Power Inputs in Gas Metal Arc Welding of Aluminum—Part 2

Three power inputs were used to investigate relative contributions to arc and cathode heating

BY M. J. LU AND S. KOU

ABSTRACT. Calorimetric experiments were carried out in GMAW of aluminum to measure: 1) the total power input, and 2) the power input due to the combined action of the arc and filler metal droplets. From the experimental results obtained here and those of the droplet heat content obtained in Part 1(1) of this study, the individual power inputs were determined, *i.e.*, the power inputs due to: 1) arc radiation/convection, 2) filler metal droplets, and 3) cathode heating. Based on these individual power inputs, the individual efficiencies were determined.

Introduction

In Part 1 of this study (Ref. 1), the power input due to the filler metal droplets, *i.e.*, the droplet heat content in gas metal arc welding (GMAW) of aluminum was measured. The purpose of Part 2 of this study is to determine the remaining two power inputs, *i.e.*, the power inputs due to the arc (by radiation/convection) and the welding current at the cathode. It is essential to know not only the total power input to the workpiece, but also these individual power inputs. This is because these individual power inputs tend to be distributed over different areas on the workpiece surface, resulting in different effects on the thermal phenomena in the workpiece.

In GMAW, the workpiece is almost exclusively the cathode (negative) and the electrode the anode (positive), *i.e.*, the so-called direct current reverse polarity. Therefore, the electric current flows from the electrode to the workpiece, while electrons are emitted from the workpiece surface to the electrode. It has been observed in GMAW of aluminum and steel with argon as the shielding gas, that current flow or electron emission occurs not uniformly over the workpiece surface under the arc, but over localized areas on the workpiece surface called "cathode spots" (Refs. 2, 3). The localized heating, called cathode heating herein, causes the surface oxide to dissociate, leaving a clean metal surface (Ref. 2).

In a recent study by Essers, *et al.* (Ref. 4), the first attempt was made to determine the relative contributions of individual power inputs to the total power delivered to the workpiece in GMAW of steel, by combining the results of calorimetric measurements in GMAW and those in plasma GMAW. It was reported that the relative contributions are 23% from arc radiation/convection, 17% from filler metal droplets and 31% from cathode heating, making an overall heat source efficiency of 71%.

In the present study, the first attempt will be made to determine the individual power inputs (and their relative contributions to the total power input) in GMAW of aluminum. An experimental approach different from that of Essers, *et al.* (Ref. 4), will be adopted, as described below.

Experimental Procedure

Two different types of experiments were carried out in the present study. In the first type of experiments, the total power input from the heat source was measured, while in the second, only the power input due to the combined action of arc radiation/convection and filler metal droplets was measured. Two different types of aluminum filler metals, *i.e.*, 4043 and 5356, were used.

The power source and the welding conditions were the same as those in Part 1 of the present study (Ref. 1).

KEY WORDS

Aluminum GMA Welding
Power Inputs
Droplet Heat Content
Arc/Cathode Heating
Calorimetric Testing
4043 Aluminum Filler
Droplet Transfer
Radiation/Convection
Thermal Phenomena
Temperature Measures

Total Power Input

A calorimeter was constructed to measure the total power input during welding. The calorimeter consisted of a rectangular, bottom-insulated stainless steel trough 30 cm long, 7.5 cm wide and 5 cm deep (12 × 3 × 2 in.), and a rectangular 6061 aluminum plate 34.0 cm long and 11.0 cm wide (13⅜ × 4⅜ in.). The aluminum plate served both as a workpiece and the cover of the stainless steel trough, its thickness ranging from 3.2 mm (⅛ in.) for low-heat-input welding to 9.6 mm (⅜ in.) for high-heat-input welding. The aluminum plate was clamped tightly on the flange of the stainless steel trough, with a flexible silicon rubber tube capable of resisting temperatures up to 400°C (752°F) placed in between the two to prevent water from leaking out of the calorimeter. In this way, the workpiece is removable and the stainless steel trough is reusable. Figure 1 is a schematic sketch of the calorimeter. To help avoid gaps between the silicon rubber tube and a 9.6-mm (⅜-in.) thick aluminum plate, which can form as a result of distortions induced by high welding heat inputs, the thickness of the plate was reduced to 3.2 mm along its four edges, as illustrated in Fig. 1.

