

Diagnosis of TIG welding based on ultraviolet radiation^{*}

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Abstract Through collecting the radiation of tungsten inert gas (TIG) welding arc, the radiation distribution in ultraviolet zone is analyzed in order to study the variation rule of ultraviolet radiation versus welding condition. The explanation for the variation is also provided based on spectral radiation theory of arc light. Furthermore, through analysis of disturbance factors, the integral intensity signal of radiation in ultraviolet zone is applied for diagnosis of welding process. The spectral signal of ultraviolet radiation can reflect the disturbance factors and welding conditions, which can be used for online diagnosis of welding process.

Key words arc spectrum, ultraviolet zone, tungsten inert gas welding, disturbance factor

0 Introduction

The state of welding arc plasma is related to welding parameters, stability of the welding process and welding quality. Different welding arc state will emit radiation with obvious difference. Earlier researchers had found that there was abundant information in the welding arc that was related to the welding process^[1]. Therefore, how to acquire the necessary signal becomes one of the critical problems for the application of arc radiation. Many of the studies are focused on the selection of special spectral zone (or spectral line) to provide suitable signal. Some of the successful applications include: obviously improving the image quality of welding arc and weld pool^[2]; improving the precision of arc length control for TIG welding^[3]; providing better signal for the droplet transfer in MIG welding^[4]. Some researchers have done some explorations on the ultraviolet radiation of welding arc^[5]. However, most of these studies are focused on the radiation in visible zone and near infrared zone. The ultraviolet zone is neglected in the former studies because it is difficult to sense and liable to be disturbed. The ultraviolet radiation can be widely used for diagnosis of welding process. In order to explore its possible application in welding process, the variation rules of ultraviolet radiation with different welding parameters

and disturbance factors are studied for TIG welding process in this paper.

1 Experimental procedure

Avaspec-2048FT-2 optical fiber digital spectrometer is applied for collecting spectral signal of welding arc (shown in Fig. 1). The spectrometer has double duct input and "Y" type optical fiber is applied in the study in order to assure that the collected arc light comes from the same point simultaneously. In order to get better measurement of the ultraviolet radiation, special ultraviolet film is coated on the CCD. The system can collect spectrum from 200 nm to 1 100 nm. The resolution of the spectrum is 0.3 nm. Besides frequency domain analysis, the system can also provide synchronism sampling for 8 different ducts of spectral coverage. This is very important for information fusion analysis and specific signal extract. WS 400 TIG welding power supply and W-Th electrode are applied to provide stable welding arc on the Q235 steel plate. Except for the welding parameters of comparing test, standard welding parameter is given as: welding current $I = 100$ A, arc length $L = 2$ mm and welding speed $v = 14$ cm/min, gas flow rate $Q = 7$ L/min.

The test contains two stages. Firstly, the spectra of

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welding arc with different welding parameters are collected and the radiation in ultraviolet zone is analyzed. Secondly, the spectral signals in ultraviolet zone are collected for

welding process with disturbance factors. The characteristic signal is analyzed in order to study the relation between disturbance factors and ultraviolet radiation.

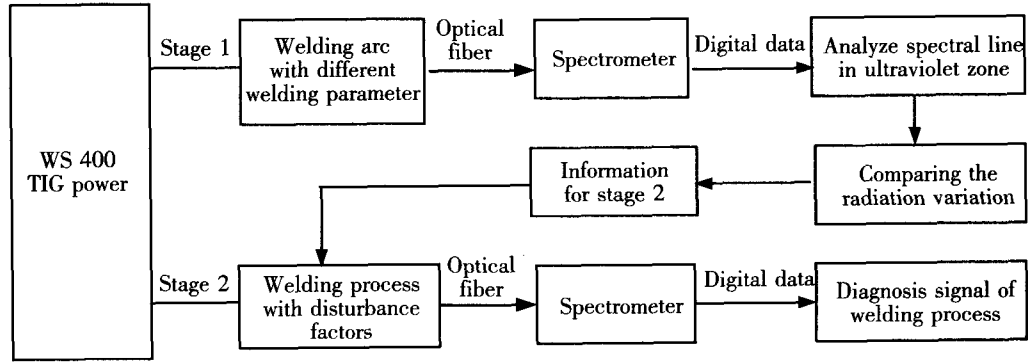


Fig. 1 Sketch of spectral collecting system

2 Spectra of TIG welding arc in ultraviolet zone

When energy of arc plasma is changed, different kinds of radiations can be formed. The main radiations in welding arc include Bremsstrahlung radiation, recombination radiation, excitation radiation and blackbody radiation^[6]. These radiations form the spectral information of welding arc. Fig. 2 provides the spectra of TIG welding arc in ultraviolet zone (230–300 nm).

