Power Inputs in Gas Metal Arc Welding of Aluminum—Part 1

Four different calorimetric and temperature measurements were carried out to determine the droplet heat content

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ABSTRACT. In order to better understand the thermal phenomena during gas metal arc welding (GMAW) of aluminum, experiments were carried out to measure the heat content of the filler metal droplets. A total of four experimental setups were used: two calorimetric-measurement-type setups, one for globular transfer and the other for spray transfer; and two temperature-measurement-type setups, also one for globular transfer and the other for spray transfer. Type 4043 aluminum filler wire of 1.6-mm diameter was used and the welding conditions were chosen from the range of practical GMAW of aluminum. The effects of the droplet transfer mode and the welding current on the droplet heat content and temperature were observed.

Introduction

Gas metal arc welding (GMAW) differs from gas tungsten arc welding (GTAW) mainly in that the electrode is a consumable filler metal wire in the former, while it is a nonconsumable tungsten or tungsten-alloy electrode in the latter. Due to the melting of the filler metal wire during welding, a significant portion of the total power input in GMAW is always due to the heat content of the filler-metal droplets transferred to the workpiece. Therefore, to better understand the thermal phenomena in GMAW, the droplet heat content must be determined.

Surprisingly, little work has so far been done to determine the droplet heat content in GMAW of aluminum. Ozawa, *et al.* (Ref. 1), measured droplet heat contents in GMAW of aluminum using 1.6-, 2.3- and 4.0-mm (1/16-, 3/32-, and 5/32-in.) diameter filler wires, and Ando, *et al.* (Ref. 2), 1.6-mm-diameter filler wire. Kiyohara, *et al.* (Ref. 3), measured droplet heat contents in GMAW of aluminum using a 1.6-mm-diameter filler wire and a constant-current-type power source. Calorimeters were used in all the measurements mentioned above.

The range of practical GMAW of aluminum using 1.6-mm-diameter filler wires (Ref. 4) is shown in Fig. 1. As shown, the welding conditions of both Ozawa, *et al.* (Ref. 1), and Ando, *et al.* (Ref. 2), are outside this range.

Experimental Procedure

A constant-voltage-type GMAW power source was employed for welding. The machine had a digital readout device for the welding voltage, the welding current, and the speed of the filler metal wire. Direct current electrode positive (reverse polarity) was used, with a commercial 4043 aluminum (essentially Al-5Si) filler metal wire of 1.6-mm-diameter, a shielding gas of pure argon at 23.6 L/min (50 ft^3/h), and a contact tube-to-cathode distance of 19 mm (3/4 in.).

In order to provide useful information, the voltages and currents selected in the present study were within the range of practical GMAW of aluminum, as shown in Fig. 1. This figure also includes the welding conditions for 1.6-mm-diameter 5356 aluminum filler wire in Part 2 of this study (Ref. 5) to be published in the *Welding Journal* at a later date.

Two different types of experiments were carried out to measure the heat content of filler metal droplets in GMAW, *i.e.*, calorimetric measurements and temperature measurements, as described below.

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

Calorimetric Measurements

Two distinct modes of filler metal transfer are commonly observed in normal (*i.e.*, not short circuited or pulsed) GMAW, *i.e.*, the globular and spray transfer modes. The former occurs at relatively low welding currents, where the electromagnetic force to pinch off droplets from the filler wire tip is small, and is characterized by the relatively large volume and low frequency of droplets. The latter, on the other hand, occurs at relatively high welding currents, and is characterized by the relatively small volume and high frequency of droplets. Due to the differences in the characteristics of droplets, different setups were used in experiments involving different modes of droplet transfer.

Globular Transfer

The experimental setup for calorimetric measurements of droplets with globular transfer, *i.e.*, Setup 1, is shown schematically in Fig. 2. The cathode was a 4.0-mm-diameter tungsten electrode of a gas tungsten arc welding torch. To prevent droplets from touching the tip of the tungsten electrode, the GMAW torch was inclined at 30 deg from the vertical position and the GTAW torch at 60 deg; the distance between the contact tube of the GMAW torch and the tip of the tungsten electrode of the GTAW torch being about 19 mm (3/4 in.).

The arrangement of the GMAW torch and the cathode in Setup 1 is similar to those of Ando, *et al.* (Ref. 2), and Kiyohara, *et al.* (Ref. 3), but the design of the calorimeter is different. First, in the present study, the copper basin for receiving filler metal droplets was surrounded by water only on the sidewall but not at the bottom wall, in order to avoid vaporizing water underneath the bottom wall. Second, in the present study, dual high-precision thermistors

