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Arc Efficiency of Plasma Arc Welding

An examination is made of the mechanisms that depend on current and voltage for arc to workpiece power transfer

BY D. M. EVANS, D. HUANG, J. C. McCLURE AND A. C. NUNES

ABSTRACT. Arc efficiency was measured for variable polarity plasma arc welds on 6061 aluminum. It was found to vary from 0.48 to 0.66 and increased with arc voltage but decreased with arc current. The current and voltage dependence of the various mechanisms for heat transfer from the arc to a workpiece are critically examined.

Calculations show that radiation from the optically thin arc contributes little to the transferred energy, but that heating of the shield gas by convection from the arc gas is a significant component of workpiece heating. Experimental values are compared to theory and show approximate agreement.

Introduction

The pool size is perhaps the most basic consideration for a welding engineer in selecting an appropriate weld schedule. The type of joint, the size and thermophysical properties of the workpiece, the available power and the welding process are considered in deciding welding parameters.

Pool size depends on the arc efficiency and melting efficiency. Arc efficiency is defined as

$$\eta_a = \frac{H_{WP}}{P_a}$$

where

H_{WP} = heat absorbed in the workpiece/unit time

P_a = power in the arc

Arc efficiency is measured calorimetrically, which requires special equipment and is not usually done. Arc efficiencies of 50 to 70% are commonly encountered in arc welding, but can range higher for such efficient processes as submerged arc welding (Ref. 1).

Melting efficiency, η_m, is the fraction of the heat delivered to the workpiece that actually melts material:

$$\eta_m = \frac{E_m}{E_{wp}}$$

where

E_m = Energy used for melting the fusion zone.

E_{wp} = Total energy transferred to the workpiece.

Melting efficiency, which has received considerable attention (Refs. 1–5), depends on such material properties as melting enthalpy and thermal diffusivity, as well as part thickness, welding speed and welding power.

The purpose of this paper is to examine the ways in which energy is transferred from the arc to the workpiece and to determine how changes in current and voltage affect these heat transfer mechanisms for the case of plasma arc welding. Theory will be compared with experiment.

KEY WORDS

Arc Efficiency
Radiation
Plasma Arc Welding
Voltage
Current
Heat Transfer Mechanism
Workpiece Heating

Experimental Procedure

Uphill bead-on-plate welds were made with a Hobart Brothers VP-300-s plasma arc welding machine on 6.3 mm (0.25 in.) thick 6061 aluminum. Each sample was cleaned with a commercial aluminum cleaner (Aluminate) prior to welding. The torch, from B&B Machining in Owens Cross Roads, Ala., was mounted on a Bug-O torch tractor Model 122168 that was carefully aligned with the workpiece. The plasma gas restriction orifice is 3.2 mm (1/8 in.) and the shield gas cup has a 19 mm (3/4 in.) diameter opening. Gas flow velocities were measured with Omega electronic flow meters. Typical welding conditions are shown in Table 1. Welds were made with a 19 m/s forward cycle and 4 m/s reverse

D. M. EVANS, D. HUANG and J. C. McCLURE are with the University of Texas at El Paso, Metallurgical and Materials Engineering Department. A. C. NUNES is with NASA, Marshall Space Flight Center, Huntsville, Ala.