Fig. 2 shows that the radiation in ultraviolet zone consists of line spectra and continuous spectra. The continuous spectra in ultraviolet zone are composed of Bremsstrahlung radiation and recombination radiation. The line spectra in ultraviolet zone are dominated by Fe II line spectra.

Table 1 provides the Fe II line spectra in ultraviolet zone. The radiation intensity variation in ultraviolet zone is

mainly caused by the FeII line spectra. The data in Table 1 are calibrated with spectra data from NIST spectral data base^[7].

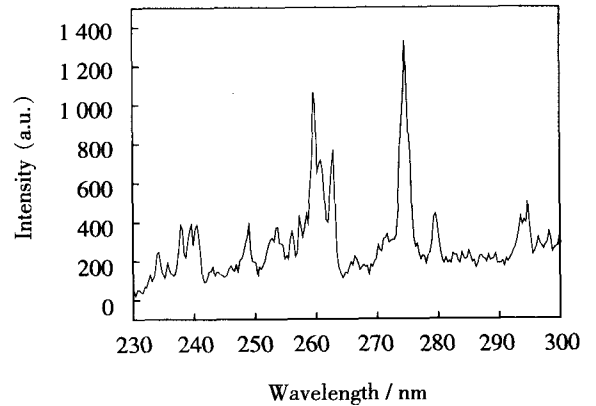


Fig. 2 Spectra of TIG welding arc in ultraviolet zone

Table 1 Main Fe II line spectra in ultraviolet zone

Wavelength /nm	234.81	234.83	238.2	239.56	239.92	240.49	259.84	259.94	263.1	263.13	274.93
Intensity (a. u.)	120	150	1 000 P	700 P	200	500 P	400 P	700 P	150	150	400 P

Line spectra are caused by excitation radiation. When excited-state electrons in atoms or ions jumped from higher energy levels to lower energy levels, excitation radiation is emitted. Excitation radiation has characteristic frequency. The radiation power in unit solid angle, unit volume and unit frequency is called emissivity (ε_{xy}).

$$\varepsilon_{xy} = h\gamma_{xy}A_{xy}N_x/4\pi \quad (\text{W}/\text{cm}^4 \cdot \text{Sr}) \quad (1)$$

Where A_{xy} is transition probability from energy level x to y ; h is plank constant; N_x is particle density in energy level

x ; and γ_{xy} is frequency of the spectral line.

The plasma of TIG welding arc is in local thermal equilibrium condition. Therefore, the particles in TIG welding arc meet the Boltzmann distribution, as shown in equation (2).

$$N_x = \frac{N_A g_x}{Z(T)} \exp\left(-\frac{E_x}{kT}\right) \quad (2)$$

Where g_x is statistic weight of energy level x ; $Z(T)$ is distribution function of atom; T is temperature of plasma; K is Boltzmann constant; E_x is potential energy of energy level x ; and N_A is neutral particle density.

Substitute equation (2) to equation (1), then:

$$\varepsilon_{xy} = \frac{1}{4\pi} h \gamma_{xy} A_{xy} \frac{N_A g_x}{Z(T)} \exp\left(-\frac{E_x}{kT}\right) \quad (3)$$

From equation (3) it is known that ε_{xy} is the function of particle content (C_A) and plasma temperature (T), that is:

$$\varepsilon_{xy} = f(C_A, T) \quad (4)$$

Equation (4) indicates that the Fe II radiation in ultraviolet zone is intimately related to the Fe fume density and its temperature. The variation of arc stability in welding process may bring the changes of Fe density and temperature of arc plasma, which affects the Fe II radiation intensity. Therefore, it is possible to diagnose the disturbance factors and weld pool by ultraviolet radiation.