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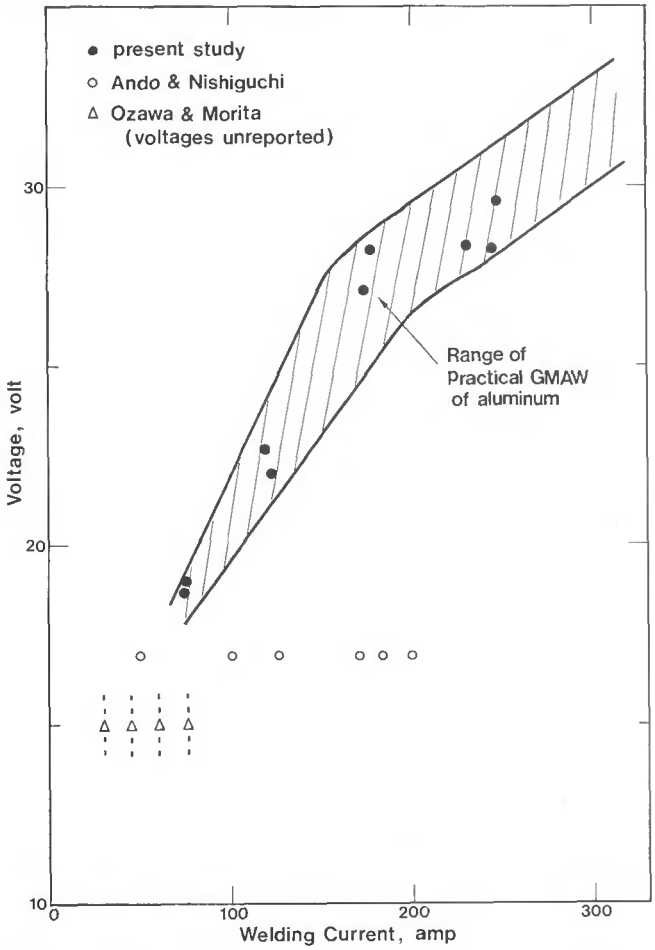

Fig. 1 — Range of practical gas metal arc welding of aluminum alloys with 1.6-mm filler metal wires and locations of droplet heat content measurements

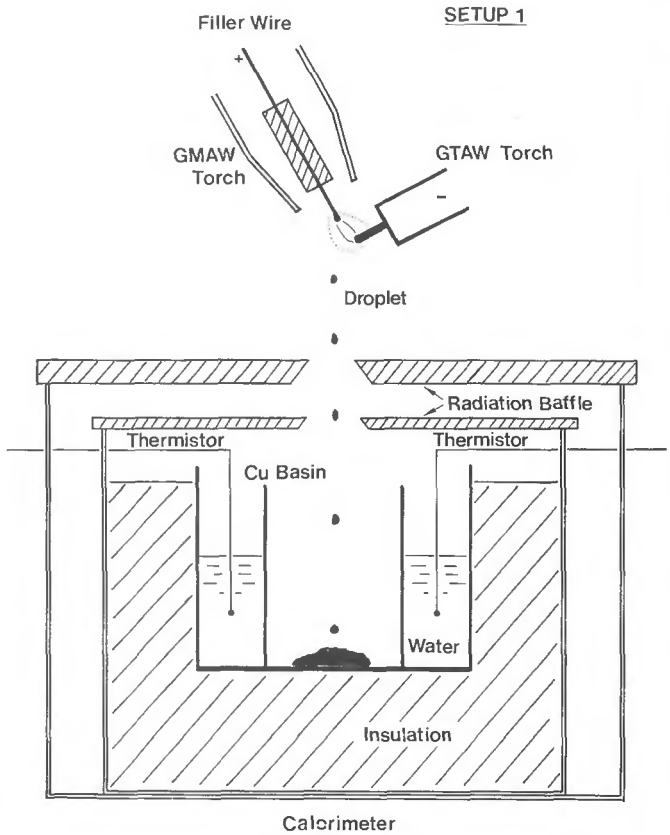

Fig. 2 — Experimental Setup 1 for heat content measurements of droplets with globular transfer

(Omega 44201), rather than a single thermometer or thermocouple, were used for measuring the average temperature rise of the water in the calorimeter. It was observed in the early stage of the investigation that the deposition of filler metal in the copper basin was not always symmetrical with respect to its axis, and as a result the water temperature in the copper basin was not always symmetrical, either. It was found that the use of dual thermistors helped avoid errors caused by this problem.

The copper basin was 38 mm (1.5 in.) in diameter and 51 mm (2 in.) high with a wall thickness of 0.8 mm (0.03 in.). The spacing between the copper basin and the outer copper wall was about 19 mm (¾ in.). The copper basin and the outer copper wall were thermally insulated from the surroundings and two baffles, each with a 25-mm (1-in.) diameter hole, were used to prevent arc radiation from above.

The calorimeter was calibrated using liquid tin of known heat contents. The temperature rise of the water in the calorimeter was plotted against the heat contents of the liquid tin poured into the copper basin, as shown in Fig. 3. Alternatively, from the weights of the copper and water in the calorimeter and their specific heats, a second calibration curve can also be constructed, as also shown in Fig. 3. The average of these two calibration curves was used.

