GTA Welding Efficiency: Calorimetric and Temperature Field Measurements

Depending on the thermal model assumed, calorimetric values can be used to develop accurate models for predicting arc efficiency

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ABSTRACT. The application of a gradient layer type calorimeter for the measurement of arc efficiency during GTA welding is described. Representative results for DC bead-on-plate welds in 12.7-mm (0.50-in.) thick 304L stainless steel plates are presented. Welding power varied from 570 to 2412 J/mm and total heat input from 31.6 to 142 kJ. Values determined for the arc efficiency are around 80%. Efficiency values of this magnitude are comparable to water-cooled anode measurements, but are high compared with published values of 21 to 65% evaluated from analytical constant property conduction heat transfer solutions using fusion zone geometry or temperature history measurements. However, when distributed heating, thermal property variation and the heat of fusion are incorporated in numerical solutions, agreement with measured temperatures is obtained with arc efficiencies in the 75 to 80% range. It is, therefore, concluded that the value of arc efficiency to be used in predictions depends on the thermal model assumed, and that calorimetric values are applicable for accurate models.

Introduction

During straight polarity welding with a gas-shielded arc from a tungsten electrode, energy is transferred to the workpiece surface primarily by the current of electrons flowing through the arc and secondarily by radiation and convection from the arc plasma. The objective is normally to melt workpiece material to a specified depth. Due to the distributed nature of heating from an arc, the molten region produced is usually wider than it is deep. The cross-sectional shape of the molten zone (characterized by the depth-to-width ratio) is thus very important in that this determines if the desired depth is achieved for a specified power input.

Because of the widespread use of GTA welding, considerable attention has been devoted to predicting the geometry of the molten zone and the surrounding temperature field. Since the heat input from the arc is a basic boundary condition for any analytical method, accurate knowledge of the fraction of the energy dissipated in the arc transferred to a workpiece is essential. This fraction is defined as the welding or arc efficiency. Values have usually been determined by requiring agreement between predicted and measured temperature histories near the molten zone or for the depth or width of the molten zone. Published values vary from 21 to 80%. This large range has prompted interest in the development of methods for measuring the energy transferred during welding rather than determining this from welding temperatures. The purpose of this paper is to describe the application of a calorimeter for this purpose and to compare and discuss results obtained with those of previous measurements.

Experimental Equipment and Procedure

Arc welding efficiencies were determined with the experimental system shown schematically in Fig. 1. A test workpiece is placed on the bottom of the calorimeter and connected to the workpiece lead as illustrated. An arc is initiated and a bead-on-plate weld formed as the workpiece and calorimeter are moved under the GTAW torch. The torch is quickly withdrawn and the calorimeter lid closed. The workpiece then cools as heat is transferred to cooling water flowing through passages under the outer surface of the calorimeter. The total heat transfer to the workpiece is determined by integrating the calorimeter signal over the time required for the workpiece to cool to its initial temperature.

The calorimeter used has internal dimensions of 150 × 150 × 75 mm (6 × 6 × 3 in.). This instrument operates on the gradient layer principle, as described in Ref. 1. The temperature drop through a thin layer of material produced by the heat flow (Fig. 2) is measured by forming the hot and cold junctions of thermocouple circuits on the inner and outer surfaces of this layer. These circuits are connected in series to form a thermopile, which multiplies the thermoelectric output. The combination of the thermopile and gradient layer forms a heat-rate meter based on the Seebeck thermoelectric effect. Since such heat-rate meters are installed in all sides, the instrument is called a Seebeck Envelope Calorimeter.

The heat-rate meters are connected in series so that the calorimeter output is a single DC signal. This signal is multiplied by a calibration constant, which accounts for the thickness and the thermal conductivity of the gradient layer material and the total wall area of the instrument. The gradient layer is thin so that thermal capacity effects are negligibly small.[1] This was verified by using three different techniques to check the calibration constant of the instrument employed. These techniques were: 1) a steady-state calibration

KEY WORDS

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[1] *The impetus for the development of this type of calorimeter appears to have been the need for a rapidly responding instrument for direct measurement of the rate of heat loss from biological systems (see Ref. 1).*

utilizing a resistance grid, 2) a transient test with a measured electrical input, and 3) measurement of the heat loss as a mass of initially boiling water cooled. Results from the latter technique plotted in Fig. 3 illustrate the linear type of response obtained. A calibration constant of 126 J/V s obtained from all three methods was within 1% of the value supplied by manufacturer (Thermonetics Corp.).

