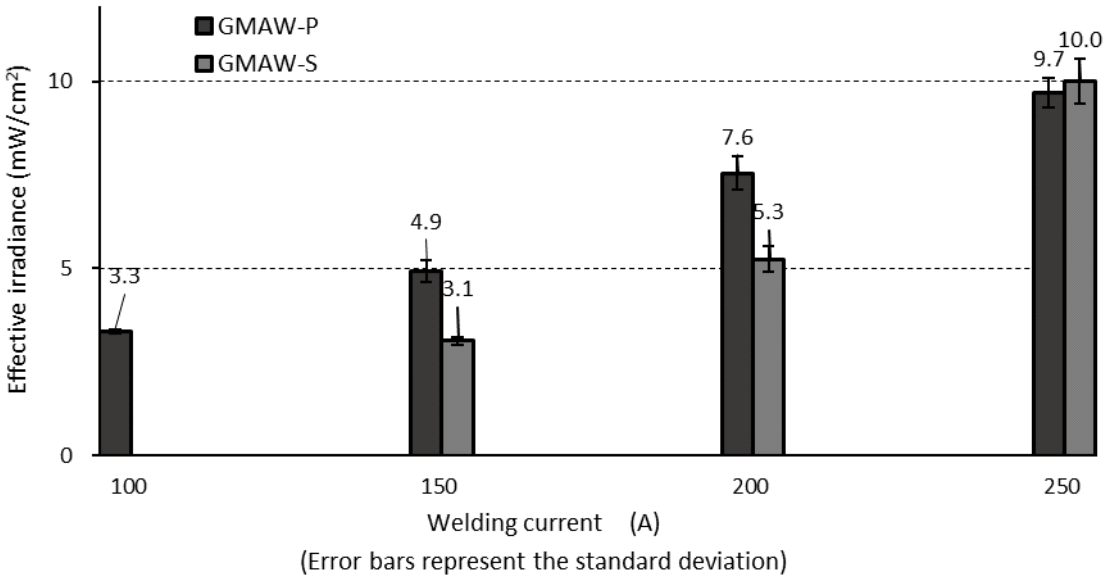


Figure 3.7 Relation of effective irradiance and pulsed and steady current control systems

3.5 Discussion

The effective irradiance observed at a distance of 500 mm from the arc was in the range of 0.30–10 mW/cm^2. At these irradiances, the allowable daily exposure times are just 0.30–10 s, which are extremely short times. These results indicate that the exposure to the UVR emitted by the GMAW of aluminum alloys is quite hazardous. It is thought that workers are often exposed to UVR when the arc is started[1)]. Although the exposure is brief for each start of an arc, the exposure can occur often because workers usually start an arc many times in a day. Therefore, the actual total exposure time can easily exceed the allowable daily exposure times determined in this study. Thus, it is concluded that if workers engage in the GMAW of aluminum alloys without adequate protection, they are exposed to hazardous quantities of the UVR for short periods of time. Assuming that the effective irradiance of the UVR decreases as the inverse square low of distance. At that time, the calculated allowable exposure time per 8 hours a day when there is no shielding between the welding arc and the irradiated surface of the UVR and the irradiated surface does not move is shown

in Figure 3.8. Assuming a working hour of 8 hours, the distance between a welding arc and a worker, which is calculated from the effective irradiance measured in this chapter and must be kept in order to avoid the acute health effects of UVR, is 28–150 m. However, welding arcs do not occur continuously for 8 hours in workplaces, and a worker's UVR-irradiated skin is moving. Therefore, the calculated distance between a welding arc and a worker is a minimum value, which is considered to be longer in practice. For example, the allowable daily exposure times at a distance of 5 m from the arc will be in the range of 30–1000 s. Thus, even at a distance of 5 m from the arc, exposure to the UVR is hazardous in cases in which the emitted UVR is intense. Moreover, even in cases in which the emitted UVR is weak, I sure that prolonged exposure is hazardous. Thus, in cases where the GMAW of aluminum alloys is performed, it is necessary to take precautionary measures to ensure that surrounding workers are not exposed to the UVR emitted by the arc.

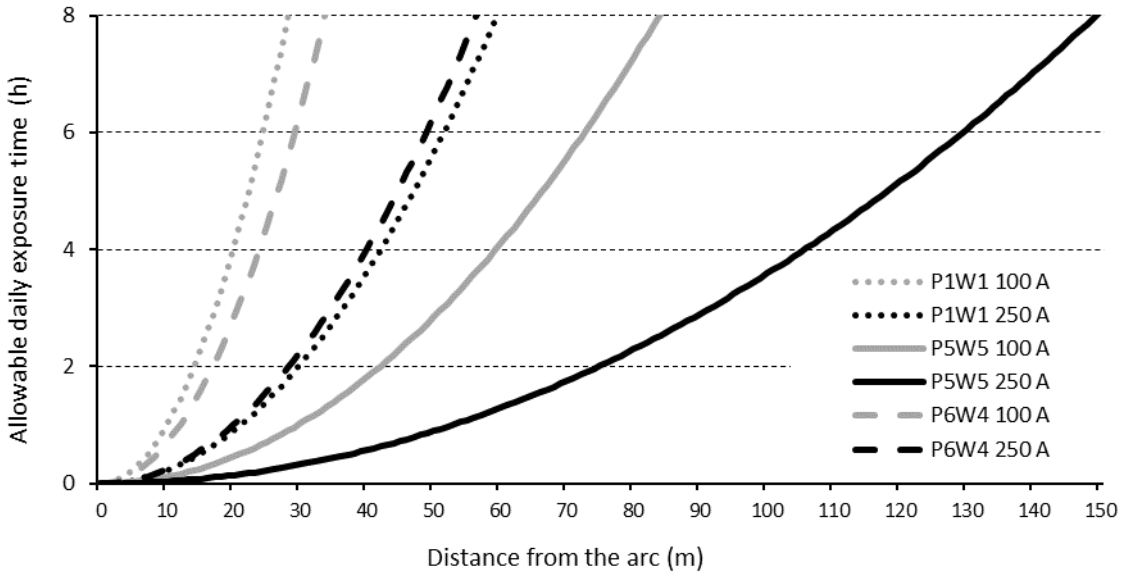


Figure 3.8. Allowable exposure time per day and distance from welding arc

3.5.1 Impact of the magnitude of the welding current and the combinations of base metal and welding wire

The effective irradiance measured in this study, regardless of pulsed or steady current and the combination of base metals and welding wires, increased with increasing welding current (Figure 3.4 and Figure 3.7). This trend was also previously observed for the GMAW of mild steel[5,11] and the GTAW of aluminum alloys[12]. Thus, the welding current is an important factor that influences the degree of hazard of the UVR emitted during the welding process; that is, the UVR hazard can be understood to be a rapidly increasing function of the welding current.

The effective irradiance was highest for P5W5, in which both the base metal and the welding wire contained magnesium. The effective irradiance was low for the combination P1W1 consisting of pure aluminum and P6W4 containing small amounts of magnesium and silicon. Figure 3.9 shows the spectral irradiance of the UVR measured for the cases of P1W1, P5W5 and P6W4. For P5W5, strong emission due to the presence of magnesium was observed in the vicinity of 280 nm. For all combinations, emission from aluminum, which was the primary component of the base metals, was observed at wavelengths of 240–260 nm and 300–310 nm. The relative spectral effectiveness[6], which is 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 GMAW of aluminum alloys is primarily determined by the emission from magnesium. Similar conclusions were obtained from the previous study of GMAW of aluminum alloys[3]. However, the research of Okuno et al.[3] does not clarify which case has the large dependence: the case in which magnesium is contained in the base metal, and the case in

which magnesium is contained in the welding wire. Therefore, we compared P1W5 in which only the welding wire contained magnesium and P5W1 in which only the base metal contained magnesium. As a result, the effective irradiance for P1W5 was 3 to 4 times higher than that for P5W1 (Figure 3.4). We attribute this to the fact that the boiling point of magnesium (1090°C) is considerably lower than that of aluminum (2470°C). This difference in boiling points ensures that magnesium is preferentially vaporized from the welding wire and thus gives rise to stronger emissions. Therefore, the effective irradiance that is emitted during arc welding is strongly dependent on the elements contained in the wire. Furthermore, magnesium contained in the welding wire has strong effect.

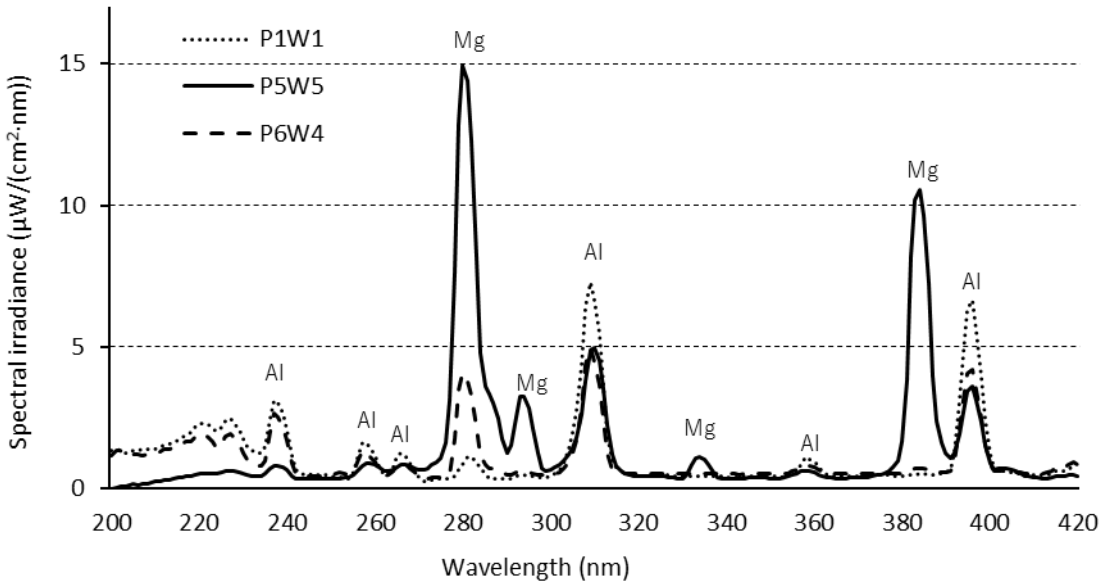


Figure 3.9 Relation of spectral irradiance and combinations of base metal and welding wire

3.5.2 Dependence on the direction of emission from the arc

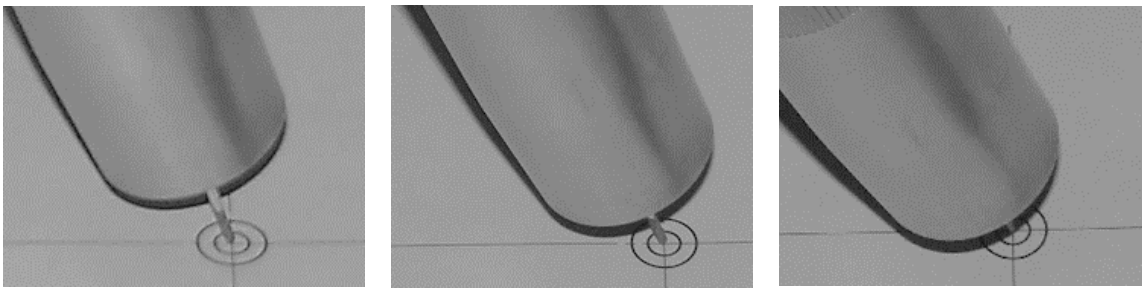
The effective irradiance is highest when the angle from the surface of the base metal is 50°, and decreases for angles greater or less than 50° (Figure 3.5). Figure 3.10 shows the positional relation between the nozzle, the simulated arc column and the simulated molten

pool, as observed from the detector. In the figure, the concentric circles show a simulated molten pool, and the black portion of the wire tip displays a simulated arc column. The UVR is emitted from around the arc column, but the apparent area of the simulated arc column decreases with the increasing angle of the detector. In contrast, the apparent area of the simulated molten pool increases with the increasing angle of the detector. Thus, it is considered that the reflected UVR from the molten pool is detected. In addition, it is presumed that the effective irradiance decreases when the apparent area of the arc column and molten pool are decreased by hiding the nozzle and the detector angle is 60° and more. In previous studies of Okuno et al.[3)] for the GMAW of mild steel, the effective irradiance was reported to have a maximum value at an angle of 50°–60°. The slight angle difference between that study and the present study is considered to have influenced the wire extension length. The wire extension length in the Okuno et al. study was the same (15 mm) as that in this study. However, in the GMAW of aluminum alloys, a contact chip is located on the inner side of the nozzle tip, whereas in GMAW of mild steel, the positions of the tip of the contact chip and the nozzle tip are the same. If the wire extension length is the same, the distance between the nozzle tip and the base metal in the GMAW of aluminum alloys becomes closer as compared to the GMAW of mild steel. In addition, the diameter of the nozzle used in the GMAW of aluminum alloys is larger than that used in the GMAW of mild steel. Therefore, a molten pool is easily obscured by the nozzle, and it is believed that the effective irradiance is reduced at 60°. It is considered that the angular dependence from the surface of the base metal is affected by the wire extension length and the nozzle diameter.

The effective irradiance was high at welding direction angles of 60° and 90°, and was found to depend on the angle of the welding direction (Figure 3.6). The reason that the effective irradiance decreased according the welding direction is thought to be absorption and scattering of the UVR by fumes that flowed toward the welding direction because the

welding torch was inclined in the welding direction.

As shows in figure 3.11, from the results of the two kinds of angle dependence of the effective irradiance, the hazard of the UVR around neck of the welding worker is the strongest in flat position forehead welding. The allowable exposure time obtained from equation (2) is 0.34 s when the welding current is 200 A. Therefore, the welding operator must fully safeguard himself with protective equipment such as a face shield.



40° 50° 60°

Figure 3.10 Angular relations of nozzle and molten pool observed from the detector

Figure 3.11 General welding position of GMAW at flat forehead welding

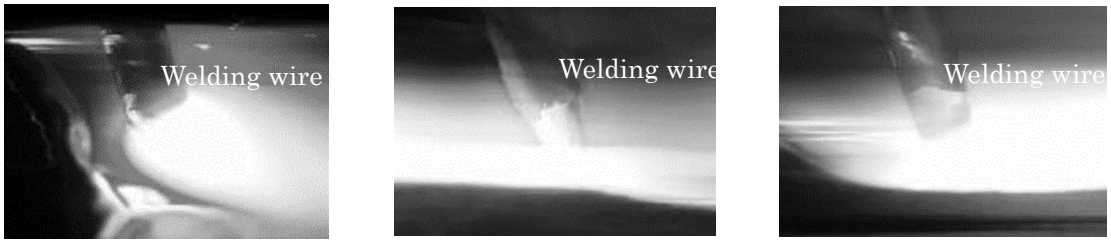
3.5.3 Influence of pulsed current

In the GMAW-S when the welding current was 100 A, the arc was not stabilized, and an

appropriate welding bead was not formed, so the data of 100 A was excluded. The effective irradiance measured in this study, regardless of the pulsed current, increased with increasing welding current. At the welding current of 200 A or less, the effective irradiance was higher in GMAW-P than in GMAW-S, but the effective irradiance for both was approximately the same at welding current of 250 A (Figure 3.7).

Figure 3.12 shows photographs of the wire tip for welding at a welding current of 150 A. Figure 3.12 (a) shows the wire tip during the GMAW-S. The shape of the tip stabilized in this state regardless of the passage of time, and the arc was continuously generated. Figures 3.12 (b) and (c) show the tip during the GMAW-P. Figure 3.12 (b) shows the aspect of the wire tip at the time of energizing the base current. Because the light emission of the arc is weak, and the molten metal has just migrated to the molten pool, the wire tip is sharp. Figure 3.12 (c) shows the aspect of the wire tip at the time of energizing the peak current. The welding arc is strong. The tip of the wire is melted by the arc thermal and its shape is dull. With the passage of time, the condition of the tip of the wire in (b) and (c) is repeated, and so the droplet transfer of GMAW-P is a spray transfer due to the pulsed current. Figure 3.13 shows the welding bead at 150 A. The weld bead formed by GMAW-P has uniform corrugation, smoothness and good compatibility with the base metal. On the other hand, the welding bead formed by GMAW-S has bead unevenness and slight meandering. It can be inferred that the difference in the transfer mode of the droplet was due to the presence or absence of the pulsed current. A similar tendency was observed also with a welding current of 200 A. Figure 3.14 shows the change in welding currents between GMAW-S and GMAW-P at 150 A. In GMAW-P, welding voltage and unit pulse conditions (peak current, peak time, base current, base time) are unitarily controlled by setting the welding current (average current). In the pulsed current, a strong welding arc is generated while the peak current is applied, and the welding arc becomes weak while the base current is applied. As shown in

Table 3.2, the peak current is nearly constant regardless of the welding current. Therefore, the factor affecting the effective irradiance is the peak current time or the base current time, that is, the factor affecting the effective irradiance is considered to be the pulsed current. On the other hand, in GMAW-S, the welding current hardly changes and an arc is continuously generated. In GMAW, the welding current is an important factor affecting effective irradiance, as is evident from previous studies[1-5,11,12]. Therefore, it is assumed that the difference in the increasing tendency of the effective irradiance is due to the difference in the transfer mode of the droplet when using the pulsed current (Figure 3.7).



