A Study on Arc Characteristics and Its Application to Height Control in Plasma Arc Cutting

The arc voltage signal is shown to be an effective characteristic for automatically controlling electrode tip-to-workpiece height

BY T. -J. LHO, D. -G. UM AND S. -J. NA

ABSTRACT. When cutting curved or thin plates, which can be easily deformed during plasma arc cutting, it is indispensable to control the motion of the torch to keep a constant electrode tip-to-workpiece distance (arc length). In this study, the characteristics of the arc were analyzed and the results were used for detecting the electrode tip-to-workpiece distance during cutting.

Analyzing the frequency power spectrum of the arc voltage signal as measured with a FFT analyzer, the first dominant frequency component was found to be 360 Hz, due to the current ripples of the rectified three-phase power source, and the second dominant frequency was 19 kHz, due to the anode spot motion. The arc voltage signal, detected from the lower peak value and filtered by the moving averaging method, increased almost linearly with the increase in electrode tip-to-workpiece distance. This arc characteristic could be effectively used to realize a reliable height control system for plasma arc cutting processes.

Introduction

Plasma arc cutting (PAC) is a process that severs a metal by melting a localized area with the heat of a constricted arc and removing the molten material with a high velocity jet of the hot, ionized plasma gas issuing from the orifice (Ref. 1). The automatic plasma arc cutting system has been widely adopted in many manufacturing fields to improve cutting productivity and to release operators from a harsh working environment.

When cutting curved or thin plates, which can be easily deformed during thermal cutting, the distance between the electrode tip and the top surface of the workpiece will be changed. In order to avoid a collision between the torch and the workpiece and to maintain good cut quality, the torch must be kept at a constant distance from the surface of the workpiece.

For the plasma arc cutting process, the plasma arc itself can play an important role in detecting the electrode tip-to-workpiece distance (arc length) during cutting. It has the advantages of requiring no extra detectors and being unaffected by the arc heat, spatter and arc light. From the viewpoint of reliability and production cost, using the arc as a sensor is suitable, especially for a high-current plasma power source.

H. Fujimura, *et al.* (Ref. 2), has developed a joint tracking system using the welding arc sensor in GMAW. H. Nomura, *et al.* (Refs. 3, 4), has developed an automatic real-time torch height control system with the welding arc sensor in GTAW and in multipass GMAW. The automatic welding systems mentioned above are now applied to many commercial arc welding robots and automatic welding setups. The cutting arc sensor, however, has been rarely used for detecting the electrode tip-to-workpiece distance in the plasma arc cutting process (Refs. 5, 6), while various joint clearance sensors such as eddy current, capacitance, pressure and tactile have been widely used.

In this study, therefore, a new measuring and processing method using the cutting arc voltage signal is proposed for sensing and controlling torch height. By applying this cutting arc sensor to a plasma arc cutting system with a rectified three-phase constant current power source, a height control system has been developed to keep a constant electrode tip-to-workpiece distance.

KEY WORDS

Plasma Arc Cutting
Arc Characteristics
Torch Control
Tip-to-Workpiece
Arc Voltage Signal
Dominant Frequency
Thin Plate
Curved Plate
Cutting Sensor
Mathematical Analysis

T. -J. LHO is a Ph.D. Candidate, D. -G. UM is a Researcher and S. -J. NA is an Associate Professor, Department of Production Engineering, Korea Advanced Institute of Science and Technology, Seoul, Korea.

Analysis of Raw Arc Voltage Signal

As shown in Fig. 1, the cutting arc sensor proposed in this study detects the distance (L_s) between the electrode tip and top surface of the workpiece by measuring the lower peak value of the cutting arc voltage (V_a) corresponding to the arc length (L_a) between the electrode tip and anode spot. Generally, the cutting arc voltage measured can be regarded as a linear function of the arc length for plasma arc cutting with a constant current power source (Ref. 7).

