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| Title        | Sensors for Arc Welding : Advantages and Limitations                        |
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| Citation     | Transactions of JWRI. 1994, 23(2), p. 135-141                               |
| Version Type | VoR   |
| URL          | <a href="https://doi.org/10.18910/12253">https://doi.org/10.18910/12253</a> |
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# Sensors for Arc Welding: Advantages and Limitations<sup>†</sup>

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## Abstract

*Sensors are the key technologies for realizing arc welding automation. For the past 30 years or more, various types of sensor have been developed, however, it has been revealed by the surveys in 1993 that only the arc sensor, the probe and electrode contact-type sensors are being widely utilized in actual arc welding processes. In the present paper, available sensors in arc welding were reviewed, and their faced main problems were also discussed*

**KEY WORDS:** (Sensor) (Arc welding) (Automation) (Joint tracking)  
(Adaptive welding conditions control)

## 1. Role and Application of Sensors

In manual or semi-automatic welding processes, the welder must continuously use his eyes to watch the position of joint, the behavior of molten weld pool, the welding arc configuration and the weld bead shape, and also commonly use his ears to monitor the welding sound, especially arc sound. If he becomes aware of a difference between that observed and his perception concerning what should be the best welding process (based on his experiences or learned from texts), he will undoubtedly take some measures to reduce it, for instance, to shift the aiming point of welding arc, to adjust the welding conditions, and so on, although the response will be associated with the skill of the individual. It is by utilizing his five senses and experiences or skills that a human welder can produce weld beads with high quality.

If the welding operation is intended to be accomplished by a mechanical manipulator, for example, a welding robot, the manipulator must be equipped with several artificial sense organs so that it can act like a human welder capable of acquiring information concerning the welding environment and the weld bead

quality. The artificial sense organ is called a sensor. A sensor for arc welding is in fact defined as follows<sup>1)</sup>: "A detector, if it is capable of monitoring and controlling welding operation based on its own capacity to detect external and internal situations affecting welding results and to transmit a detected value as a detection signal, is called as a sensor. Moreover, its whole control device is defined as a sensor system (control system)".

It is easily understood that any good robot without a sensor for arc welding can not do anything if not pre-taught. However, the pre-taught not only needs much time, but has not the capability to compensate immediately for real time variations such as part-to-part dimensional variations, edge preparation tolerances, and in-process thermal distortions. From these viewpoints, sensor technology can be considered as the most important element of an automatic welding system. **Figure 1** shows the user's understanding of the key technologies for the automation and the robotization of arc welding<sup>2)</sup>.

**Figure 2** shows a concept of the architecture for a high level automatic welding system. The sensors in the system would further be classified into two categories as

<sup>†</sup> Received on November 25, 1994

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Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

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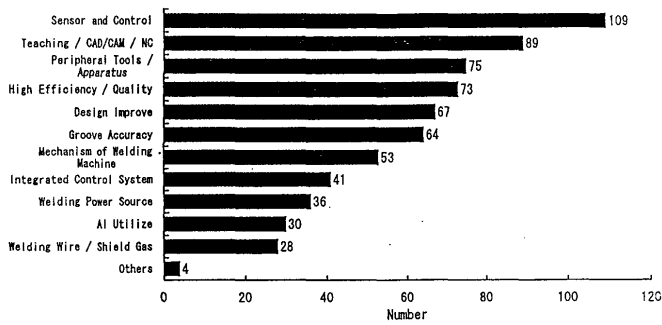


Fig. 1 Key technologies for automation and robotization of arc welding

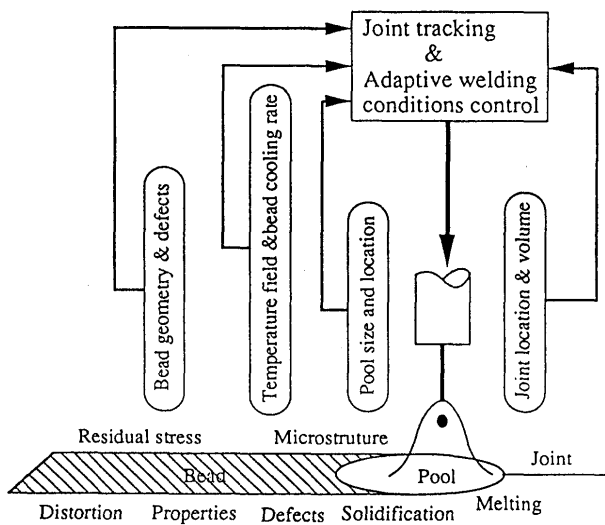


Fig. 2 A architecture of automatic arc welding

follows:

- 1) Measurement and detection of the operating environment, such as the location and orientation of welding joint, the volume of groove, and so on,
- 2) Supervision and inspection of the welding process, such as the weld molten pool behavior, the bead cooling rate, and so on.

In general, there are several types of sensor suitable for detection of one object simultaneously. In these circumstances, it is very important to balance well the sensitivity, accuracy of a sensor and the cost necessary for achieving these. For the past 30 years or more, various kinds of sensors have been developed, such as contact probes, electrode contact, temperature, arc phenomena, electromagnetic, optical and sound sensors, as shown in Table 1<sup>1)</sup>. However, to be applied to arc welding processes, the sensor must withstand the harsh environment of arc light, arc heat, spatter, electromagnetic disturbance and so on. Figure 3 shows the state of application of sensors<sup>2)</sup>. It will be noticed from Fig.3 that through-the-arc sensors, electrode and probe

Table 1 Classifications of sensors

|             | Sensor type         | Units in the sensor configurations   |
|-------------|---------------------|--|
| Contact     | Contact probes      | Micro-switches, potentiometers, and differential transformers (DTF).   |
|             | Electrode contact   | Voltage and current for contact detection that is applied to the W electrode-or the welding wire.                                      |
|             | Thermal             | Thermocouples, thermistors.  |
| Non-contact |                     | Photo-thermometers, infrared thermometers.   |
|             | Arc characteristics | Welding current, arc voltage, wire feed speed, number of shorts, number of peak current anomalies.                                     |
|             | Electromagnetic     | Electromagnetic eddy current detectors, magnetic detector by Hall devices.   |
|             | Optics              | Point sensors (phototransistors and photodiodes), linear sensors (CCD, MOS, and PSD) and area (image) sensors (CCD, MOS, PSD and ITV). |
|             | Sound               | Variable sound pressure or ultrasonic sound pressure detector probes.  |

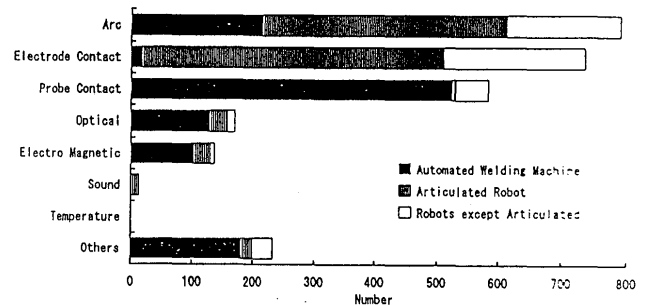


Fig. 3 Sensors used in arc welding (1993 survey)

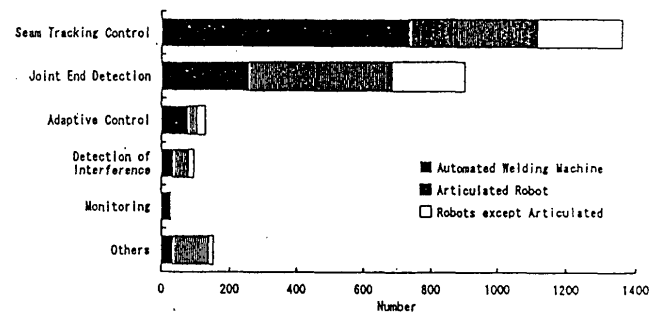


Fig. 4 Application of sensors used in arc welding (Classified by purpose) (1993 survey)

sensors have been most widely used in actual production today. The former are non-contact forms, but the latter are all contact types. All of them have the same advantages of low cost and simple maintenance. Figure 4 shows the application purpose of sensors in production<sup>2)</sup>. It will be seen that seam tracking and joint end detection are the main application fields of sensors for arc welding so far. Nevertheless, the results by no means imply that the adaptive control technology of welding conditions is not important, in contrary, mean that the research and development of sensors suitable for the adaptive control would have been slighted, or there do be many practical problems obstructive to successful application of these