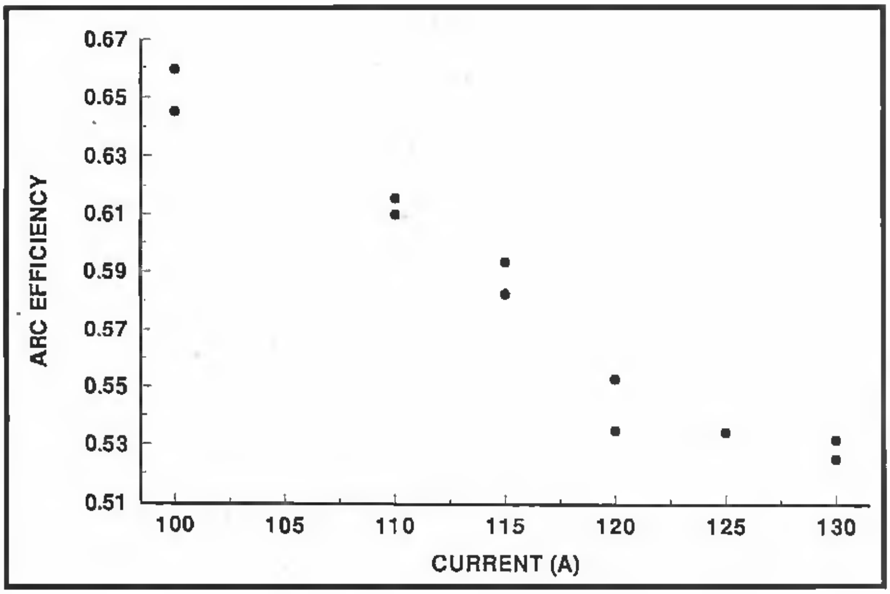

Fig. 1 — Arc efficiency vs. current. Voltage is 26 V.

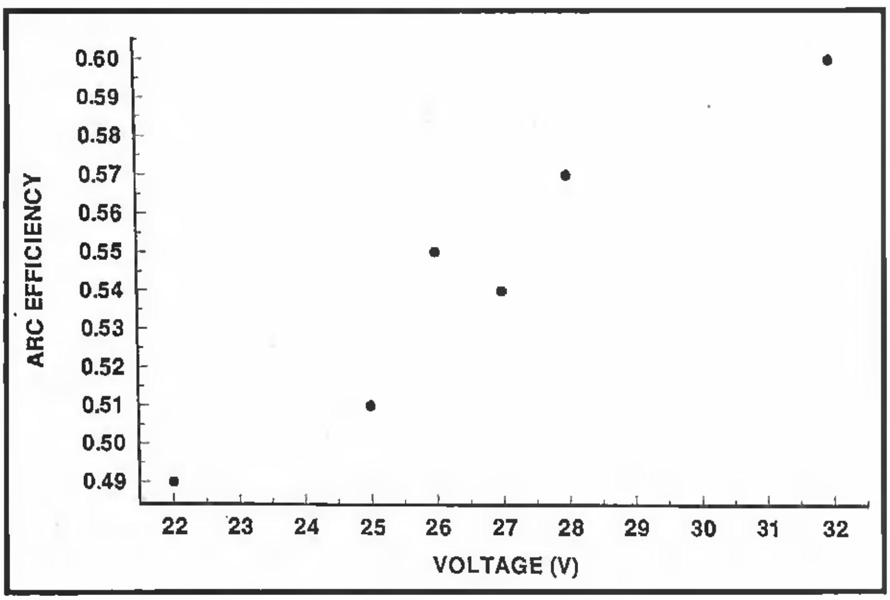

Fig. 2 — Arc efficiency vs. voltage. Current is 110 A.

cycle. A 3.2-mm (⅛-in.) 1% thoriated tungsten electrode that was ground flat was used.

Voltages were measured on a Tektronix storage oscilloscope. Voltages referred to in this paper are the DCEN voltage, and the DCEP voltage is 30% greater. Currents were measured with a shunt in the ground lead. Power was calculated from the measured current and voltage. Voltage measurements were made at the welding machine before the welding cable where it is assumed the losses at these modest currents are negligible.

Arc efficiency was determined by measuring the amount of retained heat in the workpiece after welding and dividing by the energy input from the welding machine as determined by the current, voltage and weld time. The workpiece was insulated from a quick release fixture with thermal insulating strips. After welding a few centimeters, the workpiece was quickly placed into a calorimeter and the retained heat measured after the temperature of the water in the calorimeter stabilized (about 2 min). Typical specimens were 18 x 10 x 0.635 cm (7 x 4 x 0.25 in.) and temperature increases in the calorimeter of 26°C were observed. In similar experiments, Dupont (Ref. 1) estimates that less than 1% of the heat is lost through convection prior to putting the part in the calorimeter.

Table 1 — Typical Welding Conditions

Plate thickness (mm)	Current (A)	Voltage (V)	Travel Speed (mm/s)	Plasma Flow Rate (Argon) (L/min)	Shield Flow Rate (Helium) (L/min)
6.35	90–135	22–32	3.0	0.94	19.0

Results and Discussion

Arc efficiency as a function of current and voltage is shown in Figs. 1 and 2. A decrease is seen with current while an increase is observed with voltage. This implies that the energy input to the workpiece decreases less rapidly than the current and more rapidly than the voltage. Typical values were 55%. Dupont observed plasma arc welding (PAW) arc efficiencies of approximately 45% and a decrease with current (Ref. 1). The difference may be accounted for by the large currents and heavy nozzle used that absorbed arc power. Fuerschbach (Ref. 5) and coworkers found arc efficiencies of 50 to 60% for plasma welds with a range of duty cycles. A gradual decrease in efficiency was noted at low duty cycles where currents were increased to keep a constant average power.