A cascade-type water supply system was employed to maintain a constant water flow rate throughout the experiment. Prior to the experiments, water was stored in the supply system and was allowed to reach the temperature of the calorimeter, *i.e.*, the room temperature. The calorimeter was completely filled with water before experiments were started. A schematic sketch of the overall system is

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shown in Fig. 2. No bubble formation due to vaporization of water in the calorimeter occurred during experiments.

A constant-potential-type GMAW power source was employed in conjunction with a digital readout device for the welding voltage and current, and with a traversing carriage of adjustable welding speeds. The welding speed was 10.2 mm/s (24 in./min), and the distance from the contact tube to the workpiece was 19 mm (3/4 in.). Two commercial aluminum filler metals, *i.e.,* Types 4043 and 5356, were used, both with the diameter of 1.6 mm (1/16 in.). The shielding gas was pure argon at 23.6 L/min (50 ft^3/h).

Differential thermistors were used to measure the temperature rises of the water passing through the calorimeter, their output signals being recorded continuously. The overall efficiency of the heat source (including contributions from arc heating, the heat content of filler metal droplets and cathode heating), η_{total}, was determined from the following equation (Ref. 5):

$$\int_0^\infty WC_p (T_{out} - T_{in})\, dt = \eta_{total} EIt_{weld} \quad (1)$$

where W = mass flow rate of water, C_p = specific heat of water, T_{out} = outlet water temperature, T_{in} = inlet water temperature, t = time, E = arc voltage, I = welding current, and t_{weld} = welding time. The total power input is as follows:

$$Q_{total} = \eta_{total} EI \quad (2)$$

Power Input Due to Arc and Droplets

The power input due to the combined action of arc radiation/convection and filler metal droplets was measured using the same calorimeter and water supply system for measuring the total power input. A 4-mm (5/32-in.) diameter tungsten electrode of a gas tungsten arc welding (GTAW) torch was used as the cathode, as shown schematically in Fig. 3. In the case of spray transfer, the GTAW torch was inclined forward at 35 deg from the vertical position, while the GMAW torch was inclined backward at 15 deg from the vertical position. In the case of globular transfer, on the other hand, the GTAW torch was inclined forward at 45 deg from the vertical position, while the GMAW torch was inclined backward at 30 deg from the vertical position. These larger angles were required in order to prevent globular droplets from touching the tungsten electrode. The vertical distance between lower end of the tungsten electrode and top surface of the workpiece was about 5 mm (3/16 in.), and the arc length (the distance between welding wire tip and surface of the weld pool) was about the same as that in the measurements of the total power input.

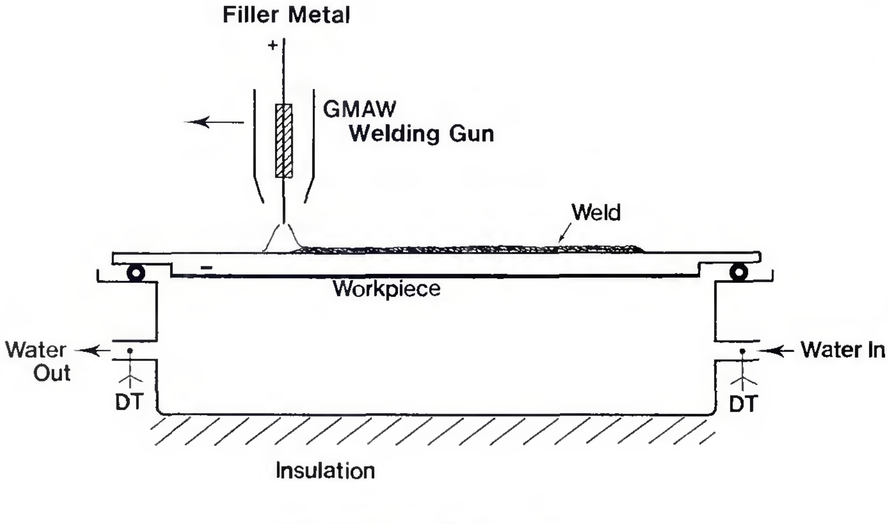


Fig. 1 — The heat source and the calorimeter for measuring the total power input due to the heat source as a whole