3 Ultraviolet radiation of TIG welding with different welding condition

3.1 Radiation caused by different arc length

Increase of arc length will cause the growth of radiation, which has been proved by earlier studies and is applied for arc length control of TIG welding^[8]. Fig. 3 provides the ultraviolet radiation spectra with different arc length. It is shown that the radiation grows stably with increase of arc length. However, the fluctuation of the radiation during the welding process makes the linearity between ultraviolet radiation and arc length not so good as in

other spectral zone (Ar I line spectra). Therefore, the ultraviolet zone is not suitable for arc length control.

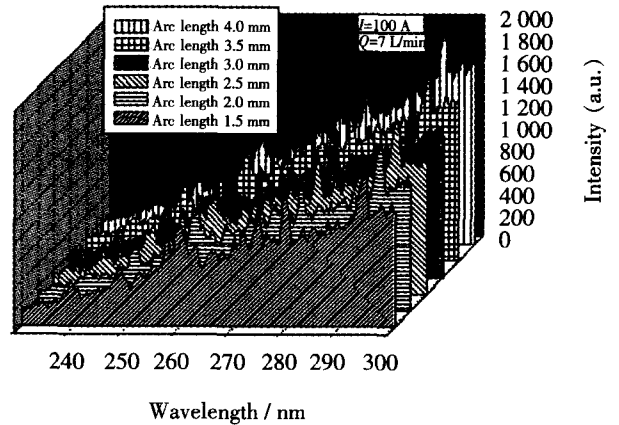


Fig. 3 Spectra in ultraviolet zone with different arc length

3.2 Radiation caused by different current

Increase of welding current will also cause the growth of radiation, but it is different from the growth caused by increase of arc length. The radiation growth for arc length increase is mainly caused by the volume growth of radiation body and the state of arc is kept stable. The relationship between radiation and arc length is basically linear. The radiation growth for welding current increase is caused by radiation intensity increase and the state change of arc. This is sensitive for the Fe line spectra, especially for Fe II line spectra. Fig. 4 gives the radiation in ultraviolet zone with different welding current. There is an obvious decrease of radiation when the welding current cuts down to certain value (as shown in the 60 A curve). The possible reason is that the heat decrease leads to less Fe fume entering the arc. When the welding current is high enough, as shown in Fig. 4 (90 A and 85 A), the radiation fluctuation causes instant higher radiation in low current than in high current. However, for the mean value of radiation, the radiation will grow with the increase of welding current.

3.3 Radiation caused by different gas flow rate

The variation of gas flow rate may cause the change of shielding gas density. When the gas flow rate is high, the radiation of arc is not affected obviously. When the gas flow rate can not meet the requirement of protecting, great

variation in radiation will be caused. Fig. 5 shows the radiation variation in ultraviolet zone with different gas flow rate. With the decrease of gas flow rate, the radiation grows gradually in the ultraviolet zone. The possible reasons include: Firstly, with the decrease of gas flow rate, more Fe fume comes into the arc from weld pool. Secondly, the heat state of the arc is disturbed by the variation of shielding gas, leading to increase of Fe II line spectra.