In a classic paper on arc efficiency, Metcalfe and Quigley (Ref. 6) separate weld power transferred to the workpiece into 1) P_R, the power transferred by radiation; 2) P_A, the power transferred by anode effects, including electron thermal energy, anode fall energy and the heat of electron condensation (electron work function); and 3) P_{CV}, the power transferred by hot gas convection. None of these mechanisms have a voltage (arc length) dependence even though weld power is generally thought of as current times voltage. The total power transferred to the workpiece, P_{Tot}, becomes the sum of these various components:

$$P_{Tot} = P_R + P_{CV} + P_A$$

We will discuss each of these three mechanisms of power transfer separately and estimate how they vary with arc current and arc voltage. In particular, it will be shown that the power transferred due to radiation is much less significant than thought previously, and convection from the shield gas is a previously unrecognized means of heat transfer that can account for the voltage dependence of arc efficiency.

Radiation

Considerable insight can be gained into the arc energy balance from Fig. 3, which shows arc voltage as a function of arc length. Using Ohm's Law

$$V=IR$$

and

$$\frac{dV}{dl}=I\frac{dR}{dl}$$

where

V = arc voltage

l = arc length

R = arc resistance

I = arc current (constant in Fig. 3)

Since dV/dl is constant (1.9 V/mm) in Fig. 3, the arc resistance is constant with changes in arc length or voltage. Since Fig. 3 was made with a current of 110 A, we note that, for these conditions, the power needed to produce 1 mm of arc is 209 W (1.9 V/mm X 110 A).

A constant arc resistance implies that average arc temperature also is constant since the resistance of a plasma varies as $T^{3/2}$ (Ref. 7) and a change in temperature would have been evident as a change of slope in Fig. 3.

Part of this 209 W/mm is carried off from the arc by radiation. It is important not to use a black-body approximation for the arc since it is optically thin and is both a poor absorber and poor radiator. If Bremstrahlung radiation dominates, the power radiated by an optically thin arc may be estimated from (Ref. 8)

$$P_R=5.35 \times 10^{-31} n_e \Sigma(n_i Z^2) T_e^{1/2}$$

where

P_R = radiated power in W/cm³

n_e = number density of electrons (cm⁻³)

n_i = number density of ions (cm⁻³)

Z = ion charge

T_e = Temperature of electrons (kilo-electron volts)

The summation is over ionization states.

Although arc temperature varies from electrode to workpiece, let us assume a singly ionized plasma at a temperature of 12,750 K, which corresponds to a 110-A arc and an electron and ion concentration of 1.1×10^{17} cm^{-3} (Ref. 9) and a 0.3-cm-diameter arc. The total power radiated would be 5.3 W/mm of arc.

The amount of power radiated is probably better determined by using the experimentally measured radiation data for an argon arc (Ref. 10), which includes power from both Bremstrahlung and characteristic radiation. From these measurements the total power radiated is 52 W/mm at 12,750 K. Thus it seems that radiation only can account for about 25% of the energy needed to create an extra mm of arc or increase the arc voltage by 1.9 V.

Let us estimate how much of this 52 W is radiated into the weld pool when the voltage is changed by 1.9 V. The portion of the arc between the torch and the surface of the workpiece radiates power in all directions and only a fraction of this radiation enters the solid angle subtended by the weld pool. This power is

$$dP=\eta P_o \frac{\pi R^2}{4\pi x^2}dx$$

where

dP = increment of power

R = radius of melt pool

x = distance from melt pool

η = emissivity of workpiece [0.1 for Al (Ref. 11)]

P_o = radiated power per unit length of arc.

