A Comparison of Pulsed and Conventional Welding with Basic Flux Cored and Metal Cored Welding Wires

Pulsed power operation appears to improve performance of both types of welding wire

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ABSTRACT. The results of a comparison between the use of a programmable pulsed power supply and a conventional (constant voltage) power supply with both basic flux cored and metal cored welding wires are described. Investigations were made of welding behavior and bead characteristics for both horizontal and uphill fillet welds for each combination of wire and power supply. In addition, all-weld-metal tensile and low-temperature impact properties, as well as weld composition and metallographic features are reported for each wire and power supply combination. The results for the basic flux cored wires indicate that the use of pulsed welding allows a major extension to the usable range of welding currents and some positional welding capability, without significant changes to deposition rates, weld metal mechanical properties, composition or microstructure. With metal cored wires, the use of pulsed welding not only resulted in a major extension to the range of usable welding currents and improved positional welding capability, but also in improved weld metal mechanical properties.

Introduction

Tubular gas-shielded arc welding wires can be divided into three general classes according to the type of slag formers present. These general classes are rutile flux, basic flux and metal cored welding wires.

Rutile flux welding wires are generally the most "user friendly." They give smooth arcing over a wide range of welding currents, good bead shape and can be used for all-position welding. Good positional welding capabilities are achieved by using a slag composition that begins to solidify at temperatures high enough to provide some support to the weld pool. Standard rutile flux wires do not produce welds with premium low-temperature impact properties or very low weld deposit hydrogen values of less than 5 mL/100 g of deposit. However, relatively recent developments, particularly the use of microalloying additions and refinements in manufacturing, have led to considerable improvements in both these aspects (Refs.1–3).

Basic flux welding wires are used when premium weld metal mechanical properties and very low deposit hydrogen levels are required. A major drawback of these wires is their operating behavior. Compared to rutile flux wires they have a harsher arc, more convex bead shape and produce higher levels of spatter. Even at small diameters, basic flux wires are not in general suited to out-of-position welding because, at the lower welding currents necessary for positional welding, metal transfer involves large molten drops which rely on gravity for satisfactory bead formation. In addition, basic slag does not give the support to the weld pool attainable with rutile slags.

KEY WORDS

Pulsed Welding
GMAW
Metal Cored Wires
Basic Flux Cored Wire
Welding Currents
Deposition Rates
Mechanical Properties
Bead Shape
Root Penetration
Weld Microstructure

Metal cored wires provide an extra high-deposition rate process with mitre-shaped fillet beads and little slag cover. They normally operate using argon-rich shielding gases and at a current density and voltage to facilitate a spray-type of metal transfer. Welding currents for these wires are therefore usually limited to relatively high values. At low currents, metal transfer is via large, gravity-influenced molten drops and as a result positional welding capabilities are restricted.

This brief description of the characteristics of these wires illustrates that, while rutile wires offer ease of use, particularly for positional welds, the basic flux and metal cored wires offer potential advantages in terms of weld mechanical properties, diffusible hydrogen levels, deposition rates and efficiencies. The main disadvantages of the basic flux and metal cored wires are the restricted current ranges in which they operate satisfactorily and their unsuitability for use in positional welding.

A possible way of overcoming the shortcomings in operating behavior of basic flux and metal cored wires is by the use of a pulsed power supply. Over the past few years, considerable development of pulsed welding power supplies has occurred (Refs. 4, 5). These have been successfully applied to solid wire

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Table 1 — Test Plate Procedure Details

	Basic Wires				Metal Cored Wires			
Flux Size Weld	1.2 mm Diameter Non-pulsed	1.2 mm Diameter Pulsed	1.6 mm Diameter Non-pulsed	1.6 mm Diameter Pulsed	1.2 mm Diameter Non-pulsed	1.2 mm Diameter Pulsed	1.6 mm Diameter Non-pulsed	1.6 mm Diameter Pulsed
Layer 1-2	2 passes	2 passes	2 passes	2 passes	2 passes	2 passes	2 passes	2 passes
Layer 3-4	3 passes	3 passes	2 passes	2 passes	3 passes	3 passes	2 passes	2 passes
Layer 5-6	3 passes	3 passes	3 passes	3 passes	3 passes	3 passes	3 passes	3 passes
Voltage	31	31	30	33	32	30	31	29
Current (A)	241	225	298	292	261	250	322	328
Wire Feed Speed (m/min)	10.4	11.0	6.0	6.3	10.5	9.3	5.6	6.3
Weld Speed (mm/min)	345	335	315	320	360	310	345	390
Heat Input (kJ/mm)	1.3	1.4	1.7	2.0	1.4	1.6	1.7	1.9

gas metal arc welding to give improved control over weld metal transfer by ensuring that a synthetic spray mode of metal transfer occurs over a wide range of average welding currents. Some reports have appeared (Refs. 6, 7) describing the use of pulsed power supplies with flux cored wires, but these have been concerned with specific applications.

This paper compares the combinations of basic flux and metal cored wires with programmable pulsed power supplies to the use of such wires with conventional (constant voltage) power supplies. It should be emphasized that in the following report the wires used were standard basic flux and metal cored wires developed for use with conventional power supplies and conforming to AWS Classifications E70T-5 (Ref. 8) and E70C-3 (Ref. 9), respectively.

Welding Equipment

The nonpulsed power supply used in these trials was a standard GMAW machine of the three-phase bridge rectifier design capable of delivering up to 650 A at a preset constant voltage. Voltage control was via a stepwise selector switch, and the current depended on the rate at which the wire electrode was fed into the arc.

