WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, MAY 1991

Sponsored by the American Welding Society and the Welding Research Council

Effective Heat Input in Pulsed Current Gas Metal Arc Welding with Solid Wire Electrodes

Investigation reveals that the standard methods of calculating heat input for pulsed welding may give below actual values

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ABSTRACT. In this work, the heat input of the welding arc, calculated from the measured values for voltage and current, is compared to the heat gained by the weldment for pulsed and nonpulsed current welding. The effects of shielding gas composition, arc length, weld geometry and weld position on heat transfer are examined. Methods for calculating the heat received by the weld during pulsed current welding are discussed.

Introduction

The use of pulsed welding machines has improved the welding performance of many solid wire and flux cored electrodes. There are benefits in reduced spatter, improved weld beads and the ease of welding out of position. Most pulsed welding machines use analog meters to display the arithmetic mean welding voltage and current. This is satisfactory for many operations for which the heat input has not been specified. When welding heat-sensitive materials, such as quenched and tempered steel, the heat input specification must be adhered to in order to obtain optimum weldment mechanical properties (Ref. 1).

Most heat input specifications apply to welding processes in which the current is relatively constant and the heat input can be calculated as the product of the arc voltage and current. The meters on gas metal arc (GMA) nonpulsed welding machines are normally adequate for measuring the arc voltage and current in order to calculate the heat input. In pulse welding, the current fluctuates between a high peak current for the pulses and a low background current in a regular cycle, often approximating a square wave. Due to inductive and resistive effects, the waveform is altered by rise times and decay times to a more rounded form. Under the circumstances present in pulse welding, the power delivered to the arc should be measured as an arithmetic mean of instantaneous power values in order to estimate the correct heat input. Depending on the ratio of peak to background current duration, there can be a considerable difference between arithmetic mean of power values and power calculated as the product of voltage and current expressed as arithmetic mean or even as root mean square values.

An investigation has been carried out to determine the most useful method of evaluating heat input during pulsed welding. To this end, total heat transfer was

KEY WORDS

Pulsed Current Welding
GMAW
Solid Wire Electrode
Heat Input
Shielding Gas Composition
Arc Length
Weld Geometry
Weld Position
Burnoff Rate
Thermal Efficiency

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Table 1—Thermal Transfer Efficiency—Summary of Results

Steel Wire Welding Electrodes 1.2 mm Diameter

Pulsed[a] or Nonpulsed	Position Note[d]	Gas Ar%[e]	Wire Speed m min^{-1}	Wire Wt kg hr^{-1}	Volts (average) volts	Arc Length mm	I_{RMS} A	$I_{AV.}$ A	P_{av}[b] kW.	P_w[c] kW.	Efficiency %
Pulsed	B-O-P	82	9.9	5.11	35.4	5.5	292	263	9.87	7.56	76
					33.8	4.5	285	249	9.17	7.08	77
					31.5	3.5	288	250	8.66	6.86	79
					30.1	3.0	284	239	8.05	6.56	79
					28.7	2.0	280	233	7.46	6.35	85
Pulsed	B-O-P	82	4.0	2.06	28.3	6.5	148	90	3.11	2.47	79
					25.8	5.5	151	90	2.97	2.37	80
					23.5	4.0	148	84	2.65	2.26	85
					20.8	2.5	149	84	2.42	2.06	85
					18.8	1.5	144	81	2.10	1.82	87
Pulsed	V-St	82	3.4	1.75	22.0	–	175	107	2.88	2.52	87
	V-We		3.4	1.75	21.3	–	174	106	2.92	2.50	86
Pulsed	B-O-P	82	9.9	5.11	33.7	–	272	235	8.74	6.64	76
			8.0	4.13	31.1	–	236	185	6.77	5.46	80
			5.9	3.04	27.7	–	200	144	4.90	3.96	81
Pulsed	N-G	82	9.9	5.11	37.3	–	268	229	8.96	7.87	88
			8.0	4.13	32.7	–	231	172	6.47	5.73	88
			5.9	3.04	28.8	–	197	130	4.65	3.99	86
			4.0	2.06	24.0	–	151	82	2.79	2.34	84
Pulsed	H/V	82	9.9	5.11	30.6	–	293	255	8.64	7.03	82
			8.0	4.13	28.8	–	264	215	7.15	5.86	82
			5.9	3.04	26.5	–	217	160	5.16	4.27	83
			4.0	2.06	25.0	–	177	112	3.56	2.97	83
Pulsed	B-O-P	95	9.9	5.11	27.5	–	243	187	6.15	4.78	78
			8.0	4.13	25.5	–	239	180	5.40	4.39	81
			5.9	3.04	23.0	–	188	124	3.69	2.87	78
			4.0	2.06	20.3	–	148	83	2.35	1.88	80
Nonpulsed	H/V	75	9.9	5.11	34.6	–	307	307	10.7	8.86	83
			7.9	4.08	30.6	–	256	256	7.82	6.76	86
			5.9	3.04	29.3	–	219	218	6.38	5.40	85
			4.0	2.06	16.8	–	170	156	2.24	2.10	94

(a) Pulsed welding machine – adaptive EPROM control. Nonpulsed welding machine – constant voltage motor-generator set.
(b) P_{av} = Average of instantaneous power values.
(c) P_w = Heat flow rate into the weldment (measured by calorimetry).
(d) B-O-P = bead-on-plate weld; N-G = narrow-gap preparation, H/V = horizontal/vertical fillet weld. V-St = vertical stringer weld; and V-We = vertical weave weld.
(e) Argon content of the shielding gas with carbon dioxide as the balance.

measured and heat transfer efficiency calculated for both pulsed and nonpulsed GMA welding. The pulsed welding machine used in this investigation operated by varying the pulse repetition rate in accordance with the wire feed setting and the arc voltage. Each type of electrode has an optimum set of pulse parameters. The influence of the weld preparation and the composition of the shielding gas on the heat transfer were also examined.