Workpieces of 304L stainless steel 0.5 in. (12.7 mm) thick were mounted on the calorimeter base. With the lid open, a direct current electrode negative (DCEN) bead-on-plate weld 75 mm (3 in.) long was made. The lid was immediately closed over the workpiece, and the output voltage from the calorimeter measured and recorded on a digital storage oscilloscope (Nicolet Model No. 4094). Up to six hours was required for the workpiece to come to equilibrium with the constant-temperature cooling water flowing through the passages near the outer calorimeter surfaces. Integration of the output voltage over the cooling time multiplied by the calibration constant then yielded the total energy transferred to the workpiece (listed as total heat input in Table 1).

Welds were made with a transistor-controlled power supply and an air-cooled torch (Linde Model HW-27) with a No. 8 gas lens cup and an argon shielding gas flow rate of 15 L/min. Four test welds were made with a 3.2-mm (⅛-in.) diameter electrode and four with a 2.4-mm (3/32-in.) diameter electrode to investigate the possible effect of electrode size. The included tip angles of these 2% thoriated tungsten electrodes were ground to 90 deg. The electrode-to-work distance was set to 3.0 mm (0.12 in).

The welding current was measured with a Hall-effect current transducer and recorded on a second digital oscilloscope for the entire weld duration. Arc voltage was also recorded with the same oscilloscope from a terminal located as close as possible to the electrode tip. The current did not fluctuate, although small voltage fluctuations were noted. The current and voltage waveforms were multiplied and integrated over the entire weld time using a data reduction feature of the oscilloscope. This result represents the true energy supplied to the arc and is reported as the total machine output in Table 1. Total machine output was noted to vary from about 90 to 100% of the nominal machine output (current × voltage × welding time) from the lowest to the highest power levels used.

All welds were sectioned at 25 and 50 mm (1 and 2 in.) from the start to measure the penetration and the cross-sectional area. The cross-sectional areas were measured from transverse weld micrographs with a planimeter. The average of the two areas was multiplied by