A pulsed welding machine with a transistorized switched output, controlled by a microprocessor, was used to prepare the pulsed weld samples in these trials. The microprocessor in the pulsed welding machine has access to a library of programs, each one configured to suit a particular electrode. Each program contains a list of arc-control parameters selected to provide the best operational conditions for the welding process and the type of electrode. Arc-control parameters such as peak current, background current, average voltage, range of pulse frequencies, pulse duration and wire feed speeds can be changed using a built-in RS-232 communication link to a computer. Normally, 11 of the control parameters need optimization when a program is prepared for a new electrode, although there are more "special" control parameters available. The initial optimization of the parameters for a particular electrode involves working through a matrix of parameters to enable the electrode to operate in the horizontal-vertical and vertical (2F and 3F) fillet welding positions with a high degree of arc stability and minimal spatter. Further optimization of the parameters may be required in order to achieve root penetration while retaining a relatively flat bead profile.

A shielding gas mixture of nominally 82% argon, 18% carbon dioxide was used for all the welds produced by each machine.

Consumables and Test Procedures

The wires used for this study were basic flux (E70T-5) and metal cored (E70C-3) ones of 1.2 and 1.6 mm (0.045 and 0.062 in.) diameter. The principal core ingredients of the basic flux wires were fluorspar, calcite and silica, to give a basic slag system, plus iron powder and alloying additions of Mn and Si. The metal cored wires contained primarily iron powder plus alloying additions of Mn and Si.

Two series of welding trials were conducted to establish the welding conditions for the two types of wire when they were used in combination with a pulsed and a nonpulsed welding machine. The first was to establish the practical operating range, deposition efficiency, fillet shape and joint penetration for single-pass welds in the 2F position using 10-mm (0.4 in.) steel plates for each wire/power supply combination. The second series of trials aimed at investigating the practicality of uphill (3F position) fillet welding of 10 mm steel. Single pass stringer and weave welds in the 3F position were examined in regard to bead profile, edge wetting, root penetration and current range for each wire/power supply combination. Weld beads with good edge wetting, minimal convexity and joint penetration to the root of the weld are indicative of good positional welding capability.

In addition to these trials, test plates were welded with each wire/power supply combination. These test plates were welded in the flat (1G) position and followed the AWS procedure (Ref. 8). Details of run sequence and average welding parameters for each case are listed in Table 1. Specimens for Charpy V-notch (CVN) impact testing, all-weld-metal (AWM) tensile testing, metallography and chemical analysis were taken from these test plates. At least three CVN tests were carried out at each temperature.

Results and Discussion

Pulsed Welding: Optimization of Parameters.

The improvement in arc stability in pulsed welding through optimization of the control parameters can extend the operational range of flux cored wire electrodes. This is because the pulse current is preprogrammed to exceed the threshold current for axial droplet transfer, even at low average currents. The high pulse current exerts a pinch effect on the molten material at the tip of the electrode sufficient to propel a single droplet axially through the arc to the workpiece. It is this effect which gives good control over metal transfer during welding. The duration of the high-current pulse is critical, as pulses which are too long or too short result in the generation of excessive spatter. The background current is preprogrammed to just maintain an arc between each pulse without extinguishing. In general, to operate successfully (*i.e.*, to achieve the transfer of one droplet per pulse from the electrode) a pulse energy of approximately 50 J was required for the 1.2-mm electrode and 90 J per pulse for the 1.6-mm electrode for both basic flux and metal cored wires.

Basic Flux Cored Wires

Horizontal/Vertical Fillet Welds

Basic electrodes normally contain fluorides which act as slag formers and aid in the prevention of excess hydrogen accumulation in the weld metal. These flu-

Table 2 — Deposition Characteristics for Pulsed and Nonpulsed Welding

Pulsed (P) or Nonpulsed (NP)	Operation	Weld Position Stringer (S) Weave (W)	Current (A)	Root Penetration (mm)	Consumption Rate (kg/h)	Deposition Rate (kg/h)	Efficiency (%)
		Basic Flux Cored Wire Electrode 1.2 mm					
P	Min.	2F	102	0.0	1.61	1.51	94
P	Opt.	2F	213	0.5	4.70	4.42	94
P	Max.	2F	249	0.25	5.01	4.76	95
P	Opt.	3F/S	117	1.0	1.85	—	—
P	Opt.	3F/W	117	0.5	1.83	—	—
NP	Min.	2F	200	0.0	3.46	3.18	92
NP	Opt.	2F	240	0.0	4.70	4.37	93
NP	Max.	2F	300	0.0	7.27	6.76	93
NP	Opt.	3F/S	150	0.0	2.59	—	—
NP	Opt.	3F/W	160	0.0	2.55	—	—
		Basic Flux Cored Wire Electrode 1.6 mm					
P	Min.	2F	108	0.0	1.63	1.43	88
P	Opt.	2F	330	0.5	5.15	4.74	92
P	Max.	2F	372	0.5	5.94	5.52	93
P	Opt.	3F/S	150	0.5	2.36	—	—
P	Opt.	3F/W	174	0.5	2.40	—	—
NP	Min.	2F	240	0.0	3.36	2.99	89
NP	Opt.	2F	300	0.0	4.92	4.62	94
NP	Max.	2F	400	0.5	8.62	7.67	89
NP	Opt.	3F/S	160	0.5	2.29	—	—
NP	Opt.	3F/W	170	0.0	2.29	—	—

orides have an adverse effect on the stability of the welding arc, particularly at low currents. The use of high currents and an argon-rich shielding gas enables the basic electrodes to operate with spray transfer giving good penetration and a bead of acceptable appearance. As the current is reduced in nonpulsed welding with basic electrodes, the instability of the arc causes excessive spatter and erratic droplet transfer. The operational ranges for nonpulsed welding with the 1.2 and 1.6-mm-diameter basic electrodes have been determined and are shown in Fig. 1 together with the operational range when the same electrodes are operated using a pulsed welding machine. The extension of the operational range to lower currents by the use of pulsed welding is readily apparent. The minimum operating currents for both diameters of electrodes were similar. At such low currents, the pulse repetition rate became too low to sustain a stable arc.