When measuring the droplet heat content, the calorimeter was positioned so that the bottom of the copper basin was about 150 mm (6 in.) below the two electrodes. The two thermistors were placed opposite to each other in the calorimeter water, and were hooked up to a strip chart recorder. About 10 s after the arc was established, filler-metal droplets were allowed to fall into the copper basin for about 15 to 25 s, during which

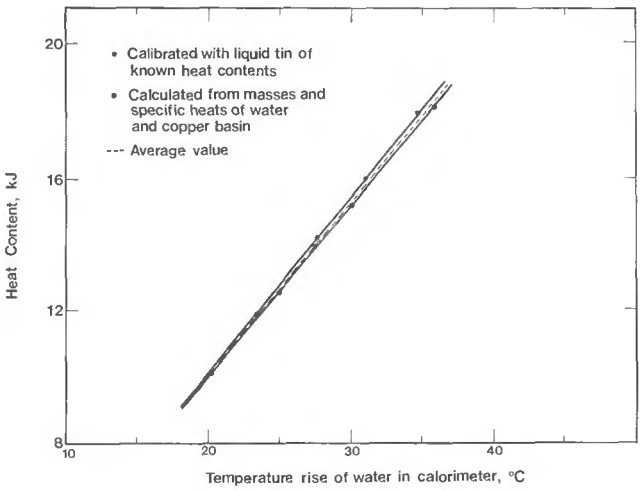

Fig. 3 — Calibration curves for the calorimeter used in experimental Setups 1 and 2

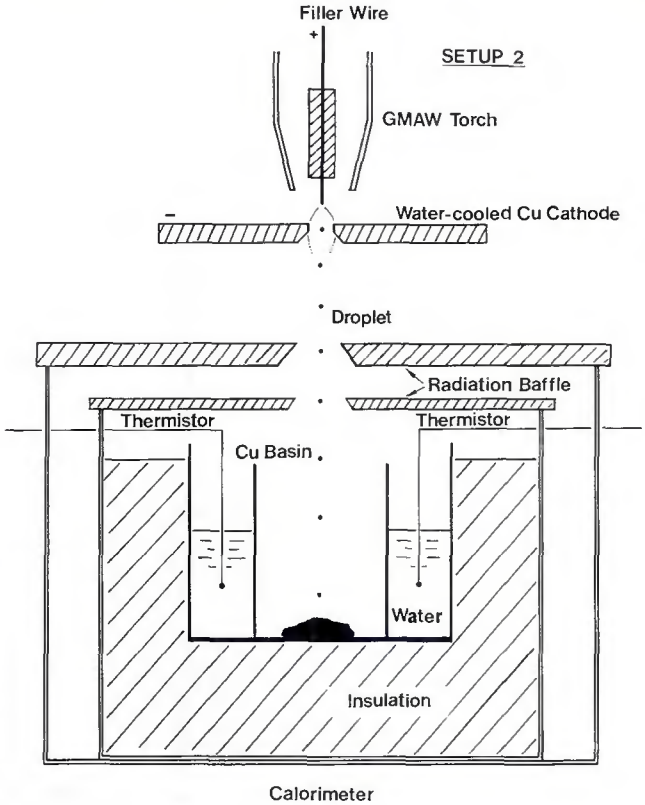

Fig. 4 — Experimental Setup 2 for heat content measurements of droplets with spray transfer

an amount of usually 4 to 7 g of filler metal was collected.

After welding was completed, the solidified filler metal was removed from the copper basin and weighed by an analytical balance.

Spray Transfer

The experimental setup for calorimetric measurements of droplets with globular transfer, *i.e.,* Setup 1 in Fig. 2, was found unsatisfactory with spray transfer. Due to their small size and high velocity, the droplets tend to spatter and thus become difficult to collect in the copper basin of the calorimeter. In order to help guide filler metal droplets into the copper basin, a water-cooled copper plate was used as the cathode, with a hole at the center to allow droplets to pass through and descend in the copper basin. This water-cooled copper cathode is similar to that in the investigation of Jelmorini, *et al.* (Ref. 6), on droplet temperature measurements, in which a thermocouple was placed under the hole in the copper cathode to directly catch filler metal droplets and measure their temperature, as will be mentioned again.

The experimental setup for calorimetric measurements of droplets with spray transfer, *i.e.,* Setup 2, is shown schematically in Fig. 4. The copper cathode had a thickness of 13 mm (½ in.) and a hole of 11 mm (7/16 in.) in diameter. The calorimeter is the same as that previously shown in Setup 1, Fig. 2.

It should be pointed out that Setup 2, though satisfactory for spray transfer, was found unsatisfactory for globular transfer. It was observed that, due to the relatively large size of the droplets in globular transfer and their relatively long residence time at the filler wire tip, they had a tendency to touch and solidify onto the water-cooled copper plate.

Temperature Measurements

Globular Transfer

The experimental setup for direct temperature measurements of droplets with globular transfer, *i.e.,* Setup 3, is shown in Fig. 5. The arrangement of the GMAW torch and the cathode was the same as that in the setup for calorimetric measurements of droplets with globular transfer, *i.e.,* Setup 1 in Fig. 2.

