Robust Sensing of Arc Length

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***Abstract*—During arc welding, the arc heats and melts the workpiece as heat flux. When the welding current is given, the distribution and the intensity of the heat flux are determined by the length of the arc. The measurement and control of the arc length are fundamental in robotic and automated welding operations. Length of welding arc determines the distribution of the arc energy and thus the heat input and width of the weld. This work aims at improving the measurement accuracy of arc length using the spectrum of arc light at a particular wavelength during gas tungsten arc welding (GTAW) with argon shield. To this end, effects of welding parameters on spectral distributions were studied. To verify the effects of base metal and arc length, the arc column was also sampled horizontally as layers for spectral analysis. Results show that spectral lines of argon atoms are determined by arc length, independent of welding parameters other than the current. Based on these findings, a compact arc light sensor has been designed to measure the arc length with adequate accuracy. A closed-loop arc length control system has been developed with the proposed sensor.**

***Index Terms*—Arc, manufacturing, radiation, spectrum, welding.**

I. INTRODUCTION

PROGRESS in microelectronics has prompted welding research and equipment development. The gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are two major arc welding processes. The GMAW process, which had been developed as a low cost method for normal quality applications, has been so improved that it is now being used in many applications which previously required GTAW [1]. However, for applications where quality and reliability are the primary concerns, GTAW remains a preferred joining process. Furthermore, the manufacturing of more and more dedicate equipment needs an even higher quality GTAW process. In GTAW, the welding current determines heat input and the arc length determines heat input distribution. They are two critical determining factors of weld quality. Application of Hall sensor and IGBT component has significantly increased the constancy and controllability of welding current. However, due to the difficulty met in measuring the arc length in practical process, precision sensing and control of arc length are the bottlenecks in achieving quality welds in GTAW.

Although machine vision may be used to precisely sense the arc length, its high cost and low robustness, with respect to the harsh environment during arc welding, reduce its competitiveness. Through-the-arc sensing, which measures the arc length based on arc voltage with no additional hardware, has been widely adopted in arc length control systems [2]–[4]. However, the arc voltage depends not only on the arc length but also on the tungsten electrode and weld joint [5]–[7]. Unavoidable variations in welding conditions limit the potential of arc voltage in precision sensing of arc length. The current sensing and control ability that this method can achieve is 0.5 mm. For many dedicate applications, the overall arc length is less than 2 mm. Obviously, this resolution is too low.

An arc voltage is the sum of voltage drops in the anode, the cathode, and the arc column. While the voltage drop in the arc column is proportional to the arc length, the voltage drops in the anode and in the cathode are independent of the arc length. In most GTAW applications, the desired arc length is relatively short, typically less than 3 mm, and thus the anode and cathode drops count for the majority of the total arc voltage.

The cathode and anode drops are affected by many factors such as workpiece material, surface condition, heat sink, geometry of the tip of the tungsten electrode, etc. [4], [6], [7] The resultant variation in arc voltage limits the best possible resolution when using arc voltage to measure the arc length. It would, therefore, be preferred to develop a method to measure the arc length, which is primarily determined by the arc length but independent of other conditions.

Researchers have found that the arc light offers a more accurate measurement of the arc length for both GTAW and GMAW [7]–[11]. This is because the intensity of the arc light is primarily determined by the arc column, rather than the anode or the cathode. In our previous effort, arc light has been used in GMAW metal transfer and arc length control [12], [13]. In addition to the intensity of the arc light, an early patent [14] also disclosed a method for arc length sensing with a sensor working at ultraviolet band.

Although the arc light signal has the potential to achieve high resolution of the arc length, the previous results are still not satisfying. The problem is that these research works all used integral arc light signal to sense the arc length. The arc light consists of continuum and spectral lines of different elements in the arc column. Their responses to arc length variation are different. The difference may be caused by the spatial distribution of different elements, and also by their relationship to the welding process. To develop a precision sensor for the arc length, the authors analyzed the spectral distribution of arc light and its determining factors. The purpose of the research work is to find a proper part of the arc light component that can reflect the arc length directly and additionally, and to develop a practical system that can reach higher accuracy than existent methods. Many interesting phenomena about the arc light were uncovered