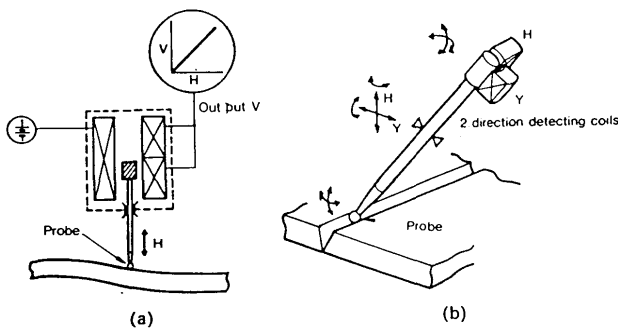


Fig. 5 Principle of probe contact sensor  
(a) One freedom (b) Two freedom

into adaptive control systems.

## 2. Contact Sensors

It can be seen from Fig.3 that contact sensors are being widely used in automatic arc welding systems today. The reasons may be the advantages of relatively low cost, simple handling and maintenance of this type of sensor.

Figure 5 shows the principles of the probe contact sensors<sup>1)</sup>. Where, Fig.5 (a) exhibits a sensor with only one degree of freedom (vertical direction). The sensor usually uses a potentiometer or a differential transformer to generate a electric signal proportional to displacement of torch height. However, Fig.5 (b) exhibits a sensor with both transverse and vertical direction degrees of freedom. The sensor generally utilizes limit switches to generate ON/OFF signals for correction of welding torch location over the welding joint.

These types of sensor, however, present such problems as unsuitability for complex curves of joints and limitation of welding speed. The probes are also subject to wear and must be located some distance in front of the welding torch when used for joint tracking.

Another contact-type sensor is shown in Figure 6 and is termed the electrode contact sensor<sup>1)</sup>. This type of sensor can help a robot to search for the central line of joint such as T-joint(Fig.6(b)) and lap joint(Fig.6(c)). However, in order to obtain a successful contact signal, the welding power source is required to supply a high voltage, ranging from 300 to 600V with a frequency of 50 ~ 600Hz, to the terminals of both the electrode wire and the base material before the normal operations of welding. When the electrode wire is brought into contact with the base material, a current of several amperes(not large enough to initiate the welding arc) will flow in the welding circuit. Thus, the robot can recognize the itself's location relative to the base material based on the electric

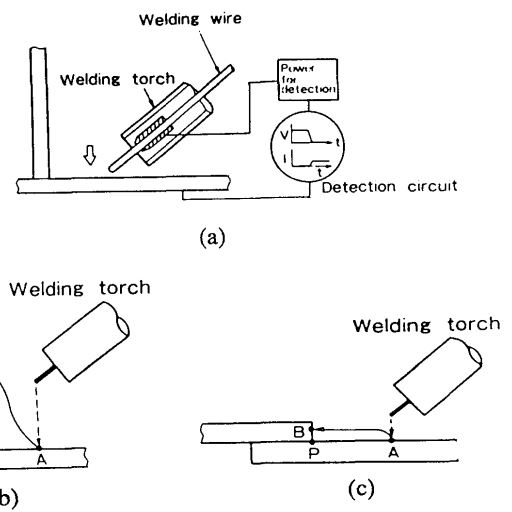


Fig. 6 Principle of electrode wire contact sensor  
(a) Principle (b) Fillet joint (c) Lap joint

signals, and finally, can lock onto the central line of the welding joint after several tries in different directions. To maintain the wire extension length constant, it is important to obtain the accurate coordinates with this method. For this reason a robot is usually equipped with a wire lock mechanism.