Since with globular transfer filler metal droplets are relatively large in volume and follow a fairly stable downhill path, they are relatively easy to catch. A thermocouple was prepared by butt joining the tips of two thermocouple wires through capacitor-discharge welding, forming a line shape junction without a visible bead, as shown in Fig. 5. These thermocouple wires were W-5%Re and W-26%Re, and were 0.13 mm (0.005 in.) in diameter. A high-speed data-acquisition system (PDP 11/73) was used to record the output voltage from the thermocouple. The thermocouple was calibrated against pure aluminum and copper, and was found to have an error of less than 5°C (9°F). Since the thermocouple was very fine and was bead free, it responded instantaneously upon contact with filler metal droplets. For the same reason, the accumulation or piling up of the filler metal on the thermocouple, which could reduce its sensitivity, was retarded. The sheaths of thermocouple were retracted about 10 mm (0.4 in.) from the junction to avoid acting as heat sinks. The thermocouple junction was positioned at about 76 mm (3 in.) below the tip of the tungsten electrode. A position of 152 mm (6 in.) below was also tried, and no significant temperature drops due to the lower position of the thermocouple junction were detected.

Spray Transfer

The experimental setup for direct temperature measurements of droplets with spray transfer, *i.e.,* Setup 4, is shown schematically in Fig. 6. The arrangement of the GMAW torch and the cathode was the same as that in the setup for calorimetric measurements of droplets with spray transfer, *i.e.,* Setup 2 in Fig. 4. The design of the thermocouple, on the other hand, was the same as that in the setup for direct temperature measurements of droplets with globular transfer, *i.e.,* Setup 3 in Fig. 5, and the same data-acquisition system was used.

As will be discussed later, this experimental setup is unsatisfactory for direct temperature measurements of droplets with spray transfer. It is worth mentioning that in the study of Jelmorini, *et al.* (Ref. 6), on droplet temperature measurements, two thermocouple wires of 0.5-mm (0.02-in.) diameter crossed each other at an angle of 120 deg to form an intersection to help catch descending filler metal droplets. The droplet temperature was deduced from that of a small growing pile of filler metal accumulated at the thermocouple junction, using an energy balance formula. This technique was not adopted in the present study because it was felt that the temperature measurement might not be accurate.

Results and Discussion

Calorimetric Measurements

Globular Transfer

The experimental results are shown in the column under Experiment 1, Table 1. A total of eight runs was made to measure calorimetrically the droplet heat content using experimental Setup 1. The average welding current was 74 A, which corresponded to a wire feeding speed of 42.3 mm/s (100 ipm), and the average voltage was 18.7 V.

Figure 7 shows an example of the water temperature in the calorimeter as a

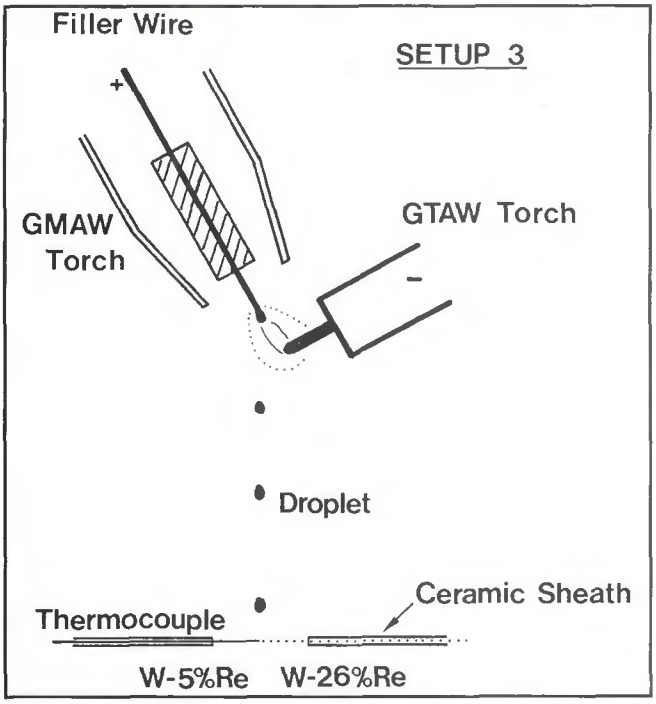

Fig. 5 — Experimental Setup 3 for temperature measurements of droplets with globular transfer

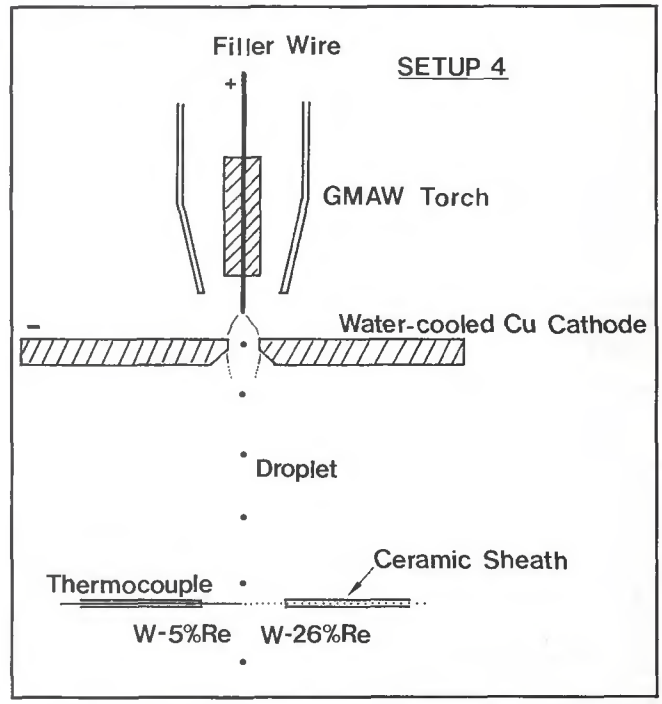

Fig. 6 — Experimental Setup 4 for temperature measurements of droplets with spray transfer

function of time. The average of the two curves produced by the two thermistors in the calorimeter was used to represent the water temperature, and the water temperature rise of calorimeter, ΔT, was determined in the way described in the appendix.