The power source used here has a rectified direct current (DC) output and a constant current characteristic with thyristor control, for which the main specification is shown in Table 1. The mixture of 50% argon and 50% nitrogen is undoubtedly widely used as a cutting gas for cutting low-carbon steel plates. However, since a pure argon gas was easily available, it was employed in this study for cutting experiments, because the main objective of this study was to investigate the feasibility of using the arc as a sensor based on the arc characteristics. The shielding gases that are used for cutting low-carbon steels are oxygen, carbon dioxide, air and nitrogen in descending order of the performance (Ref. 8). Compressed air at a rate of 5 kg/cm^2 was supplied for shielding and cooling in this study because of its lower cost and easy availability. The conditions of the experiments that may have some effects on the relationship between the arc characteristics and electrode tip-to-workpiece distance are shown in Table

Table 1 — Test Parameters

Power source	Output current range	40—100 A
	Used output current	70 A for 1.6 mm thickness 100 A for 6.4 mm thickness
	Rated output voltage	150 V
	Open circuit voltage	205 V
Cutting torch	Electrode material	Thoriated tungsten
	Electrode diameter	2.4 mm
	Orifice diameter	1.5 mm
	Cooling system	Air cooling type
	Flow delivery type	Tangential
	Arc type	Transferred
	Torch travel	Lead-screw carriage
Gases	Cutting gas	Ar gas 7.5 L/min.
	Shielding gas	Compressed air 5 kg/cm^2 (above 125 L/min.)
Workpiece	low-carbon steel plates with 1.6-mm and 6.4-mm thickness	

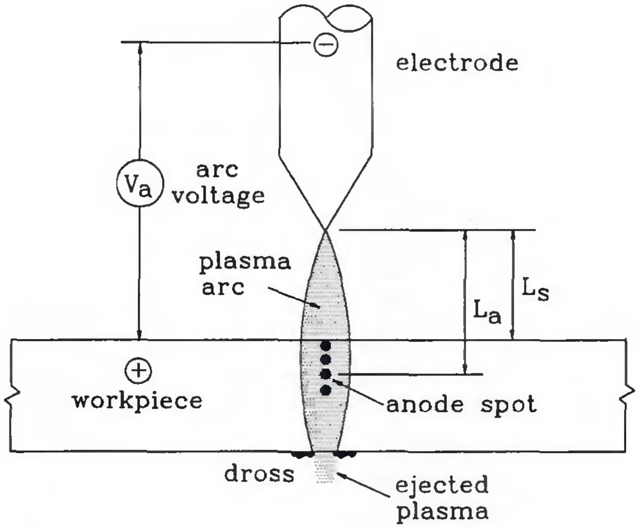

Fig. 1 — Schematic diagram showing electrode tip-to-workpiece distance measured by cutting arc voltage signal.

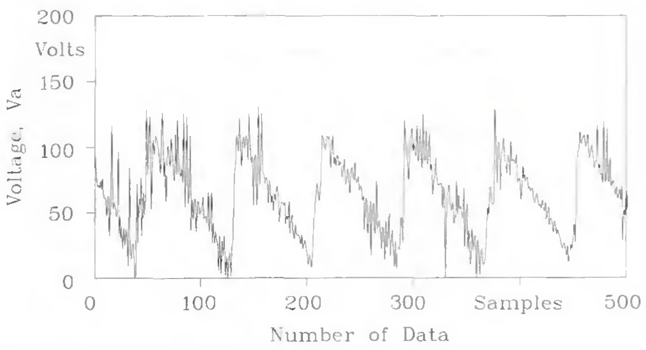

Fig. 2 — Typical waveform of arc voltage signal measured during cutting.

1. In order to establish the fundamental relationship between the cutting arc voltage and electrode tip-to-workpiece distance, the behavior of the anode spot and the arc characteristics of the power source must be first investigated for the plasma arc cutting process. The anode spot is generally defined as the portion of the positively charged workpiece within which the electrons are absorbed. The motion of anode spots during plasma arc cutting brings about the variation of the arc length, and subsequently affects the arc voltage signal measured. For plasma arc cutting, the anode spot is carried away from the upper to lower side and vice versa on the front cut surface due to the momentum of the plasma and cold surrounding gas stream, and also due to the magnetic force acting on the anode spot and plasma arc column (Ref. 9). Consequently, the anode spot periodically repeats such a motion, so that the arc voltage fluctuates in sawtooth waveforms at a frequency corresponding to the anode spot motion.