Experimental Procedure

Welding

Welding was carried out using solid wire electrodes having a diameter of 1.2 mm (0.045 in.). Flat position bead-on-plate welds, narrow square-groove welds and horizontal-vertical fillet welds were prepared under mechanized conditions at a travel speed of 300 mm/min (12 in./min). The torch was positioned normal to the plate surface for the bead-on-plate welds and narrow groove welds. The fillet welds were prepared with the welding gun equidistant from each face and normal to the direction of travel. An electrode extension of 20 to 25 mm (0.78 to 1.0 in.) was maintained for both the bead-on-plate and horizontal fillet welds. Vertical fillet welds, as stringer beads and weaves, were prepared manually using electrode extensions and travel speeds determined by the operator to give optimum results.

The flat position weld beads were prepared on the wide face of mild steel plates with approximate dimensions of 210 × 100 × 19 mm (8.3 × 4 × 0.75 in.). The fillet welds were fabricated from 200 × 100 × 10-mm (8 × 4 × 0.4-in.) mild steel plates with the web centrally located to enable two weld beads to be deposited on the same piece of material. Narrow root opening square-groove welds were simulated by tack welding 10 × 20-mm (0.4 × 0.8-in.) steel bars edge down, with a parallel spacing of 20 mm, onto the wide face of 210 × 100 × 19-mm mild steel plates.

Power Supplies

The majority of the thermal measurements were carried out using a microprocessor-controlled pulsed welding supply. A characteristic of this type of power supply is the ability to maintain a constant arc length by monitoring the arc voltage and using a feedback loop to adjust the pulse frequency (Ref. 2). The pulse parameters were optimized throughout the normal operating current range for each electrode and the programs stored in an EPROM for recall. For comparison, nonpulsed GMA welds were carried out using a constant voltage motor-generator welding set.

Voltage and Current Recording

A digitizing storage oscilloscope was used for simultaneous recording of the voltage and current values during welding. This necessitated a compromise between digitizing rate and total recording time. A digitizing rate of 50 microseconds was used to prevent aliasing. This digitizing rate gave a total recording time of 0.4 seconds. Multiple runs, under nominally the same conditions, indicated that duplication was reasonable, with a maximum error of ±3% in the energy delivered by the arc. Arc voltages were measured between the workpiece and the welding gun cable, as close as practicable to the contact tip, and were recorded directly into the oscilloscope. A low-inductance current shunt in series with the arc enabled accurate monitoring of the current waveform (Ref. 3). Arithmetic mean power was computed from the digitally stored waveforms using the following principle:

Computed arithmetic mean power

$$P_{av} = \Sigma_{i=1}^{n} (V_i I_i) \div n \qquad (1)$$

The arithmetic mean and root mean square (RMS) voltages and currents were also computed from these waveforms.

Computed arithmetic mean

$$\text{value} = \Sigma_{i=1}^{n} X_i \div n \qquad (2)$$

Computed RMS

$$\text{value} = \{\Sigma_{i=1}^{n} (X_i)^2 \div n\}^{0.5} \qquad (3)$$

where X_i = First value; X_n for n values. From these values, the RMS power and average power were derived using the equation:

$$P = V_{av} I_{av} \qquad (4)$$

$$P_{RMS} = V_{RMS} I_{RMS} \qquad (5)$$

where P is the average power, V_{av} is the arithmetic mean voltage and I_{av} is the arithmetic mean current. Similarly P_{RMS} is the RMS power, V_{RMS} is the RMS voltage and I_{RMS} is the RMS current. The welding current recorded by the meter on the welding power supply was also noted. The meter used in this welding machine was of the D'Arsonval type.