With the help of the calibration curve shown in Fig. 3, the water temperature rise, ΔT, was used to determine the total heat content of the filler metal collected in the calorimeter, and hence the droplet heat content, *i.e.,* the heat content per unit mass of droplet. The droplet heat content was 1692 ± 44 J/g.

The experimental results shown in the column under Experiment 2, Table 1, were also obtained using experimental Setup 1. A total of nine runs was made to measure calorimetrically the droplet heat content. The average welding current was 111 A, which corresponded to a wire feed speed of 51.2 mm/s (121 ipm), and the average voltage was 22.8 V. Under this welding condition, the droplet transfer mode was a mixed globular/spray transfer. The average droplet heat content was 2133 ± 204 J/g. The degree of deviation in the droplet heat content here is greater than that in Experiment 1. This is mainly due to the greater fluctuations in the welding current and voltage associated with the unstable mixed mode of droplet transfer, rather than due to the reproducibility problem of the experimental technique.

Spray Transfer

The experimental results are shown in the columns under Experiments 3–5. Moreover, these results were obtained using experimental Setup 2. The average welding currents were 174, 233 and 244 A, which corresponded respectively to the wire feed speeds of 67.7, 90.9 and 97.3 mm/s (160, 215 and 230 ipm), and the average voltages were 28.7, 28.5 and 28.1 V.

Figure 8 shows an example of the water temperature in the calorimeter as a function of time. The water temperature increased significantly more rapidly than that in the case of globular transfer, *i.e.,* Fig. 7, mainly due to the higher power

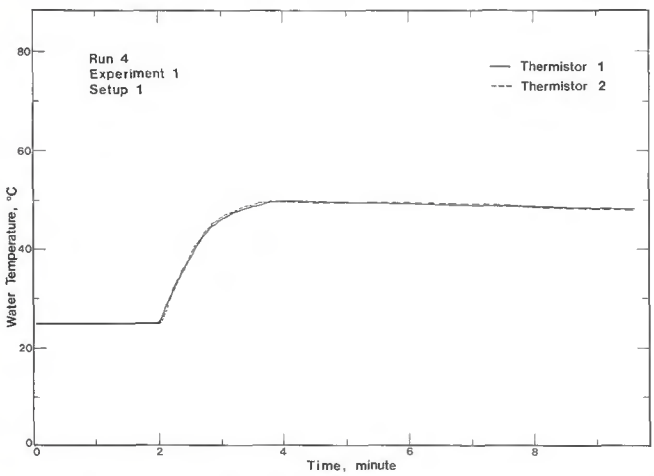

Fig. 7 — Water temperature recorded in the calorimeter of experimental Setup 1

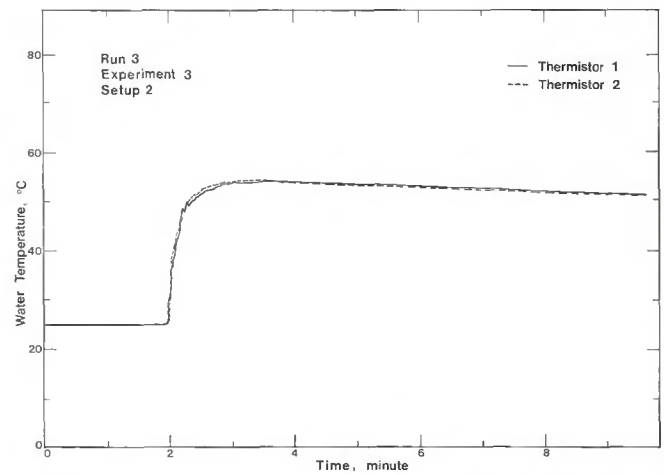

Fig. 8 — Water temperature recorded in the calorimeter of experimental Setup 2

Table 1—Droplet Heat Contents in GMAW with 4043 Aluminum Filler Wire

Experiment		1	2	3	4	5
Setup		1, 3	1	2, 4	2	2
Current (A)		74	111	174	233	244
Wire speed (mm/s)		42.3	51.2	67.7	90.9	97.3
Voltage (V)		18.7	22.8	28.7	28.5	28.1
Electrode extension (mm)		8–10	8–10	8	8	8
Transfer mode		Globular	Mixed	Spray	Spray	Spray
No. of runs	Calorimeter	8	9	5	4	3
	Thermocouple	3	–	3	–	–
Droplet heat content (J/g)	Calorimeter	1692 ± 44	2133 ± 204	2816 ± 59	3036 ± 122	3116 ± 110
	Thermocouple[a]	1705 ± 30	–	2644 ± 108	–	–
Droplet temp. (°C)	Calorimeter[b]	1191 ± 38	1565 ± 174	2146 ± 50	2333 ± 104	2401 ± 93
	Thermocouple	1202 ± 26	–	2000 ± 92	–	–

(a) Converted from measured droplet temperatures.
(b) Converted from measured droplet heat contents.

input associated with spray transfer.