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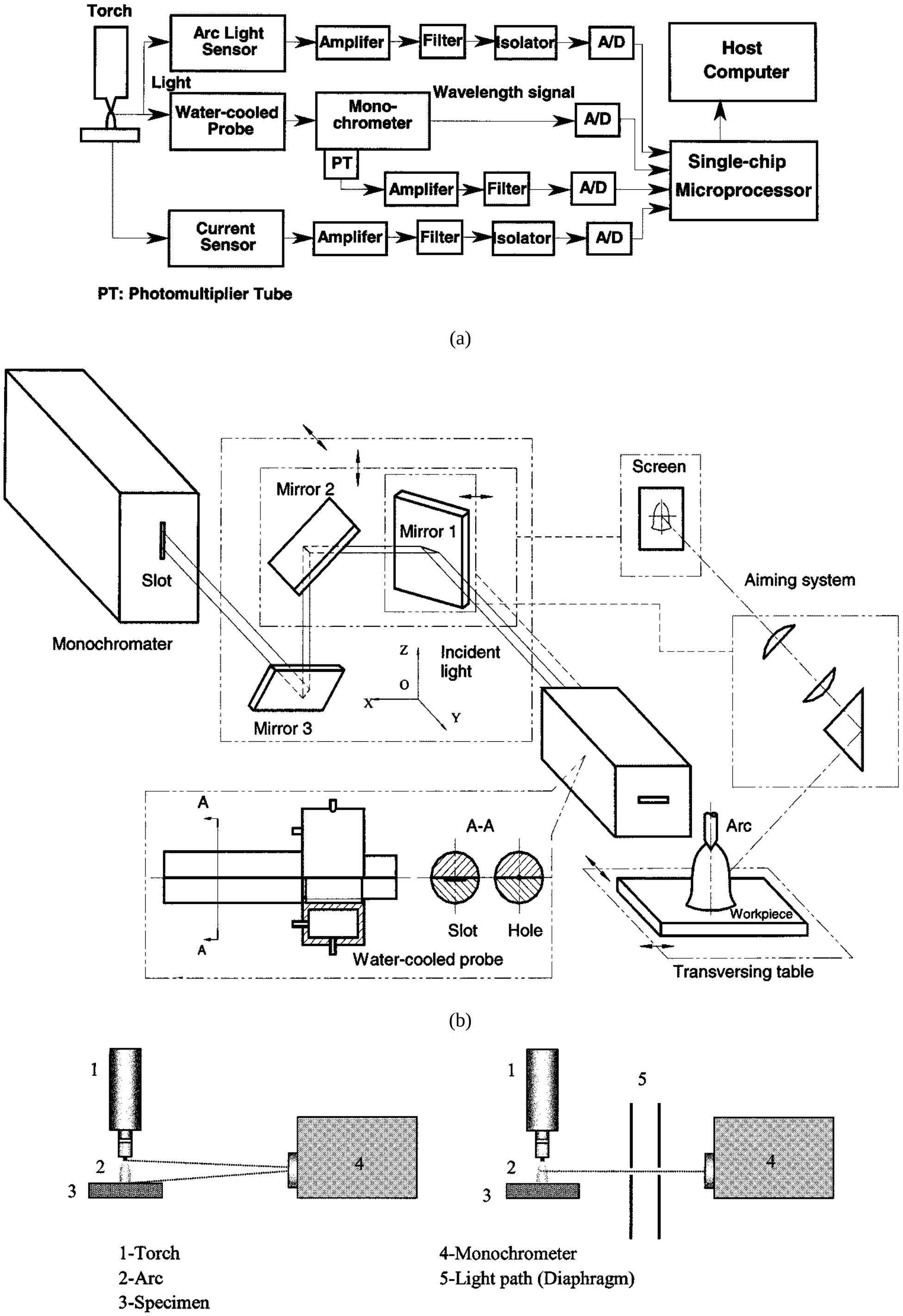

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Fig. 1. Experimental set-up. (a) Schematic. (b) Spectroscopic analysis system. (c) Sampling system.

in this work. More importantly, the findings provide a basis to improve the accuracy of the arc light based arc length sensing technology.

II. EXPERIMENTAL SYSTEM AND PROCEDURE

Fig. 1(a) is a schematic of the experimental set-up. A dc constant current welding power source ranging from 5 A to 500 A was used as the power supply. The tungsten arc welding torch was kept stationary during welding. The workpiece was placed on a two-dimensional (2-D) motion mechanism. The sensing system, including the arc light sensor, the monochromater, and its accessories, remained stationary in relation to the torch during welding. The adjustment of the three-dimensional (3-D) position of the sensing system required for different tasks was made before welding. Water-cooled copper, mild steel, low alloy steel (A202M-93), and stainless steel 304 were welded with the shield of pure argon.