(a) GMAW-S (b) GMAW-P (c) GMAW-P

Figure 3.12 State of wire tip at 150 A welding current

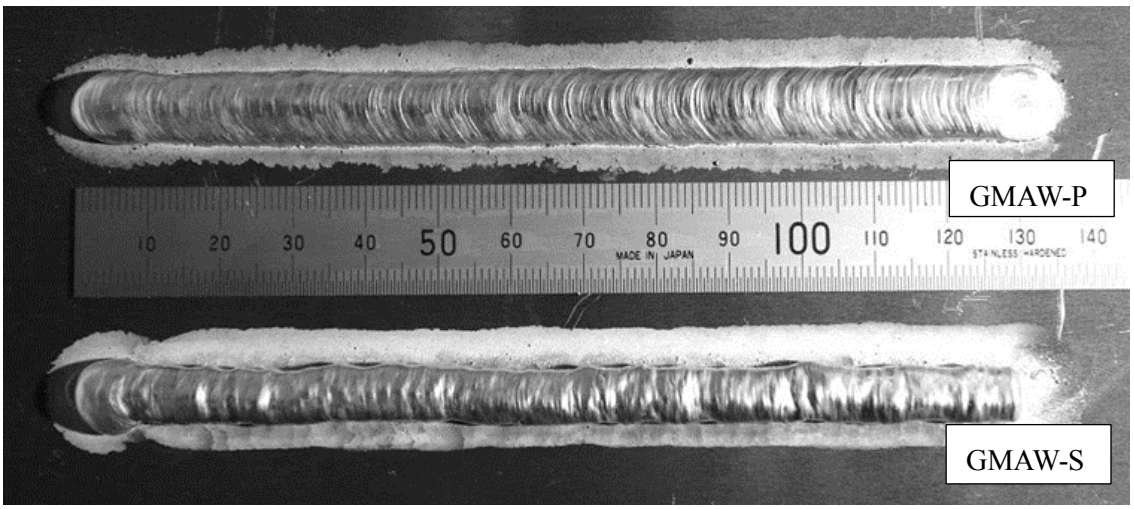


Figure 3.13 Shape of bead at 150 A welding current

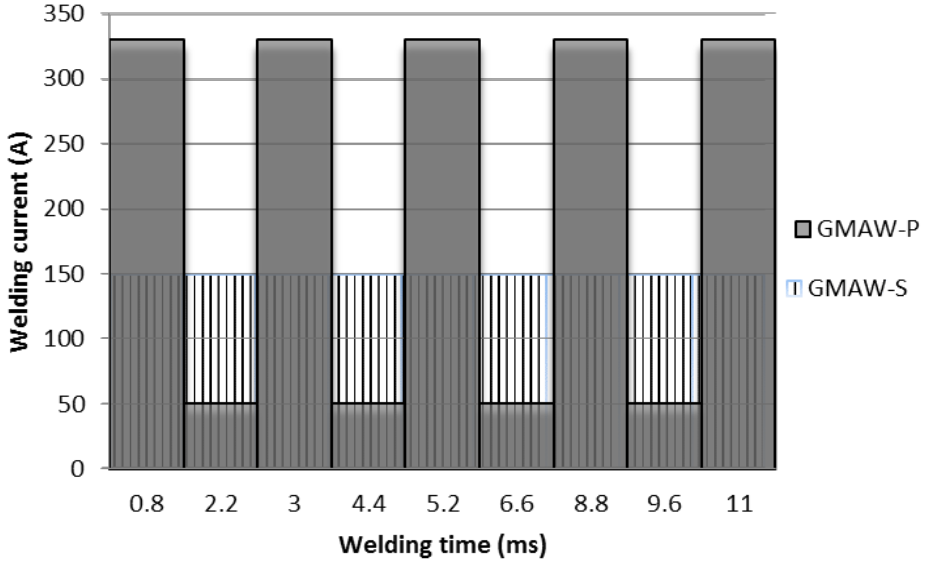
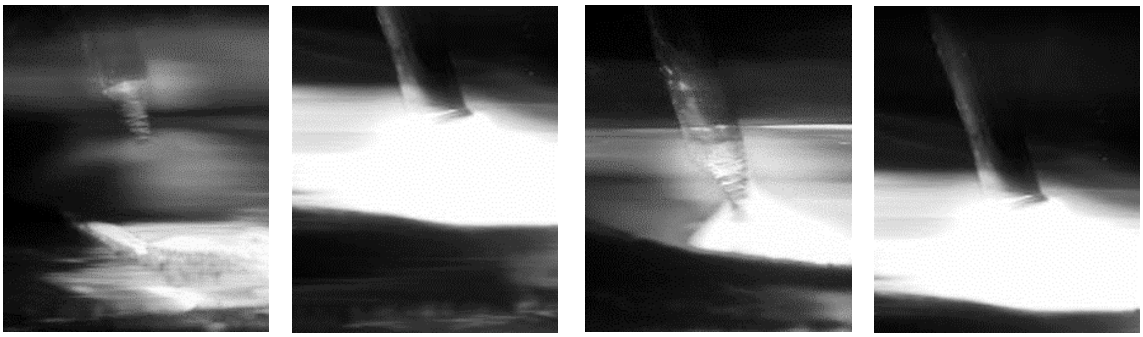


Figure 3.14 Relation of welding current and welding time at 150 A

On the other hand, at welding current of 250 A, as shown in Figure 3.15, in both GMAW-S and GMAW-P, the transfer mode of the droplets was the same as spray transfer. In addition, as shown in Figure 3.16, the weld bead shape after welding was almost the same. Therefore, since the welding result and the molten droplet transition form are the same, the effective irradiance is considered to become approximately the same value.



(a) (b) (c) (d)

GMAW-S GMAW-P

Fig 3.15 State of wire tip of at 250 A welding current

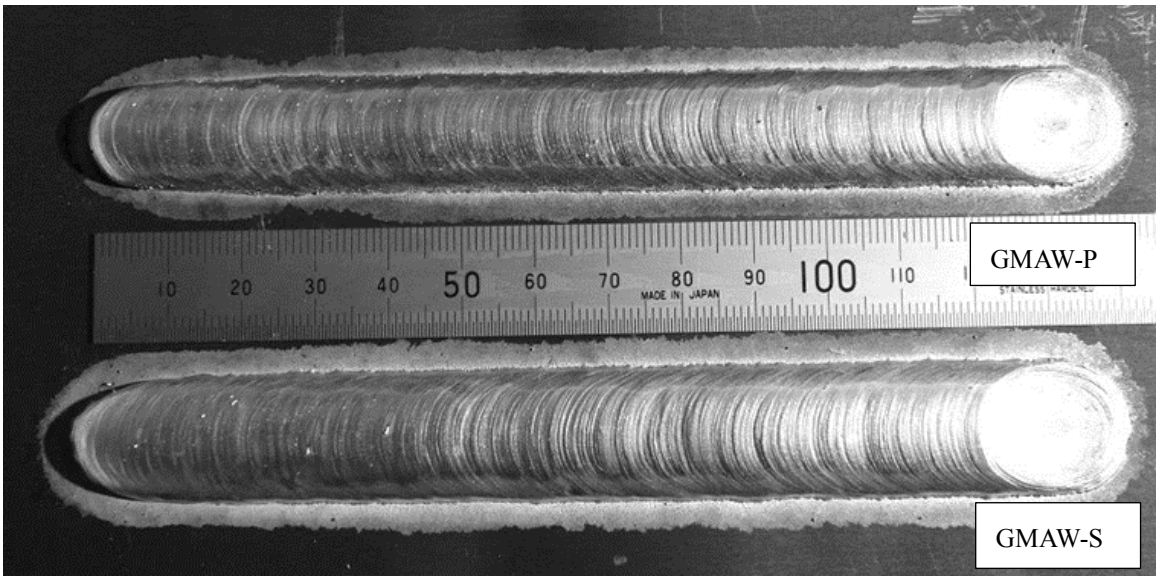


Fig. 3.16 Shape of bead at 250 A welding current

3.6 Conclusions

GMAW of aluminum alloys leads to the emission of intense UVR. Exposure to this radiation is considered hazardous according to ACGIH guidelines. The hazard of 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. In particular, the hazard of UVR becomes stronger when the welding wire contains magnesium. **(3)** The hazard depends on the direction of emission from the arc. (4) It is more hazardous for pulsed welding currents than for steady welding currents.

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Chapter IV

Hazard of Ultraviolet Radiation Emitted in Gas Metal Arc Welding of Mild Steel

Abstract

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. The UVR levels emitted in gas metal arc welding (GMAW) of mild steel were experimentally evaluated. For welding current, two types welding current were used of a pulsed current and a steady current. The shielding gases were 80% Ar + 20% CO_2 and 100% CO_2. The effective irradiance defined in the American Conference of Governmental Industrial Hygienists guidelines was used to quantify the UVR hazard. The effective irradiance measured in this study was in the range of 0.51–12.9 mW/cm^2 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. 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% CO_2 is used as a shielding gas than when 100% CO_2 is used. (3) It is more hazardous for pulsed welding currents than for steady 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.

Keywords: effective irradiance, gas metal arc welding, hazard, mild steel, ultraviolet

radiation

4.1 Introduction

The light emitted during arc welding contains intense 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 welding[1)]. UVR refers to electromagnetic waves in the range of ~1–400 nm[2)]. 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 situation [3)]. 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 include 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 performed[1)]. 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 not[1]. 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. 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% CO_2 in experiments and examined in detail the UVR emitted under these conditions[9]. 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, the UVR hazard present during the GMAW of mild steel were investigated using a shielding gas of 80% Ar + 20% CO_2 or 100% CO_2 that are most frequently used in arc welding of mild steel in Japan. 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) guidelines[10]. In particular, I studied the influence of (i) the type of shielding gas and the magnitude of the welding current, and (ii) using pulsed vs. steady welding current.

4.2 Methods

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

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

where E_{eff} is the effective irradiance (mW/cm^2), E_λ is the spectral irradiance at wavelength λ (mW/(cm^2 · nm)), $S(\lambda)$ is the relative spectral effectiveness at wavelength λ, and $\Delta\lambda$ is the bandwidth (nm).

For the UVR measurements, an $X1_3$ hazard lightmeter and an XD-45-HUV UV-hazard detector head (both from Gigahertz-Optik) were used, which are designed for measuring effective irradiance. The relative spectral responsivity of the detector head agrees well with the relative spectral effectiveness around 270 nm[11)]. 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), I consider the influence of this discrepancy to be too small to cause issues in practice. Thus, it was concluded 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/m^2). 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° from the surface of the base metal and at an angle of 90° from the welding direction. Figure 4.1 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, 3 mJ/cm^2 was divided by our measured values of effective irradiance to determine the maximum daily exposure time allowable at that irradiance (equation (2)).

$$t_{max} = \frac{3\text{m J /cm}^2}{E_{eff}} \quad \cdot \cdot \cdot \cdot \cdot \cdot (2)$$

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

The effective irradiance of the UVR emitted during three types of welding were measured: 100% CO_2 welding (using steady welding current), steady 80% Ar + 20% CO_2 welding and pulsed 80% Ar + CO_2 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, a solid wire YGW12 of diameter 1.2 mm specified by JIS[13] was used. 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% CO_2 or 100% CO_2, 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 4.1. Here the welding voltages were preset values corresponding to the welding current determined by the manufacturer of the welding equipment.

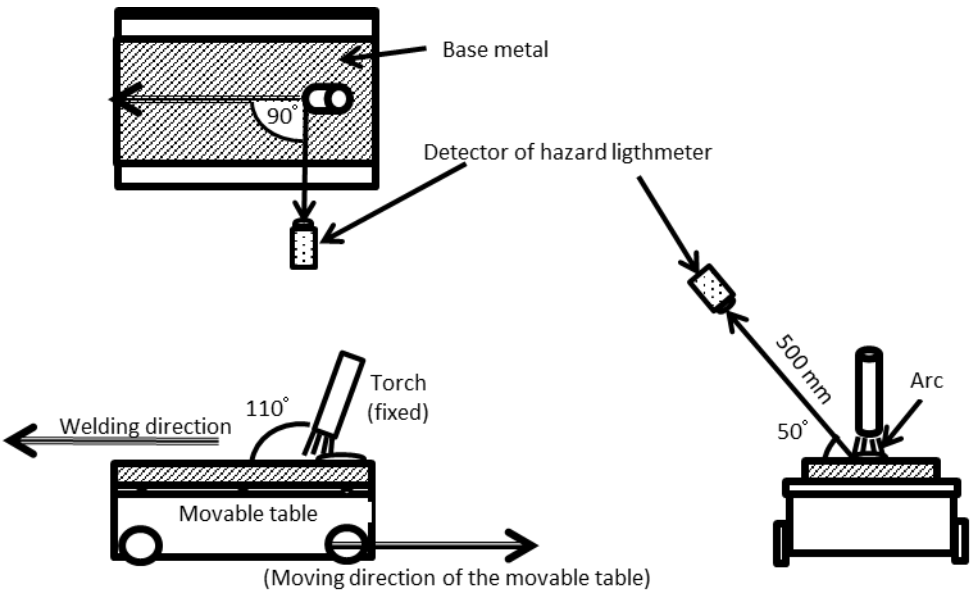


Fig. 4.1 Experimental setup for measuring effective irradiance (schematic diagram)

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

To investigate the influence of the type of shielding gas, I conducted bead-on-plate welding and measured the resulting UVR when using 80% Ar + 20% CO_2 or 100% CO_2 as the shielding gas and using steady welding current. The range of the welding current was 100–350 A as shown in Table 4.1. Because it is less expensive, 100% CO_2 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.

4.2.2 Influence of pulsed current

In order to investigate the influence of pulsed current, the pulsed 80% Ar + CO2 welding

was performed and the resultant UVR was measured. Then it compared it with the results for steady 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 4.1. The pulsed current is now commonly used in the welding of thin plates of automobile bodies.

Table 4.1 Welding parameters of 100% CO_2, steady 80% Ar+20% CO_2 welding and pulsed 80% Ar+20% CO_2 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
Steady 80%Ar+20%CO_2	Welding current, A (Steady)	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	-	-

4.3 Results

Figures 4.2 and 4.3 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/cm^2. The allowable daily exposure times corresponding to these values are 0.23–5.9 s.

Figure 4.2 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 steady 80% Ar + 20% CO_2 welding, the effective irradiance measured with welding currents of 100–350 A was in the range of 0.51–12.9 mW/cm^2. The increase in effective irradiance between current intervals is very large, starting from 250 A. For 100% CO_2 welding, the effective irradiance measured with welding currents of 100–350 A was in the range of 0.69–7.4 mW/cm^2. The effective irradiances measured with steady 80% Ar + 20% CO_2 welding and 100% CO_2 welding at 250 A or less were approximately equal. However, at 300 A and higher, the effective irradiance for steady 80% Ar + 20% CO_2 welding increased beyond that for 100% CO_2 welding.

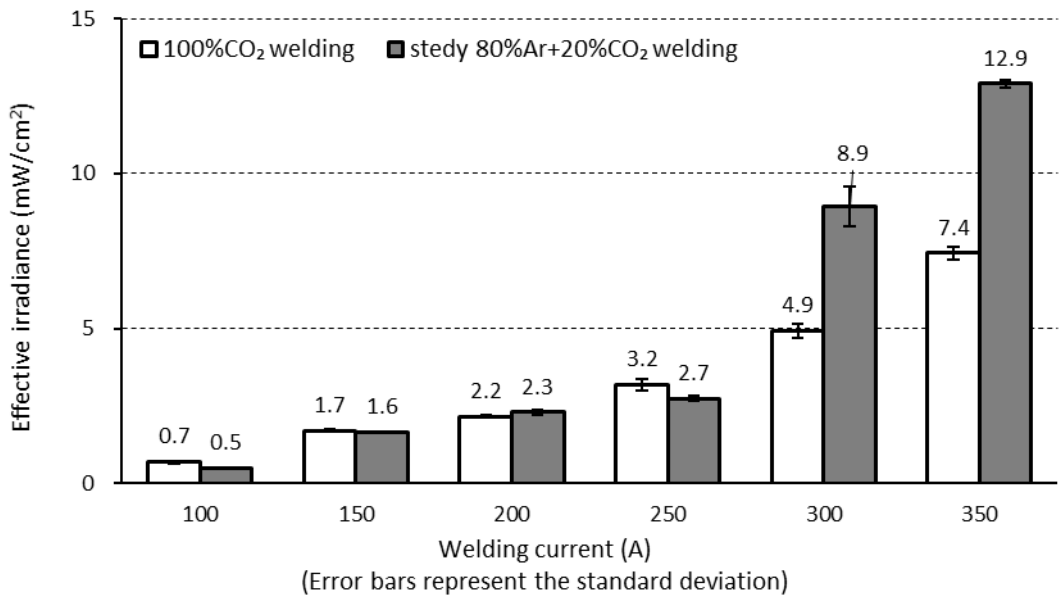


Fig. 4.2 Effective irradiance for 100% CO_2 welding and steady 80% Ar + 20% CO_2 welding. Measurements were repeated three times for each set of conditions and then averaged.

As shown in Figure 4.3, 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% CO_2 welding with welding currents of 100–250 A was in the range of 3.4–11.6 mW/cm^2. The effective irradiance increased with increasing

welding current. In addition, the effective irradiance of UVR occurring during pulsed 80% Ar + 20% CO_2 welding was very high in comparison with that during steady 80% Ar + 20% CO_2 welding.

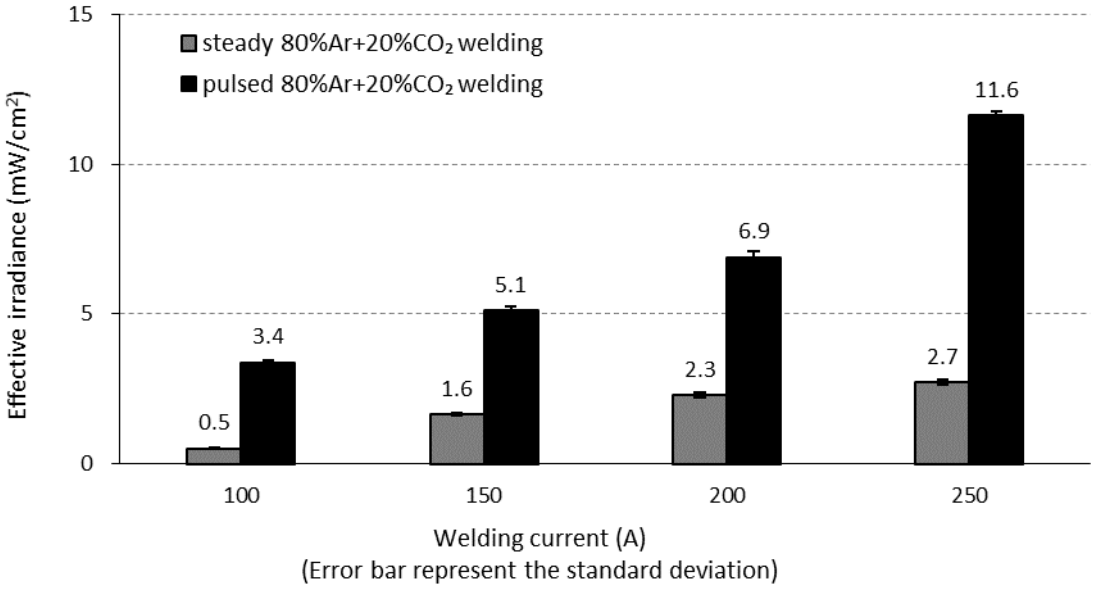


Fig. 4.3 Effective irradiance for steady and pulsed 80% Ar+20% CO_2 welding. Measurements were repeated three times for each set of conditions and then averaged.

