Abstract: It is important to determine spectra of optical radiation from light sources at workplaces, because they usually emit lights of various wavelengths simultaneously and these differ in their degree of harmfulness. Spectra of optical radiation (wavelength range: 200–1,000 nm) from the arc of various arc welding processes were measured, using a multichannel detector system. For each process, a stable relative spectrum (a shape of the spectrum) was obtained in spite of the fluctuations in intensity.

The relative spectrum is determined mainly by the welding material, such as steel or aluminum, regardless of the other parameters. Especially, it is independent of the diameter of wire, arc current and arc voltage, which have an influence only on the absolute intensity of the radiation.

Key words: Optical radiation — Spectrum — Ultraviolet — Blue light — Infrared — Welding — Arc

INTRODUCTION

It is well known that exposure of the eye or the skin to ultraviolet radiation produces photochemical injury. Moreover, optical radiation (electromagnetic radiation) of longer wavelengths and lower energy, visible (blue light) and near-infrared radiation are also considered to be harmful to the eye. For occupational exposure to each of those three radiations, the American Conference of Governmental Industrial Hygienists (ACGIH) issued a relative spectral effectiveness (an action spectrum) and the definition or the calculation method of effective values (effective irradiance or effective radiance) based on it, and recommended threshold limit values to be compared with the effective values. However, except for ultraviolet radiation, few measurements for those radiations at workplaces have been made so far, since there are no convenient instruments for measuring the effective values.

Generally speaking, it is difficult to evaluate the harmfulness of optical radiation, because light of different wavelengths differs in degree of harmfulness and light sources emit light of various wavelengths in some wavelength regions simultaneously.
except for lasers. Usually the degree of harmfulness is represented by an effective value, a definite integral of the product of a relative spectral effectiveness with unity at peak (unit: dimensionless) and an emission spectrum of the radiation (unit: W·cm\(^{-2}\)·nm\(^{-1}\) for irradiance and W·cm\(^{-2}\)·sr\(^{-1}\)·nm\(^{-1}\) for radiance) in the wavelength region (unit: nm).

There are two possible methods of obtaining effective values. One is to measure effective values directly with an instrument having relative spectral sensitivity of the same shape as that of the relative spectral effectiveness. This method is suitable for measurements at workplaces, because the effective value is obtained directly as the measured value. On the other hand, since it is impossible to adjust spectral sensitivity freely, measuring instruments of only somewhat similar relative spectral sensitivity are producible, and give us approximate values. The other method is to perform spectral measurement and to calculate the effective value by the definition using the emission spectrum obtained and the relative spectral effectiveness. Although the spectral measurements are tedious, exact effective values can be obtained. Moreover the effective value based on any relative spectral effectiveness can be calculated using the same spectrum.

Since the spectra contain a large amount of information in general, they are also useful as fundamental data for many other purposes than the mere derivation of effective values. The examples are as follows.

As mentioned above, in the case of the non-spectral method of obtaining effective values (the former of the two methods), the deviation of the measured value from the real effective value, which may not be negligible according to the relative spectrum (the shape of the spectrum) of the radiation, becomes a matter of concern. But, if the relative spectrum of the radiation and the spectral sensitivity of the measuring instrument are known, the correction factor can be calculated from them and the real effective value is obtained multiplying the measured value by this factor. The factor does not depend on the absolute intensity but on the relative spectrum of the radiation. While the former is variable according to such factors as the distance from the light source and the direction of the radiation, the latter is generally determined by the light source itself. Therefore, it is sufficient to prepare the factor for each light source or for each group of light sources that emit light of the same relative spectrum. However, the stability of the relative spectrum should be confirmed for each light source in advance.

Conversely, under the above method, since exact effective values are obtained by the correction regardless of the spectral sensitivity, the measuring instrument of any spectral sensitivity is able to serve the purpose if it is sufficiently sensitive. This facilitates the development of the measuring instruments used at workplaces.