## 3. Non-contact sensors

The limitations and inherent problems with probe contact sensors have prompted the search for non-contact sensor. Work in the past 30 years or even more has developed a number of non-contact sensors such as through-the-arc, electro-optical, magnetic, thermal, sound and so on. Nevertheless, (Fig.3) only the through-the-arc sensor (simply called arc sensor) is widely used in actual arc welding production today. It may be related with the simple physical implementation since the arc itself can act as a sensing probe when the torch is oscillated back and forth across the joint as shown in Figure 7<sup>1)</sup>. In conventional welding systems, the weaving motion of torch causes changes in the welding current and voltage. If there is a deviation of torch relative to joint line, the detected signal waveform will exhibit asymmetry. Therefore, joint tracking can be achieved by taking measures capable of reducing the difference between the characteristic values in the right and left side of the waveform. Some control strategies for application of the arc sensor are summarized in Figure 8.

The advantages of using arc sense technology may be summarized as:

- (1) No need for additional space intrusion in the vicinity of the torch,
- (2) Ability to achieve joint tracking and weld bead control simultaneously,

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(3) Sensing accuracy not affected by wire bending, smoke, welding spatter and arc heat,

(4) Real time control

(5) Relatively low cost and no maintenance.

On the other hand, a high oscillation of the torch is usually required in high speed welding processes. However, the highest weaving movement reaches at most

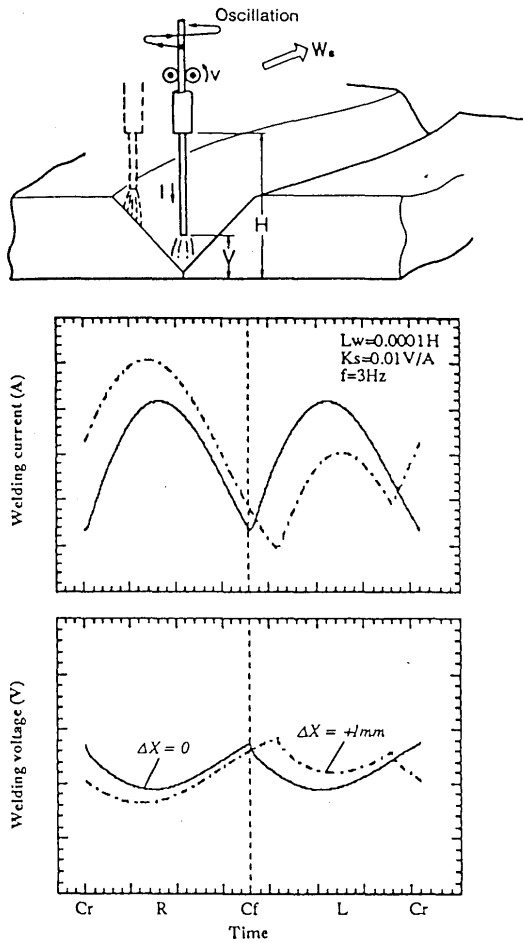


Fig. 7 Principle of the weaving arc sensor

to around 5Hz with a mechanical oscillator. This limitation has led to the development of a high speed rotating arc welding process(HSRAWP)<sup>3</sup>. With the method, the rotation easily reaches 100Hz or even higher. The principle of this method is shown in Figure 9.

The above applications of the arc sensor are only connected with joint tracking technology. Recent developments have shown capabilities of application in the adaptive control of welding variable<sup>1),4)</sup>. Figure 10 shows the principle of deposited metal control utilizing torch weaving. As soon as the sensitivity of the arc sensor is sufficient to keep the torch height constant, the weaving trace can be considered to represent the groove shape. Since the weaving reverse height( $\epsilon_0$ ) is set at a fixed level from metal surface, the weaving width( $W$ ) will increase proportionally with a increase of groove width( $G$ ). Therefore, a constant bead height can be obtained by the control of welding speed with the control rule shown in Fig.10 based on the arc sensing signal.