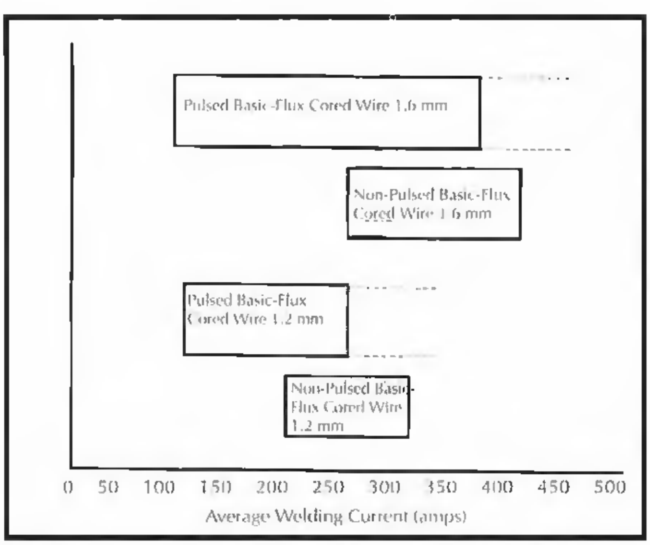


Fig. 1 — Operating range for basic flux cored welding wires in horizontal/vertical fillet welds.

The reason that the range for pulsed welding did not extend as high as nonpulsed welding is due to a built-in microprocessor program limit which prevents pulse overlap. The pulsed welding machine microprocessor control program used in these experiments was specially chosen to improve the low-current performance of basic flux cored electrodes. Higher currents can readily be achieved by a minor change to the control parameters of the microprocessor, and since this particular pulsed welding machine has a potential library capacity for a total of two hundred different control programs, higher currents could easily be catered for by selection of a high-current program when required.

The measured deposition efficiencies for nonpulsed and pulsed welds using basic electrodes were comparable, as shown in Table 2, and exceeded 85%. It would be expected that the deposition efficiencies would be considerably less if the electrodes were operated at currents below the established operating ranges due to generation of excessive spatter. The electrode deposition rates at equivalent currents for pulsed and nonpulsed welds were similar — Table 2.

Uphill Fillet Welds

Vertical stringer and weave beads of 4 to 5 mm (0.16–0.2 in.) and 8 to 10 mm (0.32–0.4 in.) leg lengths, respectively, were attempted with wires of the two diameters under both conventional and pulsed conditions — Table 2. With the 1.6-mm wire and conventional power, plausible vertical welding was only achieved by changing to electrode negative polarity and using low welding voltage (about 18 V). Even under these conditions, both the stringer and the weave