The spectra of the optical radiations are also important to the improvement from the viewpoint of occupational hygiene, because they often reflect the characteristics or the conditions of the light sources at workplaces and indicate the factors that influence the radiation. For instance, Bartley et al. measured the
ultraviolet spectrum of the arc weldings of various aluminum-magnesium alloys with an instrument similar to that used in this study and found that even low concentrations of magnesium in aluminum base metal or consumable electrode wire increased the ultraviolet radiation. In this case it is desirable for the health of workers to remove magnesium from base metal and wire if it is feasible technically.

For the reasons described above, it is desirable to measure emission spectra from various light sources at workplaces such as welding arcs and inspection holes of glass or steel furnaces. But it is difficult to determine the spectra accurately, because the intensity of the light fluctuates with time, and it takes some time to obtain one spectrum if an ordinary method of spectral measurement is applied. Therefore, quite a few studies on these spectra have been made.

In this study, using a multichannel detector system, which is able to measure a whole spectrum simultaneously unlike ordinary measuring instruments, spectra of optical radiation (wavelength range: 200–1000 nm) from the arc of various welding processes were determined. The characteristics of each spectrum are discussed and, comparing these spectra, the factors which have an influence on the spectrum and consequently on the harmfulness of the radiation are estimated. Moreover, for each welding process, ultraviolet and blue light effective irradiances based on the ACGIH relative spectral effectivenesses are calculated using the spectrum by numerical integration.

**Methods**

Spectra of optical radiation from welding arcs were measured under 14 different welding conditions. Their parameters are shown in Table 1. For convenience, each condition is given a number or symbol (in the left-hand outside column) by which it is subsequently referred to. They are divided into three groups by welding processes.

One group is of shielded metal arc welding (No. 1a, No. 1b, No. 1c, No. 2b and No. 2c), in which a core wire coated with flux (a covered electrode) is used and shielding gas is unnecessary. In this experiment, two types of electrodes, the ilmenite type (No. 1a, No. 1b and No. 1c) and the low hydrogen type (No. 2b and No. 2c), were adopted. The three conditions of the ilmenite type differ in core diameter, arc current and arc voltage, as do the two conditions of the low hydrogen type. A soft steel plate, 5 mm thick, was used as the base metal in this group.

Another group is of gas shielded arc welding with a consumable electrode (No. 3, No. 4, No. 5, No. 6, No. 7, No. 8 and No. 9), which is operated by a semiautomatic welding machine. As shielding gas, CO₂ gas is used for CO₂ gas shielded arc welding (CO₂ welding), argon gas for metal inert gas shielded arc welding (MIG welding), and the mixture of argon gas and CO₂ gas for metal
### Table 1. Welding conditions