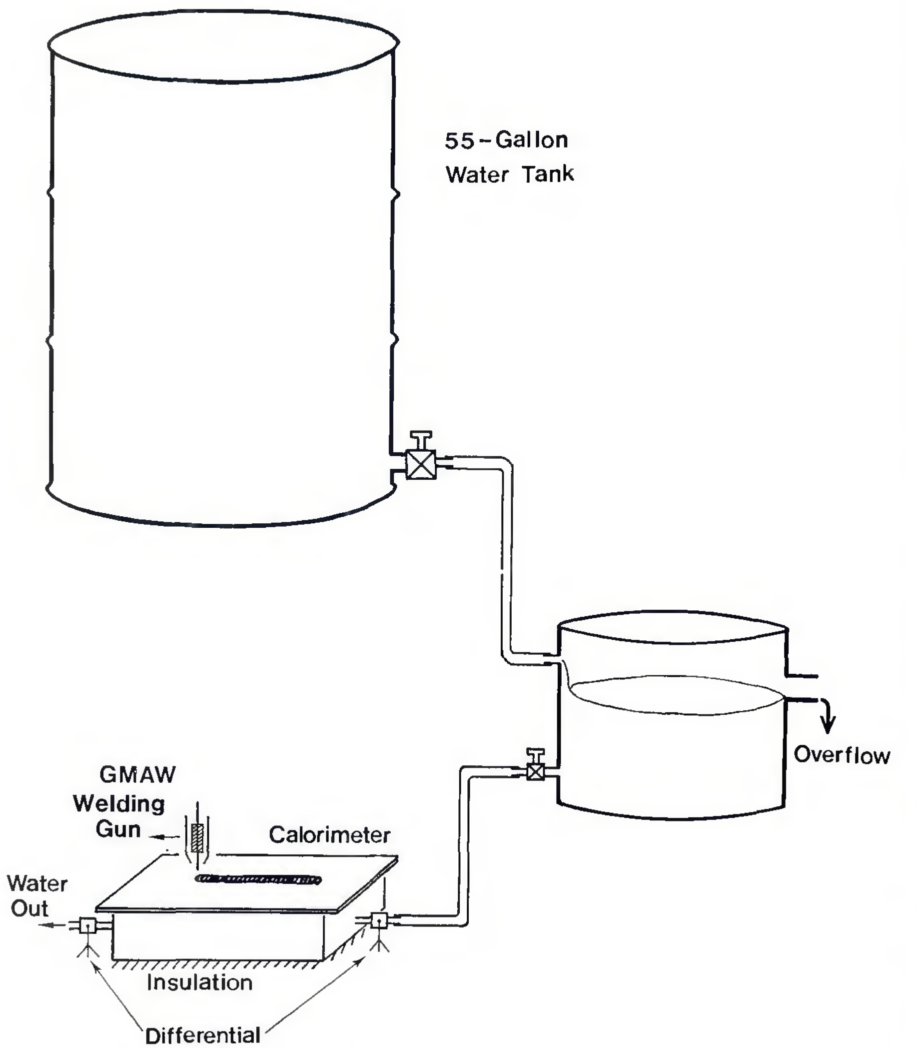


Fig. 2 — Schematic sketch of the overall system for calorimetric measurement of the total power input in gas metal arc welding