In the first part of the investigation, a typical arc voltage signal of 500 samples was measured for a sampling time of 35 μs using a data acquisition system interfaced to a microcomputer. The cutting was performed on 6.4-mm (0.25-in.) thick plate with a current of 100 A and a speed of 500 mm/min (20 in./min). The result is plotted in Fig. 2, which shows a periodic waveform of sawtooth type oscillating with a very large peak–to–peak value.

In order to analyze the frequency components of the arc voltage signal measured above, the discrete Fourier transformation of the sampled arc voltage signals, $X_i(f_m)$, was defined at the i-th averaging segment as follows (Ref. 10).

$$X_i(f_m) = \Delta t \sum_{k=0}^{N-1} x_i(k\Delta t) \cdot \exp(-j2\pi f_m k\Delta t)$$

where, f_m (= m / NΔt for m = 0, 1, ..., N – 1) is the frequency, t the time, N the number of samples, Δt the sampling time and $x_i(k\Delta t)$ the arc voltage sampled at t = kΔt for the i-th averaging segment. The one-sided power density function (PDF) $G_{xx}(f_m)$ of the signal can be then introduced and described as follows (Ref. 10).

$$G_{xx}(f_m) = \frac{2}{n_a N \Delta t} \sum_{i=1}^{n_a} x_i^*(f_m) \cdot X_i(f_m)$$

$$m = 0, 1, \ldots, \frac{N}{2}$$

where $X_i^*(f_m)$ is the conjugate complex of $X_i(f_m)$ and n_a the number of averaging.

Figure 3 shows the frequency power spectrum of the measured arc voltage signal after $n_a = 30$ averages with the FFT (Fast Fourier Transformation) analyzer. The cutting conditions were the same as above, and Δt-35 µs, N = 500, f_{max} = 50 kHz and $G^{max}{}_{xx}$ = 600 mV^2. The signal shown in Fig. 3 was averaged 30 times to eliminate the noise component from the measured raw arc voltage signal. The frequency power spectrum of the arc signal is shown again in Fig. 4 after zooming that of Fig. 3 up to the frequency of 2 kHz. The dominant frequency component is 360 Hz and its multiples. This is due mainly to the 360 Hz ripples of the direct current (DC) output of the power source used, because the alternating current (AC) output from a transformer is fed to a full-wave rectifier, which converts it to DC. Since the 60 Hz three-phase AC was used for the input of the plasma arc power source, the DC output should have 360 Hz ripples. As indicated in Fig. 5, a small fluctuation of the arc current (*i.e.*, ripples of DC output) gives rise to a large variation of the arc voltage in the constant current power source of this plasma arc cutting machine.

The variation of the cutting arc voltage filtered by a low-pass filter with a cut-off frequency of 1 kHz is shown in Fig. 6. Compared to the waveform of Fig. 2, the signal component of a small oscillation and high frequency was almost completely excluded. Moreover, it can be also seen that the values of the lower peak are more stable than those of the upper peak. This is probably due to the fact that the dross adherence on the lower part of the cutting surface is not uniform during cutting.

By increasing the frequency power spectrum of Fig. 3 up to the maximum power spectrum of $G^{max}{}_{xx}$ = 6.16 mV^2, it can be seen that the power also has a