4.4 Discussion

The effective irradiance observed at a distance of 500 mm from the arc was in the range of 0.51–12.9 mW/cm^2. At these irradiances, the allowable daily exposure times are just 0.23–5.9 s, which are extremely short times. These results indicate that the 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 started[1)]. 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, it was concluded 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% CO_2 as a shielding gas [9] and obtained an effective irradiance of 0.028–0.785 mW/cm^2 at a distance of 1 m for welding currents of 120–500 A. Assuming that the effective irradiance decreases as the inverse square distance from the arc, the effective irradiance would be 0.106–3.14 mW/cm^2 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.

Assuming 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, I sure 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.

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

The effective irradiance measured in this study, regardless of the pulsed current and the type of shielding gas, increased with increasing welding current (Figures 4.2 and 4.3). This trend

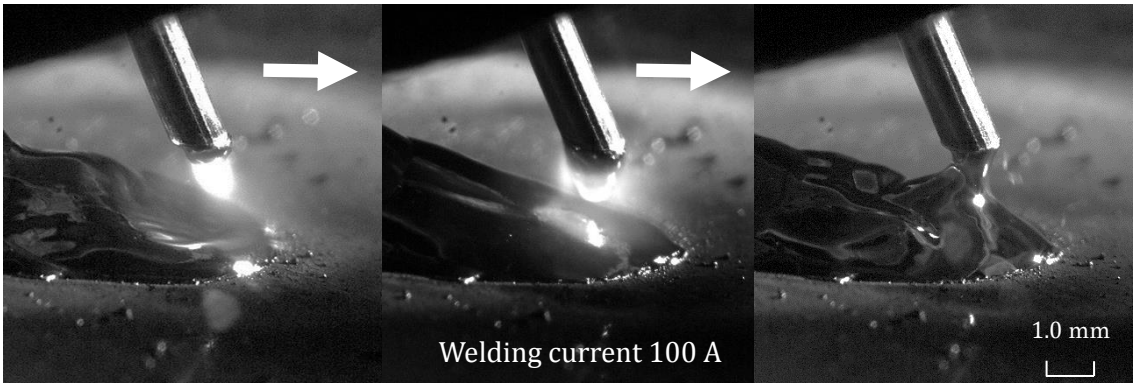
was also previously observed for the GMAW of mild steel using 100% CO_2[9] and 5% O_2 + 95% Ar[6] as the shield gas. More recently, similar trend was also observed the GMAW and the GTAW of aluminum[14,15] and magnesium alloys[16]. Thus, the welding current is an important factor influencing the degree 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 steady 80% Ar + 20% CO_2 welding was in the range of 0.51–12.9 mW/cm^2 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. In the arc welding, the shape of the electrode tip has a strong influence on the stability of the arc. In GMAW, since the welding wire of the consumable electrode is used for the electrode, the shape of the tip of the electrode always changes, and the shape of the wire tip greatly differs depending on the transfer form of the droplet. Therefore, the vicinity of the arc during welding was observed. As shown in Figure 4.4, short-circuit transfer was observed at 100 A. In short-circuit transfer, the tip of the welding wire melted by the heat of arc is short-circuited with the base metal, and is shifted to the base metal[17]. In addition, globular transfer was observed at 250 A. In globular transfer, the welding wire tip melted by the arc and grown to large drops lager than wire diameter is transferred to the base metal[17]. As also shown in Figure 4.4, it was not possible at 300 A to observe the droplets, which were blocked by the welding arc. However, the wire tip was pointed, and because no change appeared in the shape of the wire tip with the passage of time, I 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 diameter[17]. These results were consistent with the research of Takeuchi *et al.*[18]. The effective irradiance of the UVR emitted by steady 80% Ar + 20%

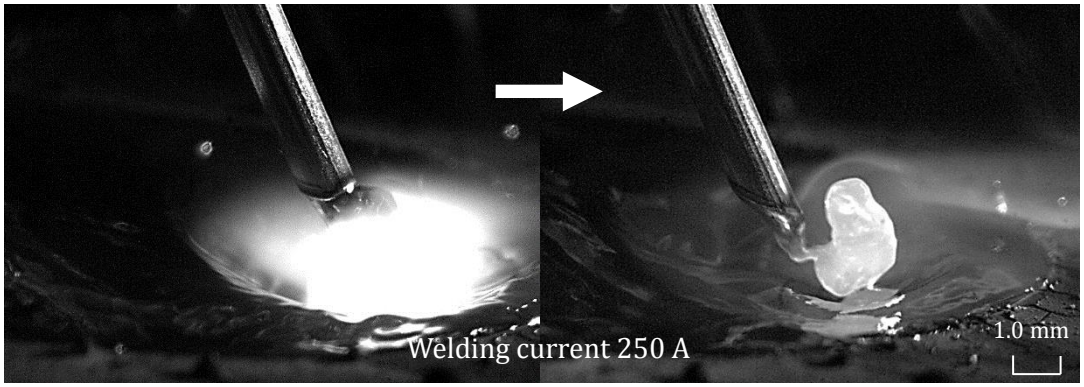
CO_2 welding increased with increasing welding current from 100 to 250 A, and no change was seen in this increasing trend (Figure 4.2). Therefore, the effect of changing the metal transfer mode from short-circuiting to globular on the effective irradiance was considered to be small. However, the effective 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 transfer[19)], and the properties of light emitted by the arc welding are affected by the amount of metal vapor blending into the arc[20)]. 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% CO_2 welding was in the range of 0.69–7.4 mW/cm^2 and increased with increasing welding current. Takeuchi *et al.* reported that for 100% CO_2 welding, the transition from short-circuit transfer to globular transfer takes place at approximately 250 A[18)]. 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 steady 80% Ar + 20% CO_2 welding and 100% CO_2 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 steady 80% Ar + 20% CO_2 welding was spray transfer and that of 100% CO_2 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 effective 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

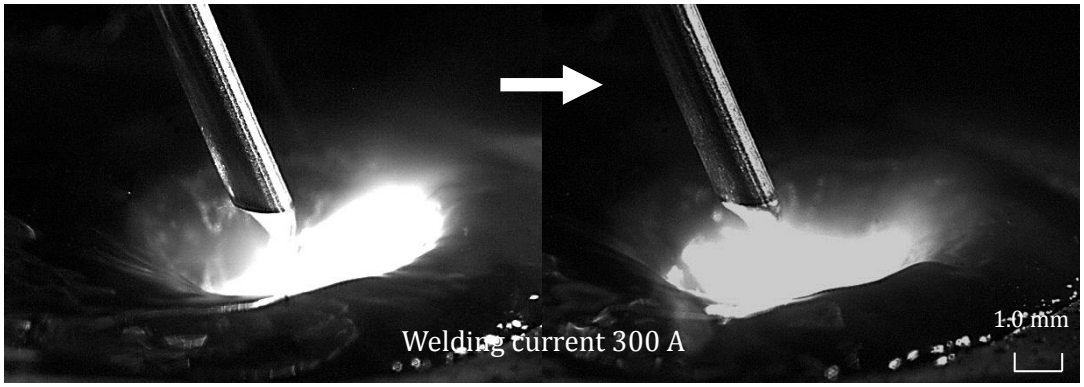
protective measures.



(a) Short-circuiting transfer. (The effective irradiance is 0.51 mW/cm^2.)



(b) Globular transfer. (The effective irradiance is 2.7 mW/cm^2.)



(c) Spray transfer. (The effective irradiance is 8.9 mW/cm^2.)

Fig. 4.4. The metal transfer at no-pulsed 80%Ar+20%CO_2 welding

4.4.2 The influence of pulsed current on the UVR hazard

The effects of pulsed current on the degree of the UVR hazard was examined. As shown in Figure 4.3, the effective irradiance of the UVR emitted during pulsed 80% Ar + 20% CO_2

welding increased with increasing current and was 3.0–6.7 times larger compared with that emitted during steady 80% Ar + 20% CO_2 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 Figure 4.5.

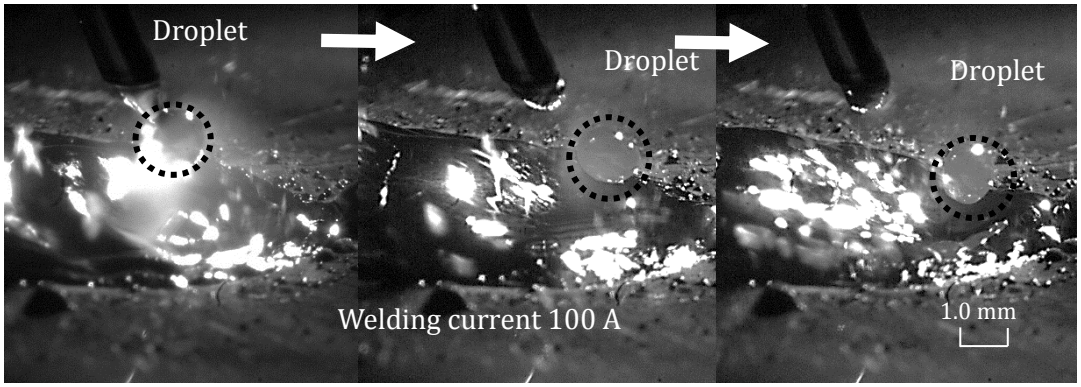


Fig. 4.5 The metal transfer at pulsed 80%Ar+20%CO2 welding (spray transfer). (The effective irradiance is 3.4 mW/cm2.)

For steady 80% Ar + 20% CO_2 welding, the short-circuit or globular transfer modes were observed at 250 A or less (Figure 4.4). The amount of metal vapor in the arc during spray transfer is large compared to that during short-circuit and globular transfer[19]. In addition, the properties of the light emitted during the arc welding are affected by the amount of metal vapor blended into the arc[20]. Therefore, I sure 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 steady 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 recent years, the demand for mild steel thin plate welding has increased to reduce the weight of equipment that needs to be transported. For thin plate welding, low welding current of less than 100 A

was used. 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% CO_2 welding at 100 A was 1.2 times greater than the effective irradiance during steady 80% Ar + 20% CO_2 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.

4.5 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% CO_2 is used as a shielding gas than when 100% CO_2 is used. **(3)** It is more hazardous for pulsed welding currents than for steady 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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Chapter V

Hazard of Ultraviolet Radiation Emitted in Gas Tungsten Arc Welding and Gas Metal Arc Welding of Magnesium Alloys

Abstract

Ultraviolet radiation (UVR) emitted during arc welding frequently causes acute health effects such as keratoconjunctivitis and erythema. The hazard of UVR varies depending on the welding method and the welding conditions. For this reason, it is important to identify the levels of UVR that are present under various conditions. In the present study, evaluated the hazard of UVR emitted during gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) of magnesium alloys were experimentally according to the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines. The distance between the arc and the UVR detector was 500 mm.

The effective irradiances measured in the present study are in the range of 0.85 to 8.9 mW/cm^2. The maximum allowable exposure times corresponding to these levels are 0.3 to 3.5 s/day, which are extremely small values for daily accumulated exposure times.

This demonstrates that, in practice, exposure to UVR emitted by GTAW and GMAW of magnesium alloys are quite hazardous. In addition, I found the following properties of the hazard of UVR. (1) The hazard of UVR generated during welding of magnesium alloys is higher for GMAW than for GTAW. (2) The hazard of UVR is higher at higher welding currents. (3) The hazard increases in GTAW when the shielding gas contains helium.

Keywords: ultraviolet radiation, effective irradiance, exposure time, gas metal arc welding, gas tungsten arc welding, magnesium alloys

5.1 Introduction

Magnesium alloys are promising as structural materials because of their excellent specific strength and vibration damping properties. However, their flammability and difficulty in plastic forming have limited the application of these alloys. Nevertheless, with the development of a flame-retardant magnesium alloy and the establishment of manufacturing technology for the expanded use of magnesium alloys, the application of this alloy to structures in various fields is expected[1,2]. Moreover, with the development of a welding wire made of flame-retardant magnesium alloy, welding of magnesium alloys is expected in the future[3].

As in the case of arc welding of steel or aluminum alloys, UVR is emitted in the arc welding of magnesium alloys. Previous studies by the present authors[4,5] have clarified that the hazard of UVR emitted during GMAW of aluminum alloys is strongly influenced by magnesium contained in the base metal and the welding wire. Based on these considerations, I assume that the hazard of UVR generated during arc welding of magnesium alloys is high. Ultraviolet radiation causes acute health effects, such as inflammation of the conjunctiva and the cornea as well as erythema (sunburn), and accounts for delayed health effects, such as cataracts and skin cancer[6]. In particular, numerous incidences of keratoconjunctivitis and erythema have been reported at actual welding sites[7,8]. As a basis for protective measures for workers, it is desirable to obtain a quantitatively evaluation of the hazard of UVR. However, there has been no report on the hazard of UVR emitted during the welding of magnesium alloys. As such, in the present study, the UVR emitted during GTAW and pulsed gas metal arc welding (GMAW-P) of magnesium alloys was measured as a basic for developing preventive measures against the adverse health effects of UVR emitted during arc welding of magnesium alloys. In the present study, the effects of welding method, welding current, and shielding gas on the hazard of UVR are quantitatively evaluated

according to the recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH)[9], the International Commission on Non-Ionizing Radiation Protection (ICNIRP)[10], and the Japanese Industrial Standard (JIS) Z 8812 (Hazardous Irradiation Measurement Method)[11].

5.2 Hazard assessment of UVR

The ACGIH defined threshold limit values (TLVs) as guidelines for exposure levels that will prevent adverse health effects in almost all healthy workers, even under daily exposure. Among these, since the hazard of UVR to the human body varies with wavelength, TLVs of UVR in the wavelength range of 180 nm to 400 nm, excluding ultraviolet lasers, have been determined. The TLV of UVR has a maximum value of 3 mJ/cm^2 for a wavelength of 270 nm, and the hazard for each wavelength is expressed as a function of that at 270 nm in terms of relative spectral effectiveness.

According to the ACGIH guidelines, the hazard of UVR as a cause of acute health effects is measured in terms of effective irradiance, which is defined as follows:

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

where E_{eff} is the effective irradiance (mW/cm^2), E_{λ} is the spectral irradiance at wavelength λ (mW/(cm^2· nm)), $S(\lambda)$ is the relative spectral effectiveness at wavelength λ, and $\Delta\lambda$ is the bandwidth (nm).

The TLV for 270 nm has been determined by the ACGIH to be 3 mJ/cm^2. If UVR is irradiated to the unprotected skin and eyes, in general, the maximum exposure time for a broadband UV source can be determined as follows:

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

where t_{max} is the maximum daily exposure time (s), and E_{eff} is the effective irradiance (mW/cm^2).

5.3 Methods

5.3.1 Outline of experimental welding

In the present study, the effective irradiance of UVR during GTAW and GMAW-P of magnesium alloys were measured. For each welding method, the flat-position forehead welding was performed using a torch inclination 110°. The torch for GTAW was fixed at a distance of 4 mm between the tip of the electrode and the base metal, where the electrode was 6 mm from the tip of the nozzle. Then, melt-run welding, in which only the base metal is melted and no filler rod is used, was carried out at 100 to 200 A using alternating current. In contrast, in GMAW-P, the torch was fixed at a distance of 20 mm between the tip of the contact tip and the base metal, and bead-on-plate welding, in which the base metal is melted with a welding wire, was performed at 100 to 170 A using a pulsed direct current (welding wire +). A voltage corresponding to the welding current preset by the manufacturer was used as the welding voltage. Table 5.1 lists the welding conditions.

Two types of base metals were used, AZ31[12)] and AZX611, and an AZX611 welding wire. Table 5.2 lists the chemical compositions of the base metals and welding wire. In GTAW, it is necessary to use a welding current appropriate for the thickness of the base metal, but it is still difficult to purchase small quantities of non-combustible magnesium alloy for testing purposes. Since AZ31 and AZX611 contain largely the same chemical components, AZ31 with thicknesses of 3 mm and 10 mm were used to investigate the influence of welding current in GTAW on the effective irradiance. All other experiments used AZX611. The planar dimensions of the base metal in all cases were 200 mm × 50 mm,

regardless of the welding method. In the present study, in the measurement of the UVR, the position of the welding torch was fixed so as to produce arcs in the same position, and the base metal was fixed on a movable table, which was moved linearly for welding.

Table 5.1 Welding conditions

	GTAW		GMAW
Welding equipment	DA300P		DP350
Manufacturer	DAIHEN Welding and Mechatronics Systems Co., Ltd.		
Welding current (A)	100, 150	200	100, 120, 150, 170
Welding speed (mm/min)	200		300
Size of base metal (mm)	t3 × 200 × 50	t10 × 200 × 50	t10 × 200 × 50
Electrode (wire) diameter (mm)	3.2		(1.2)
Inner diameter of nozzle (mm)	12.7		17.1
Shielding gas	100% Ar or 50% Ar + 50% He		
Shielding gas flow rate (l/min)	15		20

Table 5.2 Chemical compositions of base metals and welding wire (mass%)

	Alloy	Size (mm)	Mg	Al	Zn	Mn	Fe	Si	Ca
Base metal	AZ31	t3 × 200 × 50	Balance	2.90	0.87	0.28	0.00	0.02	-
		t10 × 200 × 50	Balance	2.93	1.01	0.45	0.00	0.01	-
	AZX611	t10 × 200 × 50	Balance	5.90	0.60	0.30	0.00	0.02	1.04
Welding wire	AZX611	1.2	Balance	5.90	0.60	0.22	0.00	0.03	1.00

5.3.2 Measured effective irradiance of UVR

For the UVR measurements, an $X1_3$ hazard light meter and an XD-45-HUV UV-hazard detector head (both from Gigahertz-Optik) were used, which were designed for measuring effective irradiance. The detector head has three sensors. The measurement of the effective

irradiance used two sensors UV-CB (measurement wavelength range: 200 to 320 nm) and UV-A (measurement wavelength range: 320 to 400 nm). Table 3.1 lists the characteristics of these sensors. The relative spectral responsivity of the detector head was adjusted to coincide with the relative spectral effectiveness as documented by the manufacturer. Figure 2.1 shows the relationship between the relative spectral effectiveness and the relative spectral responsivity of the detector head[13)]. The relative spectral responsivity of the detector head agreed well with the relative spectral effectiveness at around 270 nm. However, since the relative spectral responsivity of the detector head is unknown in the wavelength range of approximately 225 nm or less, some discrepancy between the relative spectral responsivity and the relative spectral effectiveness is observed from 310 to 320 nm. However, the effective irradiance of a light source that contains UVR of various wavelengths, such as welding arc emitted by arc welding, is less influenced by the difference between the relative spectral effectiveness and the relative spectral responsivity of the detector head. In the present study, the spectral irradiance at wavelengths of 200 to 400 nm was measured. For each calculated value, the effective irradiance was obtained using equation (1) and the detector responsivity. The difference between the respective values was approximately 4%, and that obtained based on the detector responsivity was larger. In addition, although the detector responsivity in the wavelength range of 180 to 200 nm is unknown, in the product of the relative spectral effectiveness and the bandwidth of the wavelength, the ratio of the integrated value in the wavelength range from 180 to 200 nm to the whole is approximately 2%. Thus, it was concluded that this detector head is well suited to measure the effective irradiance. In actual experiments, the value measured by the measurement devices is the effective radiant exposure (J/m^2). Dividing this value by the measurement time yields the effective irradiance. The measurement device was calibrated by the manufacturer and was used within the one year of 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. The distance between the arc and the detector head was set to 500 mm in order to mimic the actual distances to welders. The angles of the detector head from the surface of the base metal were 40° for GTAW and were 50° for GMAW. These angles were observed in previous studies to provide the maximum effective irradiance for each welding method for aluminum alloys[4,14]. In addition, the angle of the detector head from the welding direction was 90° for both welding methods. Figure 5.1 shows a schematic diagram of the experimental setup for measuring effective irradiance. The measurement times were set to 40 s for GTAW and 20 s for GMAW. Measurements were repeated five times for each set of conditions and then averaged. In order 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.