<table>
<thead>
<tr>
<th>No.</th>
<th>Welding process</th>
<th>Wire (JIS) diameter</th>
<th>Base metal (JIS)</th>
<th>Current, voltage polarity power source</th>
<th>Shielding gas flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Shielded metal arc welding (ilmenite type)</td>
<td>(D4301) 2.6 mm</td>
<td>Soft steel (SS41)</td>
<td>70A, 20V, AC KR500</td>
<td>unnecessary</td>
</tr>
<tr>
<td>1b</td>
<td>Shielded metal arc welding (ilmenite type)</td>
<td>(D4301) 4.0 mm</td>
<td>Soft steel (SS41)</td>
<td>170A, 30V, AC KR500</td>
<td>unnecessary</td>
</tr>
<tr>
<td>1c</td>
<td>Shielded metal arc welding (ilmenite type)</td>
<td>(D4301) 8.0 mm</td>
<td>Soft steel (SS41)</td>
<td>400A, 36V, AC KR500</td>
<td>unnecessary</td>
</tr>
<tr>
<td>2b</td>
<td>Shielded metal arc welding (low hydrogen type)</td>
<td>(D4316) 4.0 mm</td>
<td>Soft steel (SS41)</td>
<td>170A, 23V, AC KR500</td>
<td>unnecessary</td>
</tr>
<tr>
<td>2c</td>
<td>Shielded metal arc welding (low hydrogen type)</td>
<td>(D4316) 8.0 mm</td>
<td>Soft steel (SS41)</td>
<td>400A, 32V, AC KR500</td>
<td>unnecessary</td>
</tr>
<tr>
<td>3</td>
<td>CO₂ gas shielded arc welding with solid wire (CO₂ welding with solid wire)</td>
<td>(YGW12) 1.2 mm</td>
<td>Soft steel (SS41)</td>
<td>150A, 23V, DC (+) CO₂ gas 20 l/min</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Metal active gas shielded arc welding (MAG welding)</td>
<td>(YGW12) 1.2 mm</td>
<td>Soft steel (SS41)</td>
<td>150A, 21V, DC (+) Ar; CO₂=5:1 20 l/min</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CO₂ gas shielded arc welding with solid wire (CO₂ welding with solid wire)</td>
<td>(YGW11) 1.6 mm</td>
<td>Soft steel (SS41)</td>
<td>300A, 35V, DC (+) CO₂ gas 20 l/min</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Metal active gas shielded arc welding (MAG welding)</td>
<td>(YGW11) 1.6 mm</td>
<td>Soft steel (SS41)</td>
<td>300A, 33V, DC (+) Ar; CO₂=5:1 20 l/min</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CO₂ gas shielded arc welding with flux-cored wire (CO₂ welding with flux-cored wire)</td>
<td>(YFW24) 1.2 mm</td>
<td>Soft steel (SS41)</td>
<td>300A, 35V, DC (+) CO₂ gas 20 l/min</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>CO₂ gas shielded arc welding with flux-cored wire (CO₂ welding with flux-cored wire)</td>
<td>(E308T1) 1.2 mm</td>
<td>Stainless steel (SUS304)</td>
<td>270A, 35V, DC (+) CO₂ gas 20 l/min</td>
<td></td>
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<tr>
<td>9</td>
<td>Metal inert gas shielded arc welding (MIG welding)</td>
<td>A5183-WY 1.6 mm</td>
<td>Aluminum (A5083)</td>
<td>250A, 27V, DC (+) Ar gas 20 l/min</td>
<td></td>
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<td>10</td>
<td>Tungsten inert gas shielded arc welding (TIG welding)</td>
<td>not used</td>
<td>Stainless steel (SUS304)</td>
<td>100A, 13V, DC (-) Ar gas COMPA300 10 l/min</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Self-shielded arc welding</td>
<td>(YFW12) 3.2 mm</td>
<td>Soft steel (SS41)</td>
<td>400A, 25V, AC KR500</td>
<td>unnecessary</td>
</tr>
</tbody>
</table>

JIS is Japan Industrial Standard.
active gas shielded arc welding (MAG welding). Flux-cored wire was used for No. 7 and No. 8 CO₂ weldings, and solid wire for the other conditions in this group. No. 3 and No. 5 CO₂ weldings, or No. 4 and No. 6 MAG weldings differ in the diameter of the wire, arc current and arc voltage. As the base metal a stainless steel plate was used for No. 8 CO₂ welding with flux-cored wire, an aluminum plate for No. 9 MIG welding, and a soft steel plate for the other conditions in this group. They were all 5 mm in thickness.

Two conditions, No. 10 and No. 12, do not belong to the preceding two groups. No. 10 is tungsten inert gas shielded arc welding, in which a non-consumable tungsten electrode is used and the shielding gas is argon gas. In this experiment, wire as a filler metal, which is inserted into the arc by hand under ordinary circumstances, was not adopted in order to simplify the experiment. A stainless steel plate, 5 mm thick, was used as the base metal. No. 12 is self-shielded arc welding, which is operated by a semiautomatic welding machine with flux-cored wire and no shielding gas. A large amount of fumes is generated during operation. A soft steel plate, 5 mm thick, was used as the base metal.

For each condition, arc current and arc voltage were determined mainly by the adopted wire. However, before the measurement they were adjusted to the optimum values while the welding was actually taking place. They are also given in Table 1.

In Fig. 1 the measurement configuration is shown schematically.

