Real-Time Control of the Plasma Arc Cutting Process by Using Intensity Measurements of Ejected Plasma

Plasma exiting at the bottom of the plate is used as a signal to control the cutting process

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In the plasma arc cutting process, faster cutting speeds are achievable on up to 1-in .(25-mm) thick plate when compared with the oxyfuel gas cutting process, since the plasma arc supplies a high energy density. Therefore, automatic cutting machines with a NC or CNC system are often used, and in-process monitoring and control could be used to improve the cut quality and also to overcome the difficulties that may lie in varying cutting conditions. The cut quality in plasma arc cutting can be evaluated using various parameters. In this study, the cut thickness and dross attached at the bottom cut edge were considered for the process evaluation.

In order to improve the cut quality in plasma arc cutting of plates with varying thicknesses, the intensity of the plasma arc exiting the bottom of the plate was measured using a photo darlington sensor, and the cutting speed was controlled to maintain the uniform intensity of the ejected plasma arc. As a result, with a simple speed control, the amount of the attached dross was substantially reduced, and a plate with gradually varying thicknesses was cut successfully. But for cutting of plates with sharply varying thicknesses, a more sophisticated control scheme would be required.

INTRODUCTION

Plasma arc cutting is a fusion cutting process in which a gas-constricted arc is employed to produce the high-temperature, high-speed plasma jet on the workpiece. This process provides some advantages such as increased cutting velocity, excellent working accuracy and possible cutting of special metals (stainless steels and aluminum alloys, etc.), when compared to the conventional oxyfuel gas cutting. From the point of cost and reliability, plasma arc cutting has also some distinct advantages over laser beam cutting.

It is generally understood that a high-quality cut is characterized by sharp corners, a smooth cut surface, parallel sides, nonadherent dross and a narrow kerf width. For any given cut, the variables listed above have to be carefully evaluated to obtain the required cut surface quality at a minimum cost. In order to produce a high-quality cut, tables and charts (Ref.1) can be used to obtain the information on process variables, such as the most suitable diameter of cutting orifice, cutting speed, gas flow rate or pressure, etc., for a given metal thickness. However, these values area approximate and must be determined separately for specific metals.

Many articles on plasma arc cutting have appeared in the interval between the introduction of the process and the present. Some of these discuss the quality of the plasma arc cuts and methods for improving it (Refs. 2-4). Automatic cutting machines with a NC or CNC system have also been frequently investigated (Refs. 5, 6) to achieve the optimum production economy. However, very little information is found on the feedback control of the plasma arc cutting process, while some efforts have been made to use the intensity of the ejected plasma for monitoring and controlling the plasma arc welding process (Refs.7,8).

This paper describes the development of a control that could be used to monitor and control the plasma arc cutting process to produce consistent quality cuts. To accomplish this goal, the cutting speed was changed, and a monitoring system of the ejected plasma was employed for evaluating single-torch perpendicular