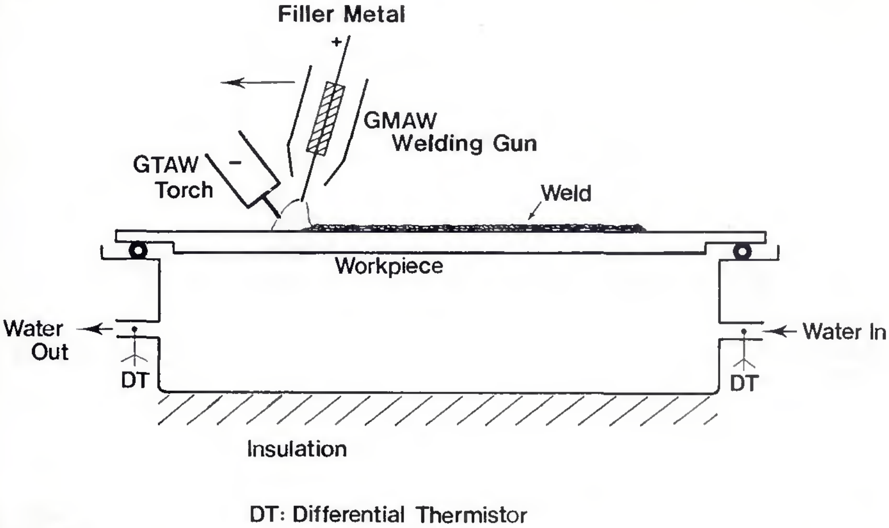


Fig. 3 — The heat source and the calorimeter for measuring the power input due to the combined action of arc radiation/convection and filler metal droplets

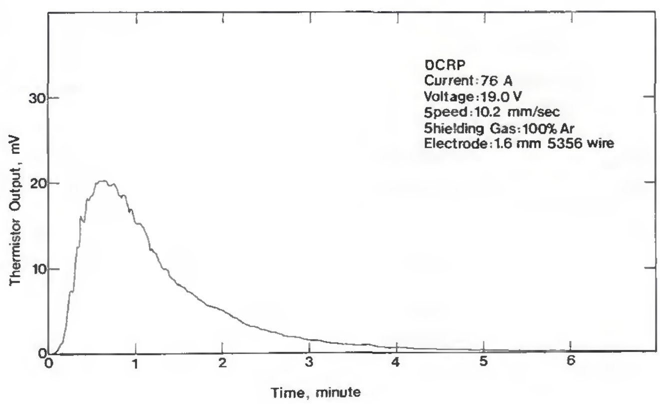
Table 1—Total Power Inputs (Q_{total}) and Efficiencies (η_{total}) in GMAW with 4043 Aluminum Filler Metal

Experiment	1	2	3	5
Current (A)	78	128	176	251
Wire Speed (mm/s)	42.3	51.2	67.7	97.3
Voltage (V)	19.4	22.6	27.8	28.2
Plate Thickness (mm)	3.2	4.8	6.4	9.5
Welding Speed (mm/s)	10.2	10.2	10.2	10.2
Transfer Mode	Globular	Mixed	Spray	Spray
No. of Runs	4	4	6	7
Q_{total} (W)	1248 ± 27	2337 ± 139	3944 ± 98	5677 ± 113
η_{total} (%)	82.5 ± 1.8	80.8 ± 4.8	80.6 ± 2.0	80.2 ± 1.6

Table 2—Total Power Inputs (Q_{total}) and Efficiencies (η_{total}) in GMAW with 5356 Aluminum Filler Metal

Experiment	1	2	3	5
Current (A)	76	124	173	246
Wire speed (mm/s)	46.6	61.4	80.4	127.0
Voltage (V)	19.0	22.0	27.2	29.5
Plate thickness (mm)	3.2	4.8	6.4	9.5
Welding speed (mm/s)	10.2	10.2	10.2	10.2
Transfer mode	Globular	Mixed	Spray	Spray
No. of runs	8	6	6	6
Q_{total} (W)	1157 ± 29	2158 ± 63	3548 ± 66	5530 ± 174
η_{total} (%)	80.1 ± 2.0	79.1 ± 2.3	75.4 ± 1.4	76.2 ± 2.4

Fig. 4 — Output from the differential thermistor in the experimental setup (Fig. 1) for measuring the total power input due to the heat source as a whole



Results and Discussion

Total Power Input

Figure 4 is an example of the output from the differential thermistor in the experimental setup shown in Fig. 1. From experimental data like this, the total power input, Q_{total}, and the overall (total) efficiency of the heat source, η_{total}, were determined using Equations 1 and 2. Figure 5 shows the total power input, Q_{total}, as a function of the nominal power input, IXE, for filler metals 4043 and 5356.