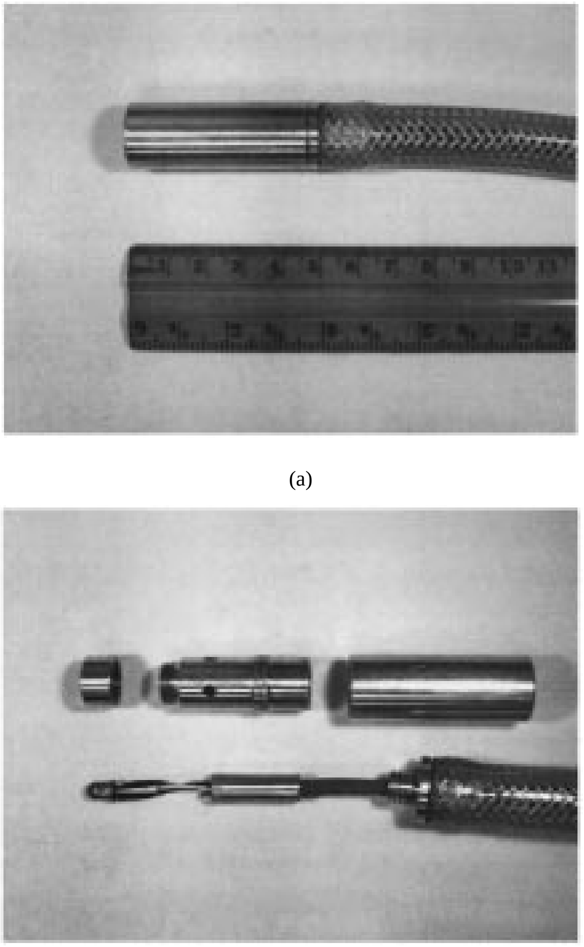

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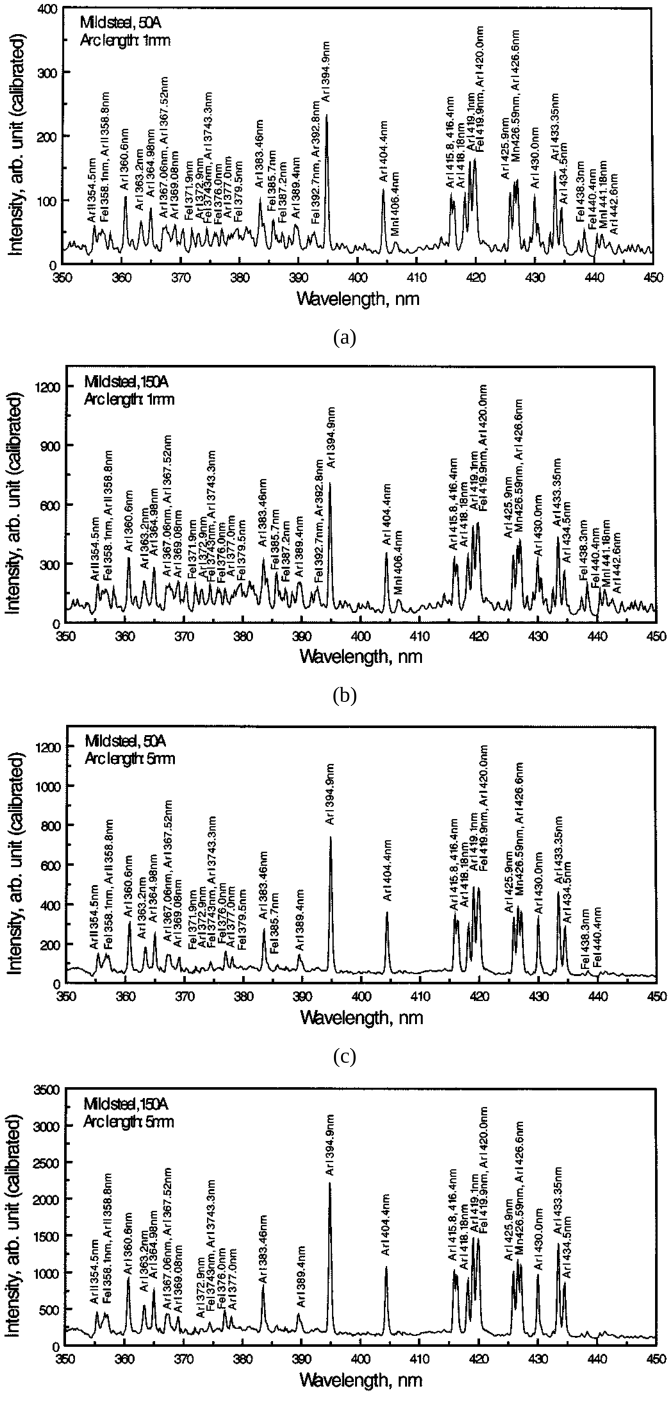
Fig. 2. Arc light sensor. (a) Assembled. (b) Disassembled.

Fig. 1(b) illustrates the spectroscopic system for spectral analysis. The arc light was sampled by the water-cooled probe either as a single object, layer by layer, or point by point, as shown in Fig. 1(c). The diaphragm shown in Fig. 1(c) provides the spatial discrimination of the arc column. The resolution of spatial discrimination is 0.01 mm × 0.01 mm. The monochromater then separated the spectral lines at wavelengths ranging from 320 nm to 820 nm with a 0.1 nm resolution. The photomultiplier enhanced the signal of the spectral lines. The signals of the spectral line and the corresponding wavelength were processed by the single-chip microprocessor and then sent to the host computer. The actual measurement of the welding current was recorded as can be seen in Fig. 1(a).