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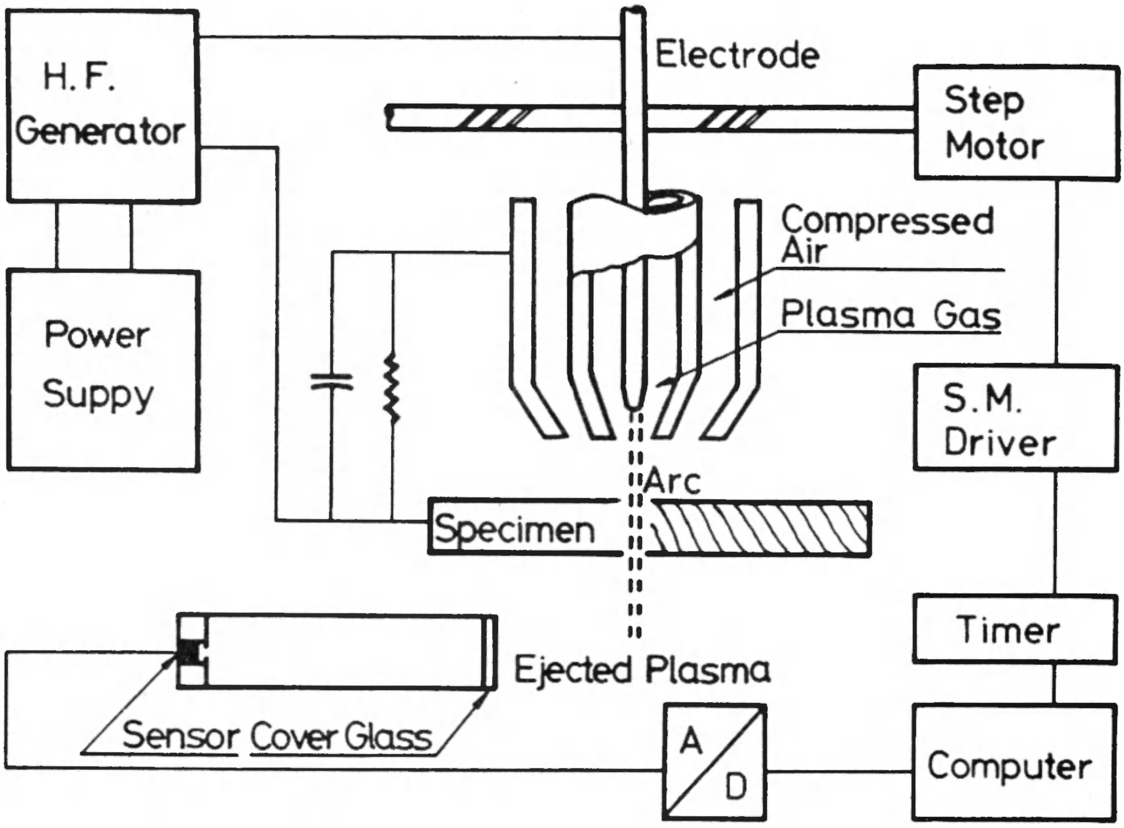

Fig. 1. *Schematic diagram of experimental setup*

cuts. The results of the measurements have shown that the radiance of the plasma in the infrared and visible range could provide control signals to reduce the dross and to produce the through-cutting of plates with varying thicknesses. A simple real-time loop system was then developed for automatic control of the plasma arc cutting process. Based on our study, the application of an automatic control system appears to be feasible.

EXPERIMENTAL METHOD

The experimental setup to evaluate cutting speed as it relates to the quality of cut in plasma arc cutting was designed to provide a record of the visible conditions for a range of cut quality. Figure 1 shows the schematic diagram of the experimental equipment used for monitoring and controlling the plasma arc cutting process. The main compononents of the equipment are as follows:

1) The power source is a DC unit, which has a rated output current of 100 A and rated output voltage of 150 V.

2) The moving part is composed of ball screws, stepping motors and stepping motor drivers. Ball screws have a lead of 20mm (0.78 in.), and the stepping motor processes a step angle of 0.72 deg - that is, 500 steps per revolution. Bipolar constant current-type stepping motor drivers were interfaced to the control part through one of 64K I/O addresses of the microcomputer.

3) The control part is composed of microcomputer and interfacing circuits. A 16-bit microcomputer, which has 256-KB main memory, was used to collect and process the measured data, and also to control the cutting speed.

4) The sensor is a photo darlington sensor[1], which is very inexpensive and can be easily obtained. It responds to light very quickly, and is sensitive for the wavelength range of 0.5-1 μm, while the maximum sensitivity is obtained at the wavelength of about 0.8 μm. The sensor was placed on one inner end of a plastic tube to prevent it from being saturated, since during preliminary trials with an open sensor, the output signal was saturated for a large range of cutting speeds. The relative intensity of the ejected plasma was selected for comparing the cutting conditions, since the temperature of the plasma jet, which has a close relationship with the wavelength of high radiation intensities,

1. Sensitive photo sensor with two transistors

and the effect of metal particles on the measured intensity cannot be determined definitely.

The cutting trials were carried out for varying cutting speeds and materials thicknesses, while the other parameters were fixed as follows : material: Al 5052, arc current : 100 A, arc voltage : 85 V (arc length : 4 mm), plasma gas flow rate : 8 L/min (80% Ar + 20% H_2), and air pressure : 6 kg/cm^2.

The cut specimens were inspected to evaluate the cut quality. The dross state of the bottom cut edge was examined with the naked eye and compared for various cutting conditions. The amount of the adherent dross was also measured by detaching it from the workpiece. The kerf width was also determined on the top and bottom surfaces of cut specimens. Finally, the closed loop control was performed in plasma arc cutting of plates with sharply and gradually varying thicknesses.