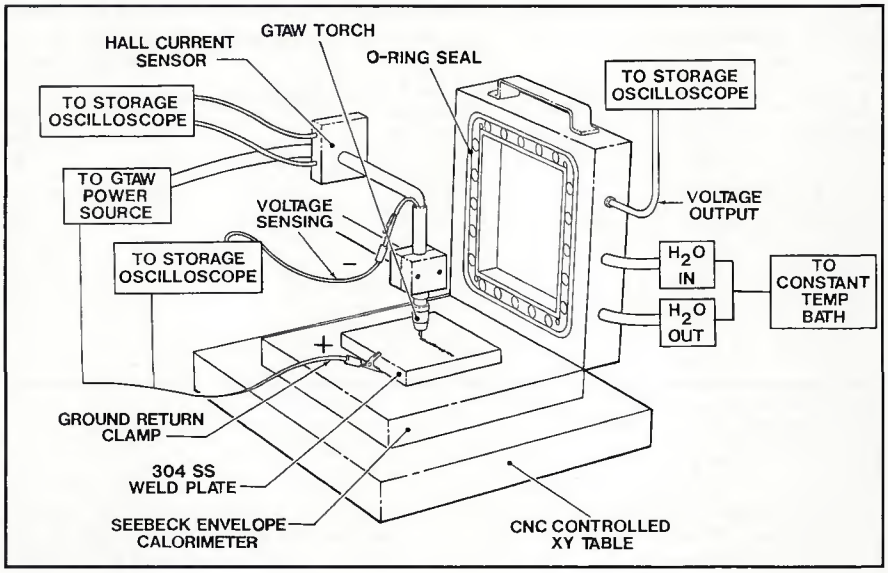

Fig. 1 — Schematic of experimental apparatus for GTAW efficiency measurements

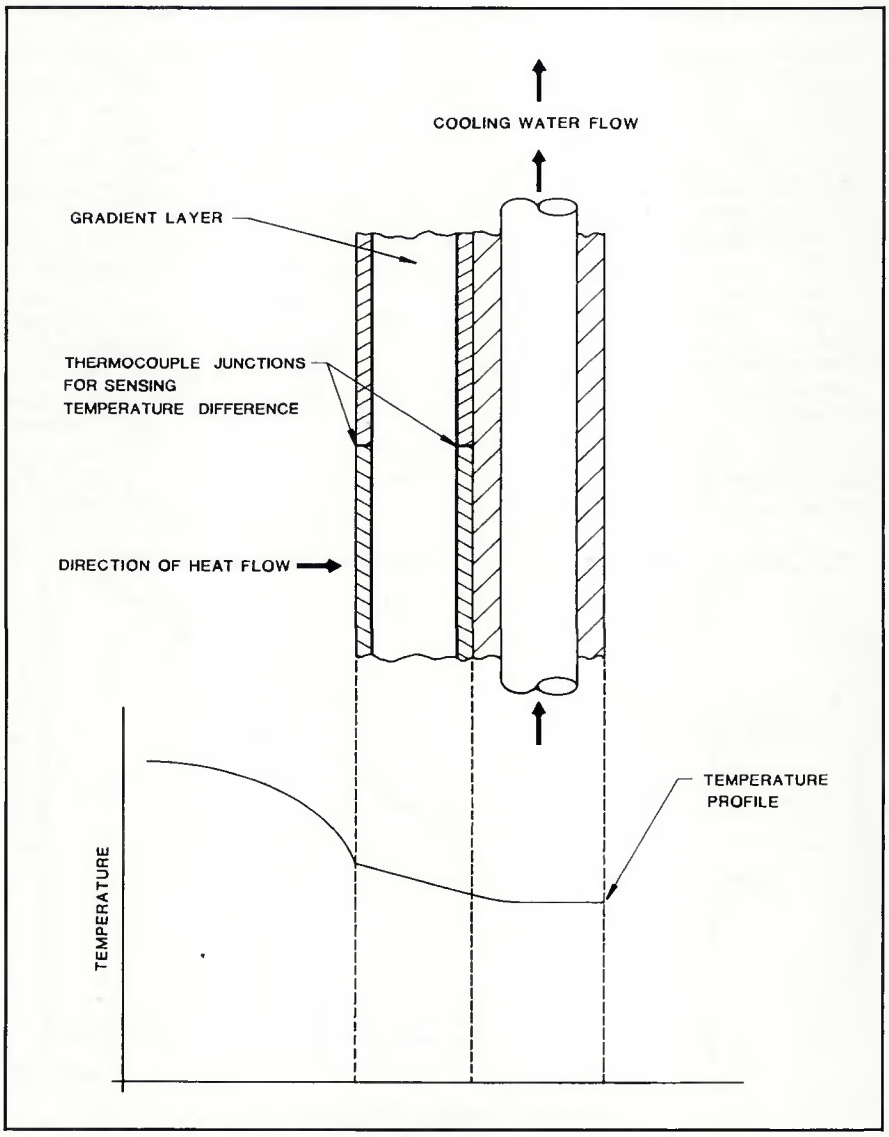

Fig. 2 — Operating principle of a gradient layer calorimeter

Table 1—Summary of Calorimeter GTA Weld Efficiency Measurements

Arc Current (A)	Arc Voltage (V)	Nominal Input Power (kW)	Total Machine Output (kJ)	Total Heat Input (kJ)	Arc Efficiency	Penetration Depth (mm)	Sectional Area (mm^2)	Heat-to-Melt (kJ)	Melting Efficiency
49.7	9.76	0.485[b]	39.3	31.6	0.80	–	–	–	0.00
100	9.77	0.977[b]	81.4	65.4	0.80	1.85	5.99	3.98	0.06
104	8.65	0.900[a]	79.6	64.7	0.81	1.72	4.54	3.66	0.06
152	10.2	1.54[b]	129	104	0.81	2.97	17.2	11.4	0.11
155	8.87	1.38[a]	122	103	0.84	3.00	16.9	11.2	0.11
200	10.3	2.05[b]	173	142	0.82	4.09	33.3	22.1	0.15
205	8.87	1.81[a]	162	131	0.81	3.71	28.6	19.0	0.15
204	9.60	1.96[a,c]	116	95.6	0.82	3.10	27.2	18.1	0.19

Welding speed = 0.847 mm/s = 2.0 ipm except as noted below.
Arc Eff. = (Heat Input)/(Machine Output)
Melt Eff. = (Heat-to-Melt)/(Heat Input)
Heat-to-Melt = (Pool Volume) (8720 J/cc)

(a) 2.4-mm-diameter electrode.
(b) 3.2-mm-diameter electrode.
(c) 1.27 mm/s.

the weld length to determine the total fused volume. It was estimated that this value could be from 2 to 3% high due to lower penetration during the starting transient period.

Experimental Results

Results for the bead-on-plate welds for heat inputs from 31.6 to 142 kJ are listed in Table 1 and plotted in Fig. 4.[2] Arc efficiency values around 80% were of the same magnitude as determined in the same apparatus for edge welds at lower heat inputs (around 4.0 kJ) (Ref. 2). The values tabulated do not include any correction for losses by radiation, convection and evaporation. These were estimated to be on the order of 1% or less of the energy dissipated in the arc. Thus, if the accuracy of the calorimeter calibration is ±1%, the possible error of the efficiencies listed in Table 1 would be +2% and −1%.

