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, one also 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 (%e; %zr, and %z-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 ft³/min), and a contact tube-to-cathode distance of 19 mm (¾ 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.

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 small 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 (¾ 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...
(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 (3/4 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...
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 used by Jelmorini, *et al.* (Ref. 6), on droplet temperature measurements, in which a high-speed data-acquisition system was used.

**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 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.

**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 function of time after welding.

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.

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.
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, $\Delta T$, was determined in the way described in the appendix.

With the help of the calibration curve shown in Fig. 3, the water temperature rise, $\Delta T$, 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 $1692 \pm 44 \, \text{J/g}$.

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 $2133 \pm 204 \, \text{J/g}$. 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...
Table 1—Droplet Heat Contents in GMAW with 4043 Aluminum Filler Wire

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Setup</th>
<th>Current (A)</th>
<th>Wire speed (mm/s)</th>
<th>Voltage (V)</th>
<th>Electrode extension (mm)</th>
<th>Transfer mode</th>
<th>No. of Calorimeter runs</th>
<th>Droplet heat content (J/g)</th>
<th>Droplet temp. (°C)</th>
<th>Calorimeter</th>
<th>Thermocouple</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1, 3</td>
<td>74</td>
<td>42.3</td>
<td>18.7</td>
<td>8-10</td>
<td>Globular</td>
<td>3</td>
<td>1692 ± 44</td>
<td>1191 ± 38</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>111</td>
<td>51.2</td>
<td>22.8</td>
<td>8-10</td>
<td>Mixed</td>
<td>5</td>
<td>2133 ± 204</td>
<td>1565 ± 174</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2, 4</td>
<td>174</td>
<td>67.7</td>
<td>28.7</td>
<td>8</td>
<td>Spray</td>
<td>4</td>
<td>2816 ± 59</td>
<td>2146 ± 50</td>
<td>2333 ± 104</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>233</td>
<td>90.9</td>
<td>28.5</td>
<td>8</td>
<td>Spray</td>
<td>8</td>
<td>3036 ± 122</td>
<td>2316 ± 104</td>
<td>2401 ± 93</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>244</td>
<td>97.3</td>
<td>28.1</td>
<td>8</td>
<td>Spray</td>
<td>8</td>
<td>3116 ± 110</td>
<td>2416 ± 50</td>
<td>2333 ± 104</td>
<td>3</td>
</tr>
</tbody>
</table>

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

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:

$$H_d = \int_{T_0}^{T_m} Cp(s) \, dT + DH + \int_{T_m}^{T_f} Cp(l) \, dT (1)$$

where $T_m$ = liquidus temperature, $T_f$ as an approximation, considering that in most aluminum alloys the fraction of liquid is very small and rises sharply as $T_m$ is approached, $T_f = room temperature$, $Cp(s)$ = specific heat of solid filler metal, $\Delta H =$ heat of fusion of filler metal, $Cp(l)$ = 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 $T_m = 630°C (1166°F)$ (Ref. 8). For this reason, the thermodynamic data for pure aluminum (Ref. 9) were used as an approximation and Equation 1 becomes:

$$H_d (in J/g) = 1032 + 1.177 (T_d - 630) (2)$$

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
droplet hitting it. The measured droplet temperature in Experiment 3 is 2000°C ± 92°C (3632°F ± 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, \( Q_{\text{loss}} \), is as follows:

\[
Q_{\text{loss}} = 4\pi R^2 \left[ \varepsilon \left( T_d^4 - T_0^4 \right) + \frac{h}{\kappa} \left( T_d - T_0 \right) \right] t_d
\]

where \( R \) = droplet radius (0.59 mm), \( \varepsilon \) = emissivity (0.1), \( T_d \) = droplet temperature (2500°C), \( T_0 \) = room temperature (25°C), \( h \) = heat transfer coefficient (163 W/m²°C), \( T_f \) = film temperature \( \left( \frac{T_d + T_0}{2} \right) \), 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 250 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 \( 2hR/k \), 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 \( Q_{\text{loss}} \) 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/cm³), the average heat content of a droplet is about 7.2 J.
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.

\[ \Delta T = \frac{T_B \cdot T_F}{2} \]

\(\Delta T = \text{Temp. rise of water in calorimeter} \)

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