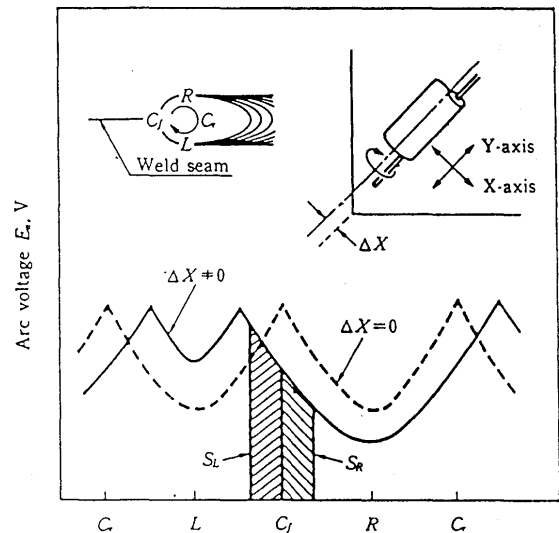


Fig. 9 Principle of the rotating arc sensor

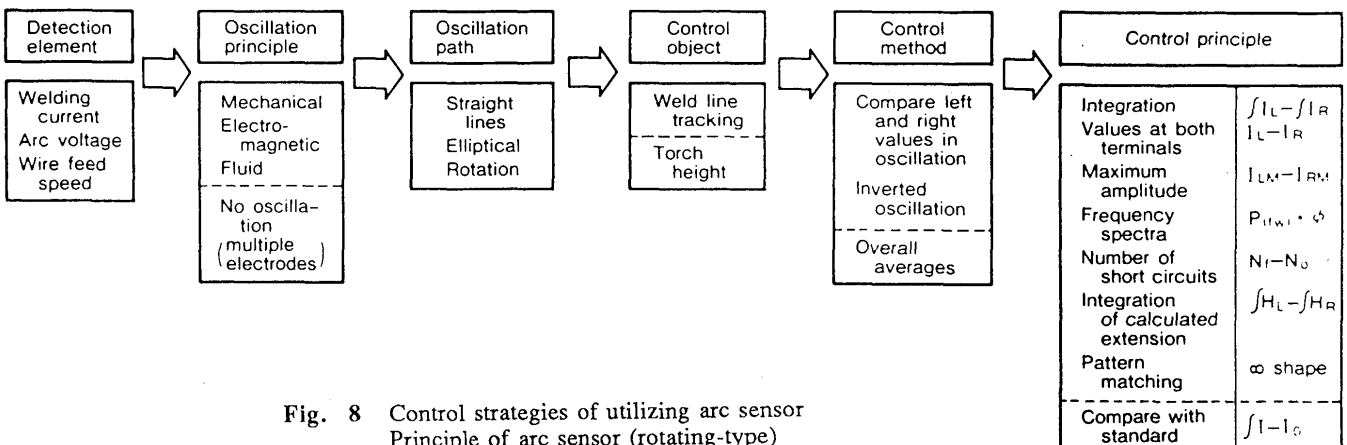
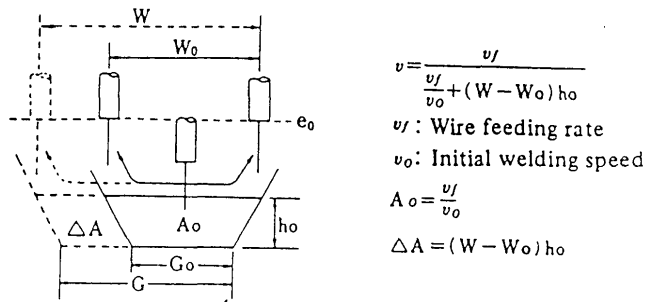


Fig. 8 Control strategies of utilizing arc sensor  
Principle of arc sensor (rotating-type)

Another example of adaptive control with the arc sensor is shown in **Figure 11**, where the HSRAWP is used. Since the welding current, the welding speed and the average arc length in this method are all held constant, the arc pressure  $P_a$  and the surface tension  $P_s$  are considered to become constant. However, the gravity pressure  $P_g$  is related to the molten weld pool height, namely, the groove volume. Therefore, when the groove volume changes, the weld pool height will change, thus, a variation of the keyhole, i.e., the regressing or progressing of the front of the molten weld pool, will occur and cause a change in the welding current at the location of Cr(rear point in the circle of torch rotation). To reduce the difference between the detected and set levels of the welding current at point Cr, the wire feeding



$$v = \frac{v_f}{\frac{v_f}{v_0} + (W - W_0) h_0}$$

$v_f$ : Wire feeding rate  
 $v_0$ : Initial welding speed  
 $A_0 = \frac{v_f}{v_0}$   
 $\Delta A = (W - W_0) h_0$