From Fig. 5, the total power input appears to be essentially a linear function of the nominal power input for both filler metals 4043 and 5356, within the range of welding conditions used. It is, however, not clear why the total power inputs for filler metal 5356 are slightly less than those for filler metal 4043. Perhaps this is due to the differences between the two filler metals in physical properties and the extent of evaporation in the arc. The welding conditions and experimental data are summarized in Tables 1 and 2.

Power Input Due to Arc and Droplets

The power input due to the combined action of arc radiation/convection and filler metal droplets, $Q_{arc+drop}$, as a function of the nominal power input, IXE, is shown in Fig. 6 for filler metal 4043. The total power input and the power input due to the droplets of the same welding wire are also included in the figure. The corresponding efficiencies, defined as $\eta = Q/(IE)$, are shown in Fig. 7. As shown, the efficiency due to the combined action of arc and droplets and the total efficiency both decrease slightly with increasing power input, within the range of welding conditions investigated. The welding conditions and the resultant data of $Q_{arc+drop}$ and $\eta_{arc+drop}$ are summarized in Table 3.

Since the workpiece was not the cathode in these experiments, surface cleaning due to plasma etching was not observed at the workpiece surface. Consequently, it was noted that wetting between the droplets and the workpiece was inferior to that in the measurements of the total power input.

Individual Power Inputs

In Part 1 of the present study (Ref. 1), the droplet heat content H_d, *i.e.*, the heat content per unit mass of droplet, was measured. The values of the power input due to filler metal droplets, Q_{drop}, shown in Fig. 6 were determined using the following equation:

$$Q_{drop} = \frac{\pi}{4} d^2 V \rho H_d \quad (3)$$

where d = welding wire diameter, V = welding wire speed, ρ = welding wire density, and H_d = droplet heat con-

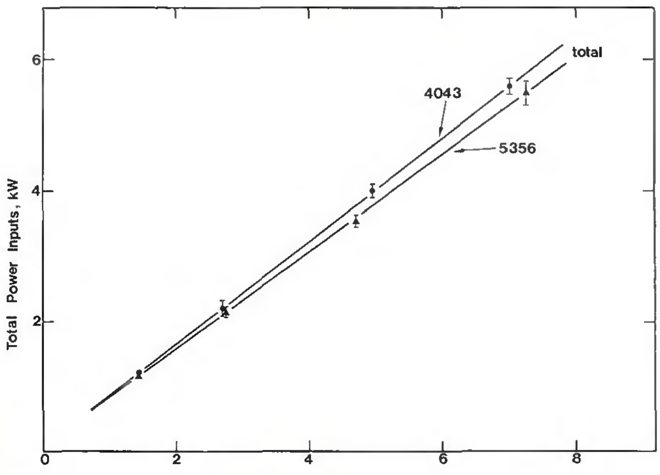


Fig. 5 — Total power inputs due to the heat source as a whole as a function of the nominal power input in GMAW with aluminum filler metals 4043 and 5356

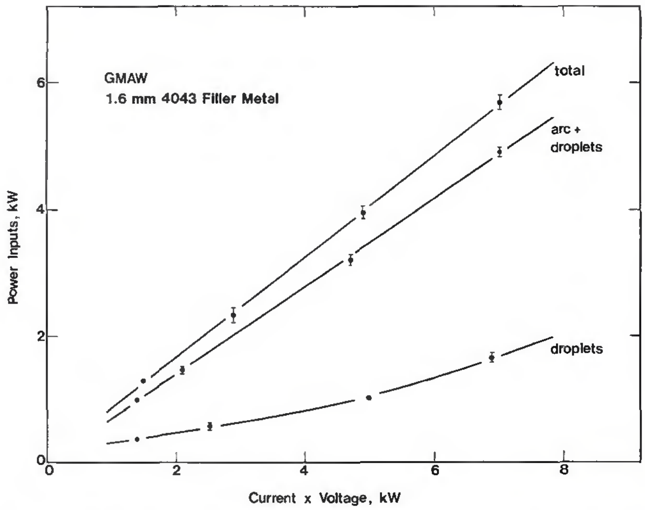


Fig. 6 — Measured power inputs as a function of the nominal power input, including those due to the heat source as a whole, the combined action of arc radiation/convection and droplets, and droplets alone

tent.