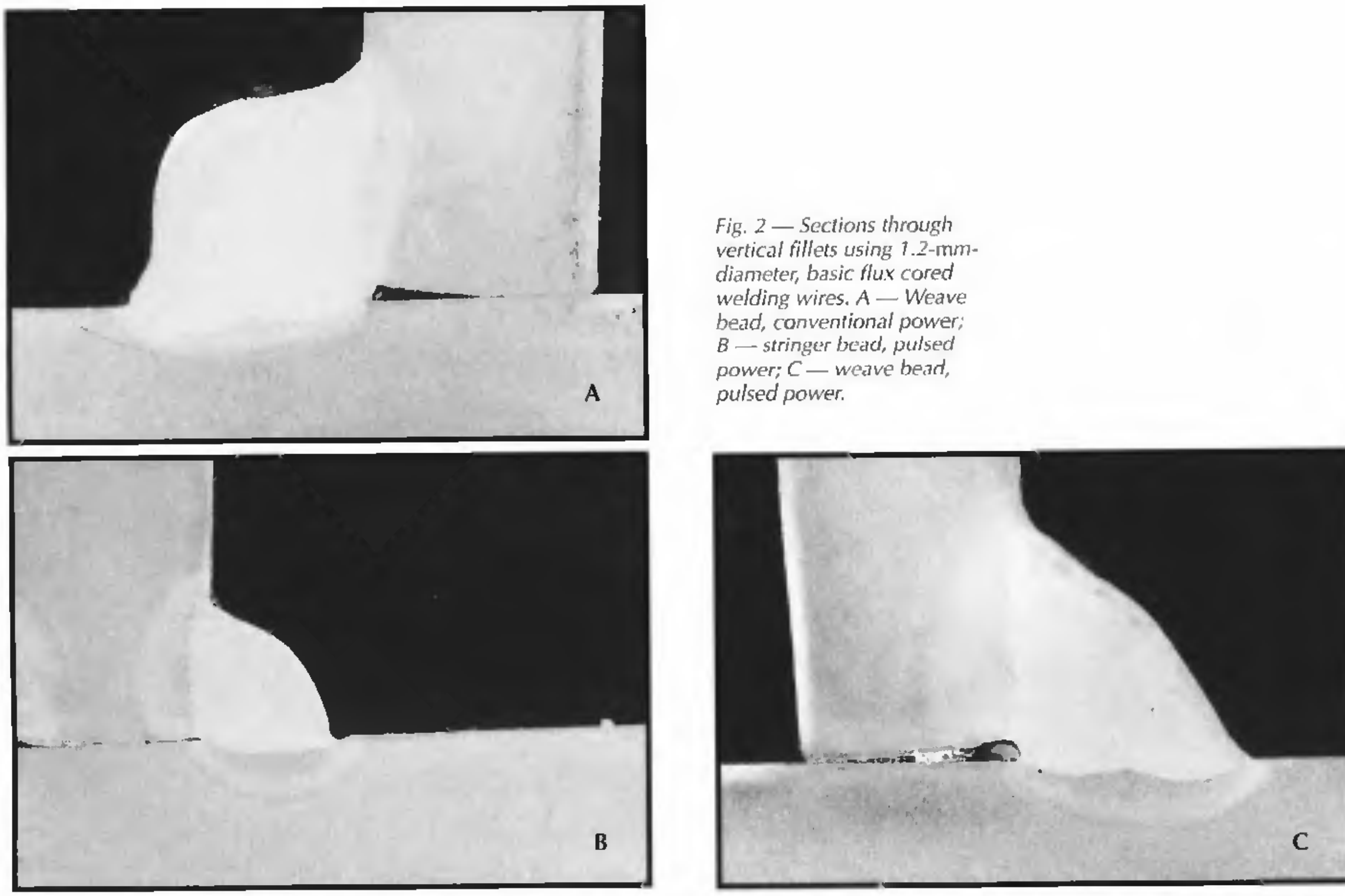


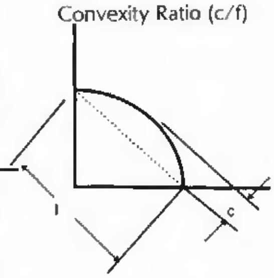
Fig. 2 — Sections through vertical fillets using 1.2-mm-diameter, basic flux cored welding wires. A — Weave bead, conventional power; B — stringer bead, pulsed power; C — weave bead, pulsed power.

beads were very convex and would be considered unacceptable in practice — Table 3. Under pulsed conditions, the 1.6-mm wire gave improved operation, with controlled metal transfer and low spatter being achieved at average currents of 150 A and above. Although the stringer beads and weave passes were not as convex as those for the nonpulsed welds (Table 3), they were still too convex for practical application. The basic flux wire of 1.6-mm diameter was therefore not suited to vertical welding with either conventional or pulsed power.

With the 1.2-mm wire and conventional power, reasonable welding operation was achieved with welding conditions of 150 A, 20 V and electrode positive polarity. However, the bead shapes from both stringer and weave passes were unacceptably convex (Table 3), with poor root penetration, as shown in Fig. 2A. Spatter levels were relatively high. In the pulsed welding trials, good metal transfer was achieved at average currents of down to about 120 A and 24 V. Stringer beads, while being somewhat convex in profile, showed improved wetting in the toe areas and better root penetration compared to those made with conventional nonpulsed welding machines — Fig. 2A. Weave beads, using a pulsed power source, were relatively flat in profile and had adequate edge wetting and root penetration. This can be appreciated by comparing Fig. 2A and 2C. Spatter levels were higher than for stringer beads but were not excessive.

Table 3 — Bead Profiles in the 3F Position

Wire Type	Wire Diameter (mm)	Pulsed (P) or Non-pulsed (NP)	Convexity Ratio (c/f)
Basic	1.2	P	0.20
	1.2	NP	0.50
	1.6	P	0.30
	1.6	NP	0.55
Metal-Cored	1.2	P	0.25
	1.2	NP	0.30
	1.6	P	0.15
	1.6	NP	0.30



Note: c = convexity of the bead.
f = face width of the bead.
c/f ratio rounded to the nearest 0.05
All beads made with stringer technique.

The few previous assessments of the usability of the basic flux cored/pulsed welding combination for positional welding have led to varying conclusions. Rodgers and Lochhead (Ref. 6) found that the weld pool was too fluid under these conditions for fully positional welding while a brief article by Melton and Aberg (Ref. 9) reported that the pulsed power source used was capable of producing high-quality uphill welds. Considering these assessments in conjunction with the present observations, it is suggested that the use of small diameter (1.2 mm or less) basic flux cored wires with pulsed welding is suitable for some, but not all positional welding applications.

Weld Metal Properties

Gross heat inputs for the test plates (Table 1) were 1.3 to 1.4 kJ/mm for 1.2-mm-diameter wire and 1.7 to 2.0 kJ/mm for 1.6-mm wire made with both pulsed and conventional welding conditions. The average voltage, welding current and welding speed were used to calculate heat input for conventional welds. In the case of pulsed welds, heat input calculated using these average values can give erroneous results, particularly at low currents (Ref. 11). Pulsed welding heat input (HI) functions (Equations 1 to 4) were derived by regression analysis of power vs. the product of average voltage (V) and current (I) data (Ref. 11) for 1.2- and 1.6-mm-diameter basic flux and metal cored wires. These equations are:

$$HI\ (kJ/mm) = (0.0838\ VI + 34.4)/v \quad (1)$$
for 1.2-mm basic flux wire

$$HI\ (kJ/mm) = (0.0637\ VI + 27.7)/v \quad (2)$$
for 1.6-mm basic flux wire

$$HI\ (kJ/mm) = (0.0592\ VI + 57.8)/v \quad (3)$$
for 1.2-mm metal cored wire

$$HI\ (kJ/mm) = (0.0810\ VI - 12.4)/v \quad (4)$$
for 1.6-mm metal cored wire

where v is welding speed in mm/min.

Charpy V-notch (CVN) impact testing was carried out at 0°, –20° and –40°C for each case. A subsize all-weld-metal tensile specimen of nominally 5-mm diameter was also extracted from each test plate.

Table 4 lists the tensile results obtained. These results indicate that, while no major differences are apparent between the tensile properties obtained from conventional and pulsed welding or between the two wire diameters, yield and tensile strength values appear marginally higher for pulsed welding. The tensile results from all test plates readily satisfied the requirements laid down in Ref. 8 and listed in Table 4.

The CVN impact results are plotted in Fig. 3. These show that the highest overall values were achieved with the 1.6-mm-diameter wire under conventional power, while the lowest overall values were obtained from the 1.2-mm wire and conventional power. The impact results from the two wire diameters under pulsed power are similar to one another and lie between the extremes. All wire/power supply combinations gave results which readily meet the requirement of Ref. 8, which stipulates a minimum average of 27J at –29°C.

Table 5 lists the weld metal chemical composition from each wire size/power supply combination. These results were obtained from cross-sections of the welds using optical emission spectroscopy for all elements except oxygen and nitrogen, which were measured using a fusion technique. These results show that, while no major compositional differences can be ascribed to the use of the pulsed power supply, the C and Mn values did appear marginally higher. This could account for the marginally higher yield and tensile strengths observed from the pulse-welded test plates — Table 4. The conventionally welded 1.2-mm wire did give a significantly higher weld metal oxygen value which could account for the lower impact values observed in this case over the whole temperature range — Fig. 3.