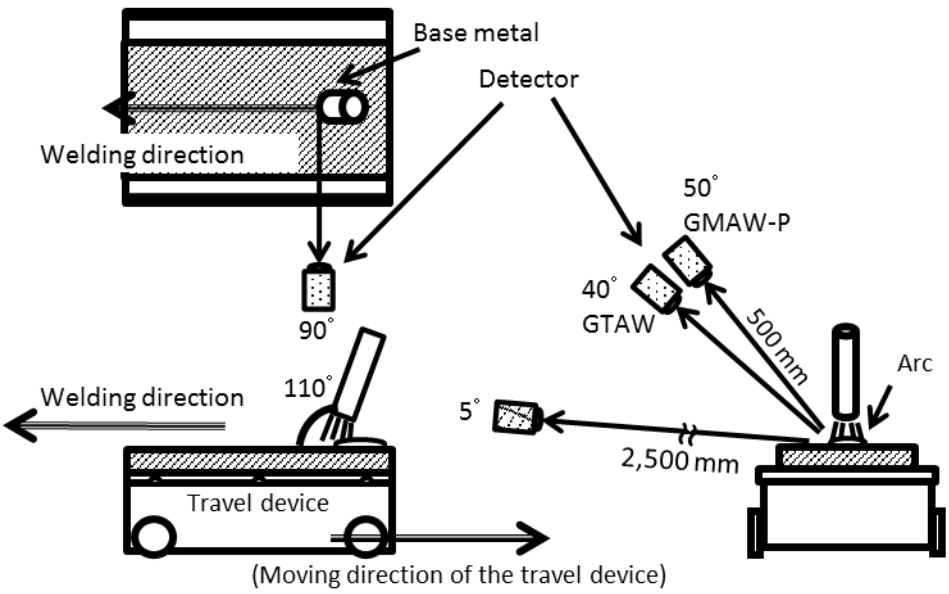


Figure 5.1 Experimental setup for measuring effective irradiance and spectral irradiance.

In the present 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).

5.3.3 Influence of the magnitude of the welding current

In order to investigate the influence of welding current, the effective irradiances of GTAW and GTAW-P were measured.

For GTAW, the effective irradiance was measured for the welding current range of 100 to 200 A. The base metal used was AZ31 of 3 mm in thickness at 100 and 150 A and 10 mm in thickness at 200A.

For GTAW-P, the base metal and welding wire used were AZX611. The thickness of the base metal was 10 mm. Regarding the range of welding current, in this experiment, welding wire with a diameter of 1.2 mm could not be applied with a welding current exceeding 170 A, so the welding current range was 100 to 170 A. Regarding the shielding gas, 100% Ar was used for each welding method. Moreover, AZX 611 was used as the base metal under all conditions (external dimensions: t10 × 200 × 50 mm).

5.3.4 Impact of the type of electrode and the shielding gas components

In order to investigate the influence of the electrode type, the effective irradiances during GTAW were measured using a pure tungsten electrode (YWP)[15)] and a 2%-cerium-oxide-containing electrode (YWCe-2)[15)], both of which are commonly used in GTAW. The electrode diameter was 3.2 mm, and the welding current was 200 A. Moreover, AZX 611 was used as the base metal under all conditions (external dimensions: t10 × 200 × 50 mm).

In order to investigate the influence of the type of shielding gas, I conducted GTAW

and GMAW-P and measured the resulting UVR when using 100% Ar and 50% He + 50% Ar. The welding current was 200 A for GTAW. Moreover, for GMAW-P, a welding current of 165 A or higher could not be applied when using 50% Ar + 50% He. Therefore, in GMAW-P, the effective irradiance was measured at 150 A, at which the welding current stabilized.

For such broadband UVR of the arc, by analyzing the intensity of irradiance of each wavelength, factors that affect the hazard of UVR can be specified. In addition, GMAW-P is more likely to exhibit light emission than GTAW. This is because the amount of penetration into the arc plasma of a metal element or the like, which causes the emission of UVR, is large in GMAW-P[16)]. Therefore, the spectral irradiance of UVR for the cases of using 100% Ar and 50% Ar + 50% He in GMAW-P were measured at a welding current of 150 A. Here, the spectral irradiance is defined with respect to the plane irradiated with light and represents the unit wavelength of light irradiated within the unit area and the energy per unit time (unit: $W/cm^2 \cdot nm$). The measurement apparatus was a multichannel spectrometer (HSU-100S, Asahi Spectra Co., Ltd.). The measurement wavelength range of the apparatus was 200 to 1,000 nm, and the wavelength precision of the apparatus was ±1.2 nm. The detector was positioned at an angle of 5° from the surface of the base metal and at an angle of 90° from the welding direction. The distance from the arc was set to 2,500 mm. The measurement time was automatically adjusted by the apparatus according to the intensity of the light. Figure 5.1 shows the experimental setup for measuring effective irradiance and spectral irradiance.

5.4 Results

Figures 5.3 and 5.4 show the effective irradiance for various welding conditions. The effective irradiance measured in the present study at a distance of 500 mm from the arc was

in the range of 0.80 to 8.9 mW/cm^2 for GTAW and 4.6 to 7.8 mW/cm^2 for GMAW-P. The allowable daily exposure times corresponding to these values are 0.33 to 3.8 s for GTAW and 0.30 to 0.65 s for GMAW-P.

As shown in Figure 5.2, in GTAW of the magnesium alloy, the effective irradiance increased as the welding current increased. For GMAW-P, although the data fluctuation was large, the effective irradiance increased roughly as the welding current increased. For the same welding current, the effective irradiance of GMAW-P was 1.5 to 5.8 times higher than that of GTAW.

As shown in Figure 5.3, in GTAW, the effective irradiance when YWCe-2 was used for the electrode was approximately 20% higher than that when YWP was used for the electrode. Moreover, the effective irradiance when 50% Ar + 50% He was used as the shielding gas was approximately twice that when using 100% Ar as the shielding gas. For GMAW-P, the effective irradiance using 50% Ar + 50% He was approximately 25% lower than that when using 100% Ar.

Figure 5.2 Effective irradiance for different welding methods and welding currents.

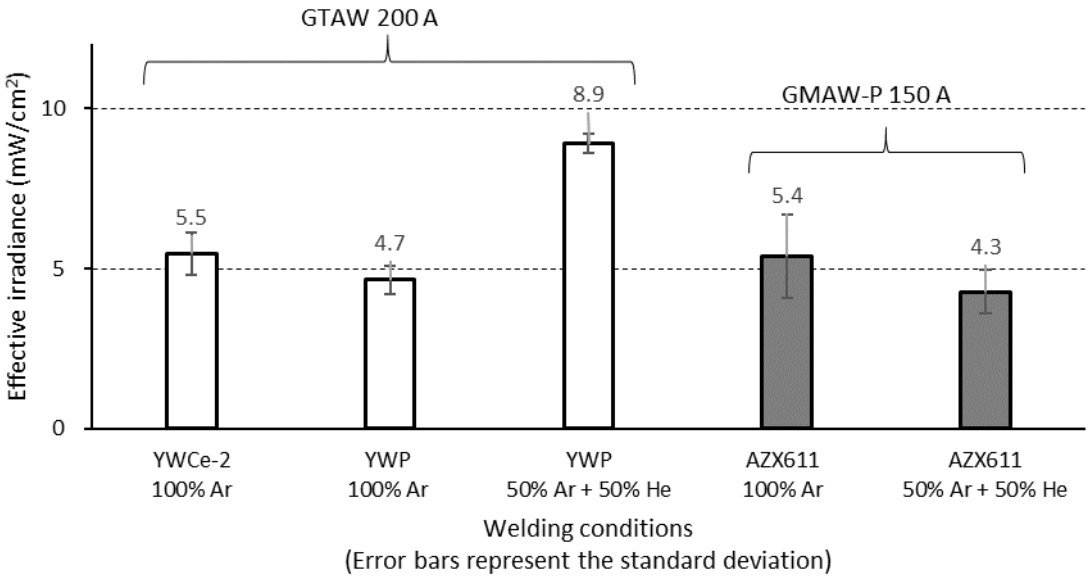


Figure 5.3 Effective irradiance for different electrodes and shielding gases.

5.5 Discussion

The effective irradiance measured in the present study at a distance of 500 mm from the arc was in the range of 0.80 to 8.9 mW/cm^2 for GTAW and in the range of 4.6 to 7.8 mW/cm^2 for GMAW-P. The allowable daily exposure times corresponding to these values are 0.33 to 3.8 s for GTAW and 0.30 to 0.65 s for GMAW-P. These results indicate that exposure to the UVR emitted by GTAW and GMAW-P of magnesium alloys is quite hazardous. It is thought that workers are often exposed to UVR when the arc is started[7)]. Although the exposure is brief for each start of an arc, this may occur often because workers usually start an arc several times a day. Therefore, the actual total exposure time may easily exceed the allowable daily exposure times determined in the present study. Thus, it was concluded that if workers engage in GTAW and GMAW-P of magnesium alloys without adequate protection, they will be exposed to hazardous levels of UVR for short periods of time.

Assuming that the effective irradiance of UVR decreases as the inverse square of the distance from the arc, then the allowable daily exposure time at a distance of 5 m from

the arc will be in the range of 33 to 380 s for GTAW and in the range of 30 to 65 s for GMAW-P. 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, I sure that prolonged exposure is hazardous. Thus, for cases in which GTAW and GMAW-P of magnesium alloys is performed, it is necessary to take precautionary measures so that surrounding workers will not be exposed to UVR emitted by arcs.

5.5.1 Influence of the magnitude of welding current on the hazard of UVR

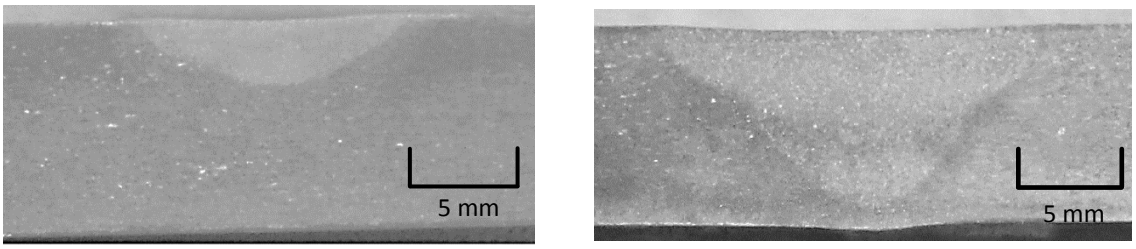
The effective irradiance measured during both GTAW and GMAW-P increases with the increase in welding current (Figure 5.1). Therefore, the effective irradiance during GTAW and GMAW-P of magnesium alloys was strongly influenced by the welding current. This trend was similarly observed in previous studies involving other metals[4,5,14,17-21]. Thus, welding current is an important factor influencing the hazard of UVR emitted during the welding process. In other words, the UVR hazard can be understood to be a rapidly increasing function of the welding current.

At 200 A, the effective irradiance of GTAW was approximately 7.4 times that at 100 A, and, at 170 A, the effective irradiance of GMAW-P was approximately 1.7 times that 100 A. Therefore, the hazard of UVR for GTAW is more sensitive to welding current, as compared to GMAW-P. This is believed to be due to the UVR being absorbed and scattered by fumes generated during GMAW-P. The amount of fumes generated during GMAW-P was larger than that generated during GTAW, and the amount of fumes increased with the welding current. Since UVR is strongly absorbed and scattered by fumes as the welding current increases, it is inferred that the dependence of the effective irradiance on welding current is reduced in GMAW-P.

5.5.2 Influence of the type of electrode and the components of the shielding gas

The effective irradiance when YWCe-2 was used was higher than that when YWP was used as the electrode in GTAW. Compared to YWP, for the case in which YWCe-2 was used as the electrode in GTAW, less melt deformation was observed at the electrode tip and better arc convergence was also observed[22]. It is thought that the temperature of the molten pool and its surroundings increased due to the high convergence of the arc. Consequently, the amount of metal vapor increased, and the effective irradiance increased.

The UVR emitted by GTAW using 50% Ar + 50% He is more hazardous than that when using 100% Ar, and the effective irradiance when using 50% Ar + 50% He was measured to be approximately twice that when using 100% Ar. A cross section of the weld is shown in Figure 5.4. In this case, 50% Ar + 50% He was used as the shielding gas, and increases in the melting width and penetration depth were observed, as compared to the case in which 100% Ar was used. Therefore, one reason the effective irradiance became high may be that the shielding gas contained He, thereby expanding the molten pool and increasing the amount of metal vapor from the molten pool surface.



100% Ar　　50% Ar + 50% He

Figure 5.4 Effect of shielding gas on penetration depth.

For GMAW-P, the effective irradiance of UVR emitted when using 50% Ar + 50% He was lower than that when using 100% Ar. This trend is different from that for GTAW. Therefore, GMAW-P was performed using 100% Ar and 50% Ar + 50% He, and the spectral

irradiances of the arcs during welding were measured. Figure 5.5 shows the relationship between spectral irradiance for different shielding gases and relative spectral effectiveness for GMAW-P. A strong emission from magnesium was observed in the vicinity of 280 nm, where the hazard of UVR is high. Emissions caused by calcium and zinc contained in the base material and the welding wire were predicted, but could not be confirmed. In addition, a similar spectral profile was observed regardless of the shielding gas, and clear emissions from argon and helium were not confirmed.

Figure 5.6 shows the scattering situation for welding fumes during GMAW-P. The amount of welding fumes generated when 50% Ar + 50% He was used as the shielding gas was larger than when 100% Ar was used, and it was observed that the duct installed above the welding torch could not completely collect dust. Since the main components of the welding wire have boiling points of 1,760 K (calcium), 1,176 K (zinc), 2,759 K (aluminum), and 1,370 K (magnesium), it was thought that these components were mixed in welding fumes. Therefore, fumes generated in GMAW-P were collected and qualitatively analyzed by a scanning electron microscope. Figure 5.7 shows the results of qualitative analysis of the collected welding fumes. Since magnesium and oxygen were detected by the qualitative analysis, the main component contained in welding fumes is likely to be magnesium oxide. Moreover, calcium and zinc were not detected. Therefore, in GMAW-P, the reason why the effective irradiance was lower when using 50% Ar + 50% He as the shielding gas is presumed to be as follows. If helium is contained in the shielding gas, the wire tip temperature and the arc column temperature increase, and the magnesium vapor amount increases, which in turn increases UVR. At the same time, however, the amount of welding fumes increases, because the amount of magnesium released outside the arc increases. The scattered fumes envelop the arc, blocking UVR, which is then not detected by detectors. Therefore, the effective irradiance of the UVR emitted when 50% Ar + 50% He is used as

the shielding gas in GMAW-P is thought to be low.

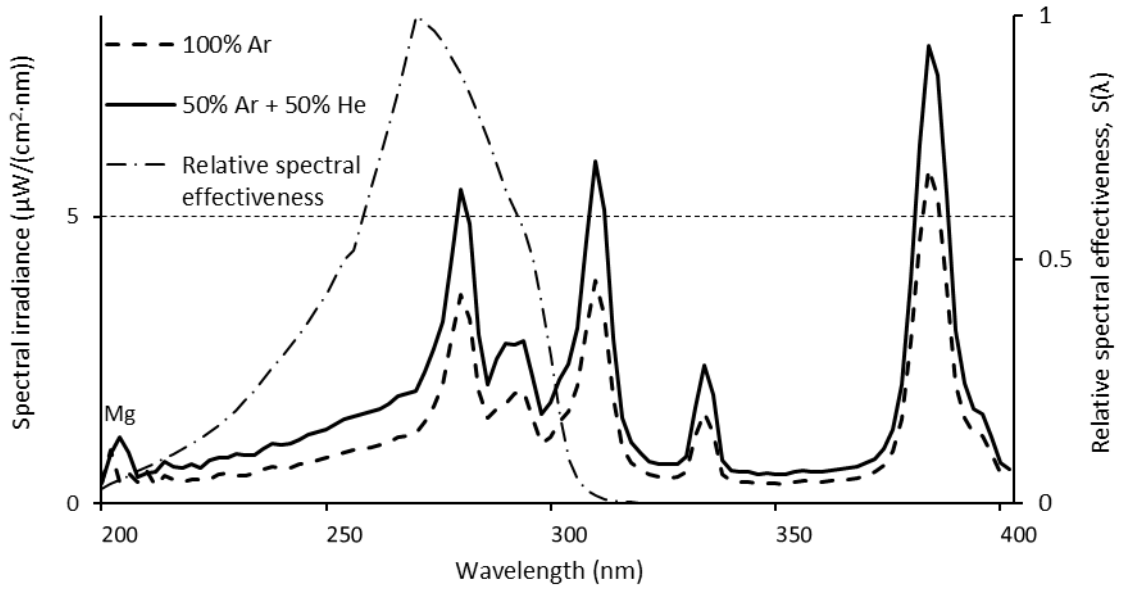
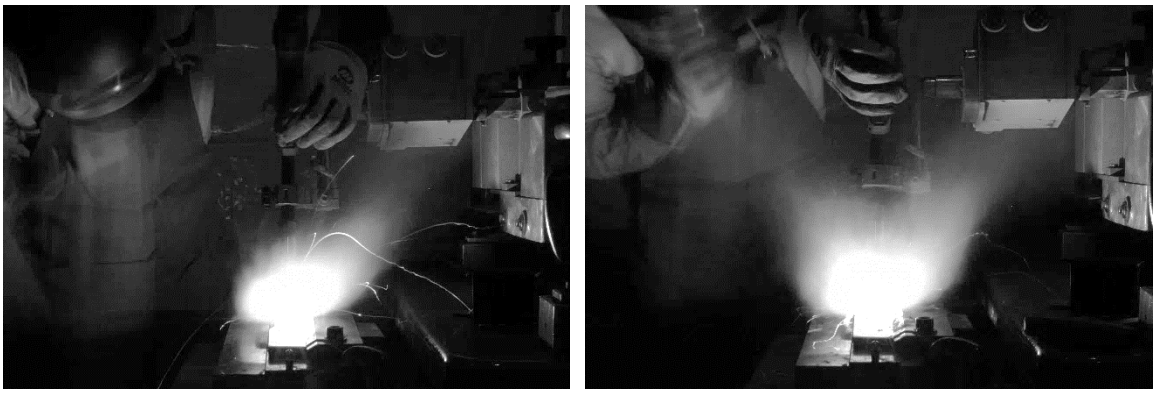


Figure 5.5 Relationship between spectral irradiance for different shielding gases and relative spectral effectiveness for GMAW-P.