For example, when the arc length changes from 6 to 7 mm, the voltage will change by 1.9 V and for a 6-mm-diame-

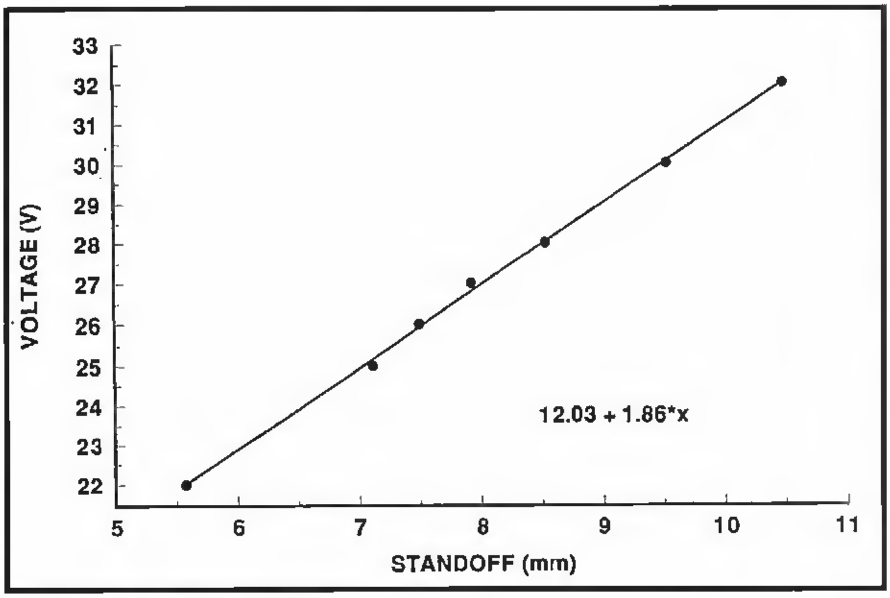

Fig. 3 — Voltage vs. standoff. Current is 110 A. Note that the linear relationship implies a constant arc temperature.

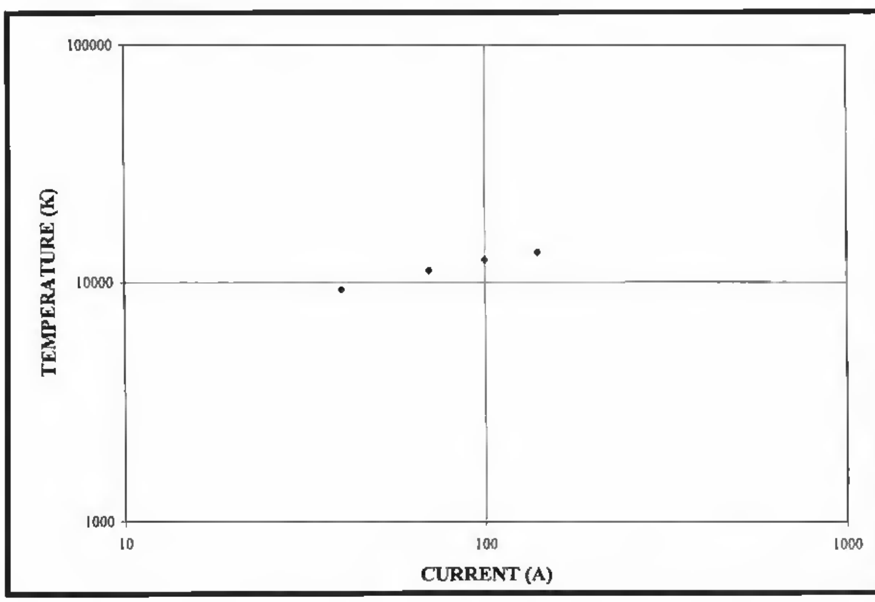

Fig. 4 — Temperature measured by optical spectroscopy vs. current from Pang (Ref. 12). Slope of regression line is 0.285.