Fig. 10 Weld bead height control with arc sensor

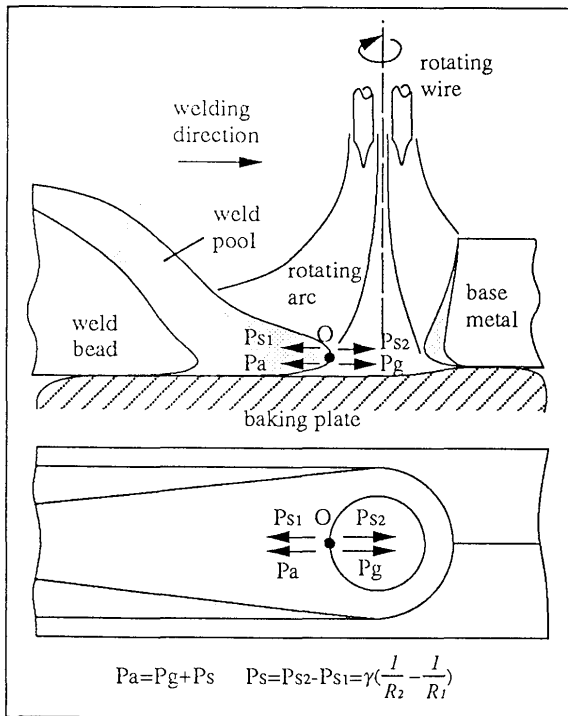
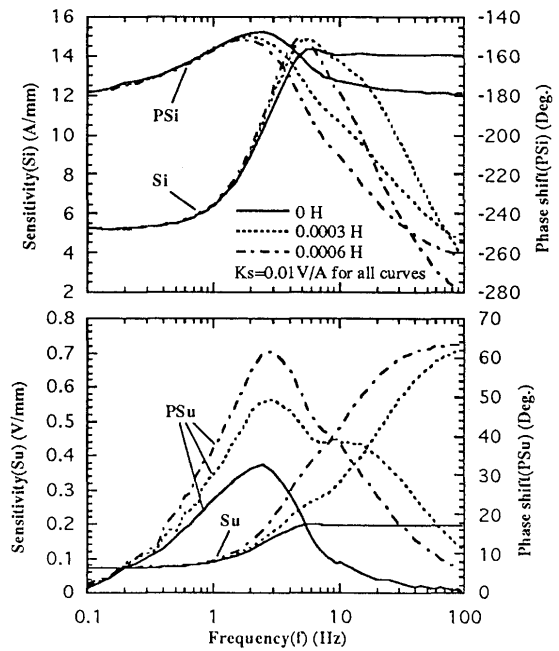


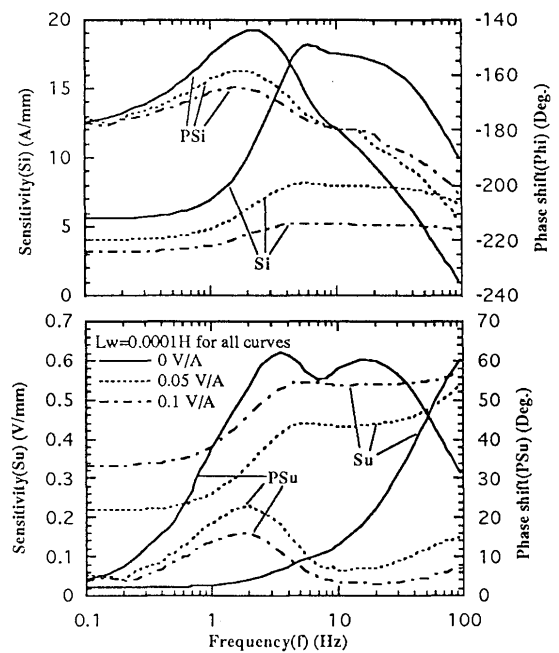
Fig. 11 Principle of simultaneous control of weld bead back bead shape utilizing arc sensor in high current and high speed rotating arc welding process

rate and the output of the welding power source are simultaneously adjusted in the present case. In this way, both the weld bead height and the back bead shape can be held constant because both the keyhole and the arc input energy are not subjected to change.