RESULTS AND DISCUSSION

Data Analysis of Cutting Experiment

The kerf width was measured on the top and bottom surfaces of cut specimens for various cutting speeds and plate thicknesses, and the results are shown in Fig. 2. The top kerf width was in the range of 3-5 mm (0.12 - 0.20 in.) for the considered plate thickness, and almost unchanged for varying cutting speeds. There is also no proportional consistency in the relationship between the top kerf width and the plate thickness. This is probably due to the fact that the size of the molten zone in the top surface, which will be blown away by the cutting gas, is nearly uniform for various

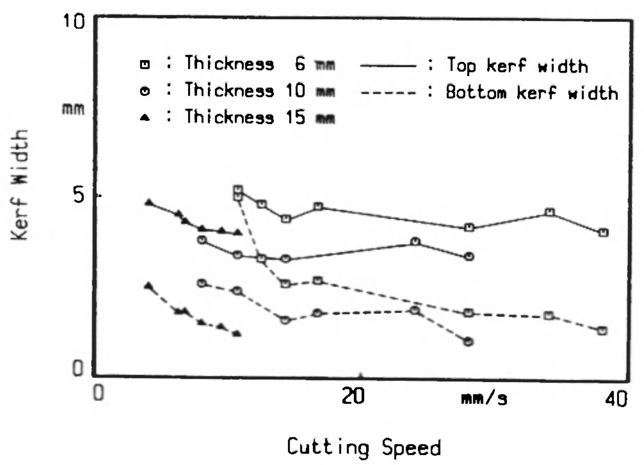

Fig. 2. *Kerf width of top and bottom surfaces for various cutting speeds and plate thicknesses*

cutting speeds and plate thicknesses, because the heat transfer onto the plate surface from the plasma arc is much faster than the heat conduction in the workpiece. Therefore, it can be expected that the top kerf width is mainly influenced by the plasma arc characteristics, such as the power and plasma arc size on the plate. The kerf width of the bottom surface remains almost unchanged with varying cutting speeds, while it increases with the decreasing plate thicknesses.

If the flow rate of the plasma jet is m_p, the enthalpy of the ejected plasma H_p, the power loss qi, the power dissipated for cutting qd, and the total plasma power qt, the following relationship is obtained from the heat equilibrium in the plasma arc cutting process.

$$m_p H_p = q_t - q_l - q_d \quad (1)$$

It was reported that the power loss ql, (i.e., the energy losses) at the cathode, at the nozzle and in the atmosphere are 3% , 10% and 10% of the total power, respectively (Ref. 4). The power dissipated for cutting qd consists of two factors, namely, melting of the removed material and heat conduction into the base metal, which will be denoted with q_c in the following section. Since the cross-sectional area of the kerf is almost unchanged for varying cutting speeds, the enthalpy of the ejected plasma can be expressed in the following equation, if the cross-sectional area of the kerf is A, the cutting speed v and the energy dissipated for melting a unit volume of the workpiece q_m.

$$H_p = \frac{q_t - (q_l + q_c) - v.A.q_m}{\dot{m}_p} \quad (2)$$

Since q_t, q_l, $\dot{m}_p$ and q_m in the above equation are kept constant in our investigation, and q_c is also approximately constant for a given thickness, the enthalpy of the ejected plasma is determined mainly by the cutting speed and cross-sectional area of the kerf. The enthalpy of the plasma jet has a close relationship with its temperature (Ref. 9), which in turn affects the wavelength range of the high radiation intensity. Therefore, the cutting speed can be controlled to maintain the uniform intensity of the ejected plasma for improving the cut quality of plate with varying thicknesses.

The intensity of the ejected plasma was measured during the plasma arc cutting process for various cutting speeds - Fig. 3. It is normal practice with plasma arc cutting to maintain the arc in one place until a keyhole is formed and then start the traverse across the workpiece. Therefore, a peak intensity of