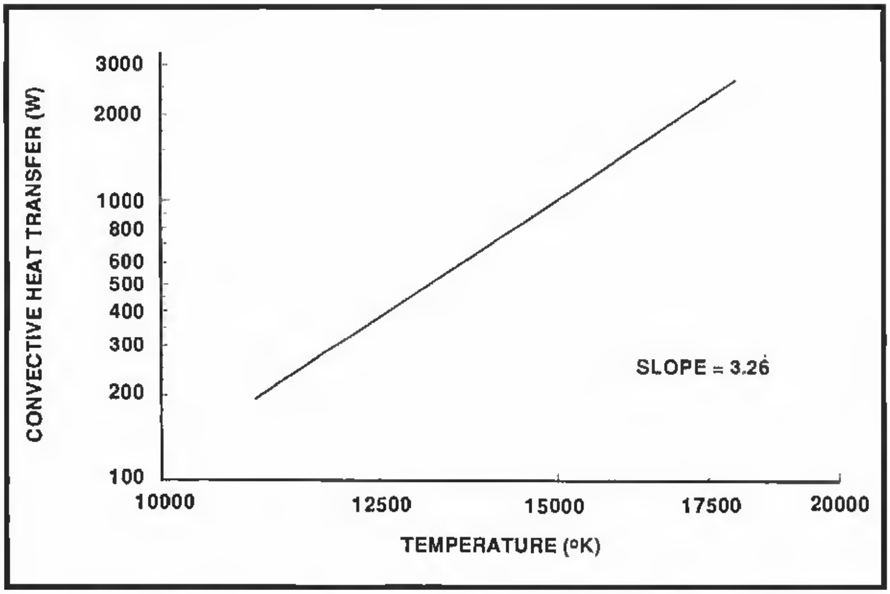

Fig. 5 — Calculated convective heat transfer from the plasma gas vs. temperature.

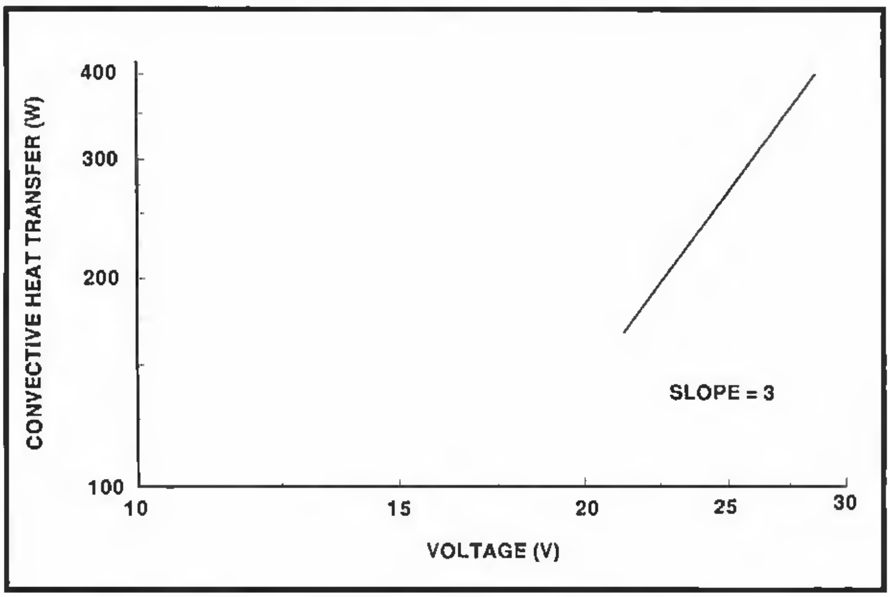

Fig. 6 — Calculated convective heat transfer from the shield gas vs. voltage.

ter melt pool. The increment in radiated power that reaches the workpiece is only 0.32 W and can be ignored.

Convection

Convective heat transfer certainly depends on the temperature of the arc, which in turn depends on the current (but not the voltage as discussed above). To determine how arc temperature depends on current, Fig. 4 from Pang (Ref. 12) shows arc temperature measured by optical spectroscopy vs. arc current. As expected, the temperature of the arc rises with current and varies as

$$T \propto I^{0.3} \qquad (1)$$

There are two sources of convective heat transfer to the workpiece: 1) the plasma gas, P_{CVpg}; and 2) the shield gas, P_{CVsg}. Calculation of heat transfer from a vertically impinging jet of hot gas is not straightforward and depends on the Prandtl and Reynolds numbers of the gas. These numbers in turn depend on temperature-dependent properties of the gas. Following the analysis by Metcalfe and Quigley (Ref. 6), Fig. 5 shows calculated heat transfer from the plasma gas. The welding conditions of Table 1 were used for this calculation and details can be found in Evans (Ref. 13). It is seen that

$$P_{CVpg} \propto T^{3.2}$$

and since $T \propto I^{0.3}$ from Equation 1

$$P_{CVpg} \propto I^{0.9} \qquad (2)$$

and is independent of voltage.