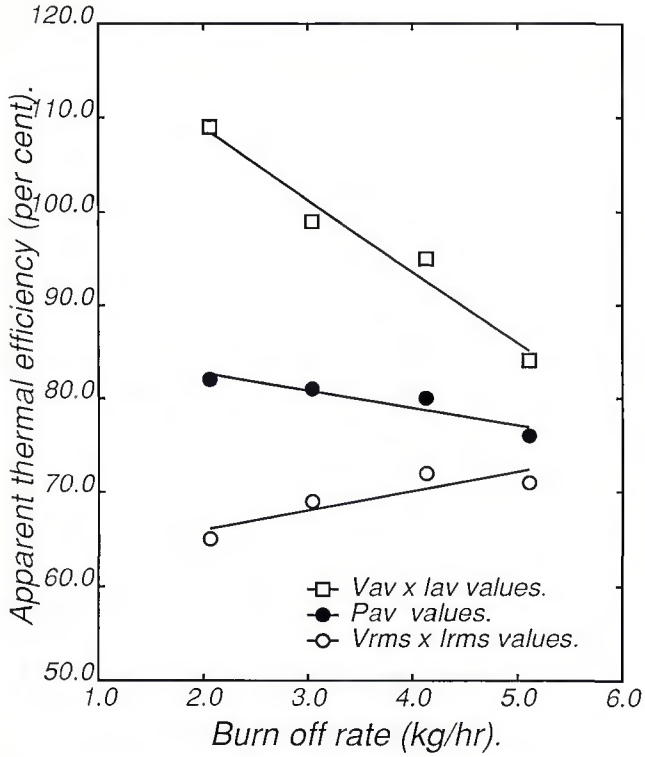

Fig. 1 — The effect of burnoff rate on the apparent thermal efficiency for pulsed GMA welding as a bead-on-plate weld with 1.2-mm diameter steel wire electrodes.

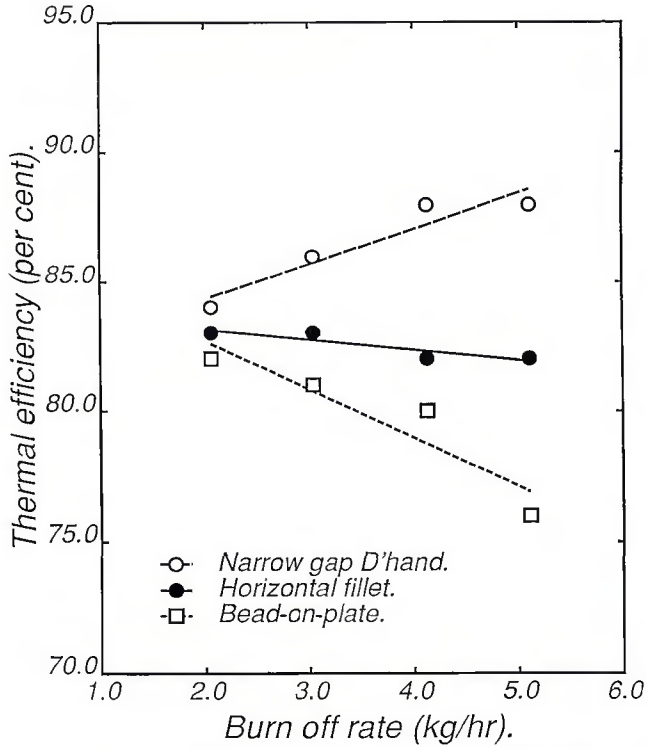

Fig. 2 — The effect of the weld preparation geometry on the thermal efficiency for pulsed GMA welding with 1.2-mm diameter steel wire electrodes.

Calorimetry

Total heat transfer to the plate was measured by monitoring the temperature rise of a water calorimeter following immersion of a welded sample. Temperature changes of the water in the calorimeter were accurately measured using a Type K thermocouple, an ice point reference and a microvoltmeter. The cooling due to the delay between the completion of a welding run and immersion of the welded sample was determined by a series of tests in which the delay times were 10, 20, 30 and 60 seconds for a constant welding condition. The heat gained by the workpiece at the cessation of welding (H_w^o) was calculated from Newton's Law of Cooling (Ref. 4) expressed in the form

$$H_w(t) = H_w^o e^{-Bt} \quad (6)$$

where B is a constant and $H_w(t)$ is the measured heat gain by the workpiece at a time t after completion of the weld. The delay time from the cessation of welding to quenching of the sample was standardized at 15 s for all of the tests. The heat input from the arc was calculated from the power delivered to the arc and welding time using:

$$H_t = P_{av}t \text{ (joules)} \quad (7)$$

the values for P_{av} being the arithmetic mean of power values calculated from the digitally recorded arc voltage and current. Thermal transfer efficiencies (E_{ff}) were calculated from the heat gained by the workpiece (H_w^o) and the heat input from the arc (H_t) according to the equation

$$E_{ff} = 100H_w/H_t \text{ (percent)} \quad (8)$$

The thermal efficiencies have been corrected for heat loss during transfer to the calorimeter and multiple determinations indicated a maximum uncertainty to the value of ±5%.

The effect of gas composition on thermal transfer efficiency in pulse welding was determined using argon-based shielding gas containing 5% carbon dioxide compared with argon containing 18% carbon dioxide. The nonpulsed GMA welds were carried out using argon containing 25% carbon dioxide. These gas compositions were chosen as being representative of the types of gas compositions normally used with these types of electrodes.

Results

Comparison of Methods Used to Measure Input Power

For nonpulsed GMA welding, the input power computed as an arithmetic mean of power values was very similar to that calculated from either the arithmetic mean or root mean square values of voltage and current for fillet welds, provided short circuiting of the arc did not occur. Short circuit transfer, due to short circuiting of the arc, resulted in a pulse-like voltage and current waveform, and the arithmetic mean power differed significantly from the power based on arithmetic mean values of voltage and current or RMS values of voltage and current as shown in Table 2. Figure 1 shows the differences P_{av}, RMS and arithmetic mean values have on the determination of thermal efficiency for pulsed welding, where thermal efficiencies in excess of 100% appeared to be possible if arithmetic mean values of voltage and current were used. Thermal efficiencies calculated using the arithmetic mean of instantaneous power values in pulsed welding tended to be in the range of 75 to 80% for the normal operating range of the electrodes tested.