A quantitative metallography (point counting) technique (Ref. 12) was used to determine the percentage areas of acicular ferrite (AF), grain boundary ferrite (PF(G)), intragranular polygonal ferrite (PF(I)), ferrite with second phase (FS) and martensite-austenite-carbide (MAC) components in the as-welded regions of each test plate. Measurements were also made of relative areas of as-welded, compared to reheated, regions of the central region of the test plates from which the mechanical test specimens were taken. The results are listed in Table 6. These results indicate that the power supply type appeared to have little influence on the as-welded microstructure for a particular wire size. The greatest difference in microstructure was between that from the wires of different diameter. As welded regions from 1.6-mm wire contained approximately 60% acicular ferrite and 25% grain boundary ferrite, while such regions from 1.2-mm wire contained approximately 75% ferrite with second phase, 15% grain boundary ferrite and virtually no acicular ferrite. This difference is illustrated by Fig. 4, which shows the mainly acicular ferrite microstructure from the 1.6-mm wire (Fig. 4A and B) compared to the mainly ferrite with second phase microstructure from the 1.2-mm wire (Fig. 4C and D). These observations are consistent with the generally lower impact values from the 1.2-mm wires and could possibly be related to the lower heat inputs used in making the test plates.

The central regions of all test plates, except that from 1.6-mm wire and conventional power, contained about 50% as-welded material. This figure was 37% for 1.6-mm wire with conventional power, a factor which could be relevant to the improved low-temperature impact properties observed in this case.

Table 4 — All-Weld-Metal Tensile Properties

Wire Type	Wire Diameter (mm)	Pulsed (P) or Non-pulsed (NP)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
Basic	1.2	P	543	582	26
		NP	492	560	30
	1.6	P	496	569	30
		NP	472	557	26
Metal Cored	1.2	P	567	628	24
		NP	523	595	30
	1.6	P	548	604	24
		NP	530	595	25
Specified minima (8)			414	497	22

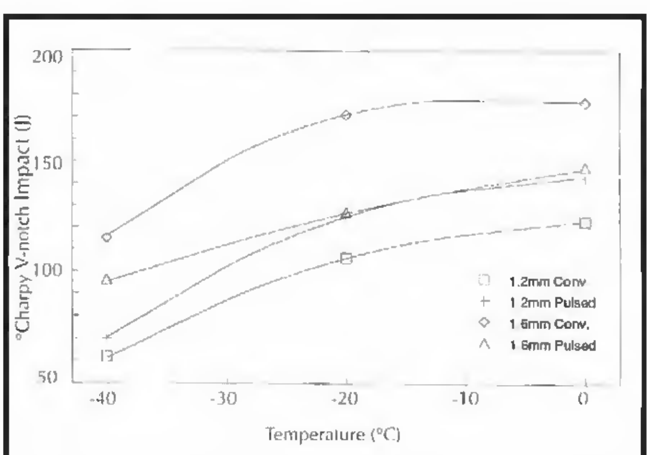


Fig. 3 — CVN impact as a function of temperature for basic flux wires of 1.2 and 1.6-mm diameters when used under conventional and pulsed welding conditions.

Table 5 — Chemical Composition of Welded Test Plates

Wire Type	Wire Diameter (mm)	Pulsed (P) or Nonpulsed (NP)	Composition (*wt*-%)								
			C	Mn	Si	S	P	Ti	Al	O	N
Basic	1.2	P	.09	1.44	.43	.011	.021	<.01	.007	.043	.0035
	1.2	NP	.08	1.34	.38	.011	.020	<.01	.006	.057	.0043
	1.6	P	.09	1.44	.43	.011	.020	<.01	.007	040	.0036
	1.6	NP	.07	1.37	.43	.011	.020	<.01	.007	.046	.0058
Metal Cored	1.2	P	.04	1.70	.91	.013	.017	.05	.022	.064	.0067
	1.2	NP	.03	1.63	.90	.013	.017	.04	.031	.074	.0097
	1.6	P	.04	1.61	.84	.012	.018	.05	.023	.064	.0099
	1.6	NP	.03	1.61	.89	.013	.017	.04	.030	.066	.0133