In order to fix the arc point during the measurement, while the metal plate was placed horizontally on a turntable which turned at a constant speed, a welding torch was fixed so that the end of the wire would be near the perimeter of the rotation above the base metal and the arc length would be suitable for each welding. In the case of the shielded metal arc weldings, an electrode was attached with

![Fig. 1. Measurement configuration](image)
the upper end to a stage which would move down by an electric motor at a speed suitable to compensate the consumption of the electrode and maintain the optimum arc length. The arcs were struck between wire (an electrode) and base metal but no actual welding took place.

A monochromator (a polychromator) with a multichannel detector head was placed at about 1.5 m from the arc so that the entrance of the monochromator would look down at the arc at an angle of 30°. A long wavelength pass color glass filter suitable for the spectral region of each measurement was attached to the entrance of the monochromator to remove the influence of light higher than a second order of diffraction, except in the measurement of the ultraviolet spectrum, where there is no such light. Condenser lenses between the arc and the entrance of the monochromator were unnecessary because of the sufficient intensity of the radiation.

Figure 2 is a schematic diagram of the measuring system and shows the outline of detector control and data manipulation. A spectrum was detected by the multichannel detector (Prinston Instruments, Inc. RY-1024) set behind the monochromator (Instruments SA, Inc. HR-320). The detector was controlled by a personal computer (Fujitsu FM-11EX) through a controller (Prinston Instruments, Inc. ST-100). Spectral data acquired by the detector consisted of 1024 numerical values which represented intensity at each wavelength of the spectrum. They were read out and digitized by the controller. Next they were transmitted to the personal computer, corrected for the dark current of the detector (the background), displayed on a CRT, and stored on a floppy disc. Finally the spectral data were transmitted from the personal computer to a computer (a host computer, Fujitsu FACOM M150-F) through an acoustic coupler and a telephone wire, with spectral data of a standard lamp acquired under the same conditions of the measuring system and divided by them point by point to be
corrected for the spectral sensitivity of the detector. A halogen standard lamp (Ushio JPD100V500WCS) was used for the correction of the visible and near-infrared spectra, and a deuterium standard lamp (Optronic Laboratories, Inc. Model UV-40) for that of the ultraviolet spectra. A real-time spectrum was displayed on an oscilloscope connected with the controller, which was useful in adjusting light path.

The wavelength ranges of the measuring system in which a spectrum was detected at one time were approximately 300–800 nm and 500–1000 nm. For some of the welding conditions, it was approximately 200–320 nm. It was adjusted by exchanging diffraction gratings of the monochromator and rotating it. The calibration for wavelength was carried out each time the wavelength range was changed, using spectral lines of a low-pressure mercury vapor lamp. The resolution of wavelength is about 0.5 nm for the wavelength ranges 300–800 nm and 500–1000 nm, and about 0.12 nm for 300–320 nm; these were confirmed in the course of the calibration for wavelength. The exposure time or the measuring time during which the output of the detector was accumulated was set to 34–544 msec depending on the intensity of the radiation. Measurement was started several seconds after the start of the welding. Under each welding condition and for each wavelength range, the measurement was repeated two or three times.

RESULTS AND DISCUSSION

Spectra acquired under the 14 conditions are shown in Figs. 3–16. The ordinate represents spectral irradiance (unit: μW·cm⁻²·nm⁻¹) at a distance of 1 m from the arc, which was calculated from the measured value assuming that irradiance is inversely proportional to the square of the distance, and the abscissa represents wavelength (unit: nm). The scale of the graphs in the figures are the same except for Fig. 15 (No. 10 TIG welding), in which the scale of the y-axis is magnified five diameters. The spectrum in each figure consists of one to three partial spectra of the different wavelength ranges. The measurements were not made under all the conditions or in the whole spectral region of 200–1000 nm. The arrows in the figures indicate the boundaries between neighboring partial spectra. Each partial spectrum is the average of two or three measurements.

First of all, it should be noted that spectra acquired under the same welding conditions, that is, those before averaging, have the same shape, including many minute spectral lines, in spite of the fluctuation in intensity, which, however, cannot be read off the figures. This fact means that the spectrum of welding indicates the characteristics of welding conditions, such as process, welding material and shielding gas.