Reviewing the results for the two electrode sizes indicates that electrode diameter does not have an effect on arc efficiency. Differences listed are considered to fall within the experimental scatter. However, it is noted that for about the same currents, arc voltages for the 3.2-mm electrode are from 12 to 15% higher than for the 2.4-mm electrode.

Although arc efficiencies of 80% are high in comparison to commonly accepted values determined by Christensen, *et al.* (21–48%) (Ref. 3), and Niles and Jackson (35–65%) (Ref. 4), they are supported by recent calorimeter-type measurements (71–84%) made by Smartt, *et al.* (Ref. 5)—Fig. 4. It is also noted that water-cooled anode measurements of arc efficiency (Refs. 6, 7) yielded values from 80 to 90%. The applicability of these measurements has been questioned (Ref. 7) because the surface to which energy is transferred is solid and at a lower temperature compared to a molten surface during welding. However, it has been pointed out (Ref. 6) that approximately 89% of the energy transfer from an arc is by the electrons. Since only convection and radiation, which account for the remaining 11%, would be affected by a lower surface temperature, this should not have a major effect on arc efficiency.

Arc efficiency measurements reported for copper in Ref. 5 varied from 84 to 91% with increasing power input. These values are 4–6% higher than the results reported for steel. This would account for at least a part of the 5 to 10% higher efficiency values obtained from water-cooled tests using copper anodes. Hence, the calorimeter results listed in Table 1 tend to support the water-cooled anode values and the applicability to actual welding conditions of heat and current flux distributions determined from this type of measurement, even though melting does not occur.

[2] Efficiencies are shown in Fig. 4 as a function of current. Magnitudes and trends would be similar if presented as a function of arc power. Efficiency is also influenced by electrode-to-work distance and tip angle, welding speed, and shielding gas flow rate and composition. The effects of these variables are normally within the ranges indicated in Fig. 4 for commonly used operating conditions.

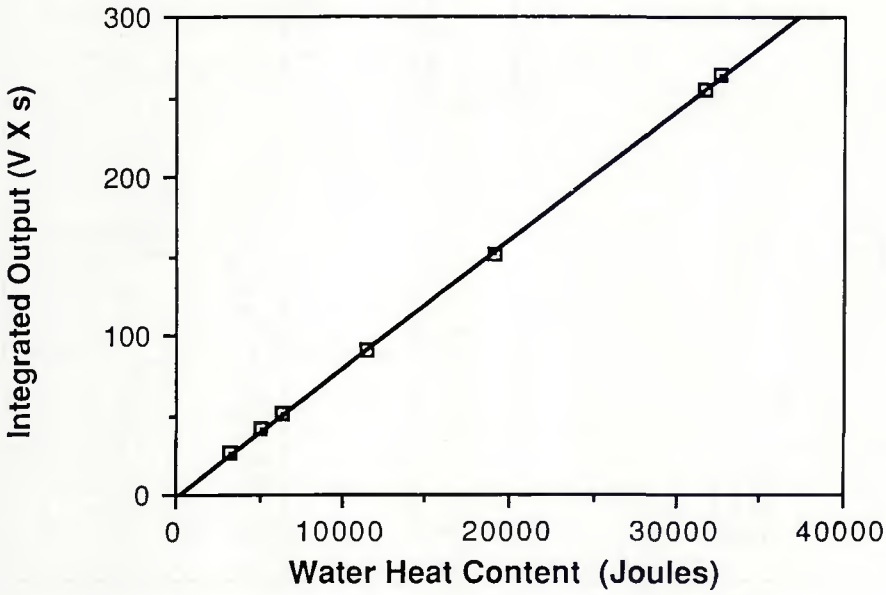

Fig. 3—Integrated calorimeter output from water-cooling calibration tests

Arc Efficiency Determination from Temperature Field Measurements

Evaluation from Moving-Point-Source Solution

The values for arc efficiency reported in Refs. 3 and 4 were determined by matching measured temperatures with temperatures predicted from the moving-point-source solution. For a heat rate source of strength q moving along the surface of a semi-infinite solid, this is given by

$$T - T_o = [q/(2\pi kr)] \exp[-(v/2\alpha)(x + r)] \quad (1)$$

Here, T is the temperature at radius r from the point source, T_o is the ambient temperature, k the thermal conductivity, α the thermal diffusivity, v the welding speed, and x the coordinate parallel to