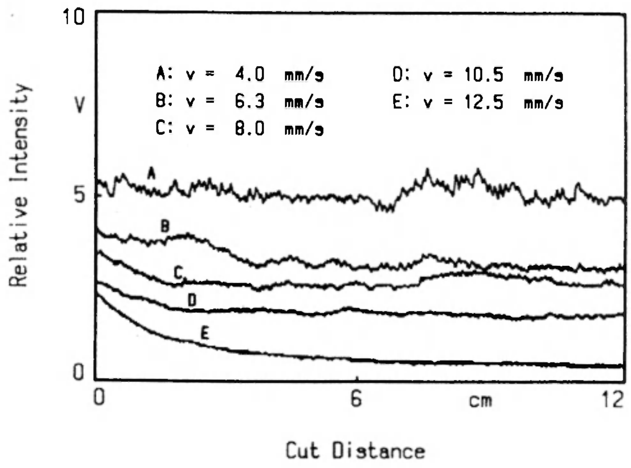

Fig. 3. *Relative intensity of ejected plasma for various cutting speeds (plate thickness - 15mm)*

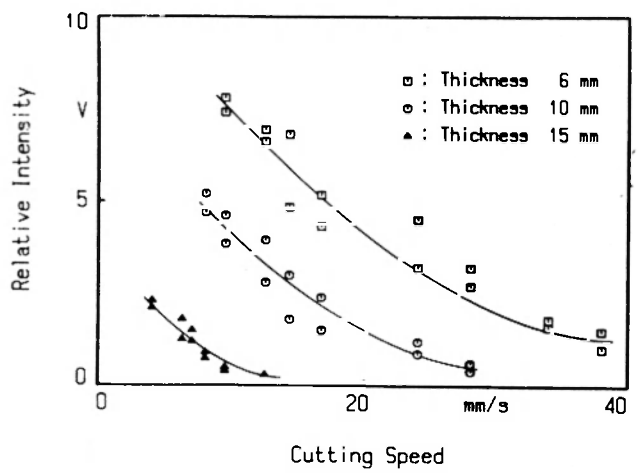

Fig. 4. *Relative intensity of ejected plasma for various cutting speeds and material thicknesses*

the ejected plasma is observed after keyholing, which will in most cases saturate the photo sensor. With the start of torch movement, the intensity of the ejected plasma will decrease first, since it takes a little time for the plasma arc acting on the upper surface to leave the lower surface as ejected plasma. The peak intensities and initial intensity variations were excluded in this figure, because it should compare the steady-state intensity for various cutting speeds. However, it could still be shown that for high cutting speeds, the relative intensity of the ejected plasma decreases gradually to a low steady-state value. This may be also due to the slow response characteristics of the saturated photo darlington sensor. Although some variations in the steady-state intensity of the ejected plasma are observed as cutting progresses, especially at low cutting speeds, it might be generally concluded that the relative intensity of the ejected plasma decreases, as the cutting speed increases, that is, as more power is dissipated for melting the workpiece.

In Fig. 4, the measured relative intensities of the ejected plasma are compared for various cutting speeds and material thicknesses. With increasing cutting speed, the relative intensity of the ejected plasma decreases regularly for all considered plate thicknesses, as can be expected from the higher value of v in Equation 2. The greater thickness of the cut specimen also causes a decrease in the relative intensity of the ejected plasma, since the larger cross-sectional area of the kerf result in more energy dissipation for cutting of material. From the comparison of the data in this figure, it can be concluded that a certain relative intensity of the ejected plasma exists, which can produce satisfactory cutting for a range of plate thicknesses.

For evaluating the cut quality, the dross was detached from the bottom cut edge of the workpiece, and its weight was measured for various cutting speeds and material thicknesses Fig. 5. The dross per unit length remains almost unchanged for a certain critical cutting speed, over which it increases very rapidly. It can also be shown that less dross is attached at the thinner workpiece. For producing a high-quality cut, therefore, the cutting speed should be limited under a certain critical value (12 mm/s for a 15-mm -0.47 in./s for 0.59-in.-thickness in this investigation). These tests demonstrated the feasibility of employing a photosensitive device for monitoring the total light output from the ejected plasma and interpreting it to perform a closed loop control of the plasma arc cutting process.