100% Ar 50% Ar + 50% He

Figure. 5.6 Scattering situation of the welding fumes.

Figure 5.8 shows the appearance of the collected fumes. A large number of secondary particles having diameters of 0.03 to 0.05 μm that formed a chain were observed, and fumes having particles of 0.1 to 0.3 μm in diameter were also observed. The relationship

between fume particle size and pneumoconiosis has been well documented, and particles of 0.1 μm to several micrometers in diameter, which can enter the lungs through respiration and become deposited on the alveoli, have various effects on the lungs[23]. According to JIS T 8151 (regarding dust masks)[24], type-RS3 and -DS3 masks can collect 99.9% or more of dust particles and so can be expected to reduce the influence of fumes on the human body.

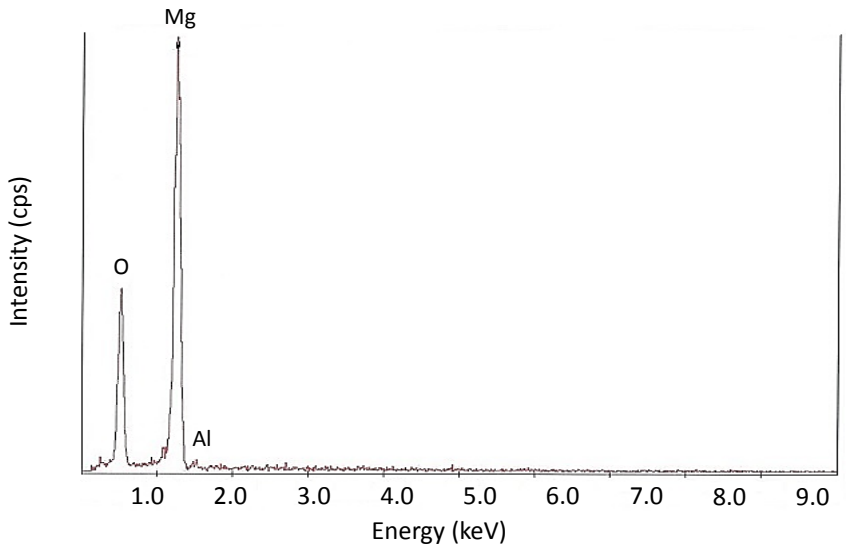


Figure 5.7 Qualitative analysis of welding fumes by scanning electron microscope.

Figure 5.8 Appearance of the collected welding fumes.

5.6 Conclusions

The GTAW and GMAW-P of magnesium alloys leads to the emission of intense UVR. According to the ACGIH guidelines, exposure to this radiation is considered to be hazardous. This UVR hazard exhibits the following characteristics. (1) The hazard of UVR generated during welding is higher for GMAW-P than for GTAW. (2) The hazard of UVR is higher at higher welding currents. In addition, GTAW is more susceptible to the welding current than GMAW-P. (3) The hazard of UVR emitted during GTAW increases when the shielding gas contains helium. (4) The hazard of UVR during the GTAW is increased by the use of cerium oxide tungsten electrodes. (5) The UVR in GMAW-P is strongly affected by fumes generated during welding, and the hazard is reduced by the increase in the amount of fumes.

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Chapter VI

Blue-light Hazard from Gas Metal Arc Welding of Aluminum Alloys

Abstract

The objective was to quantify the blue-light hazard from gas metal arc welding of aluminum alloys. The exposure level is expected to depend on the welding conditions. Therefore, it is important to identify the blue-light hazard under various welding conditions. Gas metal arc welding of aluminum alloys was conducted under various welding conditions and the spectral radiance of the arcs was measured. The effective blue-light radiance, which the American Conference of Governmental Industrial Hygienists has defined to quantify the exposure level of blue light, was calculated from the measured spectral radiance. The maximum acceptable exposure duration per 10000 s for this effective blue-light radiance was calculated.

The effective blue-light radiance measured in this study was in the range of 2.9–20.0 $W/cm^2 \cdot sr$. The corresponding maximum acceptable exposure duration per 10000 s was only 5.0–34 s, so it is hazardous to view the welding arc. The effective blue-light radiance was higher at higher welding currents than at lower welding currents, when pulsed welding currents were used rather than steady welding currents, and when magnesium was included in the welding materials. It is very hazardous to view the arcs in gas metal arc welding of aluminum alloys. Welders and their helpers should use appropriate eye protection in arc-welding operations. They should also avoid direct light exposure when starting an arc-welding operation.

Keywords: aluminum; arc; blue light; effective radiance; gas metal arc welding; MIG welding; photoretinopathy; welding

6.1 Introduction

It is well known that a welding arc emits ultraviolet radiation [1-7], which often causes keratoconjunctivitis and skin erythema in workers[8,9]. A welding arc also emits intense visible light. Extremely large numbers of workers are expected to be exposed to this visible light by accidentally or mistakenly viewing welding arcs without adequate protection. These workers include not only expert arc-welding professionals, whose numbers are estimated as 350,000 in Japan, but also workers who do not specialize in arc welding but perform it occasionally, as well as workers engaged in other tasks in workplaces where other workers are performing arc welding[8].

Light-induced retinal injury has been reported in people who have stared at a welding arc without adequate protection[10-19]. This injury appears as retinal changes such as edema or a hole and is accompanied by symptoms such as decreased visual acuity, blurred vision, or scotoma. These symptoms appear immediately or within a few hours after exposure and then improve gradually over weeks or months. In some cases, patients completely recover, whereas in other cases, patients still have symptoms several months after light exposure. Thus, light-induced retinal injury associated with arc welding can be a severe disorder that can have a significant impact on daily life.

The mechanism of light-induced retinal injury associated with arc welding is not thermal because the temperature rise in the retina is estimated to be insufficient to cause a burn; therefore, the injury mechanism is considered to be photochemical[12]. Photochemical retinal injury, known as photoretinopathy, is caused by light primarily in the wavelength region of 400–500 nm. Because the light in this region appears blue to the eye, it is called blue light. Measures to prevent retinal injury due to arc welding are necessary. As the basis for designing such measures, it is desirable to obtain a quantitative understanding of the hazard of blue light emitted during arc welding. There are two sets of internationally

recognized guidelines for protection against blue light, the ACGIH guidelines[20)] and the ICNIRP guidelines[21)] which are basically equivalent. In this study, blue light was evaluated in accordance with the ACGIH guidelines.

Arc welding is performed with various metals. Arc welding of aluminum alloys is the second most commonly used arc welding in workplaces after arc welding of mild steel. Aluminum alloys exhibit excellent properties—light weight, high strength-to-weight ratio, corrosion resistance, workability, and good appearance—and are widely used as raw materials for structural products and components in a wide variety of fields, including manufacture of railway vehicles, automobiles, ships, aerospace instruments, and chemical instruments. 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 GMAW, an inert gas (argon, helium, or a mixture of these gases) is used as a shielding gas. GMAW, which ensures good work efficiency compared to GTAW, is used more widely in the workplace.

For a long time, GMAW was performed mostly by using steady current (GMAW-S). However, because GMAW-S tends to be unstable at low welding currents, it is difficult to weld thin plates of aluminum alloys with this welding method. Thus, GMAW-S is primarily used for a plate thickness of 3 mm or more. In recent years, the welding power source of a digital inverter type was developed. The digital inverter enables pulsed control of the welding current. GMAW using the pulsed current (GMAW-P) is capable of stable welding for a plate less than 3 mm in thickness. For this reason, GMAW-P is more widely used in the workplace.

It is important to investigate the hazard of the blue light emitted in arc welding of aluminum alloys under a wide range of conditions. A few studies have measured the blue light in arc welding of aluminum alloys [22-24)], and only two of these studies have determined

the effective blue-light radiance[22,23]. In these studies, the effective blue-light irradiance (spectral irradiance weighted against the blue-light hazard function) was measured at a fixed distance from the arc. The effective blue-light radiance was then calculated from the effective blue-light irradiance by using the estimated size (area) of the arc. However, this method provided inaccurate results, because the arc has no definite boundaries and consequently no definite size. Thus, no reliable data on the effective blue-light radiance for arc welding of aluminum alloys are available.

In the present work, the hazard of blue light emitted in GMAW of aluminum alloys was quantitatively evaluated in accordance with the ACGIH guidelines (ACGIH, 2015). In particular, I studied the impact of **(i)** the magnitude of welding current, **(ii)** the use of pulsed welding current, **(iii)** the type of base metal and welding wire.

6.2 Methods

A welding arc emits visible light of various wavelengths. According to the ACGIH guidelines (2015), the exposure level of visible light for causing retinal photochemical injury is different depending on the light wavelength. For that reason, the hazard of visible light is basically indicated by the effective blue-light radiance of a light source. The effective blue-light radiance is defined by equation (1):

$$L_B = \sum_{305}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta\lambda \quad \cdot\cdot\cdot\cdot\cdot (1)$$

In this equation, L_B is the effective blue-light radiance of a light source, L_λ is the spectral radiance of that light source, $B(\lambda)$ is the blue-light hazard function and $\Delta\lambda$ is the wavelength band width. The blue-light hazard function indicates the degree of hazard at

each wavelength and has a maximum at wavelengths of 435 nm and 440 nm (Figure 6.1).

For the exposure durations (t) less than 10000 s (approximately 167 minutes or 2.8 hours), an acceptable exposure is expressed by equation (2):

$$L_B \leqq \frac{100\ (\mathrm{J/cm^2 \cdot sr})}{t} \quad \cdot\cdot\cdot\cdot\cdot (2)$$

Alternatively, when L_B exceeds 0.01 W/cm^2·sr, the maximum acceptable exposure duration per 10000 s t_{max} in seconds is calculated by equation (3)

$$t_{max}(s) = \frac{100}{L_B} \quad \cdot\cdot\cdot\cdot\cdot (3)$$

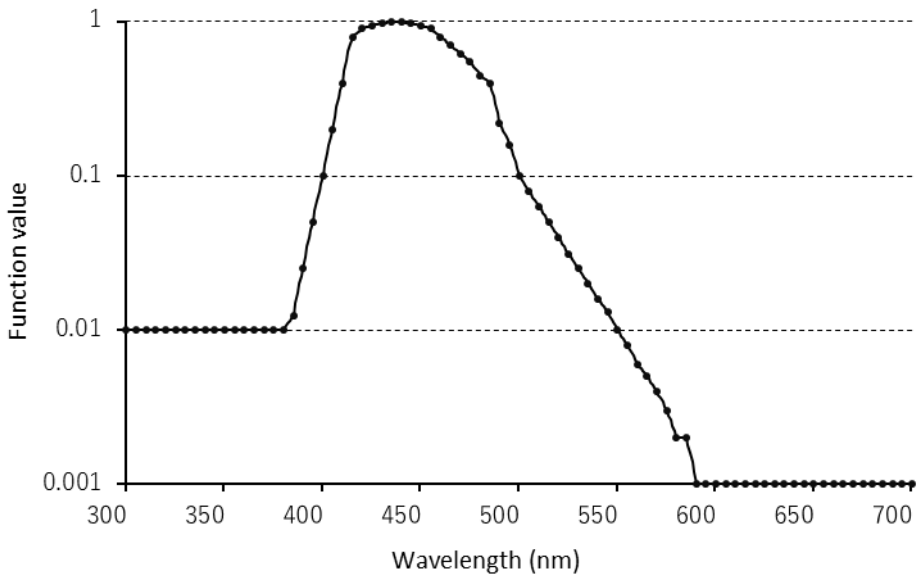


Figure 6.1 The blue-light hazard function (ACGIH, 2015). The blue-light hazard function shows the effectiveness of light to produce photochemical retinal damage as a function of wavelength.

To measure the spectral radiance, a spectroradiometer (SR-3AR, Topcon Technohouse

Corp.) was used. This spectroradiometer is capable of measuring the spectral radiance of a light source averaged over its field of view.

Although spectral radiance in the wavelength range of 305–780 nm is required to calculate effective blue-light radiance, as shown in equation (1), the shorter wavelength range of 305–380 nm was ignored in the calculation in this study, because the spectroradiometer can measure spectral radiance only in the wavelength range of 380–780 nm. This limitation can be justified because the blue-light hazard function has extremely low values in this wavelength range (Figure 6.1) and therefore its contribution to effective blue-light radiance is generally very small for broad-band light sources such as welding arcs. In fact, calculations based on spectral distribution in the range of 200 nm to 1000 nm measured for optical radiation emitted during GMAW of aluminum alloy[5)] show that the contribution of the ultraviolet radiation region (300 nm to 380 nm) would be only approximately 2%. The spectroradiometer was calibrated beforehand by the manufacturer and was used within the one-year validity of that calibration. In order to decrease the light intensity to a measurable level, the opening of the spectroradiometer was equipped with a neutral density filter (400FN46-50S, Andover Corp.). After completion of the measurement, the spectral radiance was corrected by the spectral transmittance of the neutral density filter (400FN-46-50S, Andover Corp.), and the effective blue-light radiance and the maximum acceptable exposure duration were calculated by equations (1) and (3), respectively.

The welding torch was fixed so that the arc remained in the same position, while the base metal was placed horizontally on a travel device that was translated along a horizontal line at a constant speed when the effective blue-light radiance was being measured. The spectroradiometer was positioned at an angle of 45° from the surface of the base metal and at an angle of 90° from the welding direction.

According to the ACGIH (2015), the diameter of the field of view for evaluation of

the blue-light hazard is 0.011 rad, which corresponds to a 3.3-mm-diameter circle at the position of the arc for a welder whose eyes are assumed to be 300 mm from the arc. Thus, the spectroradiometer was positioned so that its field of view would be a 3.3-mm-diameter circle at the position of the arc. Figure 6.2 shows a schematic diagram of the experimental setup for measuring the effective blue-light radiance. The integration time (exposure time) was set in the range of 50–530 ms automatically by the spectroradiometer depending on the light intensity. To exclude the time required to stabilize the arc and to accelerate the travel device to a constant speed, measurement did not begin until 5 s after the start of welding. Measurements were repeated five times for each set of conditions and the results were averaged.

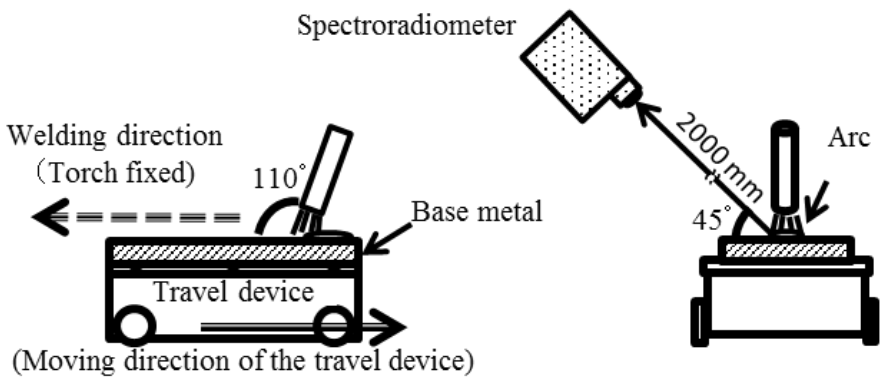


Figure 6.2 Experimental setup for measuring effective radiance (schematic diagram).

GMAW of aluminum alloys was performed in the experiments. The welding apparatus used was a digital inverter-type pulsed arc welding machine (DP350, DAIHEN Welding and Mechatronics Systems Co., Ltd.). The inclination of the welding torch was fixed at 110°. The type of welding was bead-on-plate welding (simulated welding with no joint). Flat position forehead welding was performed. The distance between the contact tip of the welding torch and the base metal was 20 mm. The welding speed was 300 mm/min. Three

different types of base metals were used. The base metals were specified by the Japanese Industrial Standards (JIS, 2014). The dimensions of the base material were 30 mm × 400 mm × 250 mm. Three different types of solid wires of diameter 1.2 mm were used. The wires were also specified by JIS (2009). Table 1 presents the composition of these base metals and the welding wires. The shielding gas was 100% Ar. The flow rate was 20 L/min.

6.2.1 Influence of the magnitude of the welding current and the use of pulsed current

To investigate the influence of the magnitude of the welding current and the use of pulsed current, we measured the effective blue-light radiance of the arcs for GMAW-S and GMAW-P. The base metal was A5083P-O (JIS, 2014) and the welding wire was A5183WY (JIS, 2009). The range of welding current was 100–250 A.

Table 6.1 Chemical composition of base metals and welding wires (mass%).

Base metal		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A1100P-H112		0.09	0.57	0.14	0	0	-	0.01	0.02	>99.00
A5083P-O		0.14	0.27	0.04	0.66	4.37	0.11	0.02	0.02	Balance
A6063BES-T5		0.44	0.19	0.03	0.02	0.5	0.02	0	0.02	Balance
Welding wire		**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
A1100WY	MAX	0.95 (Si+Fe)		0.20	0.05	-	-	0.10	-	>99.00
	MIN	-	-	0.05	-	-	-	-	-	
A4043WY	MAX	6.00	0.80	0.30	0.05	0.05	-	0.10	0.20	Balance
	MIN	4.50	-	-	-	-	-	-	-	
A5183WY	MAX	0.40	0.40	0.10	1.00	5.20	0.25	0.25	0.15	Balance
	MIN	-	-	-	0.50	4.30	0.05	-	-	

6.2.2 Influence of the type of base metal and the type of welding wire

To investigate the impact of the types of base metals and welding wires, the GMAW-P was performed and the effective blue-light radiance were measured for different combinations of base metal and welding wire. Three types of base metal were used: A1100P-H112,

A5083P-O and A6063BES-T5 (JIS, 2014). A1100P-H112 is essentially pure aluminum, A5083P-O is an alloy containing 4%–5% magnesium, and A6063BES-T5 is an alloy containing 0.45%–0.9% magnesium and additional elements other than magnesium. Three types of welding wires were used: A1100WY, A4043WY and A5183WY (JIS, 2009). A1100WY is essentially pure aluminum, A4043WY is an alloy containing small amounts of magnesium and other non-magnesium elements, and A5183WY is an alloy containing 4%–5% magnesium (Table 1). Table 2 presents the combinations of base metals and welding wires and their symbols used in this study. The welding currents were 100 A and 200 A.