Previously, laboratory instruments such as photomultiplier and phototransistor have been used as the sensor in control system prototypes. To apply spectral analysis results in the control of arc length, a robust, reliable, and compact arc-light sensor is needed. We developed such an arc-light sensor based on a phototriode that had a built-in automatic sensitivity control (ASC) system. The sensor, which is 50 mm in length and 15 mm in diameter, as shown in Fig. 2, can be fixed onto the welding torch. A small part of shielding gas (0.25 L/min) bypasses the sensor probe to keep it from being contaminated by the welding fume.



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(d)

Fig. 3. Effect of welding current and arc length on arc light spectrum. (a) Short arc length and low current. (b) Short arc length and high current. (c) Long arc length and low current. (d) Long arc length and high current.

III. SPECTRUM

The entire arc column will be analyzed as a single object in this section. The objective will be to reveal the roles of different welding parameters in determining the overall spectral characteristics of the arc light.

A. *Welding Current and Arc Length*

Fig. 3 gives experimental records for analyzing how the welding current and the arc length affect the spectral distri-

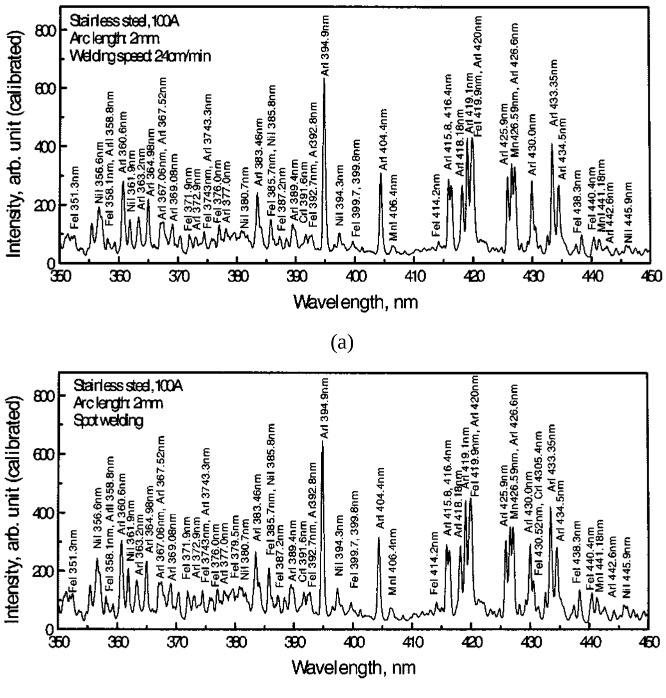

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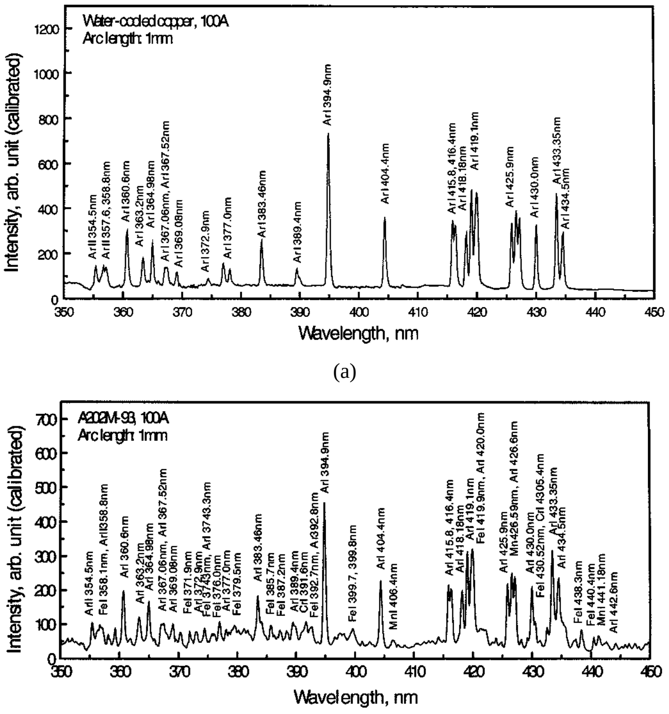
Fig. 4. Effect of welding speed on spectral distribution. (a) Normal welding speed. (b) Zero welding speed.



(a)

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Fig. 5. Effect of base metal in spectral distribution. (a) Water-cooled copper base metal. (b) Alloy steel base metal.

bution of the arc light. As seen in Fig. 3(b) and (d), when the arc length is long and/or the welding current is low, spectra of the metal vapor are weak in comparison with those of argon atoms. If the arc length is decreased and the welding current is increased, metal spectral lines become stronger [Fig. 3(a) and (c)]. This is quite understandable because decreasing the arc length actually decreases the volume of the arc column, but not the absolute amount of the metal vapor. Also, increasing the welding current increases the heat input and, thus, the absolute amount of the metal vapor. Hence, both a short arc and a large current help increase the density of the metal vapor in the arc, thus increasing metal spectral lines in the spectral distribution.