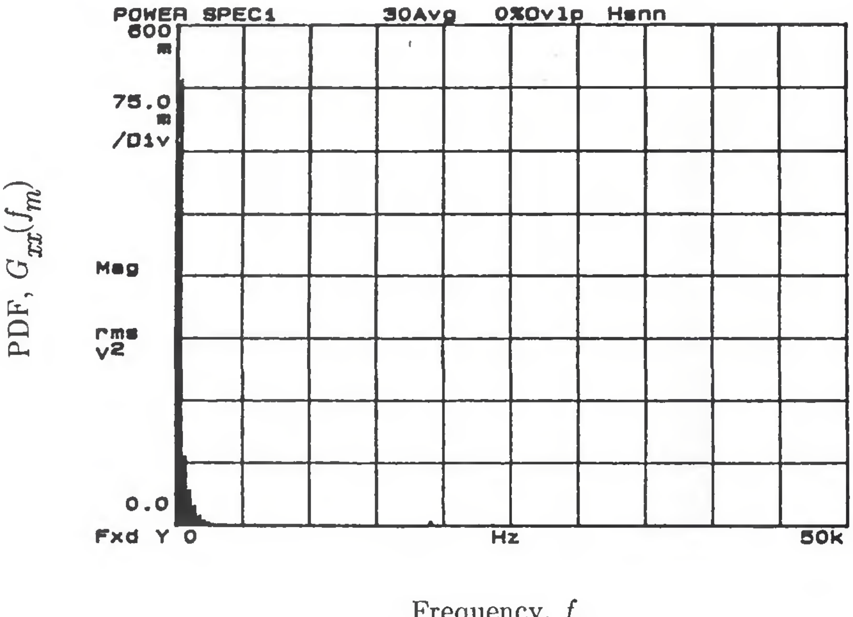

Fig. 3 — Frequency power spectrum of cutting arc voltage signal (n_a = 30, Δt = 35 µs, N = 500, f_{max} = 50 kHz and $G^{max}{}_{xx}$ = 600 mV^2).

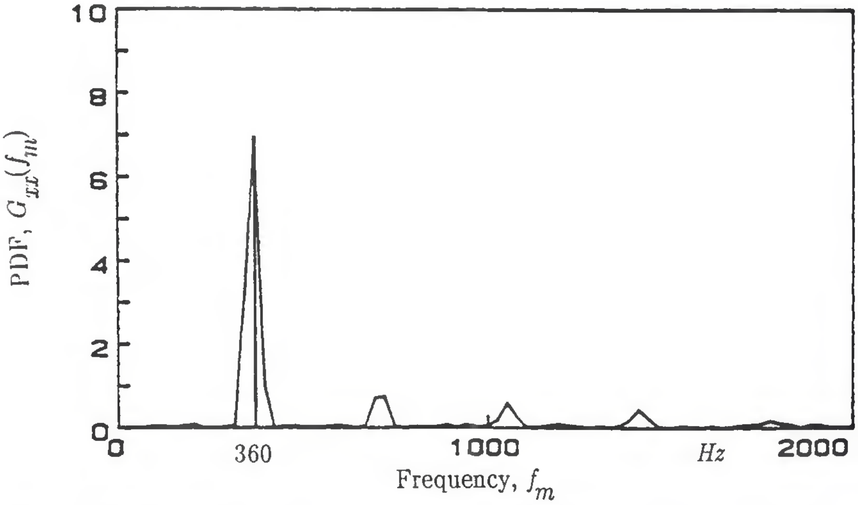

Fig. 4 — The frequency power spectrum of the arc voltage signal of Fig. 3 (f_{max} = 2 kHz).

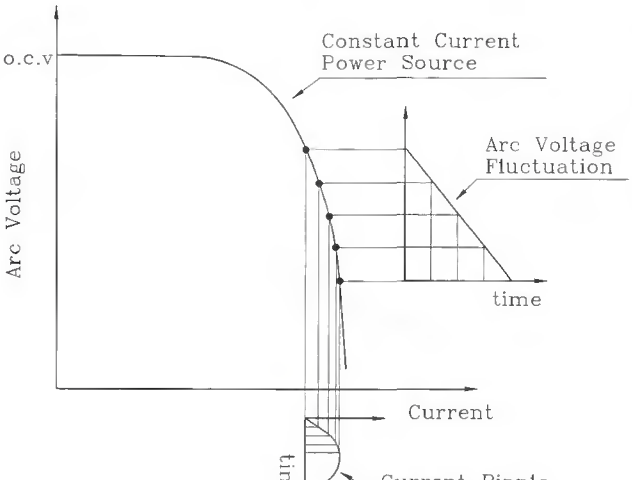

Fig. 5 — Fluctuation of arc voltage according to cutting current ripples of a power source with constant current characteristics.