From the power input due to filler metal droplets, Q_{drop}, and the power input due to the combined action of arc radiation/convection and filler metal droplets, $Q_{arc+drop}$, the power input due to arc radiation/convection, Q_{arc}, can be determined as follows:

$$Q_{arc} = Q_{arc+drop} - Q_{drop} \qquad (4)$$

Similarly, from the power input due to the combined action of arc radiation/convection and filler metal droplets, $Q_{arc+drop}$, and the total power input of the heat source, Q_{total}, the power input due to cathode heating, $Q_{cathode}$, can be determined as follows:

$$Q_{cathode} = Q_{total} - Q_{arc+drop} \qquad (5)$$

These individual power inputs, *i.e.*, Q_{arc}, Q_{drop} and $Q_{cathode}$, as well as the total power input Q_{total}, are shown in Fig. 8 for filler metal 4043. The corresponding efficiencies, again defined as $\eta = Q/(IE)$, are shown in Fig. 9.

In Fig. 9, the overall (total) efficiency of the heat source was about 80%, within range of welding conditions studied. This is consistent with the data of Christensen, *et al.* (Ref. 6), which shows 70–85% for GMAW of aluminum with nominal power inputs up to 7 kW.

Regarding the individual efficiencies,

Table 3—Power Inputs ($Q_{arc+drop}$) and Efficiencies ($\eta_{arc+drop}$) Due to Combined Action of Arc Radiation/Convection and Filler Metal Droplets in GMAW with 4043 Aluminum Filler Metal

Experiment	1	2	3	5
Current (A)	74	91	170	248
Wire speed (mm/s)	42.3	51.2	67.7	97.3
Voltage (V)	18.8	22.7	27.4	28.3
Plate thickness (mm)	3.2	4.8	6.4	9.5
Welding speed (mm/s)	10.2	10.2	10.2	10.2
Transfer mode	Globular	Mixed	Spray	Spray
No. of runs	7	5	6	7
$Q_{arc+drop}$ (W)	991 ± 11	1438 ± 37	3209 ± 102	4878 ± 112
$\eta_{arc+drop}$ (%)	71.2 ± 1.1	69.6 ± 1.8	68.9 ± 2.2	69.5 ± 1.6

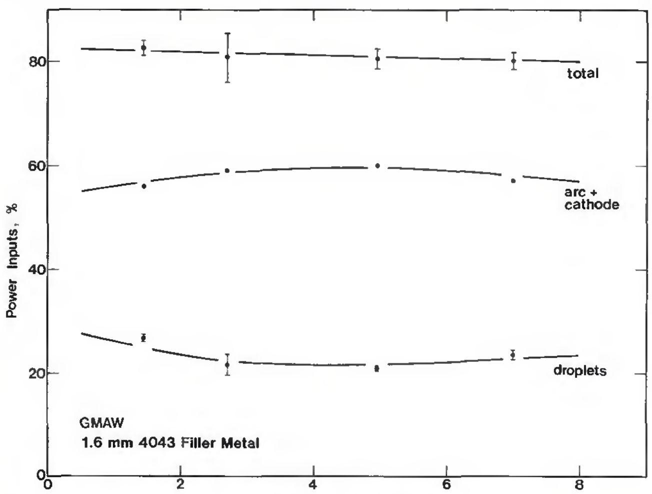


Fig. 7 — Measured efficiencies as a function of the nominal power input, including those due to the heat source as a whole, the combined action of the arc and droplets, and droplets alone. The greater scattering of the data collected in the range of 2-3 kW was due to unstable mixed mode transfer