Weld Preparation

Figure 2 shows the variation of thermal efficiency (calculated using P_{av}) with burnoff rate for three weld preparations. The thermal efficiency did not appear to be

Table 2—Power Input—Pulsed and Nonpulsed GMA Welds[a]

Weld process	Burn Off Rate (kg/h)	Power Input Pav (kW).	Vav × Iav (kW).	Vrms × Irms (kW).
Nonpulsed short circuiting	2.06	2.24	2.62	3.11
Pulsed welding	2.06	3.56	2.80	4.53
Nonpulsed spray-transfer	3.04	6.38	6.39	6.43
Pulsed welding	3.04	5.16	4.24	5.93

(a) Solid Steel Wire Electrodes 1.2 mm Diameter, Fillet Welds

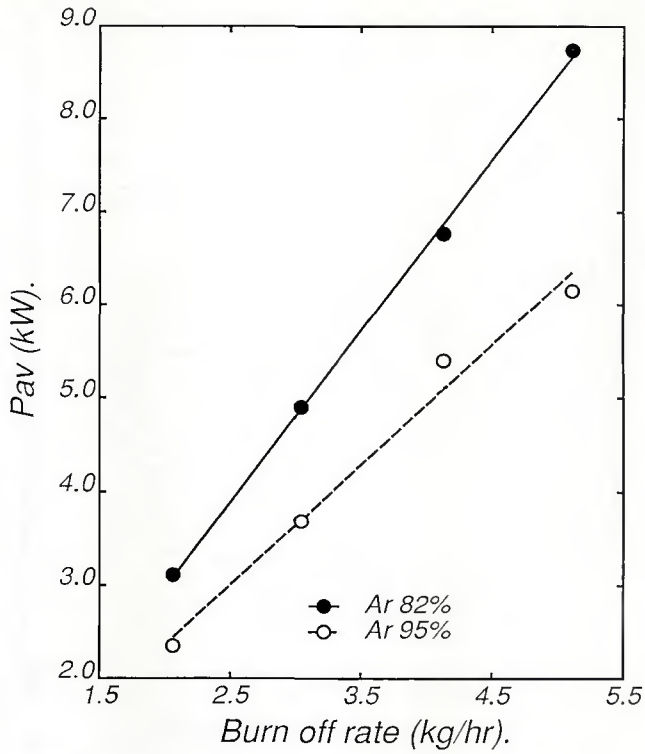

Fig. 3 – The influence of shielding gas composition on the power input for pulsed GMA welding as bead-on-plate welds with 1.2-mm diameter steel wire electrodes.

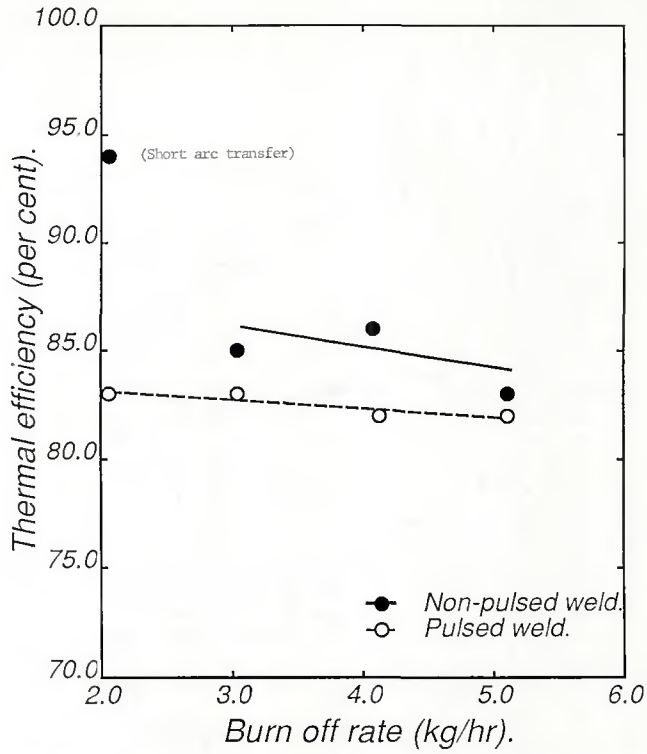

Fig. 4 – Comparison of thermal efficiency for pulsed and nonpulsed GMA welding in a fillet weld using 1.2-mm diameter steel wire electrodes.

significantly different for bead-on-plate welds, fillet welds and narrow groove welds according to burnoff rates. At higher burnoff rates, the geometry of weld preparation had a greater influence on the thermal efficiency. In descending order, the narrow groove preparation registered the highest thermal efficiency, followed by the horizontal fillet and then the bead-on-plate – Fig. 2.

Shielding Gas Composition

The use of an argon-based shielding gas with a low concentration of carbon dioxide resulted in a considerable reduction of heat input generated at the arc and received by the weld, as shown in Fig. 3. However, as shown in Table 3, there is not a significant difference in the thermal transfer efficiencies.