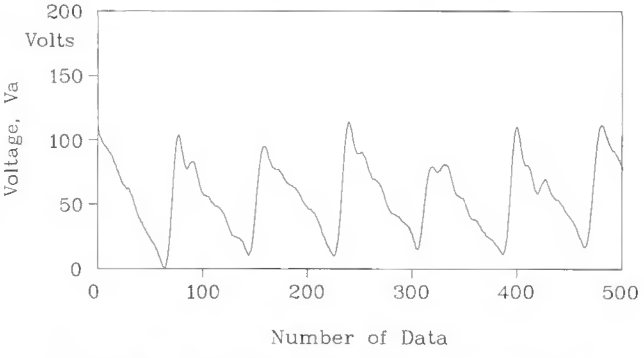

Fig. 6 — Waveform of cutting arc voltage processed by a low-pass filter with a cut-off frequency of 1 kHz.

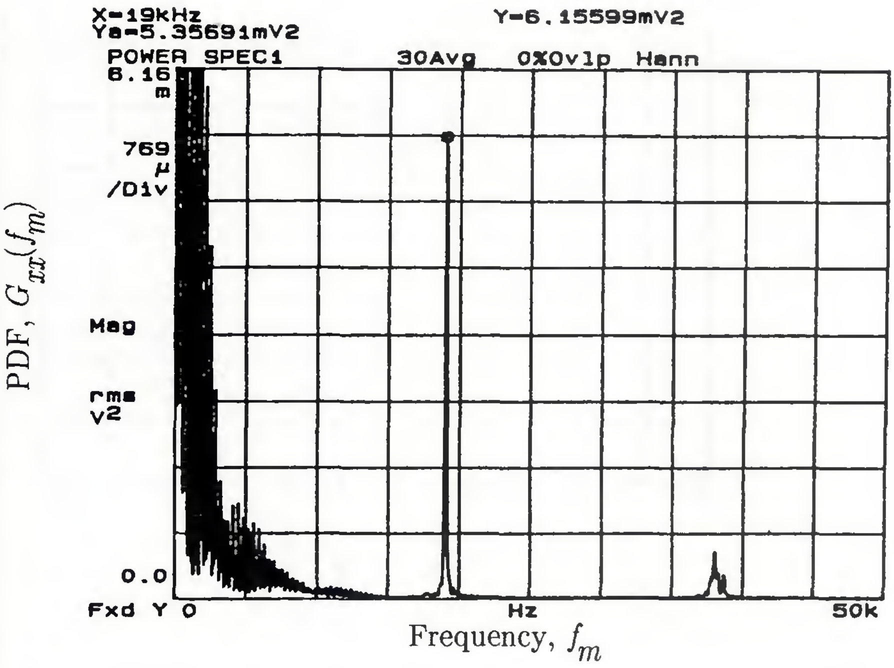

Fig. 7 — Frequency power spectrum of arc voltage signal of Fig. 3 for G^{max}_{xx} = 6.16 mV² (na = 30, Δt = 35 µs, N = 500 and f_{max} = 50 kHz).

small frequency intensity peak value at about 19 kHz, as shown in Fig. 7. This frequency is considered to be the dominant frequency of the anode spot motion, which is nearly consistent with the previous observation that the arc voltage signal fluctuates in sawtooth waves at about 20 kHz in plasma arc cutting (Ref. 9). This kind of anode spot motion results in a small oscillation of the arc voltage signal, which is combined with the 360 Hz ripples of the rectified three-phase power source — Fig. 3. Consequently the anode spot is considered to oscillate in a small amplitude at about 19 kHz, while the path of the anode spot motion moves on the cutting surface at 360 Hz.