Comparing these 14 spectra, it is seen instantly that they are somewhat similar in shape as a whole except for No. 9 MIG welding of aluminum (Fig. 14) and No. 10 TIG welding of stainless steel (Fig. 15). Moreover, the spectrum of
Fig. 3. Spectrum of No. 1a shielded metal arc welding of soft steel (ilmenite type)

Fig. 4. Spectrum of No. 1b shielded metal arc welding of soft steel (ilmenite type)
Fig. 5. Spectrum of No. 1c shielded metal arc welding of soft steel (ilmenite type)

Fig. 6. Spectrum of No. 2b shielded metal arc welding of soft steel (low hydrogen type)
Fig. 7. Spectrum of No. 2c shielded metal arc welding of soft steel (low hydrogen type)

Fig. 8. Spectrum of No. 3 CO₂ welding of soft steel with solid wire
Fig. 9. Spectrum of No. 4 MAG welding of soft steel with solid wire

Fig. 10. Spectrum of No. 5 CO₂ welding of soft steel with solid wire
Fig. 11. Spectrum of No. 6 MAG welding of soft steel with solid wire

Fig. 12. Spectrum of No. 7 CO₂ welding of soft steel with flux-cored wire
Fig. 13. Spectrum of No. 8 CO₂ welding of stainless steel with flux-cored wire

Fig. 14. Spectrum of No. 9 MIG welding of aluminum
Fig. 15. Spectrum of No. 10 TIG welding of stainless steel

Fig. 16. Spectrum of No. 12 self-shielded arc welding of soft steel
SPECTRA OF OPTICAL RADIATION FROM WELDING ARCS

No. 10 TIG welding also appears to belong in the same group if its prominent spectral lines in the near-infrared region (wavelength: 700–1000 nm) are neglected. It is conceivable that the emission spectra of arc welding of soft or stainless steel consists of a great many iron spectral lines which, as a whole, give a similar shape to the spectrum and several lines of some other elements, though few of them could be identified because the resolving power of the measuring system had been lowered to gain a wide wavelength range.

The shielded metal arc weldings with wire of the ilmenite type No. 1a, No. 1b and No. 1c weldings) differ in the diameter of the wire, arc current and arc voltage, though arc current and arc voltage generally depend on the diameter of the wire and increase with it under optimum welding conditions. On the other hand, the chemical composition of the welding materials is common to them. Their relative spectra (the shapes of the spectra) are much the same (Fig. 3, Fig. 4 and Fig. 5), though the intensity increases as the diameter of the wire, arc current and arc voltage increase. The same statements are true for the shielded metal arc weldings with wire of the low hydrogen type (No. 2b and No. 2c weldings; Fig. 6 and Fig. 7), CO₂ weldings (No. 3 and No. 5 weldings; Fig. 8 and Fig. 10) and MAG weldings (No. 4 and No. 5 weldings; Fig. 9 and Fig. 11). Therefore, the relative spectrum is generally independent of the diameter of wire, arc current and arc voltage when the other parameters are fixed.

The relative spectra of No. 3 and No. 5 CO₂ weldings (Fig. 8 and Fig. 10) and those of No. 4 and No. 6 MAG weldings (Fig. 9 and Fig. 11) are also much the same except for small argon lines in the wavelength region 700–900 nm in the spectrum of No. 6 MAG welding. The shielding gas of MAG weldings contains argon gas, and their other parameters are the same as CO₂ weldings with flux-cored wire if No. 3 CO₂ welding is paired with No. 4 MAG welding and No. 5 CO₂ welding with No. 6 MAG welding. It can be considered that there is little effect of shielding gas on the relative spectrum.

The relative spectra of the shielded metal arc weldings with wire of the ilmenite type (No. 1a, No. 1b and No. 1c; Fig. 3, Fig. 4 and Fig. 5) and those with wire of the low hydrogen type (No. 2b and No. 2c; Fig. 6 and Fig. 7) resemble each other fairly closely, but some of the spectral lines in the wavelength region 500–800 nm are more prominent in the latter than in the former. They are emissions from barium or calcium in the wire of low hydrogen type, judging from their peak wavelengths.