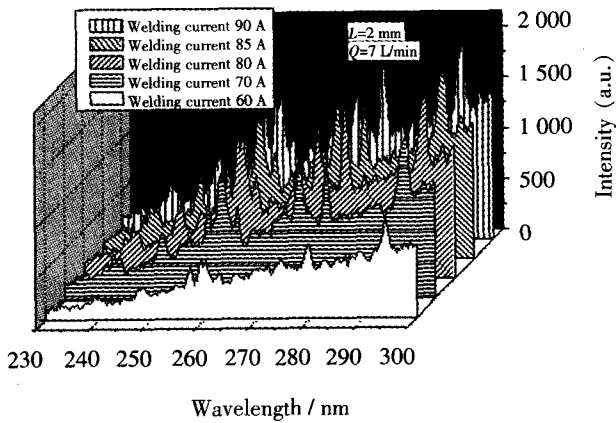


Fig. 4 Spectra in ultraviolet zone with different current

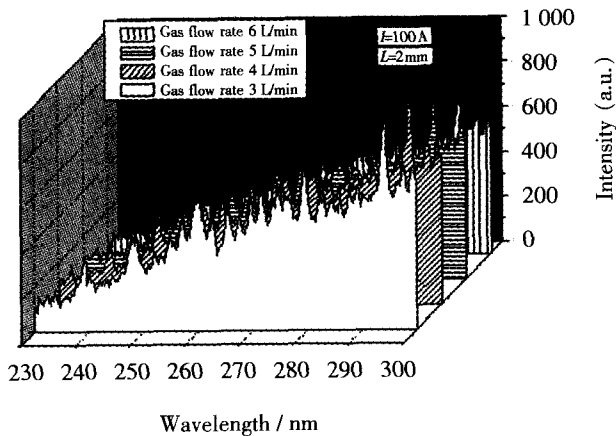


Fig. 5 Spectra in ultraviolet zone with different gas flow rate

3.4 Radiation caused by different plate condition

The surface state of welding plate, especially for rust, will affect the radiation in ultraviolet zone. This effect is more obvious when the welding current is low. Fig. 6 provides the radiation in ultraviolet zone for plate with and without surface rust when welding current is 40 A. It is shown that the plate with rust causes obvious in-

crease of radiation. The possible reason is that the ferrous ion in the rust will increase the radiation of Fe II. In fact, when there is impurity in the plate surface, the stability of arc is affected and the radiation in ultraviolet will grow.

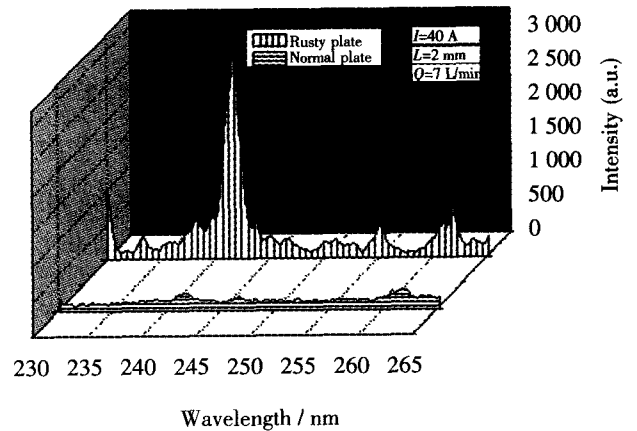


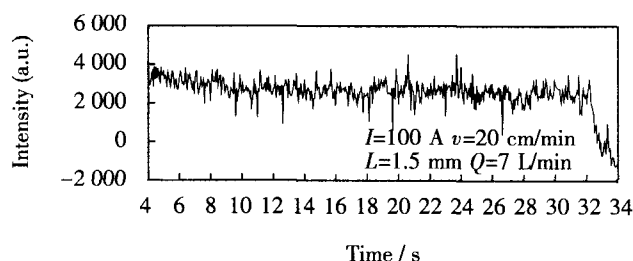
Fig. 6 Spectra in ultraviolet zone with different surface

4 Application of ultraviolet radiation in welding process diagnosis

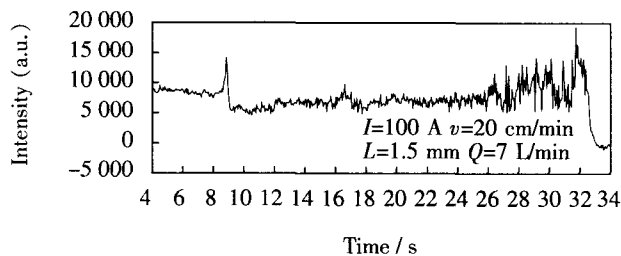
From the analysis of ultraviolet radiation, it is known that different welding conditions cause different radiations. The ultraviolet radiation is intimately related to the Fe fume entering the arc. The amount of Fe fume is related to heat state of weld pool and welding quality. The disturbance factors in welding process can be diagnosed by the ultraviolet radiation.

4.1 Diagnosis of the surface rust on plate

Fig. 7 provides the spectral signal and weld bead of the welding process with rusty plate. In order to prove the basic theory of ultraviolet radiation, signal in near infrared spectral zone is provided for comparing. The welding process starts on normal plate. With the movement of the welding tractor, the welding arc enters in the rusty zone. When the welding arc moves from normal surface to rusty surface, the rust in plate causes rapid growth in ultraviolet radiation. After that, new balance will be established for the arc. The ultraviolet radiation reduces to normal value. In the near infrared spectral zone, there is no obvious characteristic signal.