As mentioned in the previous section, radiation losses can only account for about 25% of the energy needed to create an arc. The balance of this heat must be removed from the arc and neither anode effects nor convection from the plasma gas are voltage dependent. This heat, therefore, must be convected away from the arc by the shield gas that surrounds the plasma stream. The simplest assumption is that all of this heat raises the temperature of the shield gas, which in turn impinges on the weld pool and transfers heat to the workpiece. Moreover, this heat is voltage dependent since a longer high voltage arc is in contact with the surrounding shield gas longer.

Following Ref. 6, another jet impingement calculation was performed for the shield gas using gas property data from Ref. 14. Details can be found in Evans (Ref. 13). Figure 6 shows the calculated convective heat transfer from the shield gas vs. voltage for a 12,750 K (110 A) arc and

$$P_{CVsg} \propto V^3 \qquad (3)$$

is obtained.

Recalling that the plasma gas temperature is current dependent (Equation 1), the shield gas temperature, which is in contact with the plasma gas, also will have a current dependence. Assuming that the shield gas temperature is proportional to the plasma gas temperature, calculations (Ref. 13) show that

$$P_{CVsg} \propto T^{1.9}$$

or (using Equation1)

$$P_{CVsg} \propto I00^{.57} \qquad (4)$$

Combining the voltage (Equation 3) and the current (Equation 4) dependence of the convective heat transfer due to the shield gas:

$$P_{cvsg} \propto I00^{.37} V^3 \qquad (5)$$

Anode Effects

The third mode of power transfer from the arc to the workpiece consists of various anode effects such as the kinetic energy of the electrons, the anode fall voltage and the condensation energy (work function) of the electrons.

Work function is a material property and is not a function of arc voltage or current. Although the work function is certainly dependent on surface contamination within the weld pool, we will use the value for pure aluminum, 4.2 eV (Ref. 15).

Anode fall voltage is difficult to measure since it takes place in approximately an electron mean free path (1 micron) of the anode. Anode fall voltage can be calculated under various assumptions (Ref. 16), but is not thought to be a function of arc voltage. Anode plus cathode fall voltage is sometimes estimated by extrapolating a graph of voltage vs. standoff (such as Fig. 3) to zero standoff. This probably overestimates the actual electrode falls since thermal boundary layers may exist outside of the true electrode fall regions and the arc voltage may change in these regions without actually contributing to the energy of the electrons when they enter the workpiece (Ref.17). Nevertheless, Fig. 3 shows a constant voltage vs. standoff slope suggesting a constant electrode fall voltage. Let us assume an anode fall of 1.0 V (Ref. 6).

The power transferred due to the electron work function and the anode fall voltage are proportional to the first power of current and are grouped together as P_A:

$$P_A \propto I \qquad (6)$$

The average kinetic energy of the electrons is a function of the arc temperature and hence arc current.

Energy/electron =3/2 kT
or (using Equation 1) =(3/2)k $I^{0.3}$

where k=Boltzmann's constant. The power transferred by the electron thermal energy is proportional to the current and to the energy/electron. Thus the power transferred due to electron thermal energy varies according to

$$P_{ET} \propto I^{1.3} \qquad (7)$$

with no voltage dependence.

Combining the various components of heat transfer gives the following relationship:

$$P_{tot} = P_{CVpg}+P_{CVsg}+P_A+P_{ET}$$
$$P_{tot}=A_1 I^{0.9}V^0+A_2 I^{0.6}V^3+A_3 I^1 V^0+A_4 I^{1.3}V^0$$

where A_1, A_2, A_3 and A_4 are independent of current and voltage and are calculated from Equations 2, 5, 6 and 7 for a 26-V/110-A arc. They are found to be 6.6, 0.001, 5.3 and 0.26, respectively, with power in watts, current in amperes, and voltage in volts. Figure 7 shows the various heat flows and their current and voltage dependencies.