Table 6.2 Combinations of base metal and welding wire tested and their symbols.

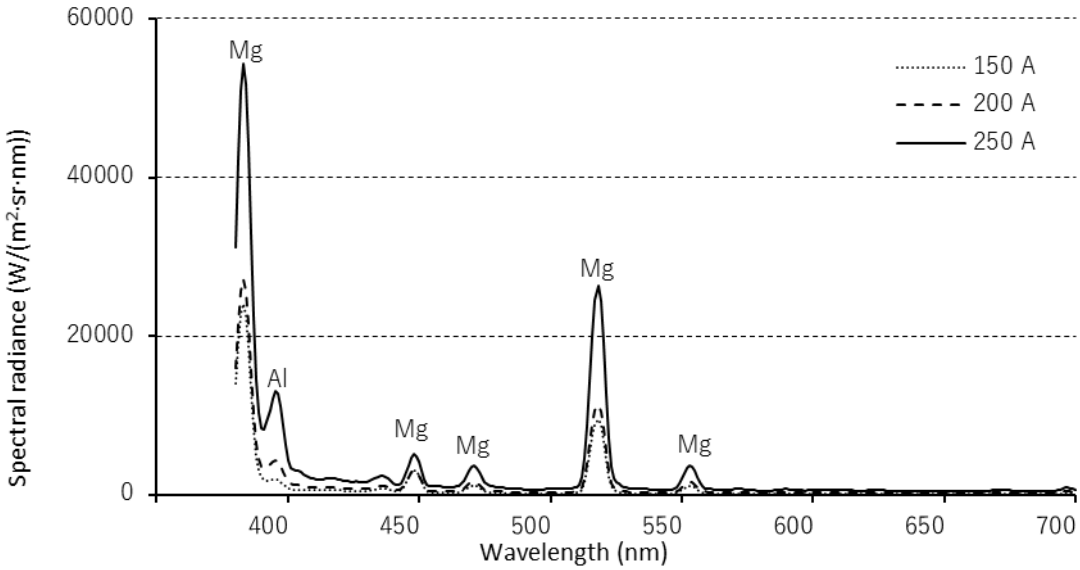
Symbol	Base metal	Important secondary element	Welding wire	Important secondary element
P1W1	A1100P-H112	None	A1100WY	None
P5W5	A5083P-O	Mg	A5183WY	Mg
P1W5	A1100P-H112	None	A5183WY	Mg
P5W1	A5083P-O	Mg	A1100WY	None
P6W4	A6063BES-T5	Si	A4043WY	Si

6.3 Results

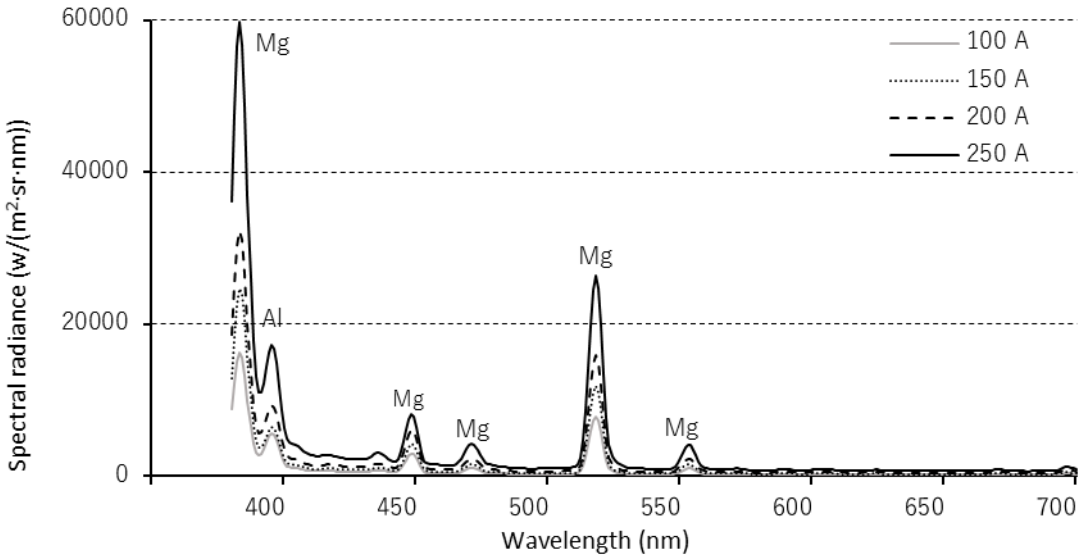
The effective blue-light radiance measured in this study was in the range of 2.9–20.0 W/cm^2·sr. The maximum acceptable exposure duration per 10000 s corresponding to these values was 5.0–34 s.

Figures 6.3(a) and 6.3(b) show typical examples of the spectral radiance of arcs for GMAW-S and GMAW-P, respectively. Figure 6.4 shows the effective blue-light radiance calculated from the spectral radiance for the two welding methods. The effective blue-light radiance for GMAW-S was in the range 5.2–14.5 W/cm^2·sr at welding current 150–250 A. No data was obtained for GMAW-S at 100 A because of the instability of the welding. The effective blue-light radiance for GMAW-P was in the range 5.7–20.0 W/cm^2·sr at welding

current 100–250 A. The effective blue-light radiance was roughly proportional to the welding current for both GMAW-S and GMAW-P. The effective blue-light radiance for GMAW-P was 1.4 to 1.7 times greater than that for GMAW-S at each welding current.



(a) Spectral radiance of arc in GMAW-S with P5W5 (A5083P-O and A5183WY)



(b) Spectral radiance of arc in GMAW-P with P5W5 (A5083P-O and A5183WY)

Figure 6.3. Comparison of spectral radiance of arc for (a) GMAW-S and (b) GMAW-P. Symbols Al and Mg indicate emission lines of aluminum and magnesium, respectively.

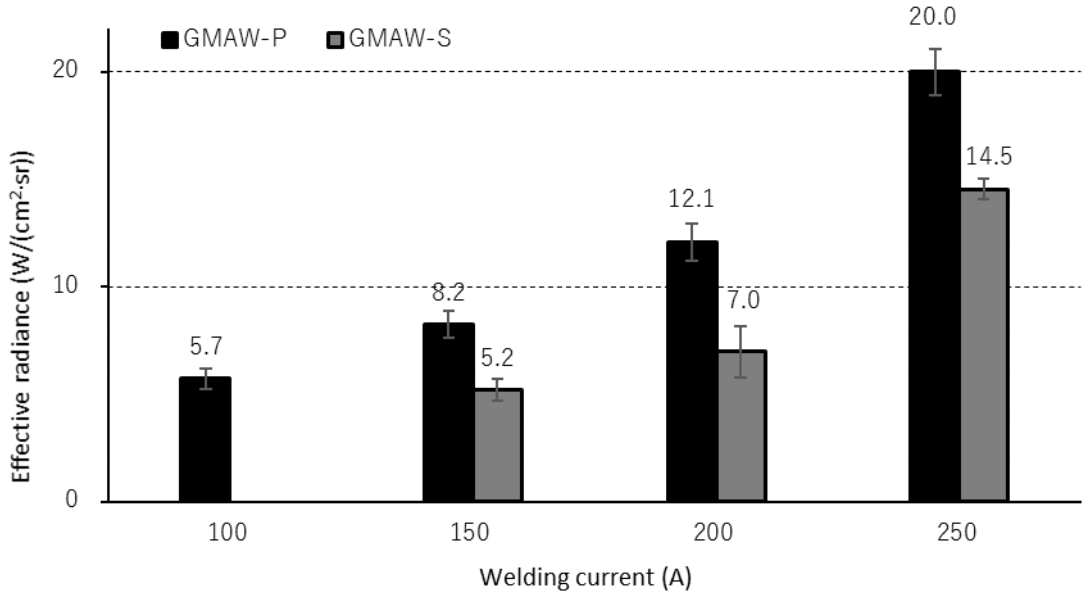
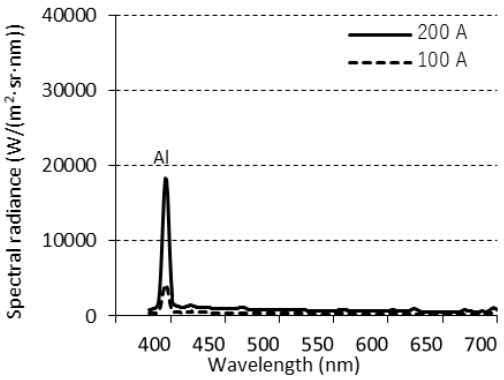


Figure 6.4. Effective blue-light radiance for GMAW-S and GMAW-P as a function of welding current. Error bars represent the standard deviation calculated from five measurements.

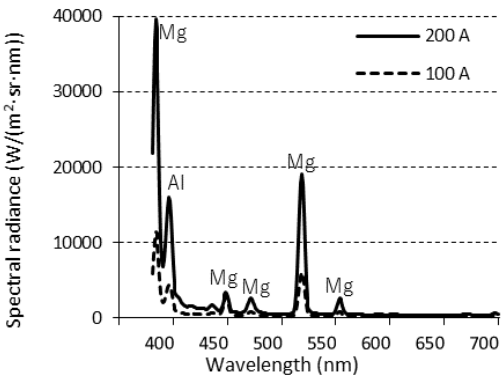
Figure 6.5 shows the spectral radiance for the following different combinations of base metal and welding wire for GMAW-P: (a) P1W1, in which both base metal and welding wire were pure aluminum; (b) P1W5, in which only the welding wire contained magnesium; (c) P5W1, in which only the base metal contained magnesium; (d) P5W5, in which both base metal and welding wire contained magnesium; (e) P6W4, in which both base metal and welding wire contained silicon and small amounts of magnesium. Emission lines of aluminum were observed in the spectral radiance for all the conditions tested, and intense emission lines of magnesium were observed when the welding wire contained magnesium.

Figure 6.6 shows the effective blue-light radiance calculated from the measured spectral radiance for the different combinations of base metal and welding wire. The effective blue-light radiance at 200 A of the welding current was 2.1 to 2.7 times higher than at 100 A for each combination. The effective blue-light radiance was different according to

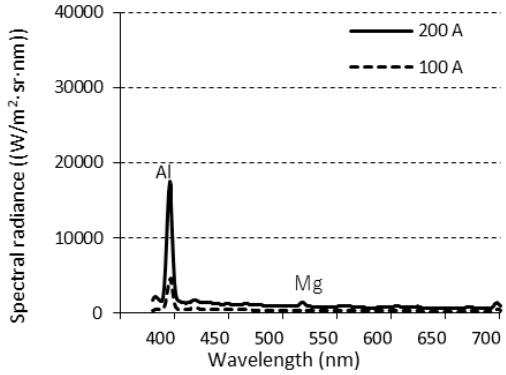
the combination of base metal and welding wire. The effective blue-light radiance was the highest for P5W5. The values for P1W5 were higher than those for P5W1. The lowest values were observed for P6W4 and P1W1.



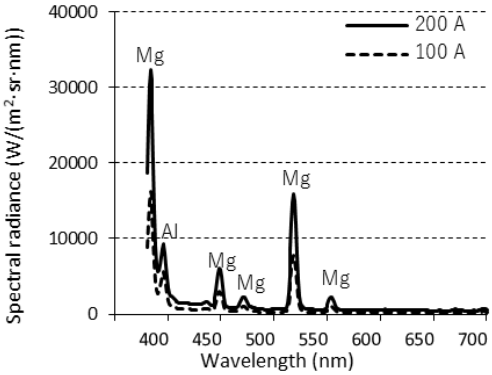
(a) Spectral radiance for P1W1



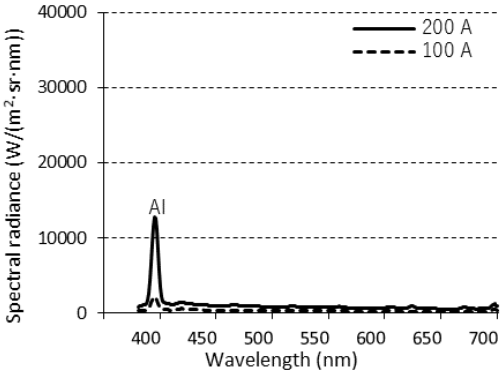
(b) Spectral radiance for P1W5



(c) Spectral radiance for P5W1



(d) Spectral radiance for P5W5



(e) Spectral radiance for P6W4

Figure 6.5. Spectral radiance of arc for different combinations of base metal and welding wire in GMAW-P.

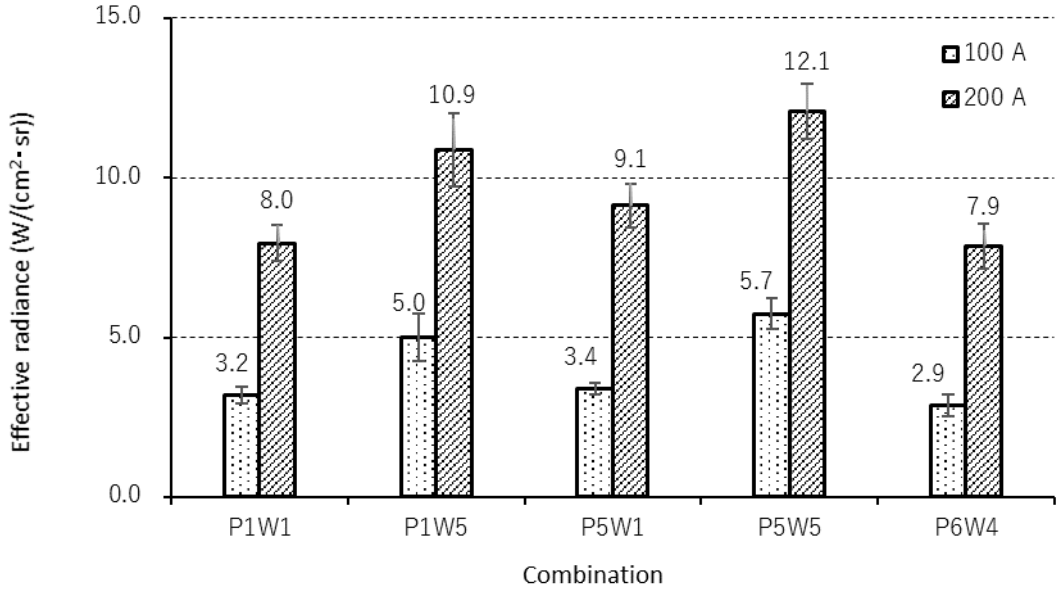


Figure 6.6. Effective blue-light radiance for different combinations. Error bars represent the standard deviation calculated from five measurements.

6.4 Discussion

This study shows that the effective blue-light radiance that indicates the exposure level of blue light to a welder in GMAW of aluminum alloys is in the range of 2.9–20.0 W/cm^2·sr, and that the corresponding maximum acceptable exposure duration per 10000 s is just 5.0–34 s. This means that directly viewing the arc of GMAW of aluminum alloys is quite hazardous. Thus, all welders and their helpers should wear eye protectors with a filter of the appropriate shade number and look through it to protect themselves from blue light when conducting arc welding.

In this study, the spectral radiance of the welding arc was measured in order to calculate the effective radiance. These measured data, when combined with the spectral transmittance of welding filters, can also be used to for the evaluation of the protection capability of welding filters against blue light, which is of practical importance.

It is thought that some workers are often exposed to blue light when striking the arc, because they mistakenly put on their face shields after starting the arc instead of

immediately before. If this brief exposure occurs many times in a few hours, the total exposure times may easily exceed the maximum acceptable exposure duration estimated in this study. Thus, every worker should always put on a face shield before starting the arc.

The brief exposure to blue light when striking the arc can be avoided by using auto-darkening welding helmets, which have been increasingly used in workplaces. An auto-darkening welding helmet has a filter that can change its transmittance and a sensor that detects light from the arc. In an auto-darkening welding helmet, its filter turns dark when the arc is being generated and transparent when the arc is off [25]. Therefore, unlike a conventional face shield, it is possible to wear an auto-darkening welding helmet at all times regardless of the presence or absence of the arc.

This study also shows that the effective blue-light radiance increases with increasing welding current when other conditions are the same (Figure 6.4 and Figure 6.6). This trend was also observed previously for GMAW of mild steel using 100% CO_2 as a shielding gas[26]. Thus, the welding current is an important factor influencing the exposure level of blue light emitted during the welding process. Welders should be particularly cautious about blue light when conducting arc welding with high welding current.

As Figure 6.4 shows, the effective blue-light radiance is always higher for GMAW-P of aluminum alloys than for GMAW-S of aluminum alloys when other conditions are the same. This suggests that arc welding of aluminum alloys with pulsed current presents a greater hazard than that with steady current. In recent years, the demand for arc welding of thin plates of aluminum alloys has increased in order to produce lightweight equipment that can be easily transported, and welding with pulsed current is widely used for this welding. Workers need to recognize the very high hazard of the blue light when welding with pulsed current.

For GMAW-P of aluminum alloys, the effective blue-light radiance is high for P1W5

and P5W5, in which the welding wire contains magnesium (Figure 6.6). This suggests that magnesium contained in the wire enters the arc and emits intense blue light. In fact, the spectral radiance for these cases (Figures 6.5(b) and 6.5(d)) shows that emission lines of magnesium account for a large portion of the light emitted by the arc. This can be attributed to the fact that, although the magnesium content of the welding wire is very low because the boiling point of magnesium (1090°C) is considerably lower than that of aluminum (2470°C), magnesium is preferentially vaporized from the welding wire and thus gives rise to stronger emission. In particular, magnesium has strong emission lines at 450 nm and 470 nm in the very hazardous wavelength region (Figure 6.1). Consequently, it is concluded that the hazard of the blue light emitted during GMAW-P of aluminum alloys is primarily determined by the emission from magnesium contained in the welding wire.