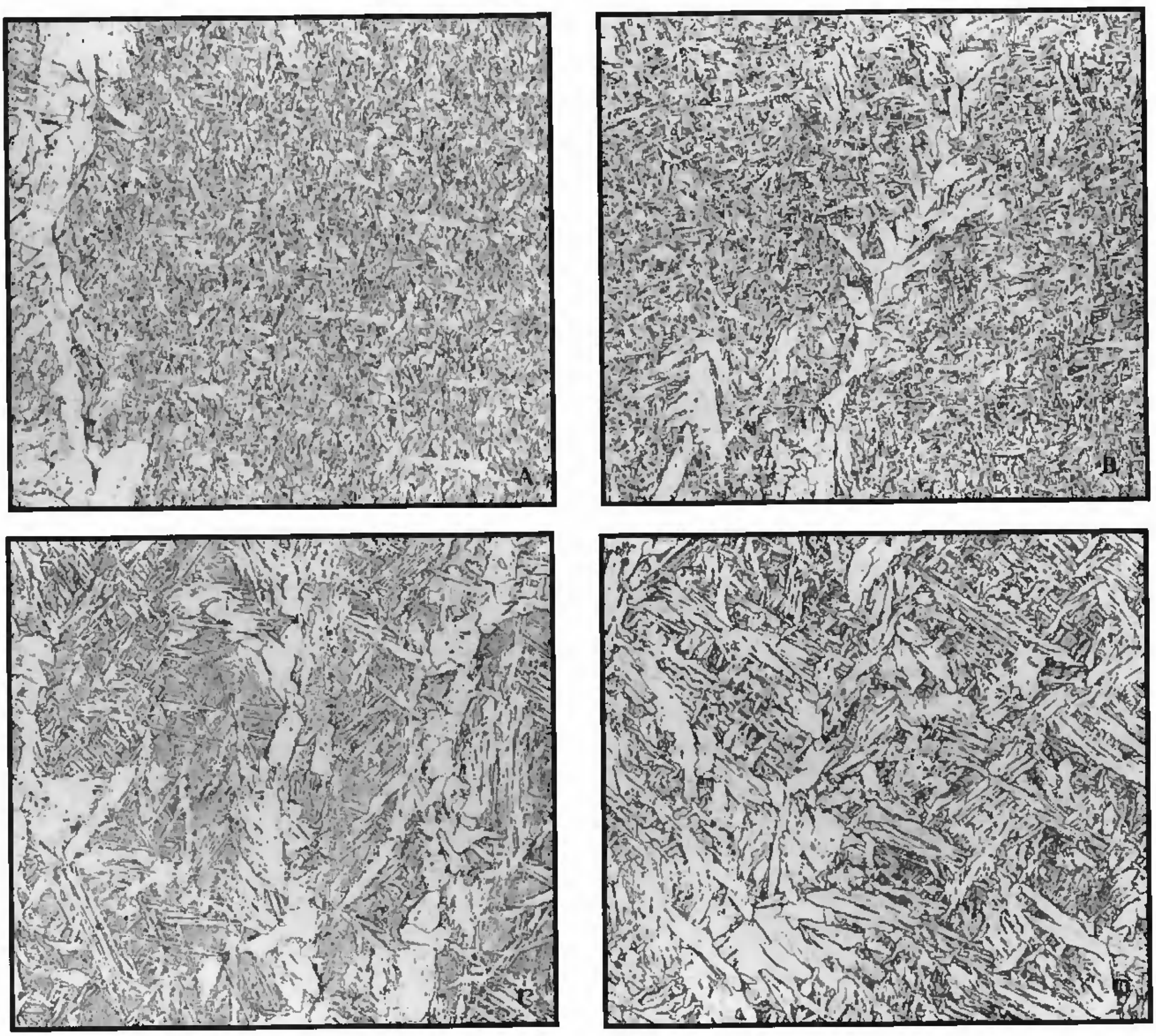


Fig. 4 — Microstructure of as-welded steel produced from: A — Nonpulsed welding with 1.6-mm-diameter basic flux cored welding wire; B — pulsed welding with 1.6-mm-diameter basic flux cored wire; C — nonpulsed welding with 1.2-mm-diameter basic flux cored welding wire; D — pulsed welding with 1.2-mm-diameter basic flux cored welding wire. 500X magnification.

Metal Cored Electrodes

Horizontal/Vertical Fillet Welds

The use of pulsed welding with metal cored electrodes showed significant advantages in operating range and bead quality when compared with nonpulsed welding. Bead appearance and arc stability were the criteria used to assess the operational range of each electrode. In the case of pulsed welding, the lower limit was difficult to clearly establish as the pulse program maintained effective control of one drop per pulse to very low average welding currents. The appearance of the bead largely determined the lower limit for pulsed welding. Therefore, in Table 7, a category "low" has been included which represents the lowest practical current for welding 10-mm-thick steel even though the arc remains stable to a lower current shown as "min." The upper limit for pulsed and nonpulsed welding was determined by an observed change from a uniform flat bead with a satin surface appearance to a somewhat ropey bead with a burnt surface appearance. The improvement in the operating range by using pulsed welding with metal cored electrodes is clearly apparent in Fig. 5.

An important aspect of a weld in regard to its strength is that the bead should penetrate full to the apex of the fillet. The depth of penetration past the apex for welds prepared by pulsed welding was found to be consistently greater than those prepared by nonpulsed welding particularly at low currents. Sectioning of the weld beads for depth-of-penetration measurements also disclosed a high incidence of cold lapping of the bead and pore defects within the nonpulsed short-arc welds. The depth of penetration for each current is shown in Table 7.

Deposition efficiencies were measured for each electrode over a range of currents in both pulsed and nonpulsed welding modes. Metal cored electrodes normally have high deposition efficiencies due to the limited amount of slag-forming constituents in the core of the electrode. Marginally higher deposition efficiencies were recorded for pulsed welding (Table 7). The higher deposition efficiency for pulsed welding may be attributed to the reduction of metal lost as spatter.

Uphill Fillet Welds

The approach taken was similar to that for the basic flux wires. With the 1.6-mm wire and conventional power, the welding parameters needed to be about 150 A and 18 V to achieve usable vertical welding operation. These parameters resulted in a metal transfer mode similar to the short circuiting mode used in solid wire GMAW. The resulting stringer heads were unacceptablely convex with poor

Table 6 — Proportion of Microstructure Constituents

Wire Type	Wire Diameter (mm)	Pulsed (P) or Nonpulsed (NP)	Constituents (area %) AF	PF(G)	PF(I)	FS	MAC	As-welded (area %)
Basic	1.2	P	0	15	5	77	0	45
	1.2	NP	0	13	2	77	8	50
	1.6	P	62	22	11	5	0	50
	1.6	NP	63	25	7	5	0	37
Metal Cored	1.2	P	70	29	1	0	0	59
	1.2	NP	77	21	1	0	0	52
	1.6	P	71	26	3	0	0	67
	1.6	NP	69	20	10	1	0	76

Table 7 — Deposition Characteristics for Pulsed and Nonpulsed Welding

Metal Cored Wire Electrode 1.2 mm

Pulsed (P) or Nonpulsed (NP)	Operation	Weld Position Stringer (S) Weave (W)	Current (A)	Root Penetration (mm)	Consumption Rate (kg/h)	Deposition Rate (kg/h)	Efficiency (%)
P	Min.	2F	102	0.0	1.46	1.36	93
P	Low	2F	207	0.0	3.80	3.80	100
P	Opt.	2F	270	1.5	5.08	5.08	100
P	Max.	2F	378	3.5	7.70	7.62	99
P	Opt.	3F/S	140	0.5	2.30	—	—
P	Opt.	3F/W	140	0.5	2.30	—	—
NP	Min.	2F	220	0.0	3.63	3.48	96
NP	Opt.	2F	280	1.0	4.97	4.92	99
NP	Max.	2F	320	2.5	7.06	6.49	92
NP	Opt.	3F/S	150	0.1	1.37	—	—
NP	Opt.	3F/W	150	0.0	1.37	—	—