Table 3—Thermal Transfer Efficiency—Effect of Gas Composition[a]

Burn Off Rate (kg/h)	Gas Composition Ar (%)	Arc Voltage (V)	Power Input Pav (kW)	Efficiency (%)
2.06	82	23.7	3.11	82
	95	20.3	2.35	80
4.13	82	31.1	6.77	80
	95	25.5	5.40	81
5.11	82	33.7	8.74	76
	95	27.5	6.15	78

(a) Pulsed GMA welding as bead-on-plate welds using steel wire electrodes 1.2 mm, argon-based shielding gas with the balance carbon dioxide.

Comparison of Pulsed and Nonpulsed GMA Welding

As shown in Fig. 4, for all but short circuit transfer (at low burnoff rates), the measured thermal efficiency for nonpulsed GMA welding was marginally higher than pulsed GMA welding. At low burnoff rates, nonpulsed GMA welding operated in the short circuit transfer mode, and the thermal efficiency was considerably greater than for pulsed welding.

Effect of Arc Length

Optical means were used to measure the arc length for a solid wire electrode operated using a pulsed welding machine for a range of program voltages. The voltages were recorded and processed to give arithmetic mean values. The results summarized in Fig. 5 show a linear relationship between the arc voltage and arc length. In addition, the thermal efficiency was found to decrease as the arc voltage increased and this rate of change was similar for both low and high welding currents as shown in Fig. 6.

Table 4—Effect of Welding Position on Thermal Transfer[a]

Welding Position	Burn Off Rate (kg/h)	Power from the Arc P_{av} (kW)	Power Received by Weldment (kW)	Efficiency (%)
Vertical stringer	1.75	2.88	2.52	87
Vertical weave	1.75	2.92	2.50	86
Standing fillet	1.75	3.02	2.50	83

[a]Pulsed current welding, in a fillet weld, steel wire 1.2 mm diameter, shielding gas Ar 82%, CO_2 18%.

Effect of Vertical Welding

The vertical welds were made manually, as stringer beads and weaves, using solid wire electrodes of 1.2 mm with a pulsed welding machine. The deposition rate and fine tuning of the pulse parameters were optimized by the welding operator to achieve a high quality weld for each of the electrodes tested. Despite the manual operation, the results showed a high level of reproduceability comparable to automatic welding. As shown in Table 4, the thermal efficiencies for the welds were essentially equal for both stringer and weave welding techniques.

The results for all these tests are summarized in Table 1.

Discussion

Thermal Transfer Efficiency and the Weld Process

The attainment of maximum mechanical properties in welded joints in harden-

able material is dependent in part on the development of an optimum metallurgical structure in the weld, which in turn is influenced by its thermal history. This temperature cycle is related to the effective welding heat input, and its importance is indicated by heat input restrictions shown in recommended welding procedures (Ref. 5). The *Metals Handbook* that deals with welding (Ref. 6) indicates adjustments to the heat input based on the welding process, and it recommends a heat transfer efficiency of approximately 90% should be employed for gas metal arc welding and flux cored arc welding. Allum and Quintino (Ref. 7), in their study of fusion characteristics in pulsed current welding, recorded transfer efficiencies of 62% and 72% for 1.2-mm electrodes for an arc current of 100 A at high and low voltages, respectively. The present work recorded thermal efficiencies of 75 to 80% for 1.2-mm steel wire electrodes when operated at normal welding currents using a pulsed welding machine. Solid wire nonpulsed GMA welds recorded values of 85 to 95%. Importantly, it was found that the heat input into the weld was lower for pulsed GMA welding than nonpulsed GMA welding, except for short circuiting arc welding. The reason pulsed current welding has a lower heat input is due to the optimization of the pulse parameters so that sufficient energy is supplied in the pulse current in order to transfer only one droplet of metal per pulse and that the lowest possible energy is supplied between pulses to maintain the arc plasma. In nonpulsed current welding, the arc current is maintained at a relatively high level whether a metal droplet is being transferred or not. Short circuiting arc welding is a special case of nonpulsed welding in that the regular transfer process in effect simulates the pulsed current welding process and therefore also has a low heat input.

Comparison of Arithmetic Mean and Root Mean Square Values

Traditionally, whenever welding voltages and currents have been stated for direct current machines, the arithmetic mean values have been quoted. This convention appears to have been adopted as the norm for pulsed welding machines (Refs. 6, 7). Dilthey and Killing (Ref. 8) have examined the thermal input in regard to arithmetic mean values and root mean square (RMS) values for current and voltage during pulsed welding with solid wire electrodes. The heat gained by the weldment was determined from measurements of the cooling time of the weld between 800° and 500°C (1472° and 932°F). The welding currents required to produce this heat input were calculated from these measured values. In their experiments, the arithmetic mean current showed good correlation with the current determined from heat measurements on the weldment. The present work on pulsed current welding showed, using calorimetric methods, that heat transfer efficiencies based on arithmetic mean currents to be very sensitive to the electrode burnoff rate and may exceed 105% at low burnoff rates (Fig. 1), which is clearly unrealistic. This discrepancy results from the fact that the product of arithmetic mean voltage and current does not equal the integrated arithmetic mean power input. Although the voltages and currents in pulsed welding can be measured as RMS values, the product of these values will not give the correct power values. Ideally, the effective heat inputs for pulsed welding should be derived from the arithmetic mean of instantaneous power values and corrected for thermal transfer efficiency.