B. Welding Speed

Experimental results show that the relative intensities of metal lines increase when the welding speed decreases with other welding parameters, such as the welding current and the arc length remaining unchanged. This is apparent because decreasing the welding speed increases the heat input and, thus, the size of the weld pool. More melted metal tends, of course, to produce more metal vapor. As seen in Fig. 4, with the same welding parameters and conditions other than the weld speed, the metal vapor spectra increased significantly when the welding speed changed from a normal level to zero. Again, the increase of the metal vapor promoted fluctuations in the intensity and spectral distribution of the arc light.

C. Material

The material of the base metal makes a more significant contribution to the spectra of the arc light than the tungsten electrode. In fact, the amount of tungsten vapor is negligible in comparison with that of the base metal. It was found, when water-cooled copper plates were used as the base metal, that only argon atomic and ionic lines were observed in the spectral distribution. For Fig. 5(a) and (b), the welding parameters and conditions were exactly the same except for the base metal. It can be seen that while the spectral distribution for the water-cooled copper shows no metal lines, iron, chromium, and nickel lines can be observed for the alloy steel. For practical application of arc length control, the sensor should not be sensitive to the metal lines or subject to any influence of the base metal or welding conditions other than the arc length. From this point of view, the effect of the base metal on the spectral distribution of the arc light is undesirable and should be removed.

D. Flow Rate of Shielding

Experimental results show that the spectral distribution of the arc light does not change with the flow rate of the shielding gas, argon in this study, if the flow rate is within the normal range (5–10 L/min). However, if the flow rate is very low (less than 2 L/min), the metal lines become relatively pronounced. As a result, both the intensity and the spectral distribution of the arc light fluctuate more significantly.

IV. SPATIAL ANALYSIS

As shown in Fig. 1(c), the arc light can be sampled either as a single object, layer by layer or point by point. By sampling the arc light layer by layer, one will be able to examine how the spectral distribution changes with the distance from the electrode or from the base metal. It is evident that such an examination will give an insight into the spectrum of the arc light.

Figs. 6 and 7 show arc spectral distributions at three different layers: close to the base metal, middle, and near the electrode

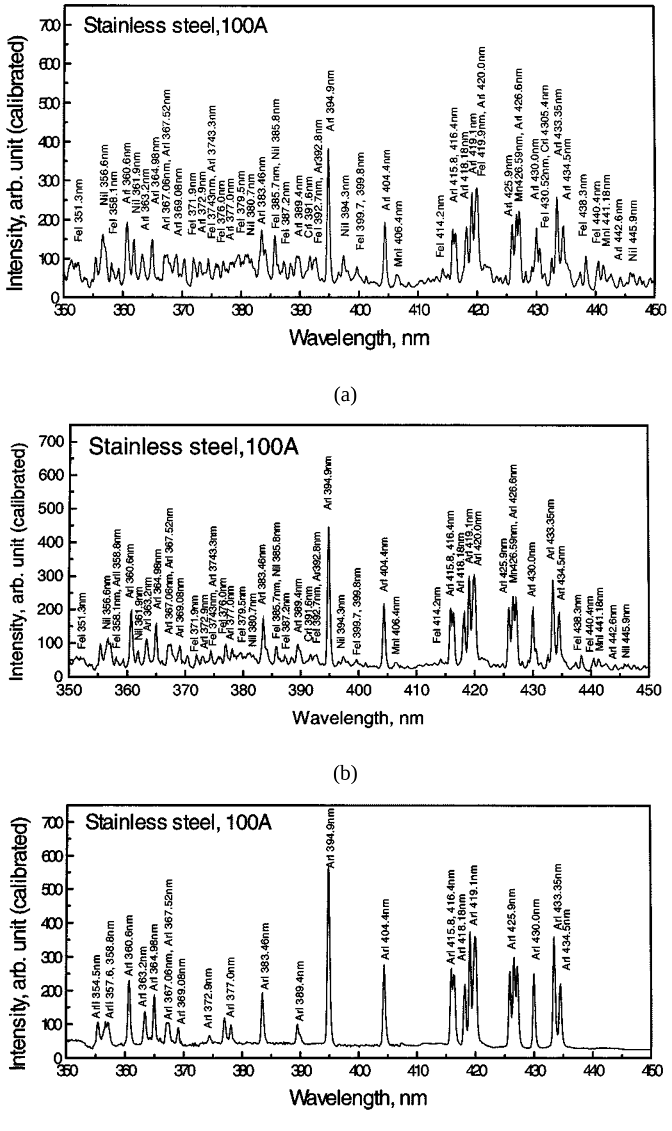

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Fig. 6. Effect of the distance from base metal: stainless steel 304: (a) 0.25 mm from base metal; (b) 2 mm from the base metal and the tungsten electrode; (c) 0.5 mm from the tungsten electrode.