When the anode spot is on the upper surface of the cutting zone, which corresponds to the condition of the bottom of the output current, the cutting arc voltage should become a lower peak value due to the shortest arc length. In order to identify the distance between the electrode tip and top surface of the workpiece during cutting, it is reasonable to measure the lower peak value of the arc voltage signal. Moreover, from the view point of signal stability, the lower peak value is very suitable as a process control parameter. Thus, the electrode tip-to-workpiece distance could be determined by detecting the lower peak value of the arc voltage signal sampled in a sampling time longer than ¹⁄₃₆₀ s, which is related to the 360 Hz ripples of the power source.

Real-Time Signal Processing and Height Control

Figure 8 represents the variation of the raw arc voltage signal measured for the linearly varying electrode tip-to-workpiece distance under the cutting current of 100 A and cutting velocity of 50 mm/min (2 in./min). It can be seen that the arc voltage signal represents considerably high peak-to-peak values, while its averaged value rises with the increasing electrode-to-workpiece distance of 2 to 10 mm (0.08 to 0.4 in.). As indicated in this figure, however, it is very difficult to directly use the raw arc voltage signal for detecting the electrode tip-to-workpiece distance without any special processing of the signal because the fluctuation (*i.e.*, peak-to-peak value) of the signal is too large.

Figure 9 shows the result of plotting the lower peak value $x_p(i)$ of the raw signals $x_i(k\Delta t)$ sampled with Δt = 40 µs and N = 1000 in the i-th peak detecting period from $t = (i-1)T_p$ to $t = iT_p$, T_p = 40 ms, where the cutting condition was the same as above. This output signal was processed using a lower peak detecting method, which detects the lower peak value through the use of a software program. As shown in Fig. 9, however, it is also difficult to directly use the lower peak signals for detecting the electrode tip-to-workpiece distance, because the signal is somewhat unstable and its peak-to-peak value is still too large.

The output signal $V_m(i)$ of a moving averaging filter (Ref. 11) at time $t = iT_p$ can be defined as follows:

$$V_m(i) = (1-\frac{1}{w})V_m(i-1) + \frac{1}{w}x_p(i)$$
$$i = 1,\ 2, \ldots,\ n$$

where $V_m(i-1)$ is the moving averaged voltage signal at $t = (i-1)T_p$, n the number of moving averaging segments, and w the weighting factor. The output waveform of the signal shown in Fig. 9 from

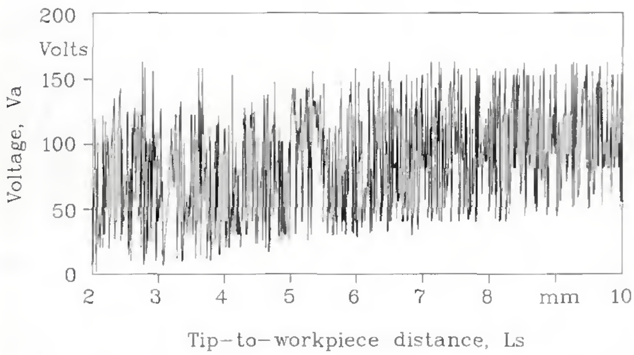

Fig. 8 — Variation of raw arc voltage signal for a linearly varying electrode tip-to-workpiece distance.

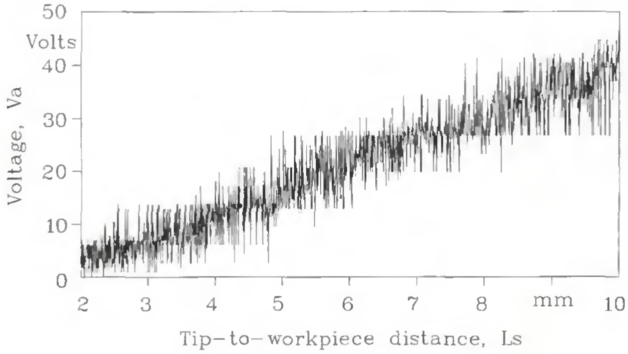

Fig. 9 — Lower peak values of sampled raw arc voltage for linearly varying electrode tip-to-workpiece distance (Δt = 40 µs, N = 1000, Tp = 40 ms).

the moving averaging filter with w = 3, T_p = 40 ms was plotted in Fig. 10. As shown in the figure, the arc voltage signal rises almost linearly with the increasing electrode tip-to-workpiece distance from 2 to 10 mm, which can be used to realize a height control system for keeping a constant electrode tip-to-workpiece distance during cutting. The signal processing procedure, such as the lower peak detecting and moving averaging, is presented concisely in the flowchart of Fig. 11.