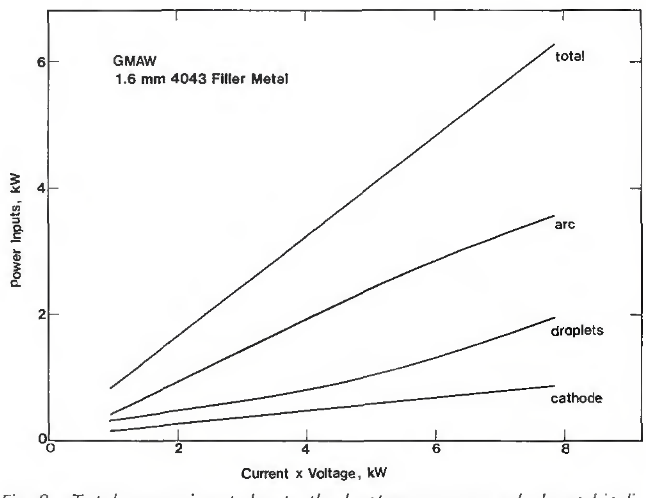


Fig. 8 — Total power input due to the heat source as a whole and individual power inputs due to arc radiation/convection, droplets and cathode heating

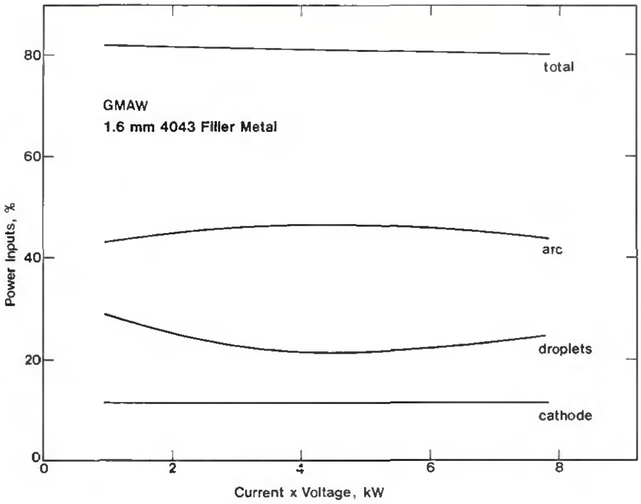


Fig. 9 — Overall efficiency due to the heat source as a whole and individual efficiencies due to arc radiation/convection, droplets and cathode heating

Fig. 9 shows that η_{arc} is about 45%, η_{drop} about 23% and $\eta_{cathode}$ about 12%, within the range of welding conditions investigated. This suggests that arc radiation/convection dominates the total power input in GMAW. Since this is the first investigation of this kind on GMAW of aluminum, there are no other experimental data to compare with. It is, however, interesting to note that in the recent study by Essers, *et al.* (Ref. 4) on GMAW and plasma GMAW of steel, it was shown that η_{arc} = 23%, η_{drop} = 17% and $\eta_{cathode}$ = 31%, with an overall (total) efficiency η_{total} = 71%. Since his η_{arc} value appears much lower than that in the present study while his $\eta_{cathode}$ value is much higher, it is believed that the differences in these η values are not merely due to the use of different filler metals and welding conditions in the two studies.

In the study of Essers, *et al.* (Ref. 4), Q_{total} was measured from a regular GMAW welding gun. However, $Q_{cathode}$ was measured from a plasma GMAW torch, where the arc was largely surrounded by a constricted, water-cooled copper gas nozzle, and thus, only a portion of the arc was actually available for heating up the workpiece (by radiation and convection). Consequently, the η_{arc} so measured is lower than that in the present study, and the $\eta_{cathode}$ is higher. We believe that our approach to measuring the individual power inputs in GMAW is a reasonable one.

Conclusions

1) The individual power inputs due to: 1) arc radiation/convection, 2) filler metal droplets and 3) cathode heating have been determined in GMAW of aluminum.

2) The present study has demonstrated that these individual power inputs can be determined by measuring: 1) the total power input, 2) the combined power input due to the arc and filler metal droplets and 3) the droplet heat content.

3) The individual efficiencies are about 45% due to arc radiation/convection, 23% due to filler metal droplets and 12% due to cathode heating; the overall efficiency of the heat source being about 80% within the range of welding conditions used (up to 7 kW).

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