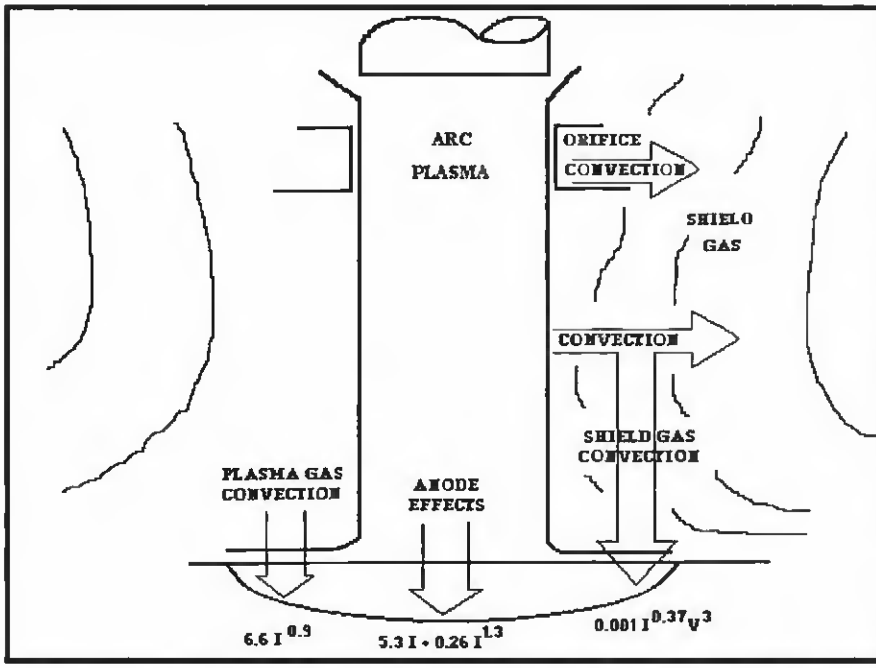

Fig. 7 — Dominant heat transfer mechanisms to weld pool. Estimated quantitative values in watts for the heat transfer are entered below arrows. Current is in amperes and voltage in volts. Convection to the orifice, which also plays a role in arc efficiency determination, is shown but was not calculated here.

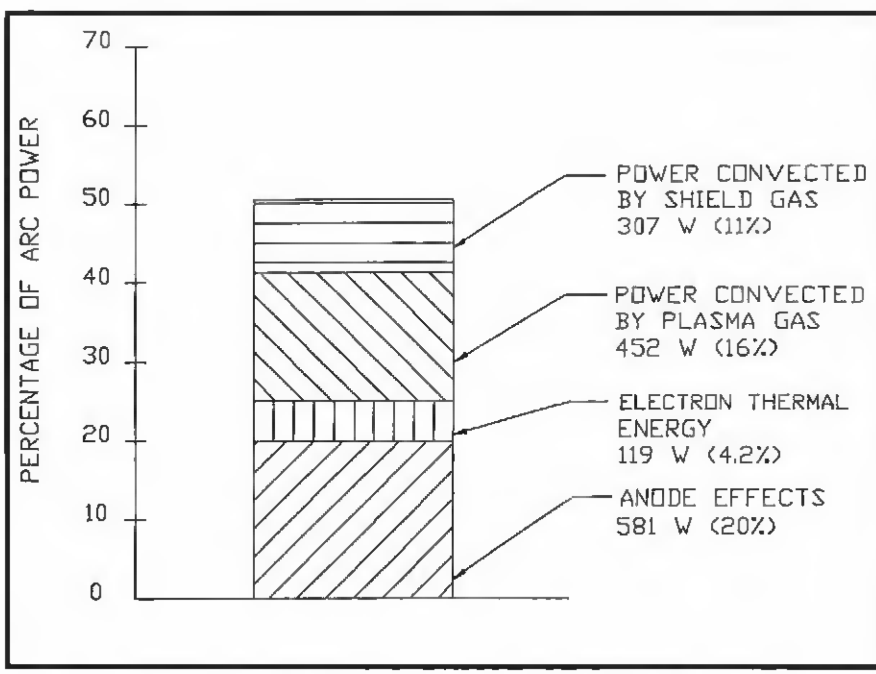

Fig. 8 — The various components of power delivered to the workpiece for a 110-A/26-V arc.

Figure 8 shows how the various components of power combine to make the total power into the workpiece for a 26-V/110-A arc. Quigley (Ref. 6) made a similar calculation, but used a black-body approximation for the arc radiation and neglected convection from the shield gas. Graphs of measured power into the workpiece vs. current and voltage are shown in Figs. 9 and 10. The calculated values are included on the graphs for comparison, but note that no fitting parameters were used in the calculations. The calculated value of the arc efficiency agrees reasonably well with the observed