In this study, the spectral radiance of the arc was measured at a distance of 2000 mm using a spectroradiometer with a 48-mm-diameter aperture. This means that the light emitted within the solid angle of 1.4 ° from the arc was measured. If the measurement had been made at a different distance, light emitted within a different solid angle from the arc would have been measured, and if the emission from the arc had been anisotropic, different results would have been obtained. However, considering the mechanism of light emission from a welding arc, the emission is essentially isotropic. Thus, the measurement distance is expected to have a negligible effect on the present results.

6.5 Conclusions

It is very hazardous to view the arcs in gas metal arc welding of aluminum alloys. The hazard is higher at higher welding currents, when pulsed welding currents are used instead of steady welding currents, and when magnesium is included in the welding materials. Welders and their helpers should use appropriate eye protectors in such arc-welding

operations. They should also avoid direct light exposure when starting an arc-welding operation.

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Chapter VII

Summary and Conclusions

7.1 Hazard of UVR

The Ultraviolet radiation (UVR) emitted during arc welding has been measured by researchers and the related hazards have been quantitatively evaluated[1-7], according to the acceptance criteria of The American Conference of Governmental Industrial Hygienists (ACGIH) and International Commission on Non-Ionizing Radiation Protection (ICNIRP)[8,9]. In these studies, the effective irradiance of UVR emitted during gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) of aluminum alloys and GMAW of mild steel was measured. Dependence of effective irradiance on the welding current and adaptation of the inverse square law of distance were also verified. In arc welding, welding results, such as the shape of weld bead and the depth of fusion, have been dependent on welding materials (components of a base metal and a filler metal), the pulsed current, the shielding gas, and the type of electrodes. It is considered that these elements also have an effect on UVR, because there is a close relationship between the state of the arc and the welding result. However, the influence of these elements on the hazard from UVR has not yet been investigated. In addition, because the UVR emitted during arc welding is influenced by reflections from the surface of a base metal and the liquid surface of molten pool, and by absorption/scattering due to fumes, the effective irradiance of UVR is thought to be subjected to the angular dependence. However, it is considered to be insufficient because the angular dependency of the effective irradiance had only been investigated regarding the angle from the surface of the base material in GMAW of mild steel[5].

In actual welding workplaces, the arc welding is performed under various conditions; hence, welding workers and surrounding workers are exposed to various environments.

Therefore, it is necessary to clarify the influence of elements: pulsed current, shielding gas, type of electrodes and angular dependence, as a basis to improve the welding ambient environment.

7.1.1 Hazard level of UVR in this study

In this study, the effective irradiance of UVR observed at 500 mm from the arcs was 0.09–13 mW/cm^2. The allowable daily exposure time calculated from these irradiances was 0.23–33 s. Therefore, because the cumulative allowable exposure time calculated by the effective irradiance is extremely short, it is considered that the cumulative exposure time of welding workers easily exceeds the threshold value when exposed to a welding arc without applying appropriate precautionary measures. Table 7.1 shows the effective irradiance and the allowable exposure time for each type of welding for various materials.

Table 7.1 Effective irradiance and allowable exposure time for each welding

Type of welding	Base metal	welding current (A)	Effective irradiance (mW/cm^2)	Allowable exposure time (s)
GMAW	Aluminum	100－250	0.33－10	0.30－9.1
	Mild steel	100－350	0.51－13	0.23－5.9
	Magnesium	100－175	4.6－7.8	0.39－0.65
GTAW	Aluminum	100－200	0.10－0.91	3.3－33
	Magnesium	100－200	0.85－8.9	0.30－3.5

Assuming that the daily working time is 8 hours and that the effective irradiance of UVR decreases relative to the inverse square law of distance, the allowable exposure time on the fixed exposed surface at each distance is shown in Table 7.2. In an actual workplace, arcs rarely occur continuously for 8 hours, and because workers are moving, it is not considered that only certain surfaces will be exposed to UVR. Therefore, the actual

allowable exposure time is underestimated. However, even at a distance of 5 m from the arc, exposure to UVR is hazardous irrespective of the UVR intensity, thus it is believed that prolonged exposure is also hazardous. In cases where arc welding is performed, it is necessary to take precautions to ensure that all surrounding workers are not exposed to the UVR emitted by the arc.

Table 7.2 Relationship between the allowable exposure time and the distance from the arc

Distance (m)	0.5	1	5	10	20
Allowable exposure time(s)	0.23－33	0.92－130	23－3300	92－13000	368－52000

7.1.2 Factors affecting hazard level of UVR

In this study, it was revealed that five new factors, besides welding current, influence the hazard level of UVR. These elements exhibit the following characteristics. In addition to workers engaged in arc welding, workers engaged in other tasks around arc welding must be fully aware of these factors in order to protect themselves from exposure to UVR.

(a) Welding current

Consistent with previous studies, the influence of welding current on the hazard level of UVR was confirmed[1-7]. The effective irradiance of UVR emitted during GTAW (Figure 2.4) and GMAW (Figure 3.4) of aluminum alloys, during GMAW of mild steel (Figures 4.2 and 4.3) and during GTAW and GMAW of magnesium alloys (Figure 5.2) sharply increases with the increase of welding current, as measured in this study. Welding current is, therefore, an important factor affecting the hazard level of UVR emitted during arc welding.

(b) Elements contained in welding materials

In this study, the hazard level of UVR was strongly influenced by the elements contained in base metals and filler metals, as shown by the measured effective irradiance of UVR emitted during GTAW and GMAW of aluminum alloys (Figures 2.4 and 3.4). In particular, the hazard level of UVR emitted during GMAW was more strongly influenced by magnesium in the welding wire than by magnesium in the base metal.

Aluminum alloys containing magnesium are currently widely used because they have excellent strength characteristics after welding. Welding operators and their supervisors should be aware that UVR with high hazardous level is emitted during arc welding of aluminum alloys containing magnesium.

(c) Pulsed current

It was clarified that the hazard level of UVR is strongly affected by the pulsed current, as shown by the measured effective irradiance of UVR emitted during GMAW of aluminum alloys and mild steel (Figures 3.7 and 4.3). In addition, the hazard level becomes higher particularly in the low current range as compared to the steady current. In recent years, the demand for welding structures corresponding to the environment has increased, and welding of thin plates with a thickness of 3 mm or less is increasing. Because the pulsed current provides arc stability in the low current range, it is anticipated that the use of pulsed current will increase in the future. Therefore, workers in the vicinity of arc welding have to be aware that the hazard level of UVR is high even in the low current range when using pulsed current.

(d) Shielding gas

In this study, it was revealed that the type of shielding gas used during GMAW influences the hazard level of UVR. In GMAW of mild steel, as shown in Fig. 4.2, the shielding gas affected the effective irradiance at welding current of 300 A or more, and the effective

irradiance was almost doubled in 80% Ar + 20% He compared to 100% CO_2. In the case of magnesium alloy GTAW, as shown in Figure 5.3, the effective irradiance approximately doubled in 50% Ar + 50% He compared to 100% Ar. In contrast, in GMAW, due to added He, the amount of fumes generated during arc welding increased and the effective irradiation decreased.

In recent years, the use of 80% Ar + 20% He has been increased in GMAW of mild steel, due to less spatter generation and easiness of post-weld treatment. Therefore, it is considered that special attention is required for exposure to UVR.

(e) Type of electrode

The effective irradiance of UVR emitted during GTAW of aluminum alloys and magnesium alloys is affected by the type of electrode. As shown in Figure 2.8 and Figure 5.3, the effective irradiance is about 10-20% higher when using electrodes containing oxides than when using pure tungsten electrodes.

Generally, electrodes containing oxides are more durable, so continuous welding is possible for a longer period of time than with pure tungsten electrodes. Therefore, when an electrode containing an oxide is used, it is considered that the cumulative exposure time of UVR per day becomes longer. Welding workers employees should be aware that the hazard level of UVR is high, in recent years, as using of oxide-containing electrodes is increasing due to high working efficiency.

(f) Angle from welding arc

The hazard level of UVR depends on the angle from a welding arc, according to the effective irradiance of GTAW and GMAW of aluminum alloys measured in this our study (Figures 2.6 and 3.5). Regardless of the welding method, in flat-position welding, the effective

irradiance of UVR depends on the angle from the surface of the base metal. The angle with the highest effective irradiance of UVR is 40°–50°. Therefore, when welding workers employees perform arc welding in a normal posture, the hazard level of UVR is highest around their head and neck.

7.2 Hazard level of blue light in this study

Arc welding also emits intense visible light. An extremely large number of workers is predicted to be exposed to visible light by accidentally or mistakenly looking directly at the welding arc without adequate protection. It has been reported that many light-induced retinal injuries have occurred in people who were looking at welding arcs without adequate protection[10-19]. The light-induced retinal injury with arc welding is a severe disorder that has a significant impact on daily life. However, measurement of the blue light during arc welding has not been actively studied. In particular, few studies have measured the blue light emitted during arc welding of aluminum alloys[20-22], and no reliable data on blue-light effective radiance have been reported. In this study, similar to the measurement of the effective irradiance of UVR, the effective radiance of blue light emitted during GMAW of aluminum alloys was experimentally measured under welding conditions simulating an actual welding operation. In addition, the effective blue light radiance of the welding arc was measured under a stable environment with a fixed welding arc.

In this study, the radiance distributions in visible radiation emitted during GMAW of aluminum alloys under various conditions were measured, and the hazard of blue light was quantitatively evaluated according to the recommendation of the ACGIH[23]. The effective radiance of blue light measured in this study was in the range of 2.9–20.0 W/cm^2·sr. The corresponding maximum acceptable exposure duration per day when the exposure time is shorter than 10000 s was only 5.0–34 s. Therefore, as the cumulative acceptable exposure

duration per day is very short, it is considered that directly looking at welding arcs during GMAW of aluminum alloys, without appropriate prevention measures, will exceed the threshold exposure duration. The effective radiance of blue light emitted during GMAW of aluminum alloys was higher at a higher welding current than at a lower welding current. This trend is similar to the effective radiation of blue light when welding mild steel. The welding current was also an important factor affecting the hazard level of blue light emitted during welding. In addition, the effective radiance of blue light increased when the pulsed current was used and when the welding materials contained magnesium.

7.3 Measures against light emitted during arc welding

The effective irradiance of UVR measured at 500 mm from the welding arc was 0.09–12.9 mW/cm^2 in this study. According to these irradiance values, the allowable maximum exposure time per day was just 0.23–33 s. Furthermore, the effective radiance of blue light measured in this study was 2.9–20.0 W/(cm^2· sr). The maximum acceptable exposure duration corresponding to these radiance values per 10000 s was 5.0–34 s. Because UVR and blue light with high hazard levels are emitted during arc welding, it is hazardous to directly expose workers to these light sources without adequate protection. Therefore, it is considered that protective measures are necessary. Here, two cases were considered: (1) Protection measures of welding workers. (2) Protection measures of surrounding workers engaged in tasks other than welding. Regarding UVR, protection measures are necessary for the eyes and the skin, because keratoconjunctivitis and erythema have been reported in actual welding places[24,25]. Regarding blue light, eye protection measures are required, because retinal injury is caused by staring looking at a welding arc[10-19]. Furthermore, because UVR and blue light are simultaneously emitted during arc welding, all protection measures should be taken at the same time.

7.3.1 Welding workers

As a protective measure against keratoconjunctivitis caused by UVR and retinal injuries caused by blue light, it is essential to look at the welding arc through a filter with an appropriate light shielding number standardized by the JIS[26)], etc. Welding workers have been using a face shield with appropriate filters. However, eye injuries due to arc welding have been reported by welding workers despite wearing a face shield. Because the filter attached to a face shield is very dark, the welding spot is not obvious before the arc is struck. Therefore, some welding workers wear the face shield immediately just before the arc is struck, therefore they may be exposed to UVR and blue light by accidentally wearing a face shield without a filter after the arc is generated. Although the accidental exposure is brief for each strike of the arc, exposure may occur recurrently, because workers usually strike an arc repeatedly during a day. Consequently, another hazard is that total exposure time could easily exceed the allowable daily exposure time determined in this study.

The brief exposure to UVR and blue light when striking the arc can be avoided by using auto-darkening welding helmets, which have been increasingly used in workplaces. An auto-darkening welding helmet has a filter that changes its transmittance and a sensor that detects light from the arc. In an auto-darkening welding helmet, the filter turns dark when the arc is being generated and transparent when the arc is off [27,28)]. Therefore, instead of a conventional face shield, it is possible to wear an auto-darkening welding helmet at all times regardless of the presence of the arc.

It is necessary for welding workers to wear appropriate welding protective equipment to prevent their skin from UVR exposure. As clarified in Chapters 2 and 3, the effective irradiance of UVR depends on the angle from the base material and becomes strongest near the welding worker's head and neck. Welding workers must completely protect these areas with a face shield or other protective gear. In particular, during hot summer weather, the risk

of exposure to UVR is higher, because welding workers often neglect to wear neck protection.

7.3.2 Surrounding workers engaged in tasks other than welding.

Table 7.2 shows the relationship between allowable daily exposure time and the distance from arcs calculated by the inverse square law of distance. For example, the range of allowable permitted daily exposure time of UVR is 23–3300 s at a distance of 5 m from the welding arc. Thus, even at a distance of 5 m from the arc, exposure to UVR is hazardous when the emitted UVR is intense. Furthermore, prolonged exposure is dangerous even when the emitted UVR is weak. Thus, in workplaces where arc welding is performed, it is necessary to take precautions to ensure that surrounding workers are not exposed to the UVR emitted by welding arcs.

The workplaces located near the arc welding area need to be compartmentalized in order to protect the eyes and the skin of the workers who perform tasks other than arc welding in the surrounding areas (Article 325 of the Occupational Health and Safety Regulations stipulates that companies must partition places where a hazard of diverging intense light, such as a welding arc, exists). However, when partitioning by walls and opaque materials, the work space becomes separated and workers might possibly feel a sense of pressure or loneliness.

Therefore, as a reference experiment in this study, the spectral irradiance was measured through a glass plate (colorless), a polycarbonate plate (colorless) and a light-shielding curtain (yellow or green) during 100% CO_2 welding of mild steel. The experimental arrangement was the same as that shown in Figure 3.2, and the welding current was 100 A. Figure 7.1 shows the measurement results. Among the hazardous lights emitted by arc welding to the surrounding environment, UVR can be blocked by installing a glass

plate or a polycarbonate plate, or another suitable material. In addition, it is possible to reduce the hazard from blue light with a yellow light-shielding curtain for welding. The transmittance through the green light-shielding curtain was too low to measure the spectral irradiance. Therefore, it is thought that a yellow light-shielding curtain is the most suitable partitioning material to protect from UVR emitted to the surrounding environment. However, the supervisor needs to educate the surrounding workers to not directly look at the welding arc, because this curtain is insufficient to protect from blue light.

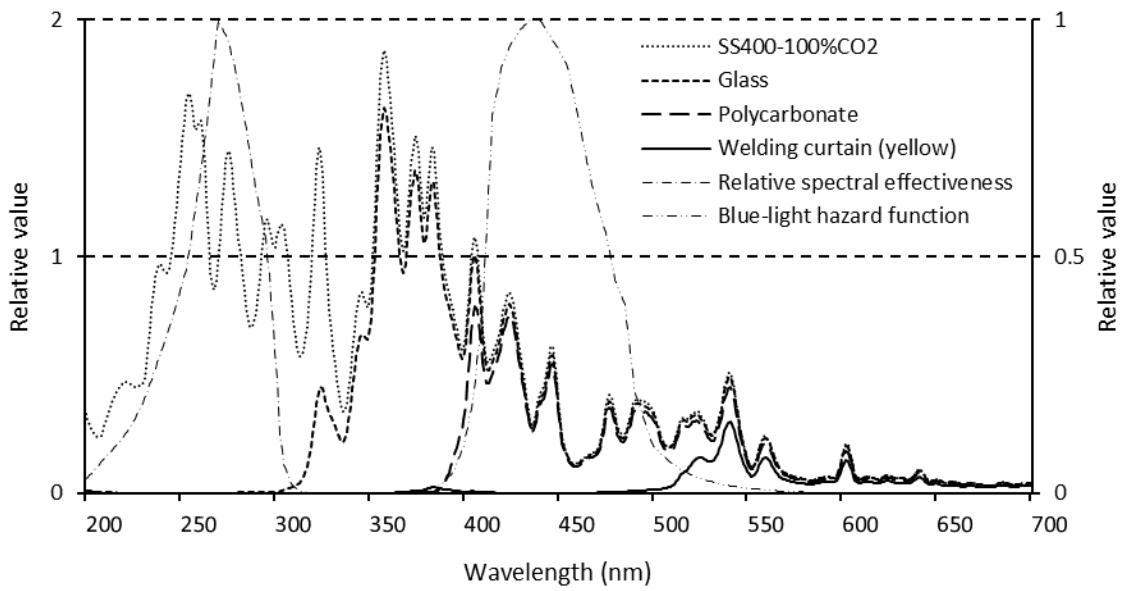

Figure 7.1 The spectral distribution of the welding arc that passed through each light shielding material.

7.4 Application of the results of this research

As mentioned above, the hazard levels of UVR and blue light of the welding arcs emitted under various welding conditions are high and adequate protection measures against these lights are necessary. Eye protectors, face shields, work clothes and light shielding curtains for welding are commonly used as protective equipment against welding arcs. Only the filter

lens attached to the eye protector and the filter plate attached to the face shield, whose light shielding performance value is specified by JIS[26)], are shown in Figure 7.2. There is no regulation regarding the light shielding performance of other light shielding protective equipment, and unified performance evaluation has not been performed yet. In addition, JIS has defined the light blocking effect values of the filter lens and filter plate against UVR and visible light. Transmittance at 313 nm and 365 nm for ultraviolet radiation and average transmittance for visible light have been determined. However, it is difficult to quantitatively evaluate the performance of light shielding protectors by these values only, because the hazard levels of UVR and blue light vary depending on the wavelength. Additionally, the intensity distribution of light emitted during arc welding is influenced by the base metal and filler metal.

The quantitative evaluation of performance is considered necessary for the selection of light shielding protective equipment in the actual work site. Quantitative evaluation of the performance of light shielding protective equipment becomes possible by applying the spectral irradiance, the effective irradiance and the spectral radiance measured in this study, provided that it is possible to measure the spectral transmittance of a light shielding protector.