In No. 7 and No. 8 CO₂ weldings with flux-cored wire, the welding materials are soft steel and stainless steel, respectively. The relative spectrum of the latter (Fig. 13) includes more spectral lines than the former (Fig. 12), though they resemble each other in shape as a whole. Some of the spectral lines in the spectrum of No. 8 welding were identified as those of chromium, which is contained in stainless steel.

In the shielded metal arc weldings (No. 1a, No. 1b, No. 1c, No. 2b and
No. 2c), CO₂ weldings with flux-cored wire (No. 7 and No. 8) and self-shielded arc welding (No. 12), wire coated with flux or flux-cored wire was used, unlike the other weldings. Their spectra have broad spectral lines in common at about 770 nm and 820 nm, which are considered to be those of some components of the flux. These lines may account for some part of ACGIH effective irradiance of the radiation because there are few other lines in the near-infrared region and ACGIH near-infrared relative spectral effectiveness rises at 770 nm perpendicularly and is unity in the region 770–1400 nm.

The relative spectrum of No. 10 TIG welding of stainless steel (Fig. 15) consists of the visible part and the near-infrared part. The visible part resembles those of the other weldings of soft or stainless steel in shape and can be considered as a cluster of iron lines. The near-infrared part includes some very prominent lines which are apparently argon emissions judging from both their peak wavelength and their appearances in the spectra of No. 6 MAG welding of soft steel and No. 9 MIG welding of aluminum. Contrary to the spectrum of No. 6 MAG welding, the visible part is much smaller than the near-infrared part. It is conceivable that the quantity of the iron in the arc was smaller because filler metal was not used in this experiment. It also explains the weakness of the whole spectrum. It is necessary to determine the spectrum of TIG welding using filler metal, because it is indispensable for actual TIG welding.

The relative spectrum of No. 12 self-shielded arc welding (Fig. 16) is characteristic in that the part in the region 300–500 nm is smaller than the part in the region 500–650 nm, contrary to the spectra of the other weldings of soft or stainless steel. It is presumably the effect of Rayleigh scattering by the fumes generated in huge numbers, under which light of shorter wavelength is scattered and attenuates more intensely than that of longer wavelengths. Therefore the ultraviolet part of the radiation is considered to be weakened further, though its spectrum was not measured in this experiment.

The relative spectrum of No. 9 MIG welding of aluminum (Fig. 14) is quite different in shape from those of the other weldings. It is apparently not characteristic of MIG welding itself but of that of aluminum as welding material. The spectral lines in the region 650–700 nm are, however, argon emissions, which also appear in the spectrum of No. 10 TIG welding stainless steel (Fig. 15). Most of the lines in the region 200–700 nm were identified as those of aluminum or magnesium, which is contained at a concentration of 4–5% in both wire and base metal. The ultraviolet part of the spectrum is much larger than its visible or near-infrared part and is considered to be important. It is shown particularly in Fig. 17. The ordinate represents relative intensity, unlike those of the preceding graphs. Almost all of the prominent lines in the ultraviolet region, those at 277.9, 279.0, 279.5, 280.2, 285.3, 291.5, 292.9, and 293.6 nm, are magnesium emissions. In other words, magnesium accounts for a large part of the ultraviolet radiation from arc welding of aluminum if it is contained in aluminum base metal or wire,
Fig. 17. Ultraviolet spectrum of No. 9 MIG welding of aluminum

Fig. 18. Ultraviolet spectrum of No. 6 MAG welding of soft steel with solid wire
To make a comparison between the ultraviolet spectra of arc weldings of aluminum and those of steel, that of No. 6 MAG welding of soft steel is shown in Fig. 18 on behalf of the latter.

ACGIH ultraviolet and blue light effective irradiances at a distance 1 m from the arc which were calculated from the spectrum for each welding condition are shown in Table 2. The ultraviolet irradiance of No. 9 MIG welding is the largest, while its blue light one is the second smallest. This can reasonably be expected taking account of its relative spectrum.

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