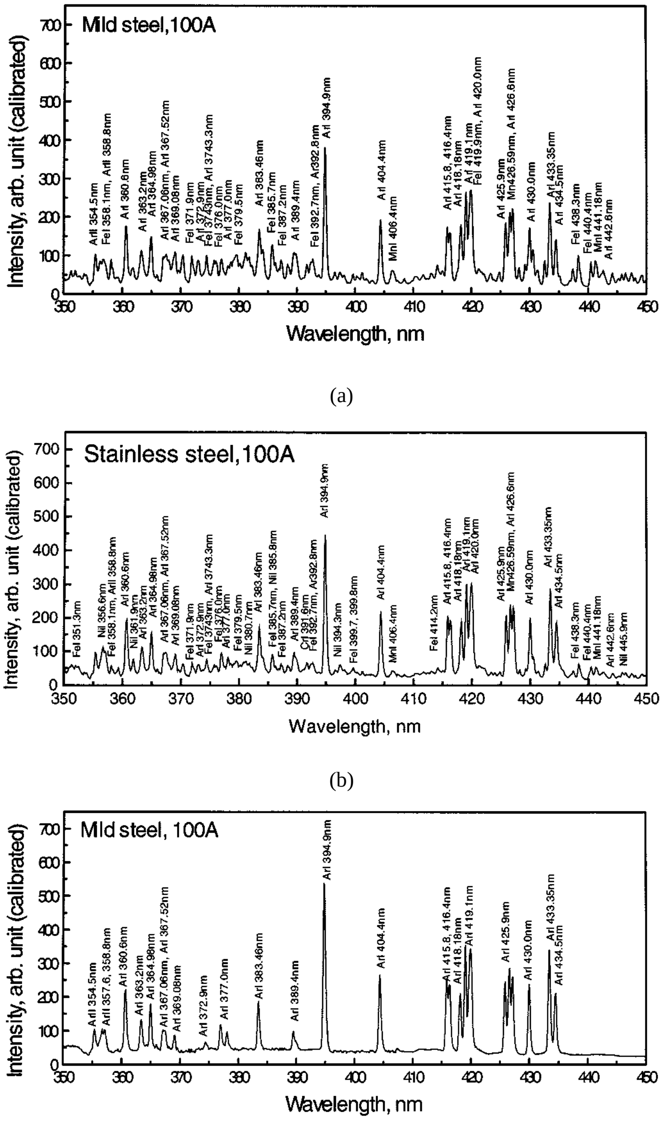

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Fig. 7. Effect of the distance from base metal: mild steel: (a) 0.25 mm from base metal; (b) 2 mm from the base metal and the tungsten electrode; (c) 0.5 mm from the tungsten electrode.

with two different base metals. It can be seen that the spectral distributions for the layer near the electrode look nearly identical for the two different base metals. Also, no spectral lines of metal vapor are observed. For the layer in the middle between the electrode and the base metal, similar results can be noticed. However, the spectral distributions demonstrate noticeable differences between the two different base metals for the layer close to the base metal due to the presence and variation of the spectral lines of metal vapor. Further experimental results revealed that metal vapor spectral lines are very sensitive to the distance from the base metal.

Fig. 8 plots the measurements of the arc voltage for different amperage at different arc lengths. For each given arc length and welding current, 50 measurements of the arc voltage were made. Fig. 8(a) is a direct record of the measurements for 70 A current, and Fig. 8(b) gives the average of the 50 measurements. Fig. 9 depicts the measurements of the arc light sensor without a filter. It is evident that the arc light sensor can achieve much better measurement accuracy of arc length than the arc voltage.

Another interesting phenomenon is that spectral distributions for the layers near the electrode or in the middle are very close. This seems to suggest that the energy emitted from different layers of the arc column does not significantly change if the distance between the layer sampled and the base metal is sufficient. Analysis shows that this speculation may be correct. In fact, the arc voltage is approximately proportional to the arc length. Due to the continuation of the welding current, this implies that the conversion of the electrical energy into the arc column remains nearly the same along the arc column. The intensity of the arc light at particular points of course does depend on the distance from the electrode, but the diameter of the arc also changes with the distance. As a result, it is understandable that the distance is not a determining factor for the spectral distribution of the arc light layer.

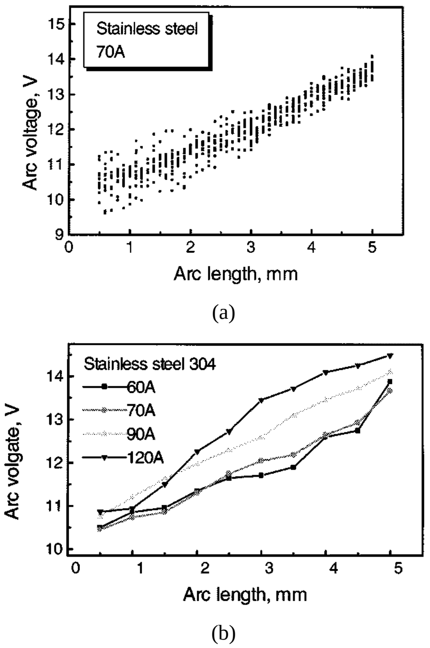

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Fig. 8. Arc voltage versus arc length. (a) Measurement distribution. (b) Averaged measurement.