(a) Spectral signal in near infrared zone



(b) Spectral signal in ultraviolet zone



(c) Weld bead photo

Fig. 7 Welding process with rust in plate

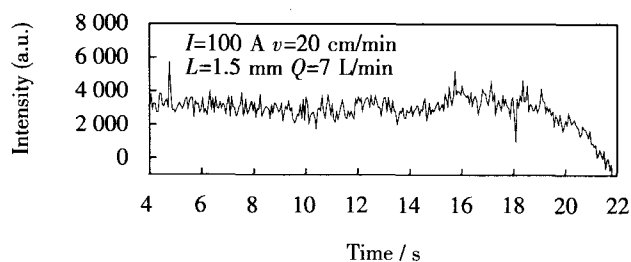
4.2 Diagnosis of the shielding gas

Fig. 8 provides the spectral signal and weld bead of the welding process with destroy of the shielding gas. The cross blasting air consists of an instant blow and continuous blows. In the signal of ultraviolet zone, the instant blow causes a pulse and continuous blows cause the great fluctuation in the latter time. There is no obvious characteristic signal in the near infrared spectral zone.

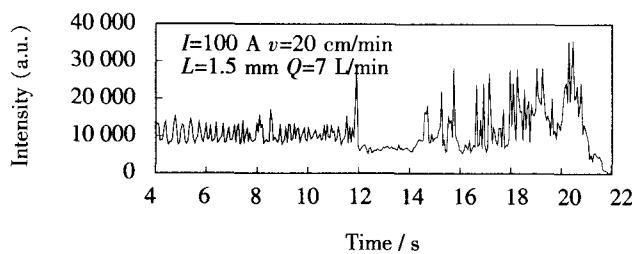
4.3 Diagnosis of the weld formation

Fig. 9 provides the spectral signal and weld bead of the welding process with variation of welding speed. The welding process starts with 14 cm/min. Then it is adjusted to 28 cm/min quickly in preset time. In the former stage of signal, regular fluctuations can be observed in the ultraviolet zone. The nine pulses correspond to the nine ripples in the weld bead. There is no obvious characteristic signal in the near infrared spectral zone.

From the application of ultraviolet radiation for diag-



(a) Spectral signal in near infrared zone

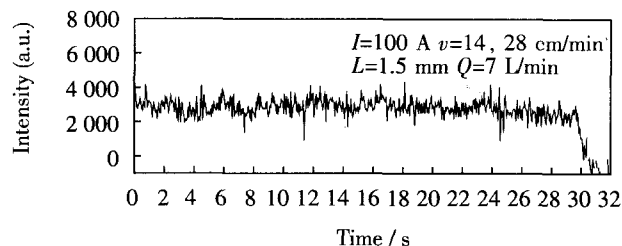


(b) Spectral signal in ultraviolet zone

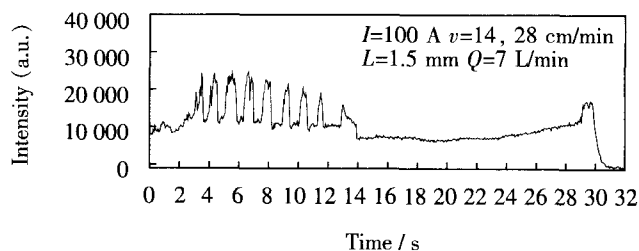


(c) Weld bead photo

Fig. 8 Welding process with blasting air



(a) Spectral signal in near infrared zone



(b) Spectral signal in ultraviolet zone



(c) Weld bead photo

Fig. 9 Welding process with different welding speed

nosis of welding process, it is proved that ultraviolet radiation can provide signal related to the weld bead, which is better than the signal in the near infrared spectral zone.

5 Conclusions

(1) The ultraviolet radiation of TIG welding arc consists of line spectra and continuous spectra. The continuous spectra are mainly composed of Bremsstrahlung radiation and recombination radiation. The line spectra in ultraviolet zone are dominated by Fe II line spectra.

(2) Different welding conditions cause different radiations. The ultraviolet radiation is intimately related to the Fe fume entering the arc. The disturbance factors in welding process can be diagnosed by ultraviolet radiation.

(3) Ultraviolet radiation can provide signal related to the weld bead, which is better than signal in the near infrared spectral zone.

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