In practice, this would require the welding machine to process the instantaneous values of voltage and current and display the result as arithmetic mean power. However, the meters normally installed in most pulsed welding machines read the arithmetic mean values for arc current and voltage.

If the heat input requirements are not highly stringent, then the power input from the welding arc of a pulsed welding machine at a given arithmetic mean current or electrode burnoff rate can be approximately estimated from Figs. 7–9. The above methods do not take into consideration the effect of weld preparation, shielding gas composition and arc length on thermal transfer efficiency.

If the thermal transfer efficiencies measured for the specific cases above apply more generally to other similar welding

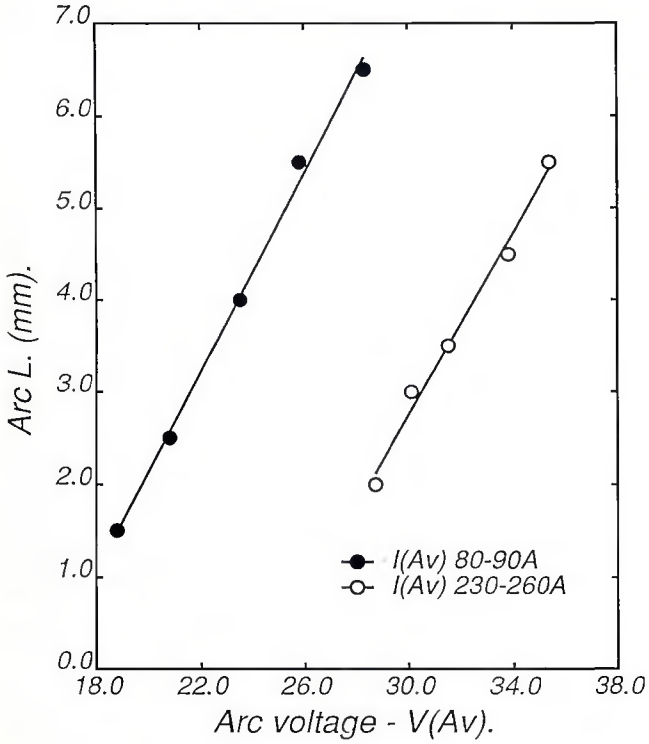

Fig. 5 — Effect of welding current and voltage on the arc length for pulsed GMA welding with 1.2-mm diameter steel wire electrodes.

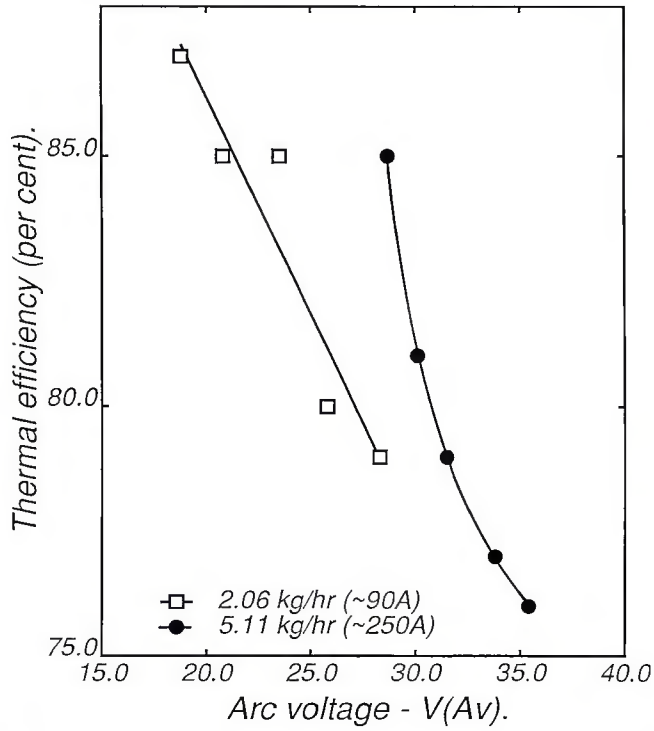

Fig. 6 — The effect of arc voltage on thermal efficiency for pulsed GMA welding as bead-on-plate welds using 1.2-mm diameter steel wire electrodes.

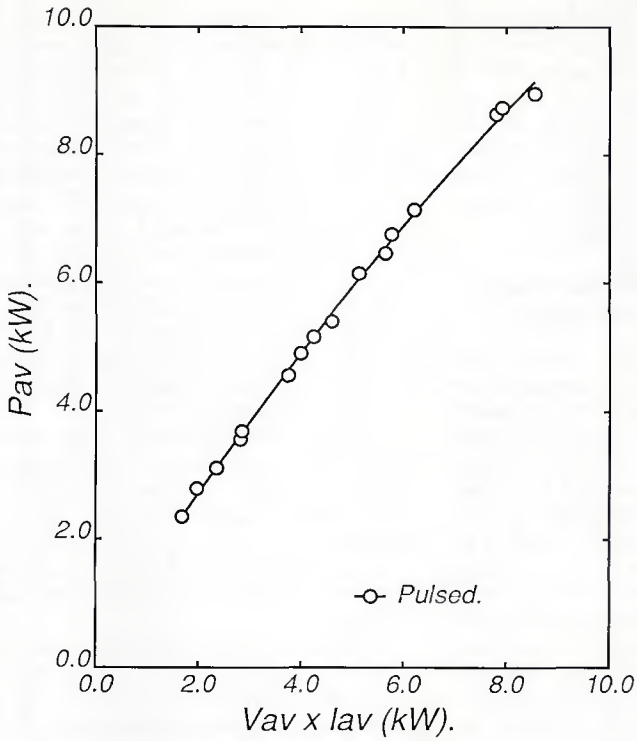

Fig. 7 — Input power compared to the product of average voltage and average current in pulsed GMA welding using 1.2-mm diameter steel wire electrodes.