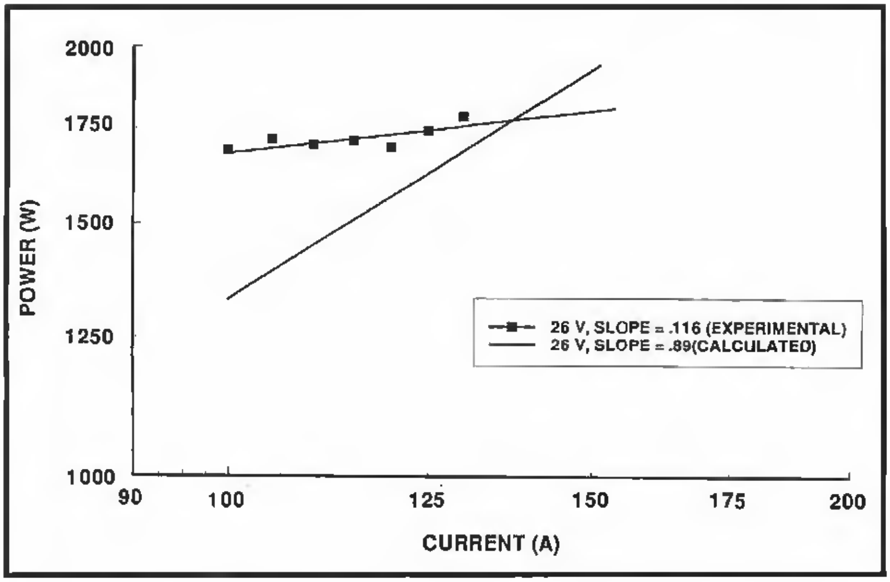

Fig. 9 — Power delivered to the workpiece vs. current for a 26-V arc.

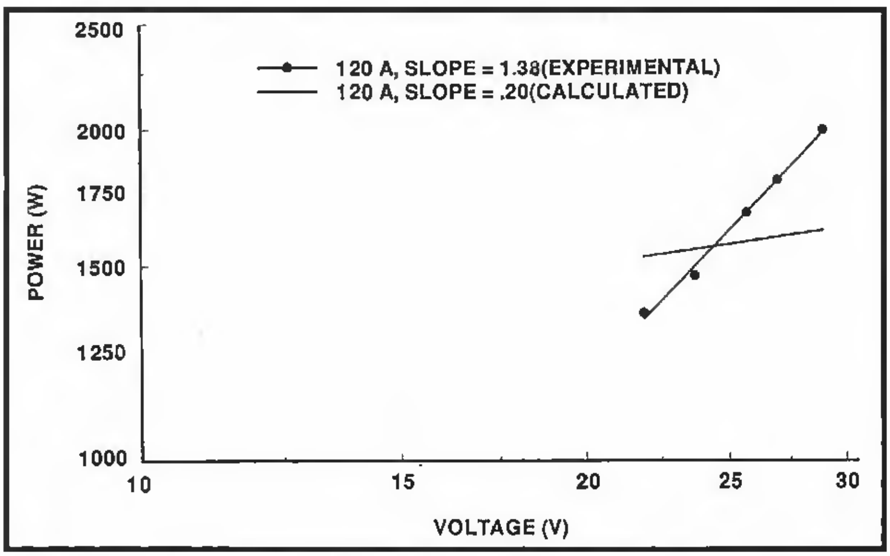

Figure 10 — Power delivered to the workpiece vs. voltage for a 120-A arc.

data, but the changes with current and voltage differ. At least some of the difference can be accounted for by the neglect of heat absorption in the constricted nozzle (Ref. 5) of the plasma torch. At higher current, a hotter and wider arc is expected to cause more heat to be lost. The only voltage-dependent heat transfer term is the convection from the shield gas, so errors in the voltage dependence must lie in the assumptions behind that calculation. In particular, the separate jet impingement calculations that were made for the plasma gas and shield gas may be in error. There is some interaction between the extremely hot plasma gas after it strikes the workpiece while flowing away from the weld pool and the coaxial stream of shield gas that also strikes the workpiece and delivers heat. How the turbulent interaction of these two flow changes with shield gas temperature would be quite complicated to calculate and is not attempted here.

Conclusions

1) For the conditions examined in this work, arc efficiency decreases with current and increases with voltage. The increase with voltage is primarily caused by an increase in convective heat transfer by the shield gas.

2) The welding arc should be treated as an optically thin medium that absorbs and radiates energy very weakly.

3) Arc temperature does not vary with voltage. The average arc temperature stabilizes based on the number of electrons flowing through it.

Acknowledgments

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