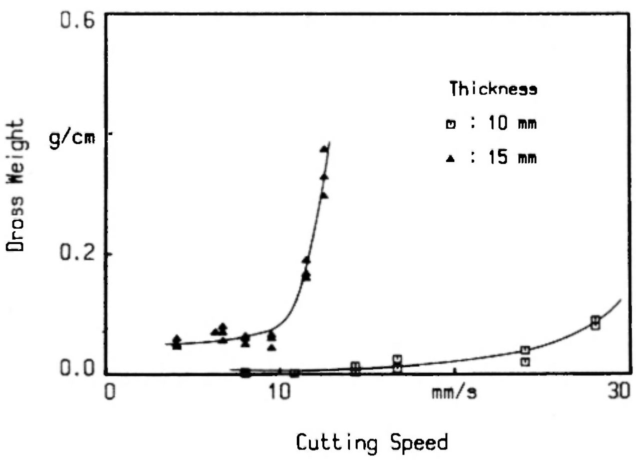

Fig. 5. *Weight of dross attached at the bottom of the cut edge for various cutting speeds and material thicknesses*

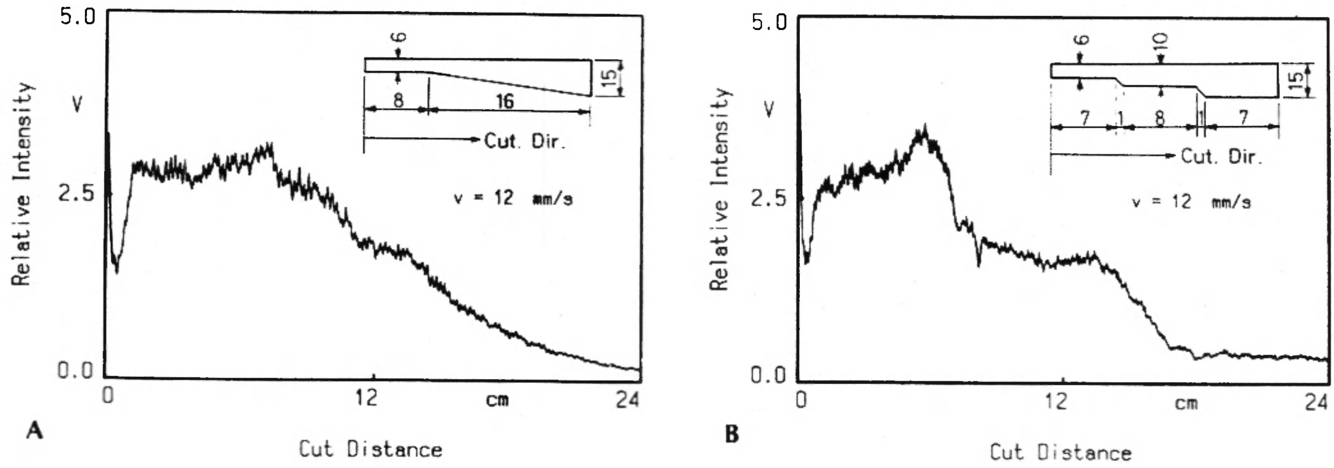

Fig. 6. *Relative intensity variation of ejected plasma during cutting of plates with varying thicknesses. A - Gradually varying thicknesses; B - sharply varying thicknesses.*

REAL-TIME CONTROL FOR VARYING THICKNESSES

The relative intensity of the ejected plasma was measured using a constant speed for cutting plates with varying thicĸnesses Fig. 6. As can be expected from previous results, the relative intensity corresponds to the plate thickness very well. It decreases smoothly for a gradually increasing part thickness, decreases sharply for a stepped increase in part thickness, and maintains uniformity for unchanged part thickness. The high intensity of the ejected plasma at cut distance 0 and its steep decrease and increase alter start of the torch movement are also shown in this figure. This is certainly due to the normal practice at the start of the plasma arc cutting process as explained in the previous section.

A simple system was devised with direct feedback from the monitoring device to control the cutting speed, for which the proportional controller form was specified as follow:

$$V = \frac{V_s\,(1 + K^{l-l}\,ref)}{l_{ref}} \qquad (3)$$

where V is the controlled speed, V_s the start speed, K the proportional gain, 1 the measured intensity of the ejected plasma and 1_{ref} the reference intensity . The variations in the measured intensity of the ejected plasma and the input value of the cutting speed are shown in Fig. 7. for the controlled cutting of plate with gradually varying thickness. For the given plate thickness, the relative intensity of the ejected plasma is substantially high, when compared with the results of Fig.8. These differences were caused by the different arrangements of the experimental equip-