Metal Cored Wire Electrode 1.6 mm

Pulsed (P) or Nonpulsed (NP)	Operation	Weld Position Stringer (S) Weave (W)	Current (A)	Root Penetration (mm)	Consumption Rate (kg/h)	Deposition Rate (kg/h)	Efficiency (%)
P	Min.	2F	96	0.0	1.20	1.20	100
P	Low	2F	279	1.0	3.93	3.85	98
P	Opt.	2F	324	2.0	4.97	4.77	96
P	Max.	2F	429	3.0	6.77	6.70	99
P	Opt.	3F/S	165	0.5	1.94	—	—
P	Opt.	3F/W	150	1.0	1.76	—	—
NP	Min.	2F	270	0.0	3.75	3.56	95
NP	Opt.	2F	340	0.0	4.90	4.75	97
NP	Max.	2F	400	4.5	6.65	6.52	98
NP	Opt.	3F/S	160	0.3	1.70	—	—
NP	Opt.	3F/W	160	0.0	1.64	—	—

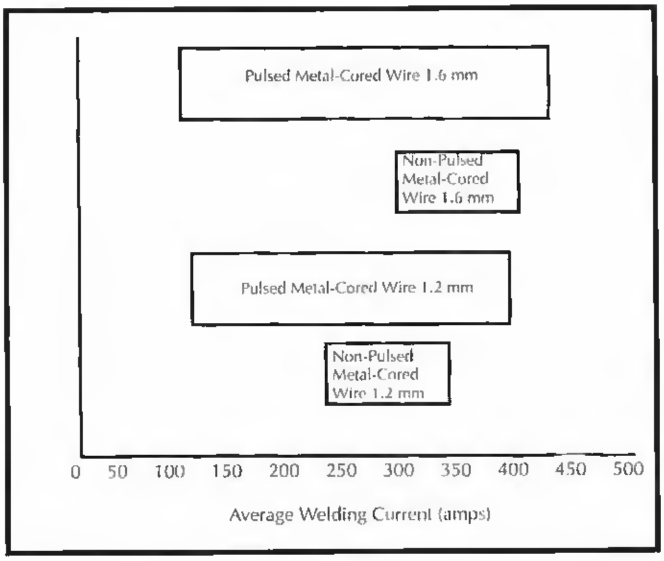


Fig. 5 — Operating range for metal cored wires in horizontal/vertical fillet welds.

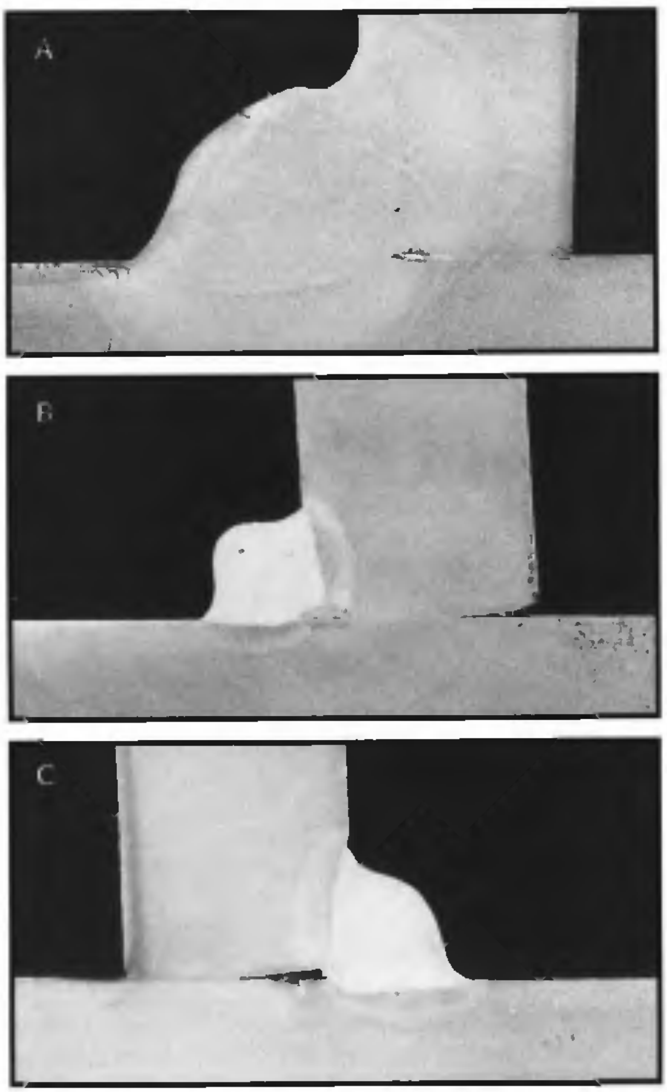


Fig. 6 — Sections through vertical fillet welds from metal cored welding wires. A — Weave bead with 1.6-mm-diameter wire, pulsed welding; B — stringer bead with 1.2-mm-diameter wire, conventional power supply; C — weave bead with 1.2-mm-diameter welding wire, pulsed welding. 4X magnification.

edge wetting and no root penetration (Table 3). Bead-shape was improved by using a weave technique, but again root penetration was unsatisfactory. When the 1.6-mm wire was used under pulsed conditions, a synthetic spray mode of transfer with low spatter was achieved with optimum vertical operation at about 150 A and 21 V. Stringer beads were slightly convex but showed acceptable edge wetting while weave beads were relatively flat in profile (Fig. 6A and Table 3). Quite adequate root penetrations of the order of 1 mm were achieved in both stringer and weave beads under pulsed conditions.