The arc sensor shows many advantages as mentioned above, but its characteristics depend on the welding



(a)



(b)

Fig. 12 Effects of inductance in welding circuit and power source output characteristic on the characteristics of arc sensor

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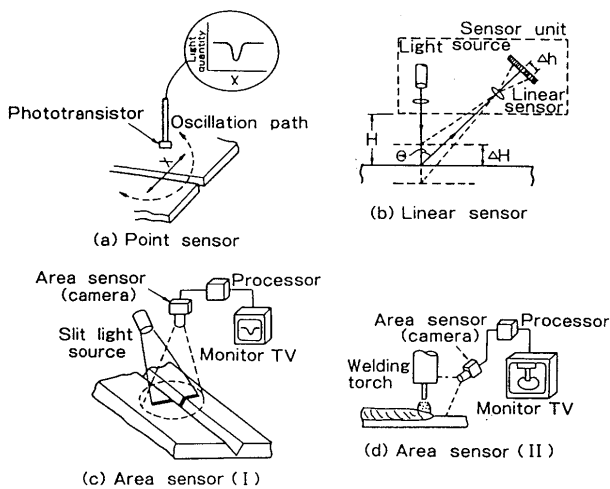


Fig. 13 Principle of using optical sensors for joint tracking

process and system parameters. Figure 12 shows the effects of both the inductance of the welding circuit and the output characteristics of the welding power source on the frequency response of the arc sensor. These results show that a correct selection of arc sensing condition is the key to achieving a high sensitivity of arc sensor system<sup>5</sup>).

Another problem involves the removal of the noises imposed on the welding current and voltage due to the droplet transfer, the fluctuation of wire feeding, the movement of current pick-up point and so on. The noises in general reduce the quantity and quality of information gleaned from arc signals.

In contrast to the arc sensor, optical sensors are independent of a welding circuit system. Although optical sensor technology has not been widely used in welding production yet, it is considered to possess the most potential in future because it can provide directly the joint contour, the molten weld pool outline, the arc shape, the wire position and the solidified weld bead shape simultaneously. It can work during or before welding rather than the arc sensor which only works during welding. Thanks to the great progress in electronics and computer data processing, a number of optical sensor technologies have been developed as shown in Figure 13<sup>1),6~7)</sup>. Here, the light source may be laser, light from the arc and the molten pool or lamp. The detector can be point sensors (phototransistors or photodiodes), linear sensors (CCD, MOS, PSD) or area (image) sensors (ITV, CCD, MOS, PSD). If the area sensor is used, joint tracking and the adaptive control of welding condition can be realized simultaneously. Figure 14 shows an example where both the location and volume of the groove are able to be detected at the same time<sup>1)</sup>.

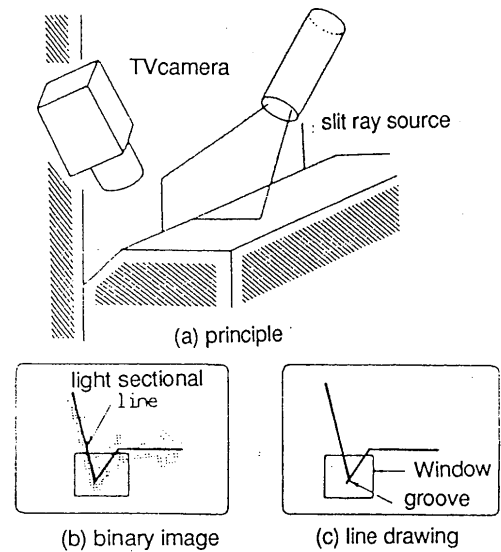


Fig. 14 A area optical sensor for both joint tracking and deposited metal control adaptive to groove shape