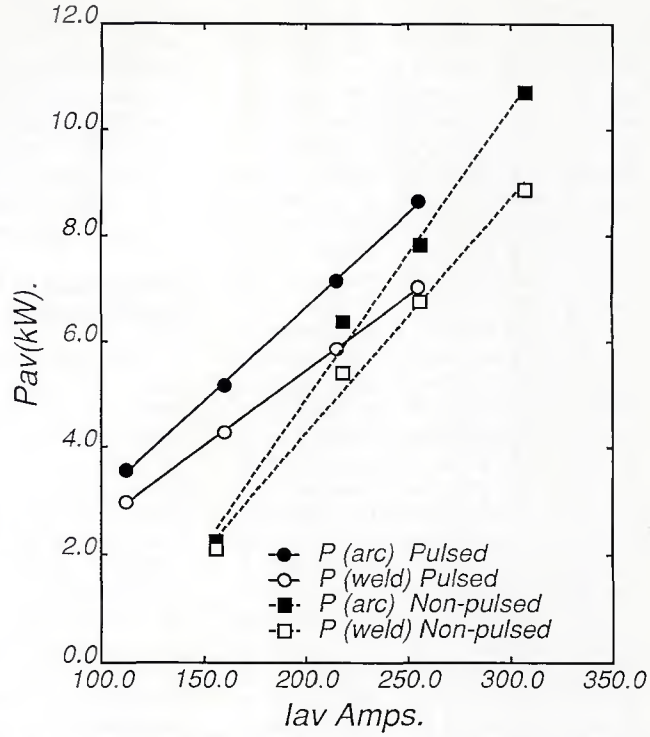

Fig. 8 — Input power and power received by the weldment compared with the average current for pulsed and nonpulsed GMA welding processes using 1.2-mm diameter steel wire electrodes in a fillet weld.

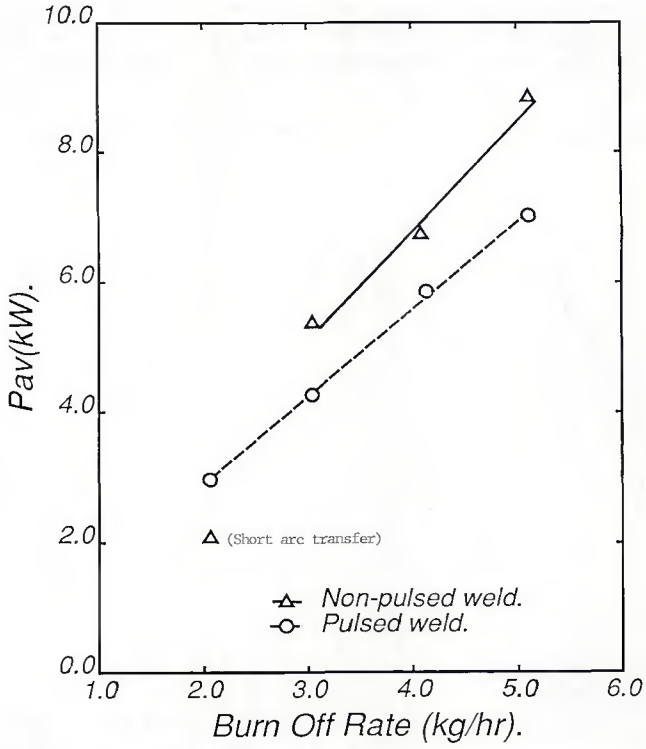

Fig. 9 — Comparison of pulsed and nonpulsed GMA welding in a fillet weld on the power received by the weldment in relation to the burn-off rate of 1.2-mm diameter steel wire electrodes.

electrodes and the arithmetic mean power of the arc is known, then the heat transferred to the weldment (H_n) can be calculated from:

$$H_n = E_{ff} P_{av} / v \qquad (8)$$

Where E_{ff} = thermal efficiency, P_{av} is the arithmetic mean power and v is the welding speed (mm/s).

Thermal Efficiency and Weld Preparation

With reference to Fig. 2, the bead-on-plate and the horizontal fillet welds were prepared using the same pulse controlling program. The arc length had been adjusted to achieve optimum welding conditions. At low burnoff rates, the thermal efficiencies for both welding preparations were essentially equal, but as the current was increased, the thermal efficiency for the bead-on-plate weld diminished more rapidly than for the fillet weld. It would appear that the more confined geometry of the fillet weld prevented the loss of radiant and convective heat from the arc to the atmosphere. As mentioned previously, the narrow groove is a special case. The pulse parameters in this case were considerably different from those used previously. This was necessary in order to stabilize the arc in the deep and narrow confines of the preparation. As can be seen from Fig. 2, the thermal efficiency increased at high burnoff rates to achieve an efficiency considerably greater than the horizontal fillet and bead-on-plate welds.