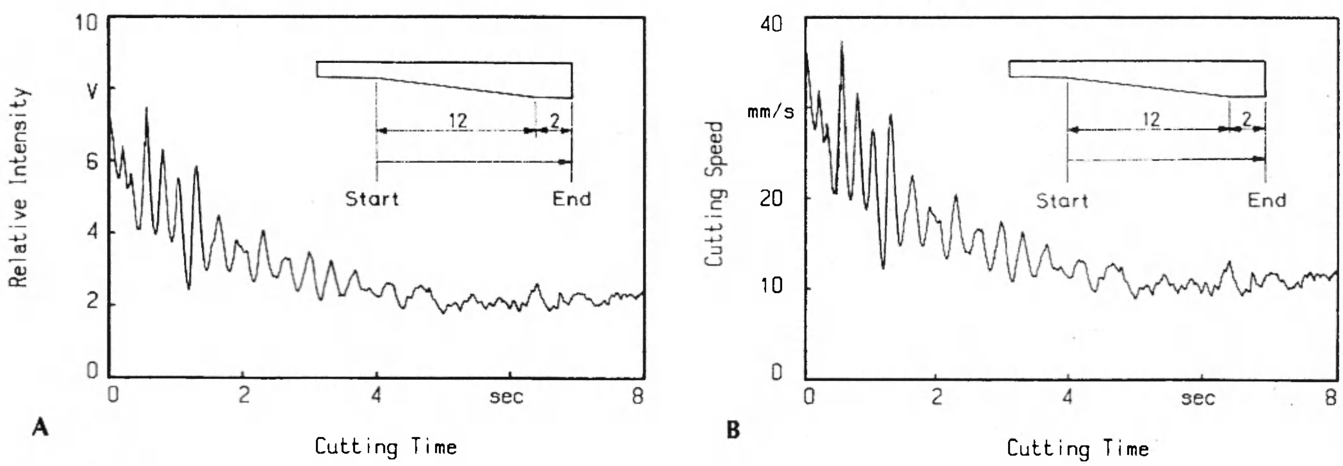

Fig. 7. *Results of controlled cutting of plate with gradually varying thicknesses (K = 1.0). A - Relative intensity of ejected plasma (l = 2.0 V); B - input value of cutting speed (v = 10 mm/s).*

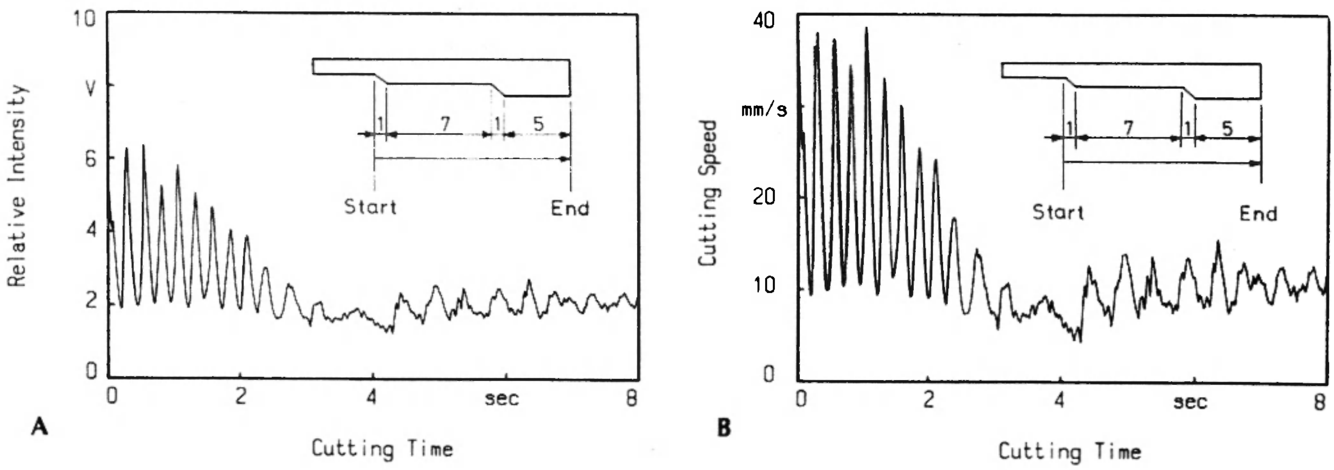

Fig. 8. *Results of controlled cutting of plate with stepped variations in thickness (K = 1.5). A - Relative intensity of ejected plasma (I = 2.0V); B - input value of cutting speed (v = 10 mm/s).*