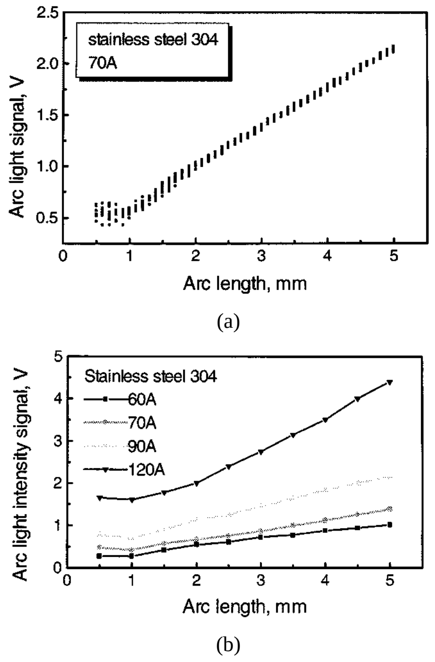

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Fig. 9. Arc light sensor output versus arc length. Arc light intensity was measured without filter. (a) Measurement distribution. (b) Averaged measurement.

V. Precision Sensing of Arc Length

For GTAW, arc length determines the arc voltage and the arc distribution, thus the heat input into the base metal. Together with the welding current and travel speed, the arc length is considered as one of the most important welding parameters. Although commercial equipment is available to achieve far more than adequate accuracy for the welding current and travel speed, the precise and low cost sensors are strongly needed for length control.

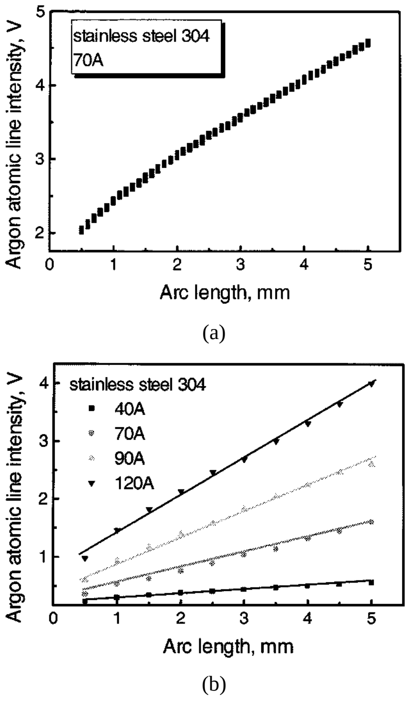

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Fig. 10. Filtered arc light sensor output versus arc length. Half-band: 30 nm, central wavelength: 696.5 nm. (a) Measurement distribution. (b) Averaged measurement.

For precision joining, GTAW requires the arc length be controlled at an accuracy of ±0.2 mm. Although through-the-arc sensing, i.e., measuring the arc voltage, is currently the most common arc length sensor, it has difficulty achieving an accuracy of ±0.2 mm. To investigate the potential of using arc light sensors in precision control of arc length, extensive experiments have been conducted to compare arc light and arc voltage sensing.

Although Fig. 9 clearly demonstrates the advantages of arc light intensity over arc voltage, the limitation of the arc light intensity in short arc length is also exposed. As seen in Fig. 9, the arc light intensity versus arc length measurements illustrates a great fluctuation as well as a zero slope when the arc length is short (less than 1 mm). Hence, the arc light intensity does not provide a useful measurement for a short arc length.

The above phenomenon is evidently caused by the metal vapor as discussed in the spectral analysis. To remove the effect of the metal vapor, a narrow band of spectrum which is determined by the arc length, but insensitive to the metal vapor, should be sensed instead of the whole spectral range. Ideally, this band should only contain the spectral lines of the argon atoms and be far away from metal lines.

Argon atomic lines of 696.5 nm, 750 nm, and 394.8 nm are all acceptable. Due to the convenience of narrow band filter, peak wavelength of 696.5 nm of 15 nm half-width was selected. To investigate the sensing accuracy of the improved sensor, two group experiments were conducted. In the first group experiment, the arc was ignited with 0.5 mm arc length and the torch was moved upwards to 5 mm step by step with an increment of 0.1 mm. Stainless steel 304 was used as workpiece. As shown in Fig. 10, the sensor output predicted the arc length well in all the range of the arc length. In this experiment, the workpiece