The droplet heat contents were 2816 ± 59, 3036 ± 122, and 3116 ± 110 J/g for Experiments 3, 4 and 5, respectively.

Temperature Measurements

Globular Transfer

The results are shown in the column under Experiment 1, Table 1. A total of three runs was made to measure the droplet temperature using experimental Setup 3.

Figure 9 shows an example of the thermocouple output as a function of time. Each peak of the thermocouple output represents a contact between the thermocouple and a filler metal droplet. The four highest peaks were selected and the droplet temperature for this run was 1202° ± 26°C (2196° ± 47°F). The lower peaks were not used since they represent situations where droplets hit the thermocouple at a point away from the thermocouple junction or where droplets merely touched the thermocouple.

It is interesting to note from the result shown in Fig. 9 that the sensitivity of the thermocouple eventually decreased as a result of the gradual piling up or accumulation of filler metal on the thermocouple.

The droplet temperature measured under the condition of Experiment 1 was 1202° ± 26°C. The reproducibility of the temperature measurement was very good. The corresponding droplet heat content H_d was determined as follows:

$$H_d = \int_{T_o}^{T_m} Cp(s)\, dT + \Delta H + \int_{T_m}^{T_d} Cp(\ell)\, dT \quad (1)$$

where T_m = liquidus temperature, T_L, as an approximation, considering that in most aluminum alloys the fraction of liquid is very small and rises sharply as T_L is approached, T_o = room temperature, Cp(s) = specific heat of solid filler metal, ΔH = heat of fusion of filler metal, $Cp(\ell)$ = specific heat of liquid filler metal, and T_d = droplet temperature. Unfortunately, the thermodynamic data needed for 4043 aluminum are not available (Ref. 7), except that T_L = 630°C (1166°F) (Ref. 8). For this reason, the thermodynamic data for pure aluminum (Ref. 9) were used as an approximation and Equation 1 becomes:

$$H_d(\text{in J/g}) = 1032 + 1.177\,(T_d - 630) \quad (2)$$

The average droplet temperature 1202 ± 26°C in Experiment 1, Table 1, was converted, with the help of Equation 2, to 1705 ± 30 J/g. This compares favorably with 1692 ± 44 J/g, which was measured calorimetrically. The droplet heat contents measured calorimetrically in Experiments 1 through 5 were also converted to temperatures using Equation 2 and are included in Table 1 for comparison.

Spray Transfer

The experimental results are shown in the column under Experiment 3, Table 1. A total of three runs was made to measure the droplet temperature using experimental Setup 4.

Figure 10 shows an example of the thermocouple output as a function of time. As shown, the thermocouple output fluctuated wildly and the thermocouple failed during the experiment. Since with spray transfer filler metal droplets are smaller in size and less consistent in the direction of flight, they missed the thermocouple junction most of the time. Consequently, the thermocouple junction was too "cold" to be instantaneously brought up to the temperature of a