ment for cutting with a constant speed and cutting with a controlled speed. This indicates the great influence of sensor sensitivity on the measured value and is the reason why the relative intensity of the ejected plasma was adopted in this investigation, and not the absolute intensity. The initial velocity of 10 mm/s (0.39 in./s) was changed to about 35mm/s (1.4 in./s), immediately after the speed controller begins to work near the end of the 6-mm (0.24-in.) thick part, since the cutting of a thin plate with such a low speed generates a high intensity of ejected plasma. However, this high speed conversely reduces the ejected plasma intensity and consequently the cutting speed. As a result, some fluctuations in ejected plasma intensity and cutting speed are observed in the applied proportional control system, especially during cutting the relatively thin part of the plate. On the other hand, a substantially uniform intensity and cutting speed can be obtained during cutting the thick plate part, while the relative intensity and cutting speed remain low when compared with the thin part.

In cutting the plate with stepped variations in thickness, more fluctuations in ejected plasma intensity and cutting speed are observed than with a gradually varying thickness, especially when cutting the part with varying thickness from 6 mm to 10 mm (0.24 to 0.39 in.). With the cutting progress of the 10-mm-thick part, however, the fluctuations are gradually reduced. And accordingly, when cutting the part with varying thicknesses from 10 to 15 mm (0.39 to 0.59 in.) and the subsequent part of 15-mm thickness, a considerably stable intensity in ejected plasma and cutting speed can be obtained. Based on the above results, the application of a real-time automatic control system appears to be feasible in plasma arc cutting operations.

Figure 9 shows the cut surfaces of plates with gradually varying thicknesses obtained under a constant and controlled cutting speed. The cutting with a constant speed of 20 mm/s (0.79 in./s) produces a high-quality cut for the thin part, since only very little dross remains attached at the bottom surface. But the amount of the attached dross increases with increasing thickness, and the through-cutting is interrupted at a certain critical thickness. On the other hand, plasma arc cutting with a controlled speed using the intensity of the ejected plasma can produce through-cutting over the

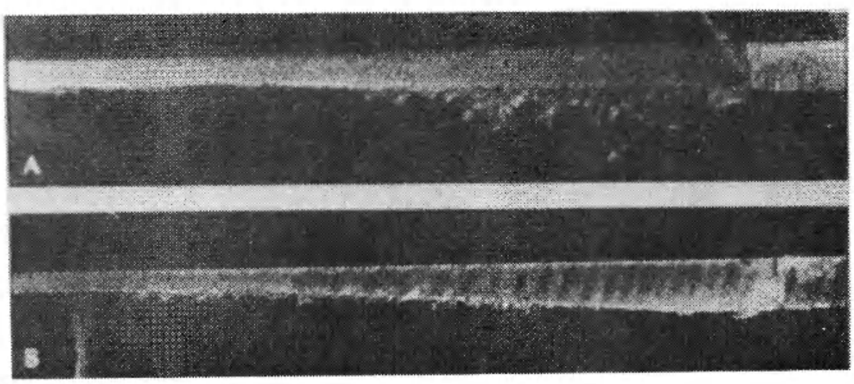

Fig. 9. *Cut surfaces of plates with gradually varying thicknesses. A - Constant cutting speed of 20mm/s; B - controlled cutting speed*

whole length of the plate by gradually varying the thickness from 6 to 15 mm. For the thin part, the amount of the attached dross is a little more than with the constant cutting speed, since the controlled speed is higher than the constant speed. But for the thick part of the workpiece, the dross state is also improved when compared to the constant speed cutting.

CONCLUSION

This investigation has shown that the cut quality can be improved in plasma arc cutting of plates with varying thicknesses by applying a real-time control of the cutting speed. The kerf width remains almost unchanged for varying cutting speeds, which consequently has a close relationship with the intensity of the ejected plasma. Under a constant cutting speed, increasing workpiece thickness reduces the intensity of the ejected plasma, since a large cross-sectional area of the cut kerf causes significant dissipation of plasma energy available for melting the workpiece. Therefore, the in-process measurement of the ejected plasma intensity provides signals usable for real-time automatic control in plasma arc cutting of plates with varying thicknesses.

A photo darlington sensor was used to measure the relative intensity of the ejected plasma, and the cutting speed was controlled to maintain its uniform intensity. As the result of a simple speed control, plates with gradually varying thicknesses were cut successfully, and the amount of the attached dross was reduced substantially. For cutting plates with stepped variations in thickness, a more sophisticated control scheme is required. Different arrangements with direct feedback from the monitoring device could also be used to control one or more of the other process parameters, such as arc current, arc length and gas flow rate.