Figure 12A and B show the appearance of the resultant cuts of the curved plates manufactured by using a CNC plasma arc cutting system equipped with the developed height control system. It can be demonstrated that the cutting arc voltage signal effectively controls the electrode tip-to-workpiece distance in real time.

Conclusions

Based on the lower peak detecting and moving averaging method, the arc voltage signal was processed from the measured raw values to control the electrode tip-to-workpiece distance during plasma arc cutting. The conclusions can be summarized as follows:

1) Analyzing the frequency power spectrum of the cutting arc voltage signal measured with a FFT analyzer, the first dominant frequency component was found to be 360 Hz, due to the ripples of the rectified three-phase cutting power source used, and the second dominant frequency was found to be 19 kHz, due to the anode spot motion.

2) The distance between the electrode tip and top surface of the workpiece can be determined by detecting the lower peak value caused by the anode spot motion on the upper part of the cut surface, where the sampling time should be longer than 1/360 s.

3) The arc voltage signal detected from the lower peak value and filtered by using the moving averaging method rises almost linearly when increasing electrode distance from 2 to 10 mm. This voltage signal can be effectively used to

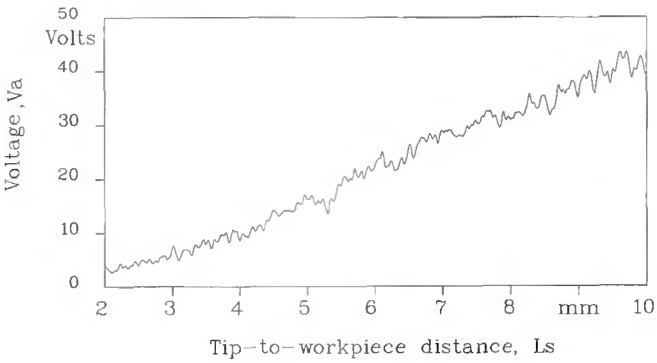

Fig. 10 — Output waveform processed from arc voltage of Fig. 9 by using moving averaging filter with w = 3.

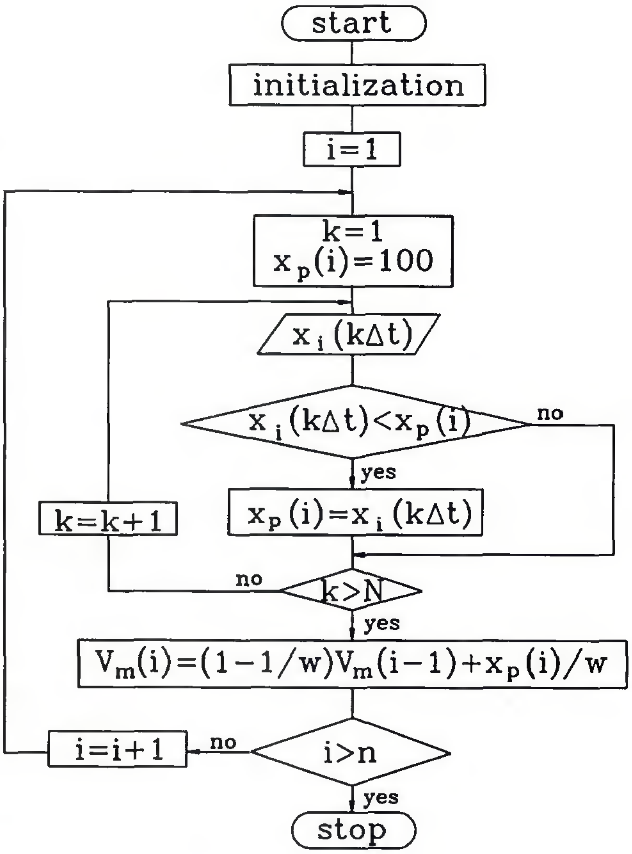

Fig. 11 — Flowchart of signal processing procedure of lower peak detecting and moving averaging method.