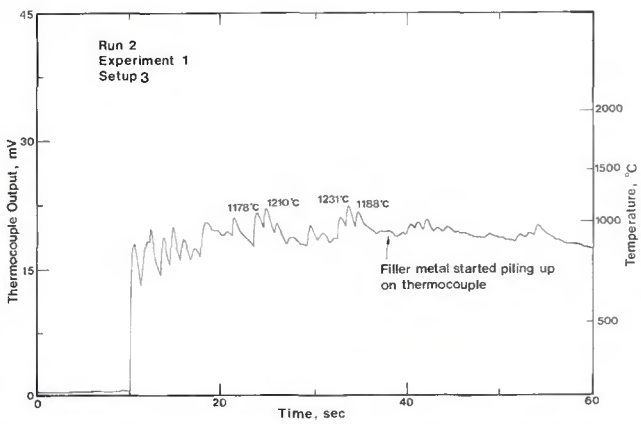

Fig. 9—Result of droplet temperature measurement using experimental Setup 3

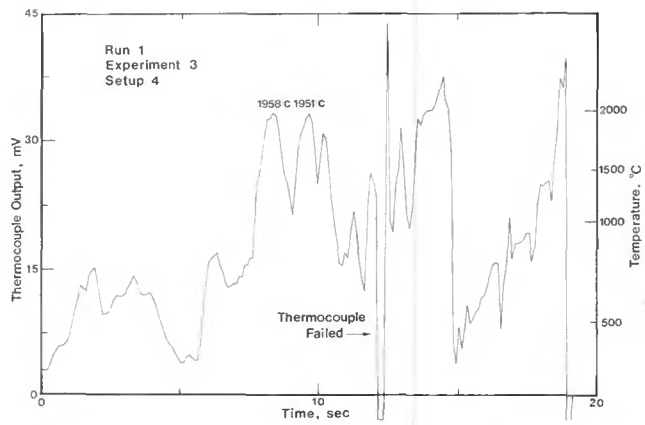

Fig. 10—Result of droplet temperature measurement using experimental Setup 4

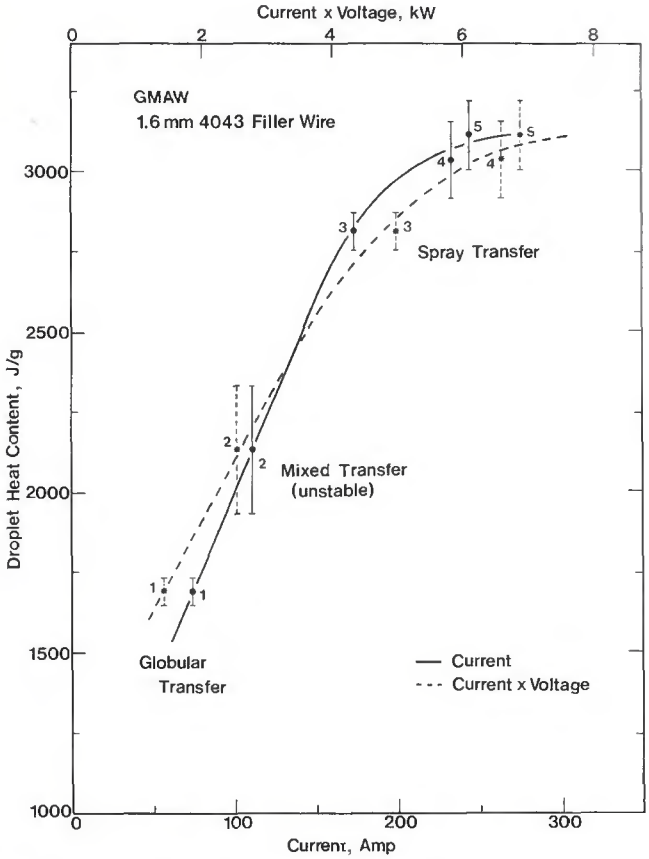

Fig. 11—Droplet heat content as a function of welding current and nominal power input

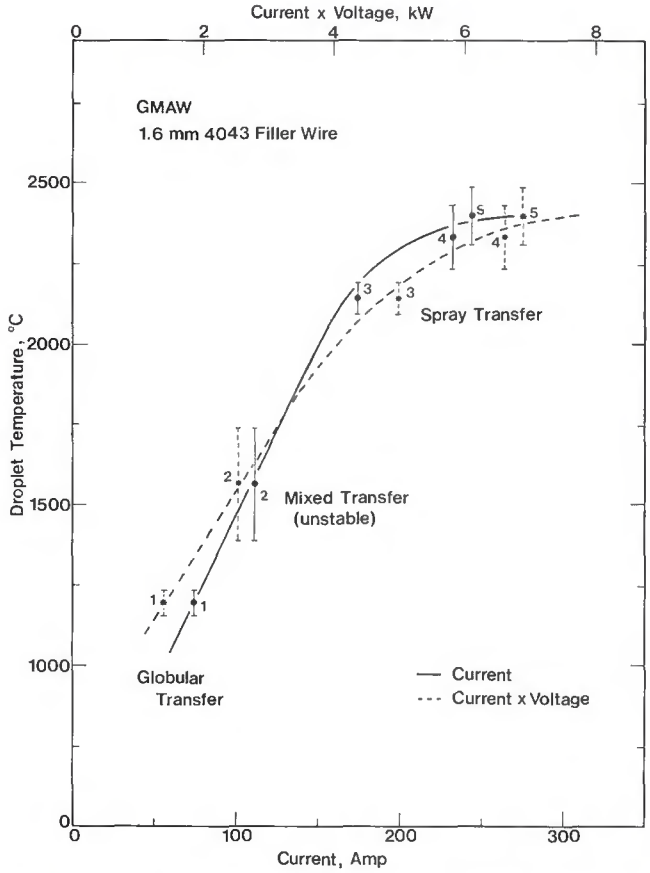

Fig. 12—Droplet temperature as a function of welding current and nominal power input

droplet hitting it. The measured droplet temperature in Experiment 3 is 2000° ± 92°C (3632° ± 166°F). This corresponds to a droplet heat content of 2644 ± 108 J/g, which is significantly lower than the value of 2816 ± 59 J/g measured calorimetrically using experimental Setup 2.

The measured droplet heat contents and temperatures are shown respectively in Figs. 11 and 12 as a function of welding current or current times voltage. As shown, the droplet heat content and temperature increase uniformly with the current throughout the range between globular and spray transfer. Upon entering the spray transfer area, the droplet heat content and temperature increase less rapidly. The transition from globular to spray transfer occurs around a welding current of 130 A. This value of the transition current is consistent with that of 125 A observed in an aluminum filler wire of the same diameter (1.6 mm) by Needham (Ref. 10).