Acknowledgment

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APPLICATIONS OF GMAW

The applications of the process are related to the modes of transfer described earlier.

Applications of Dip Transfer

The typical applications of dip transfer fall into two categories:

- Thin sheet, and
- positional welding.

This process is used for joining plain carbon steel from 0.5 mm to 2.0 mm thick in the following applications:

- Automobile bodies,
- exhaust systems,
- storage tanks,
- tubular steel furniture and
- heating and ventilating ducts.

With suitable shielding gases (eg helium/ argon/ carbon dioxide) high quality welds may also be made in stainless steel sheet.

The process is applied to positional welding of thicker plain carbon and low alloy steels in the following areas.

- Oil pipelines,
- marine structures and
- earth moving equipment.

Applications of Spray Transfer

Spray transfer is suitable for downhand and horizontal vertical welds in a wide range of materials. Applications include:

- Earth moving equipment,
- structural steel (eg 'I'beams),
- pre-fabricated structures,
- weld surfacing with nickel or chromium alloys,
- aluminium cryogenic vessels, and
- military vehicles.

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Pulsed Transfer Applications

Pulsed transfer was originally introduced for improved control and positional welding of stainless steel and aluminium alloys. The range of applications has been extended by recent equipment developments to include positional welding of high strength low alloy steels and weld surfacing with Inconel.

Typical applications include:

- Aluminium boat hulls and masts,
- cryogenic vessels,
- stainless steel liners for nuclear waste storage ponds, and
- submarine hulls in quenched and tempered steel.

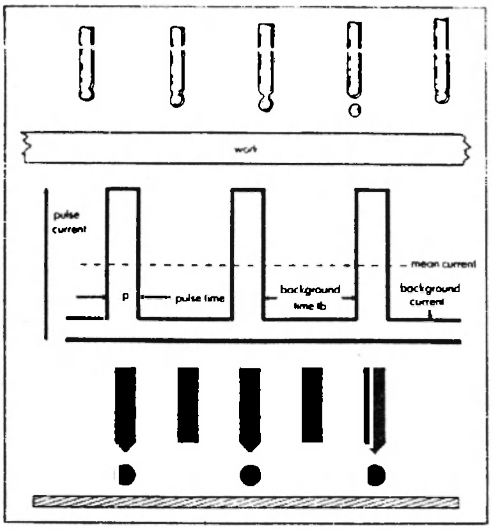

Fig. 5. *Pulse transfer. Droplets are detached during pulse.*

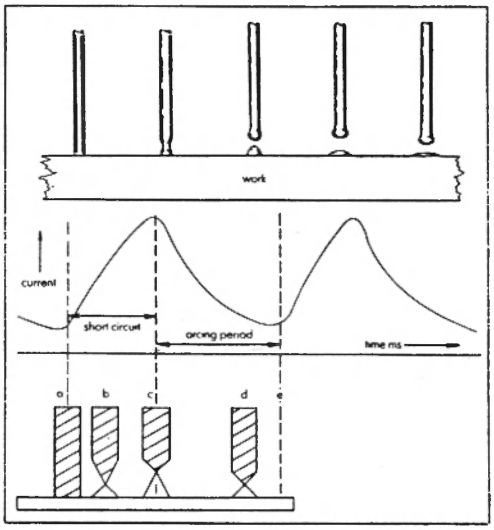

Fig. 6. *Dip transfer. The filler wire dips into the weld pool at (a) and the current rises, causing the bridge of metal to neck, as shown in (b). The short circuit ruptures at (c) and the arc is reestablished. The arc gap decreases (d) until the next short circuit occurs at (e).*

Table 1. Features of the GMAW process

Feature	Comment
Low heat input	All modes of transfer, particularly dip and pulse give low heat inputs compared to the MMA process. This is useful for thin plate and positional work but care must be taken to avoid fusion defects on thicker material.
Continuous operation	High operating efficiency High duty cycle High productivity
High deposition rate	Higher deposition rate compared to the MMA process particularly with spray transfer.
No heavy slag	The absence of slag means that little cleaning of the weld is required after welding.
Low hydrogen	Absence of flux coating and the use of dry gas controls the hydrogen level. This reduces the risk of cold cracking.