The effective irradiance of UVR transmitted through the light shielding protector can be obtained by the following equation, and evaluation of protector performance is possible.

$$E'_{eff} = \sum_{180}^{400} E_{\lambda} \cdot S(\lambda) \cdot T(\lambda) \cdot \Delta\lambda \quad \cdots\cdots(1)$$

In this equation, E_{eff}' is the effective irradiance after transmission (W/cm^2), E_{λ} is the spectral irradiance at wavelength λ (W/(cm^2·nm)), S(λ) is the relative spectral effectiveness at wavelength λ, T(λ) is the spectral transmittance at wavelength λ, and Δλ is the wavelength

bandwidth (nm).

The maximum exposure time: t_{max}'(s) per day against the effective irradiance when the protected skin or eye is irradiated with UVR is obtained using Equation (2):

$$t'_{max} = \frac{3}{E_{eff}'} \cdot \cdots\cdots (2)$$

In addition, the effective radiance of blue light transmitted through the light shielding protector can be obtained by the following equation, and evaluation of a protector performance is possible.

$$L_B' = \sum_{305}^{700} L_\lambda \cdot B(\lambda) \cdot T(\lambda) \cdot \Delta\lambda, \cdots\cdots (3)$$

L_B' is the effective radiance (W/(cm^2·sr)), L_A is the spectral radiance W/(cm^2·sr·nm) of the wavelength λ, T(λ) is the spectral transmittance at wavelength λ, and B(λ) is the blue-light hazard function.

The maximum acceptable exposure duration after transmittance through work clothing in one day, t'_{max} (s), based on the effective blue-light radiance can be obtained with Equation (4):

$$t'_{max} = \frac{100}{L_B} \cdot \cdots\cdots (4)$$

Personal eye protectors for optical radiations Personal face protectors for welding

Figure 7.2 Protective equipment for welding in general using

7.4.1 Adaptation example of quantitative evaluation on UVR shielding performance for work clothes

Workers working around arc welding work including welding workers usually wear work clothes. Working clothes protect from exposure to UVR, but the effectiveness against UVR emitted during arc welding has not been quantitatively evaluated. Therefore, quantitative evaluation of light shielding performance of work clothes was attempted with equations (1) and (2). Work clothes subjected to the experiment are similar to widely used by workers; clothes with a composition of 65% polyethylene + 35% cotton (130 g/m^2) or 100% cotton (180 g/m^2) are generally used in the summer, and with 100% cotton (280 g/m^2) or 100% aramid are used in the winter. Details of the fabric are shown in Table 7.3.

The spectral transmittance of each fabric was experimentally obtained using a spectrophotometer (Figure 7.3). In addition, the spectral irradiance and effective irradiance of UVR emitted during GMAW-P of aluminum alloy measured in this study were applied, and the effective irradiance and allowable exposure time after transmittance through each fabric were calculated. The welding current used is 250 A. Table 7.3 shows the effective irradiance after transmittance through each fabric and the allowable exposure time for each distance.

As described above, provided that the spectral transmittance of the light shielding protector can be obtained, quantitative evaluation of light shielding performance against UVR of various protectors becomes possible by adapting the data obtained in this study.

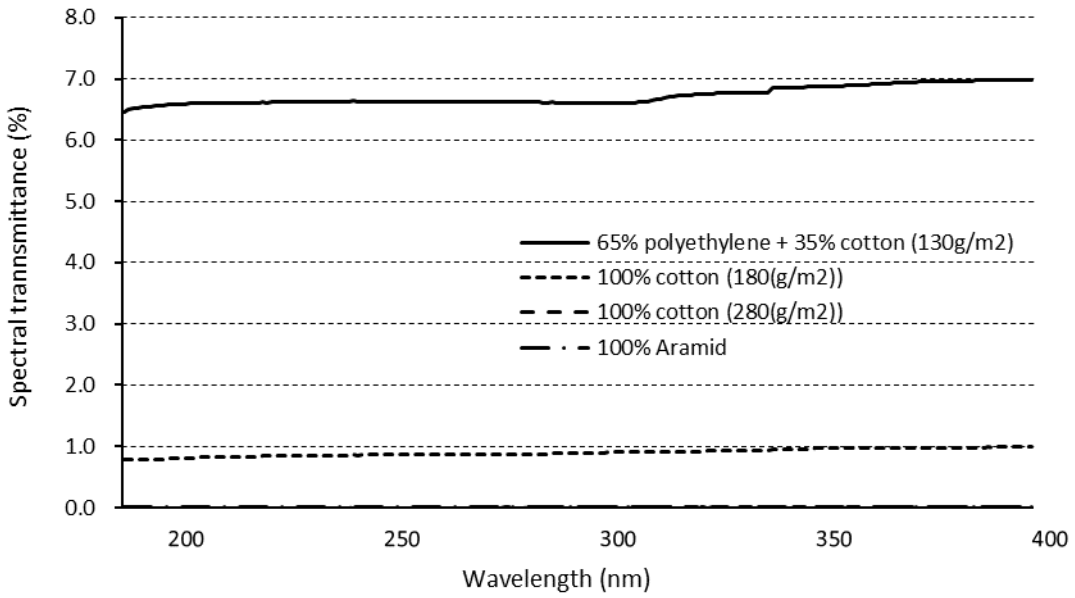

Figure 7.3 Spectral transmittance of each type of clothes

Table 7.3 Shielding performance of working clothes against UVR

Type of fabric	—	PE+CO*	Cotton (100%)		Aramid**
Weight (g/m^2)	—	130	180	280	210
Effective irradiance (mW/cm^2)	10	0.66	0.08	0.00	0.00
Average transmittance (%)	100	6.9	1.0	0.03	0.09
Allowable exposure time (s) (50 cm)	0.3	4.5	35	∞	∞
Allowable exposure time (s) (5 m)	30	450	3500	∞	∞
Allowable exposure time (s) (10 m)	120	1800	14000	∞	∞

* PE+CO: 65% polyester + 35% cotton,

**Aramid: DuPont™ Nomex®

7.4.2 Adaptation example of quantitative evaluation of light shielding performance against blue light for filter lens and filter plates

JIS specifies the average transmittance in the visible radiation range with respect to the light shielding performance against the blue light of the filter lens and filter plate as shown in Figure 7.4. However, as clarified in this research, in arc welding, the spectral distribution of the welding arc is different due to the influence of the welding material. Therefore, the performance evaluation of the light shielding protector according to the current JIS standard is insufficient, and it is considered that performance evaluation is required when considering the hazard level of each wavelength.

The light shielding performance of filter lens and filter plates were quantitative evaluated with equations (3) and (4). Figure 7.5 and Figure 7.6 show the experimentally determined spectral transmittance of the filter lens and filter plate. For the spectral radiance, the value measured in GMAW-P of the aluminum alloy measured in this study was applied. The welding current used was 250 A. The effective radiance after transmittance through the filter lens or filter plates and the allowable exposure time are shown in Table 7.4 and Table 7.5.

As described above, after the spectral transmittance of the filter lens and the filter plate is obtained, it is possible, by applying the data measured in this study, to quantitatively evaluate the light shielding performance against the blue light corresponding to various welding conditions.

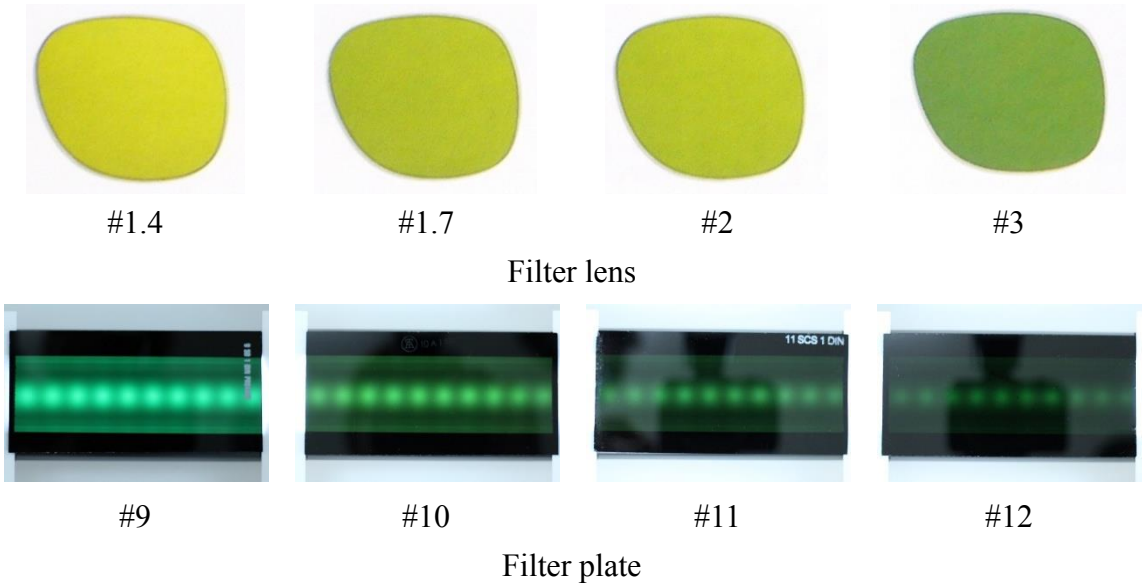

Figure 7.4 Filter lens and plate for personal eye protectors for optical radiations

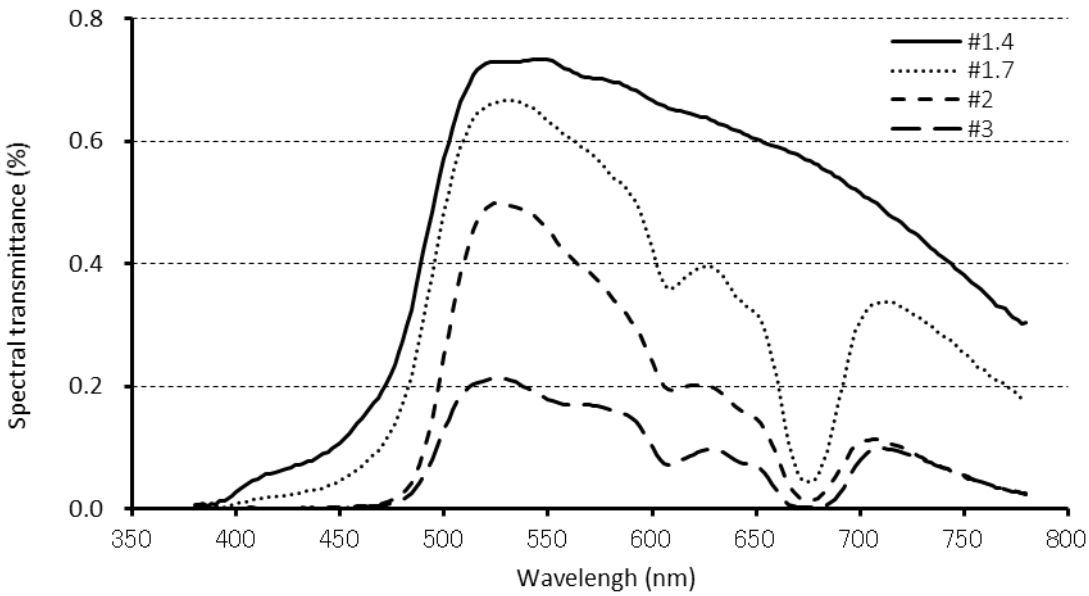

Figure 7.5 Spectral transmittance of filter lens for visible radiation wavelengths

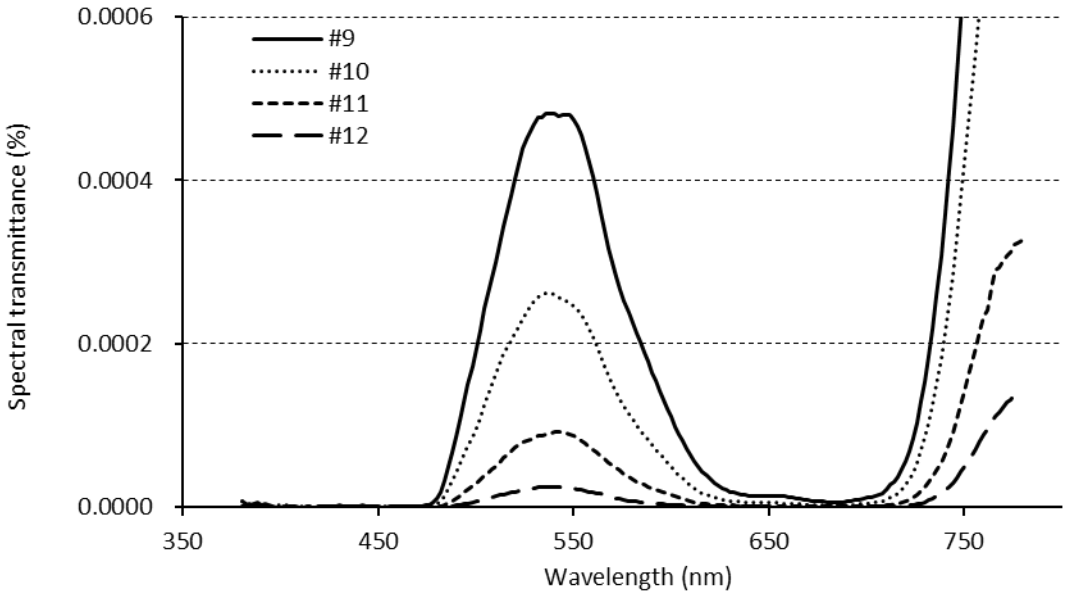

Figure 7.6 Spectral transmittance of filter plates for visible radiation wavelengths

Table 7.4 Shielding performance of filter lens against blue light

Shade number.	—	#1.4	#1.7	#2	#3
Effective radiance (W/(cm^2· sr))	20	2.7	1.6	0.54	0.25
Allowable exposure duration (s)	5.0	37	64	180	390

Table 7.5 Shielding performance of filter plates against blue light

Shade number.	—	#9	#10	#11	12
Effective radiance (W/(cm^2· sr))	20	4.2×10^{-4}	2.2×10^{-4}	7.3×10^{-5}	1.9×10^{-5}
Allowable exposure duration (s)	5.0	∞	∞	∞	∞

7.5 General conclusion

It became clear that the welding arcs measured in this study include high levels of hazardous radiation of UVR and blue light. It is suggested that sufficient protection measures are necessary, because the exposure to welding arcs for welding and surrounding employees is at a high hazard level.

The main factors affecting the hazard level of UVR and blue light are the following.

(1) Welding current: The hazard level of UVR and blue light increases with increasing welding current.

(2) Elements contained in welding materials: The hazard level of UVR and blue-light were affected by welding wire containing magnesium, in particular.

(3) Pulsed current: The hazard level of UVR and blue light increases by using pulsed current. In particular, the hazard level increases in the low current range.

(4) Shielding gas: The shielding gas influences the metal transfer mode and the depth of fusion, and as a result influences the hazard level of UVR.

(5) Type of electrode: The effective irradiance of UVR is about 10-20% higher when using electrodes containing oxides than when using pure tungsten electrodes.

(6) Angle from welding arc: In flat-position welding, the hazard level of UVR around the head and neck of the welding worker is higher.

In addition, the following protection measures are considered effective for hazardous light.

(1) Welding workers must constantly wear suitable welding protective equipment prescribed by JIS. as protection measures against UVR and blue light. In particular, auto-darkening welding helmets are effective against UVR and blue light exposure.

(2) The surrounding workers during a welding operation, need protection measures against UVR, and it is effective to compartmentalize the welding space using welding curtains as a protection measure. In addition, safety education related to photoretinopathy of workers is necessary to protect from blue light exposure.

(3) It is desirable to use constant current as the welding current rather than pulsed current.

(4) It is necessary that better care should be taken against UVR and blue light exposure, when magnesium is included in the welding material.

The following conclusions were obtained in each chapter.

In Chapter II, the hazard of UVR emitted during GTAW of aluminum alloys was quantitatively evaluated. The following conclusions were obtained.

GTAW of aluminum alloys leads to the emission of intense UVR. Exposure to this radiation is considered hazardous according to the ACGIH guidelines. UVR exhibits the following hazardous 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 level depends on the direction of emission from the arc. **(5)** Electrodes containing oxides yield a stronger hazard than electrodes of pure tungsten. **(6)** Under the welding conditions typically used at actual workplaces, the hazard of GTAW is approximately 1/10 of that of GMAW.

In Chapter III, the hazard of UVR emitted during GMAW of aluminum alloys was quantitatively evaluated and the following conclusions were obtained.

GMAW of aluminum alloys leads to the emission of intense UVR. Exposure to this radiation is considered hazardous according to ACGIH guidelines. UVR exhibits the following hazardous characteristics. **(1)** It is more hazardous at higher welding currents. **(2)** It is more hazardous when the welding materials include magnesium. In particular, the hazard level of UVR becomes higher when the welding wire contains magnesium. **(3)** The hazard level depends on the direction of emission from the arc. (4) It is more hazardous when using pulsed welding currents than using steady welding currents.

In Chapter IV, the hazard of UVR emitted during GMAW of mild steel was quantitatively evaluated. The following conclusions were obtained.

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 in 80% Ar + 20% CO_2 shielding gas than in 100% CO_2. **(3)** It is more hazardous when using pulsed welding currents than using non-pulsed welding currents. **(4)** It appears to depend on the metal transfer, because the hazard of the UVR emitted during spray transfer is the highest.

In Chapter V, the hazard of UVR emitted during GMAW and GTAW of magnesium alloys was quantitatively evaluated and the following conclusions were obtained.

The GTAW and GMAW-P of magnesium alloys leads to the emission of intense UVR. According to the ACGIH guidelines, exposure to this radiation is considered to be hazardous. This UVR hazard exhibits the following characteristics. **(1)** The hazard of UVR generated during welding is higher for GMAW-P (pulsed current) than for GTAW. **(2)** The hazard of UVR is higher at higher welding currents. In addition, GTAW is more susceptible to the welding current than GMAW-P. **(3)** The hazard of UVR emitted during GTAW increases when the shielding gas contains helium. **(4)** The hazard of UVR during GTAW is increased with the use of cerium oxide tungsten electrodes. (5) The UVR in GMAW-P is strongly affected by fumes generated during welding, and the level of hazard level is reduced with the increase of the amount of fumes.

In Chapter VI, the blue-light hazard from GMAW of aluminum alloys was quantitatively evaluated and the following conclusions were obtained.

It is highly hazardous to look directly at the arcs in gas metal arc welding of aluminum

alloys. **(1)** The hazard is higher at higher welding currents. **(2)** The hazard is higher when using pulsed welding currents compared to steady welding currents. **(3)** The hazard is higher when magnesium is included in the welding materials. Welding workers and their assistants should use appropriate eye protectors in arc welding operations. They should also avoid direct light exposure when starting an arc welding operation.

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