It is interesting to note from Fig. 12 that at high welding currents the droplet temperature approaches 2400°C (4352°F), which is not far from the boiling point of pure aluminum (2520°C/4568°F), thus suggesting that evaporation of high-vapor-pressure alloying elements *(e.g.,* Mg in 5000 series aluminum alloys) from droplets can occur in the arc column during GMA welding.

Finally, it is desirable to check the level of errors in the measured droplet heat contents caused by radiation and convection heat losses from the surface of a droplet before it reaches the copper basin in the calorimeter. This will be demonstrated using Experiment 5 as an example, since heat losses are expected to be most significant due to the high droplet temperature (about 2500°C/4532°F) in this case. The sum of heat losses due to radiation and convection, Q_{loss}, is as follows:

$$Q_{loss} = 4\pi R^2 \left[\sigma\epsilon \left(T_d^4 - T_o^4\right) + h\left(T_d - T_f\right)\right] t_d \qquad (3)$$

where R = droplet radius (0.59 mm), σ = Boltzmann constant (5.67×10^{-8} W/m^2°K^4), ϵ = emissivity (0.1), T_d = droplet temperature (2500°C), T_o = room temperature (25°C), h = heat transfer coefficient (163 W/m^2°C), T_f = film temperature $\left(\frac{T_d + T_o}{2}\right)$, and t_d = flight time of droplet (0.1 sec).

From the wire feed speed of 100 mm/s, the wire diameter of 1.6 mm, and the frequency of 230 droplets/s observed in the case of a 1.6-mm-diameter aluminum wire at 250 A (Ref. 10), the average droplet radius R is estimated to be 0.59 mm (0.02 in.). The droplet velocity is estimated to be 1.5 m/s (4.9 ft/s) from high-speed cinematography taken under a similar welding condition of 260 A and 1.6-mm-diameter aluminum filler wire (Ref. 11). Referring to experimental Setup 2, the distance between the bottoms of the copper plate and the copper basin is 150 mm (6 in.). Therefore, the flight time of a droplet, t_d, is about 0.1 s. The heat transfer coefficient is estimated from the droplet size and velocity, and properties of air (Refs. 12, 13). It should be pointed out that the droplet surface temperature in Equation 3 is taken as the temperature of the droplet, T_d. This is justified since the Biot number is about 0.001 and is, therefore, much less than one. The Biot number Bi is defined as 2h R/k, where k is the thermal conductivity of the droplet and is about 163 W/m°C for 4043 aluminum (Ref. 14).

From Equation 3 and the data provided, the value of Q_{loss} turns out to be about 0.18 J. From the heat content per unit mass of droplets (3116 J/g), the droplet radius (0.59 mm) and the droplet density (2.68 g/cm^3), the average heat content of a droplet is about 7.2 J.

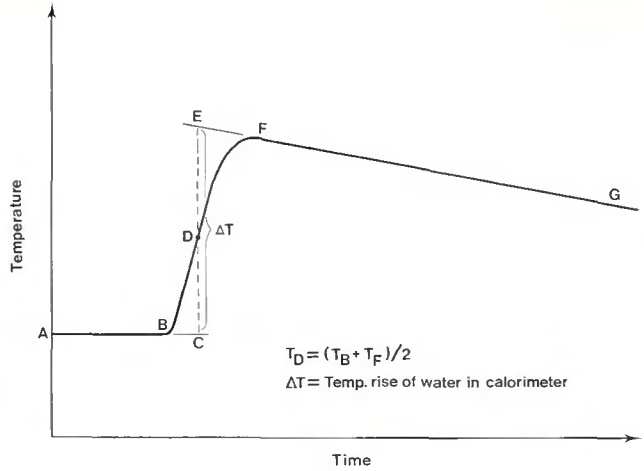

Fig. 13 — Determining the water temperature rise in the calorimeter, ΔT

Therefore, the error caused by heat losses due to radiation and convection is about 2.5%.

Conclusions

1) Three experimental setups adopted in the present study for measuring droplet heat contents in GMAW of aluminum appear to be satisfactory. These include a calorimetric-measurement setup for globular transfer, a calorimetric-measurement setup for spray transfer, and a temperature-measurement setup for globular transfer.

2) The heat content and temperature of aluminum filler wire droplets increase with increasing welding current, the rate of increase being significantly slowed down at higher currents where the welding operation is well in the spray transfer region, and where the droplet temperature approaches the boiling point of aluminum.

Acknowledgments

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Appendix

The water temperature rise in the calorimeter, ΔT, was determined, as shown in Fig. 13. A vertical line is drawn through the curve at point D, which corresponds to half the total temperature increase. The temperature-time curves in the preliminary and final periods, AB and FG, respectively, are extrapolated to intersect this vertical line at points C and E. The temperature difference CE is then taken as the corrected water temperature rise ΔT (Ref.: Kubaschewski, O., and Alcock, C. B. 1979. *Metallurgical Thermochemistry,* 5th ed., Pergamon Press, Oxford, England, pp. 71–74).