Reasonable welding operation could be achieved with the 1.2-mm metal cored wire and conventional power at welding parameters of approximately 150 A and 17–18 V. The transfer mode was again of the short circuiting type. Stringer beads tended to have convex profiles while both stringer and weave beads lacked root penetration. This is illustrated by Fig. 6B which shows a section through a stringer bead made with the 1.2-mm wire. When the 1.2-mm wire was used with pulsed welding, smooth operation and minimal spatter were achieved with the optimum operating conditions being approximately 140 A and 23 V. Stringer beads were relatively flat in profile with good edge wetting and root penetration (Fig. 6C), while weave beads were also of good appearance and profile with adequate edge wetting and penetration.

Overall, the combinations of 1.6-mm and particularly 1.2-mm metal cored wires with pulsed power proved quite suitable for uphill welding using both stringer and weave techniques. The metal cored wire/pulsed welding combinations did not suffer from the incomplete root penetration observed when these wires were used for vertical welding using conventional power and a short circuiting mode of transfer. These observations are in accord with a previously described application of pulsed welding with metal cored wires (Ref. 7) although, in this instance, the joints being welded were rotated so all-position capability was not assessed.

Weld Metal Properties

Test plates were welded with each wire diameter/power supply combination. For comparison of welding machine types, the test plates for each wire size were welded at similar melt-off rates. From these test plates, weld metal CVN specimens were extracted for testing at 20°, 0° and –20°C. A subsize (5-mm-diameter) all-weld tensile specimen was also taken from the test plates. Gross heat inputs, calculated in the way described for the basic flux wires, were 1.4 to 1.6 kJ/mm for 1.2-mm wire and 1.7 to 1.9 kJ/mm for 1.6-mm wire — Table 1.

The tensile results obtained are listed in Table 4. These suggest that yield and tensile strengths are slightly higher in the pulsed welded plates but that all of the results readily meet the minimum requirements of Ref. 9, which are also listed in Table 4.

Figure 7 shows the variation of mean CVN impact energy with temperature for each wire diameter/power supply combination. This indicates that, for both wire diameters, better impact values were achieved under pulsed welding conditions. The largest difference in impact values between pulsed and conventional conditions is with 1.2-mm wire where mean values from the pulse-welded plate are 40 to 50 J higher across the test temperature range. For the 1.6-mm wire, pulsed welding resulted in increases in mean impact energy of 10 to 15 J for each test temperature. The usual minimum impact requirement (Ref. 9) for wire of this type is 27J at −18°C, which is achieved by all of the combinations.

The weld metal chemical composition from each wire diameter/power supply combination is listed in Table 5. This indicates that no outstanding compositional differences exist between weld metals deposited under conventional and pulsed conditions. Weld-metal O and particularly N values may, however, be marginally lower for pulsed welding, and this difference may explain the improved low-temperature impact properties observed from pulsed welded test plates.

Table 6 lists the quantitative metallography results obtained from weld metal from the various wire and power source combinations. This suggests that the as-welded microstructure is little influenced by wire size or type of power source as, in all cases acicular ferrite (AF) made up about 70% (by area), and the other main constituent was grain boundary ferrite PF(G), comprising 20 to 30%. The proportion of as-welded area was higher for the 1.6-mm wire, in line with the lower number of weld passes, but did not appear to be dependent on power supply type.

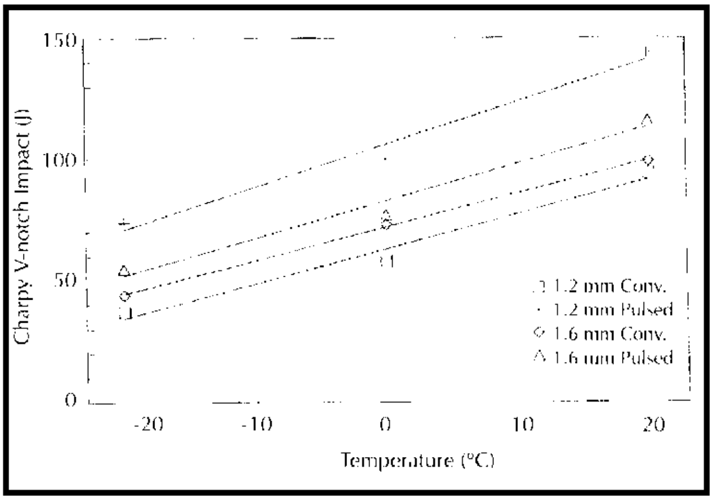


Fig. 7 — CVN impacts as a function of temperature for metal cored wires of 1.2-mm and 1.6-mm diameters when used under conventional and pulsed welding conditions.

Conclusions

1) Compared to their use with conventional power supplies, the combination of basic flux cored wires with pulsed welding resulted in the following:

◆ A major extension of the usable range of welding currents, particularly at the lower end of the average current range.

◆ Improved horizontal/vertical fillet welding capabilities in terms of flatter profile fillets and improved edge wetting.

◆ A vertical position welding capability with the 1.2-mm-diameter wire, which met the base requirements of bead convexity, edge wetting and root penetration.

◆ Only marginal changes in deposition rate and efficiency, weld mechanical properties, composition and microstructure.

2) The combination of metal cored wires with pulsed welding, in comparison to their use with conventional power, resulted in the following:

◆ A major extension to the usable range of welding currents, particularly at the lower end of the range.

◆ Comparable horizontal/vertical fillet welds at high current but with the ability to weld thinner sections and produce smaller beads.

◆ Impressive all-position welds which had good bead shape and adequate root penetration.

◆ Similar, or marginally increased deposition rates and efficiencies, weld tensile properties and weld microstructure.

◆ Improved weld metal low-temperature impact properties, probably due to lower weld metal O and N levels.

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