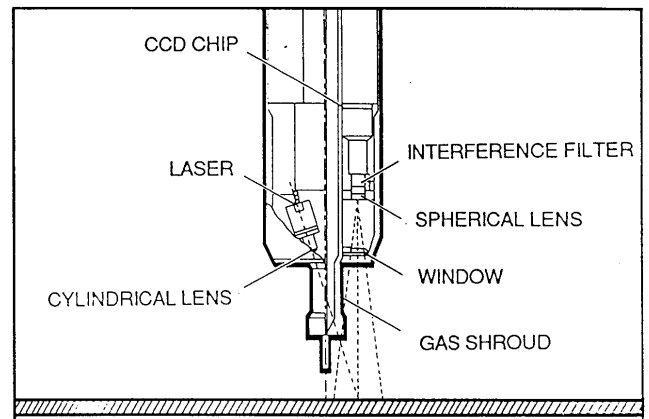


Fig. 15 Metatorch welding head with integrated laser and camera

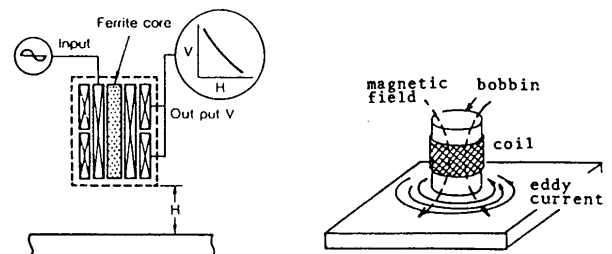


Fig. 16 Principles of reluctance and eddy sensors

However, optical sensors are relatively expensive and delicate by comparison with the arc sensor. In order to protect them from the harsh welding environment such as spatter, fume, dust, and high temperature, the sensors must be well enclosed in a case of compact size and light weight. A good idea for that was proposed by Richardson, R.W. et al<sup>(6~7)</sup>, and is shown in Figure 15, but it is obvious that further improvements are necessary.

Another problem with optical sensors is the removal or reduction of the interference with arc light. Optical filters are generally used for this purpose<sup>1)</sup> but weaken the useful signal coming from the detected objects at the same time.

To obtain a three-dimensional profile of detected object, image processing technology is needed<sup>1),8)</sup>. However the technology requires an increase in data processing speed, an improvement in the resolution of images and a reduction in cost before it is applied in actual welding production.

There are other types of non-contact sensors being used in welding productions. Figure 16 shows an electromagnetic type of sensors, and they are being used for joint tracking or torch height control at present. The ultrasonic sensor has also been reported to be capable of detecting the joint line, the degree of penetration and defects in the weld bead<sup>1),9)</sup>. However, further work is obviously necessary in order to promote its application into production.

#### 4. Conclusion

Overall, there seems not to be a sensor capable of satisfying all possible applications. It is necessary to utilize different sensors to support a high level of arc welding control system. There is no question, however, that it is essential to have a good understanding of the features and characteristics of arc welding processes for the development of sensors and sensor control systems. The urgent problems now faced may be accuracy and repeatability of the sensor system itself, the ability to adapt to groove shape change, and so on, as summarized in Figure 17. These problems are considered to be the challenges for the further advance of automatic arc

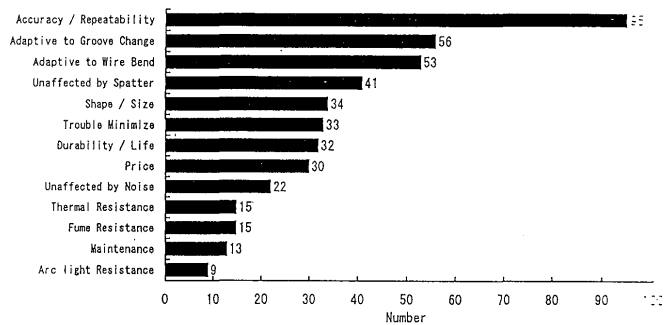


Fig. 17 Urgent problems to be solved in sensor technology

welding in today and the near future.

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