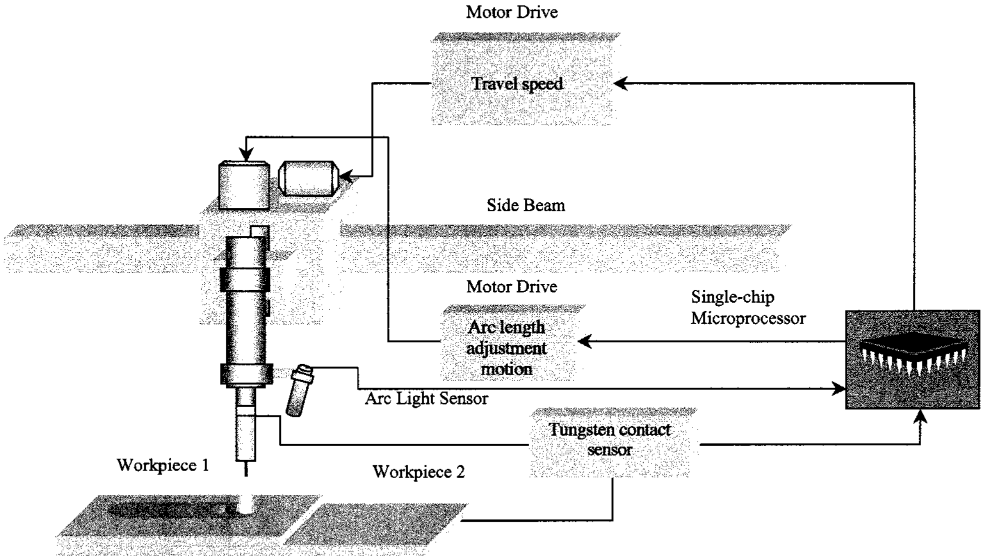

Fig. 11. Arc length control system.

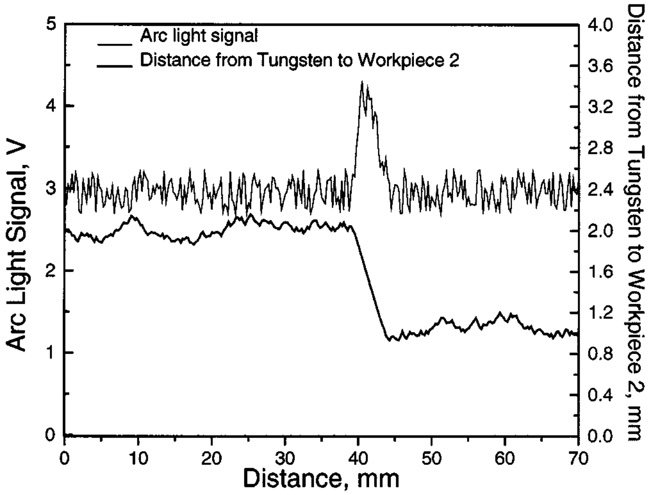

Fig. 12. Arc length control experiment under step disturbance.

did not move and the accuracy of arc length control can achieve 0.1 mm.

VI. Arc Length Control

An arc length control system has been developed based on the proposed method. Fig. 11 shows the schematic of the system. Experiments have been conducted to verify the effectiveness of the developed sensor and the control system. It was found that the arc length can be controlled with an accuracy of ±0.2 mm when the welding speed is in the normal range.

In the experiment corresponding to Fig. 12, a step disturbance in arc length was applied by overlapping a 1 mm stainless steel plate with another 1 mm stainless steel plate as shown in Fig. 11. Before igniting the arc, the torch was moved down toward workpiece 1 and a contact sensor monitored the contact between the tungsten electrode and the workpiece. When the contact was detected, the torch was moved upwards 1 mm. During welding, the single-chip microprocessor-based control system corrected the arc length, each 0.25 s based on the arc length signal, using a PID algorithm. The set-point of the arc length was 1 mm and the travel speed of the torch was 4 mm/s. The arc light signal and the torch adjustment were recorded by the microprocessor. As seen in Fig. 12, the effect of the step disturbance on the arc length was corrected in approximately 1.5 s (6 mm travel distance). The steady state error of the arc length was bounded by ±0.2 mm.

VII. Conclusion

Arc length, welding current, welding speed, and base material all play critical roles in determining the spectral lines of the metal vapor in arc light spectral distribution. Short arc length, large current, and low welding speed intend to increase the density of the metal vapor in the arc column, thus promoting metal spectral lines. The material of the base metal changes the type of the metal vapor and spectral lines. Spectral analyzes showed that the majority of the metal vapor exists close to the base metal.

Compared with the arc voltage, the arc light intensity can predict the arc length with much better accuracy. However, if the arc length is very short (less than 1 mm), the arc light intensity is incapable of predicting the arc length with adequate accuracy. It is believed that the presence of the metal vapor, with its sensitivity to many welding parameters and conditions, is the cause. A method to overcome the effect of the metal vapor is to sense only an argon atomic spectral line. A practical method is to sense the intensity of the arc light within a small spectral band around an argon atomic line, which is far away from the metal lines. The argon atomic line at 696.5 nm was selected. By attaching a narrowband filter (15 nm half-width), the arc light sensor output gave accurate predictions for the arc length in the range from 0.5 mm to 5 mm. Control experiments showed that the arc length can be controlled with an accuracy of ±0.2 mm when the welding speed is in the normal range using the developed arc light sensor.

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Dr. Zhang received the Donald Julius Groen Prize from The Institution of Mechanical Engineers for his research on machine vision recognition of weld pool in gas tungsten arc welding.