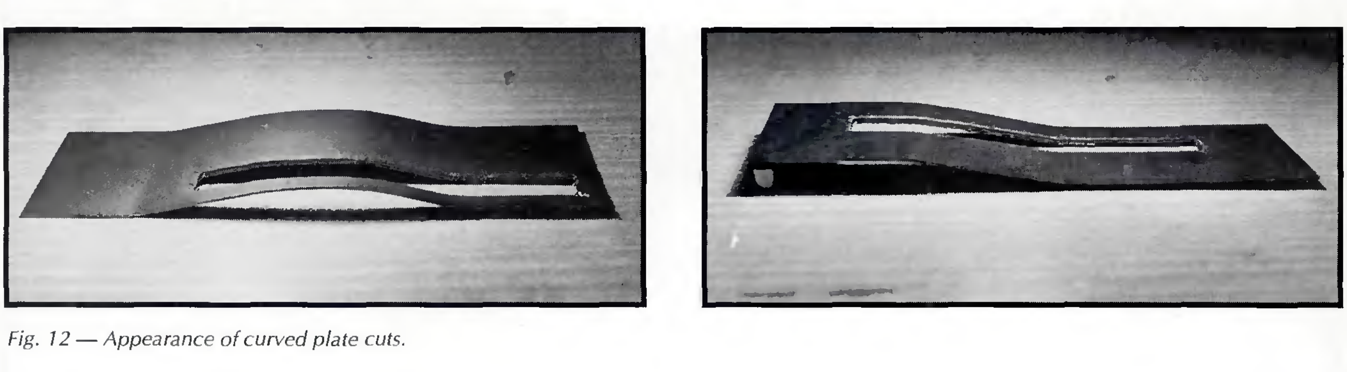

Fig. 12 — Appearance of curved plate cuts.

keep a constant electrode tip-to-workpiece distance during plasma arc cutting, resulting in good cut quality on curved or thin plates, which easily deform during plasma arc cutting.

References

1. *Recommended Practices for Plasma Arc Cutting* C5.2-83, pp. 1–5. 1983. American Welding Society.

2. Fujimura, H., Ide, E., and Inoue, H. 1987. Joint tracking control sensor of GMAW. *Trans. of JWS*, Vol. 18, No. 1, pp. 32–40.

3. Nomura, H., Sugitani, Y., and Tamaoki, N. 1987. Automatic real-time bead height control with arc sensor in TIG welding. *Trans. of JWS*, Vol. 18, No. 2, pp. 35–42.

4. ibid. pp. 43–50.

5. Boehme, J., Odrich, D., Wenzel, B. D., and Jagieniak, P. 1984. Plasma torch standoff distance control for precision control of plasma cutting (patent). *WPI* 85-0322306/06.

6. Frohlich, H., Berger, A., Roloff, H. J., and Telzer, H. J. 1985. Automatic nozzle stand-off distance control for plasma arc cutting torch (patent). *WPI* 85-249671/41.

7. Cook, G. E. 1983. Robotic arc welding: research in sensory feedback control. IEEE, *Trans. of Industrial Electronics*, Vol. IE-3, No. 3, pp. 252–268.

8. Severance, W. S., and Anderson, D. G. 1984. How plasma arc cutting gases affect productivity. *Welding Journal* 57(2) 35–39.

9. Nishiguchi, K., et al. 1972. Fundamental studies on cutting phenomena in plasma arc cutting (1st Report). *Quarterly J. of JWS*, Vol. 41, No. 7, pp. 781–791.

10. Bendat, J. S., and Piersol, A. G. 1986. *Random Data (Analysis and Measurement Procedures)*. John Wiley and Sons, pp. 361–422.

11. Braun, S. 1986. *Mechanical Signature Analysis (Theory and Applications)*. Academic Press, pp. 141–171.