Although these thermal efficiency differences appear large, according to Adams (Ref. 9), the influence of the weld preparation geometry on heat extraction paths has a more significant effect on the cooling rate and must be taken into consideration as it is the cooling rate and not the heat input that predominantly determines the metallurgical structure.

Positional Welds

Generally, positional welds are restricted to relatively low currents and at a minimal arc voltage sufficient to sustain the arc without creating undue spatter. The geometry of the weld preparation for the vertical welds was very similar to the horizontal fillets. Therefore, it was not surprising to find the thermal transfer efficiencies for stringer beads and weaves prepared in vertical fillets were very similar to the values obtained for horizontal fillet welds prepared at the same electrode burnoff rate — Table 4.

Thermal Efficiency and Shielding Gas Composition

French (Ref. 10) determined that for an argon-carbon dioxide shielding gas mixture, a decrease in carbon dioxide concentration reduced the thermal transfer efficiency for nonpulsed GMA flux cored electrode welding. The present work indicates that the same change of shielding gas during pulse welding with 1.2-mm steel wire electrodes had negligible effect on thermal efficiency — Table 3. However, a reduction in the carbon-dioxide content of argon-based shielding gas resulted in a lower average arc current and voltage for an equivalent electrode burnoff rate. As a consequence, the heat generated at the arc, and importantly the heat received by the weldment, was considerably lower for pulsed welds using argon-based shielding gases containing a low concentration of carbon dioxide — Fig. 3.

Thermal Efficiency and the Effect of Arc Length

The experimental results showed that the thermal transfer efficiency in pulsed welding decreased as the arc voltage was increased for a given burnoff rate — Fig. 6. The welding current also increased as the arc voltage increased, and therefore, the heat input generated at the arc increased. This increase in heat input, despite the reduction in thermal transfer efficiency, resulted in raising the heat received by the weld for an increase in arc voltage.

Conclusions

1) The calculation of heat inputs based on meters measure arithmetic mean voltage and current for pulsed welding has been demonstrated to give values considerably lower than the effective heat input. This error in calculating the heat input during welding may result in undesirable metallurgical properties. Where possible, the arithmetic mean of instantaneous power values for the arc should be measured during pulse welding in order to minimize errors in heat input calculations.

2) Nonpulsed GMA welding was found to have a higher heat input than pulsed current welding for the same electrode burnoff rate (with the exception of short circuiting arc welding). Nonpulsed GMA welding in the short circuiting mode had a low heat input compared to spray-type transfer and pulsed GMA welding.

3) With the exception of short circuiting arc welding, the thermal efficiency of nonpulsed GMA welding is similar to that of pulsed current welding. The thermal efficiency for nonpulsed GMA welding for a range of burnoff rates was approximately constant at 85%, with the exception of short circuit transfer in which a thermal efficiency value of approximately 95% was measured. Thermal efficiency for pulse welding was dependent on the burnoff rate and ranged from approximately 85% for low burnoff rates to 80% at high burnoff rates.

4) Unlike nonpulsed GMA welding, the carbon dioxide content of the argon-based shielding gas had little effect on the thermal transfer efficiency in pulsed welding. However, the heat input, and therefore the heat gained by the weldment, was considerably less when argon-based shielding gases containing a low concentration of carbon dioxide was used in pulsed welding.

Acknowledgment

The assistance of Mr. T. Gordon in the preparation of vertical welds is greatly appreciated.

References

1. Standards Association of Australia, 1980. *Australian Standard 1554, Part 1.*
2. Ogilvie, G. J., and Ogilvy, I. M. 1983. The Pulsed Welding Process in Automatic Welding. *Proceedings of the 31st Annual Conference of the Australian Welding Institute, pp. 16-19.*
3. Street, J. A. 1987. Practical Measurement of Voltage and Current in Arc Welding. *Metal Construction*, pp. 646-648.
4. Ference, M., Lemon, H. B., and Stephenson, R. J. *Analytical Experimental Physics*, 3rd *Edition*, University of Chicago Press.
5. AWRA Technical Note 1, 1978. *The Weldability of Steels. Australian Welding Research Association, pp 24-25.*
6. *Metals Handbook Ninth Edition*, 1983. Volume 6 — welding, brazing, and soldering. ASM International, Materials Park, Ohio, pp 31-32.
7. Allum, C. J., and Quintino, L. 1985. Control of fusion characteristics in pulsed current MIG welding — Part 2. *Metal Construction*, Vol. 17, pp. 21-24.
8. Dilthey, U., and Killing, R. 1987. Contribution to calculating the heat input in pulsed arc gas-shielded metal-arc welding. *Welding and Cutting* 39(10):E160-E162.
9. Adams, C. M. 1958. Cooling rates and peak temperatures in fusion welding. *Welding Journal* 37(5):210-s to 215-s.
10. French, I. E. 1984. Influence of shielding gas composition on heat transfer in flux cored arc welding. *Australian Welding Journal* 29(3): 25-28.