Fume Generation During Solid- and Metal-Cored Wire Welding

Various arc voltage and wire-feed settings were used to investigate fume generation during GMAW using solid-wire and metal-cored welding consumables

BY H. XIN, Z. GENG and T. H. NORTH

ABSTRACT. Fume generation during gas metal arc welding using solid-wire and metal-cored welding consumables were investigated in tests involving a wide range of arc voltage and wire-feed-speed settings. Both direct current electrode positive (DCEP) and direct current electrode negative (DCEN) polarity welding were investigated. The fume generation rate during DCEP welding using 1.4-mm-diameter solid wire attained a minimum value when a critical power input of 9.5 kW was exceeded. The low fume generation rate produced during solid-wire welding using power levels ≥9.5 kW resulted from preferential absorption of metal vapor when the arc was buried in the molten weld pool.

Although DCEP solid-wire and metal-cored-wire welding produced similar fume generation rates, the operating range that provides the lowest fume generation rates and optimum arc stability was larger when using metal-cored wire. The amount of fume generated during DCEN metal-cored-wire welding using a high wire feed speed was similar to the best results produced during DCEP solid-wire welding.

The fume generation rate can be readily calculated using simple relations involving the power input and intensity of fume formation (β_a = g/kW h) during DCEP and DCEN solid-wire welding and DCEP metal-cored wire welding.

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Introduction

Improved working conditions, occupational hygiene and safety in the workplace are key goals for all fabricators, particularly since the permissible exposure limits for welding fume are expected to decrease in the future. For example, the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) have suggested significant reductions in the Ni, Mn and hexavalent chromium contents in welding fume (Ref. 1). This decrease in permissible exposure limits readily explains the driving force for continued research throughout the world (Refs. 1–16).

Fume generation during arc welding is generally expressed using two measures, namely, one that assesses fume generation in terms of the amount of fume generated per minute during the welding operation, and the other that assesses the amount of fume generated per gram of deposited weld metal. These two monitors are termed FFR (g/min) and FGR (g/kg or mg/g).

FFR values measure fume generation with time as the welding operation proceeds, *i.e.*, they provide some indication of the time during which the welder operator will be exposed to welding fume. However, this measure can be misleading; different welding processes or different modes of operation used during a given welding process produce quite different deposition rates.

FGR values are employed in this case since they take the deposition rate into account. It is worth emphasizing there is no simple relationship between the FFR and FGR values and the actual exposure the welder operator will be subjected to while in the workplace. For example, the FFR and FGR measures take no account of critical factors such as different modes of exhaust ventilation, the problems produced when working in enclosed workspaces and others. Fume generation measures are, however, particularly useful when the results produced using different types of welding consumables, different consumable formulations or manufacturers' products are compared (Ref. 2).

Welding fume results from the vaporization and subsequent condensation and oxidation of electrode, base metal and flux components (Refs. 3, 4) and the combustion of spatter particles ejected from the arc envelope (Ref. 4). Almost all welding fume emanates from the electrode itself (Refs. 1, 3, 5, 6), with minimal contributions resulting from changes in welding speed, plate composition and thickness (Ref. 3), and in contact-tip-to-work distance (Ref. 6). The amount of fume generation decreases when smaller wire diameters are used (Ref. 7) and when pulsed arc welding is applied (Ref. 8). Also, fume generation markedly depends on the oxygen potential of the shielding gas composition employed during arc welding and increases when

KEY WORDS

Fume Generation
GMAW
Metal-Cored Arc Welding
Metal Transfer Modes
DCEN
DCEP

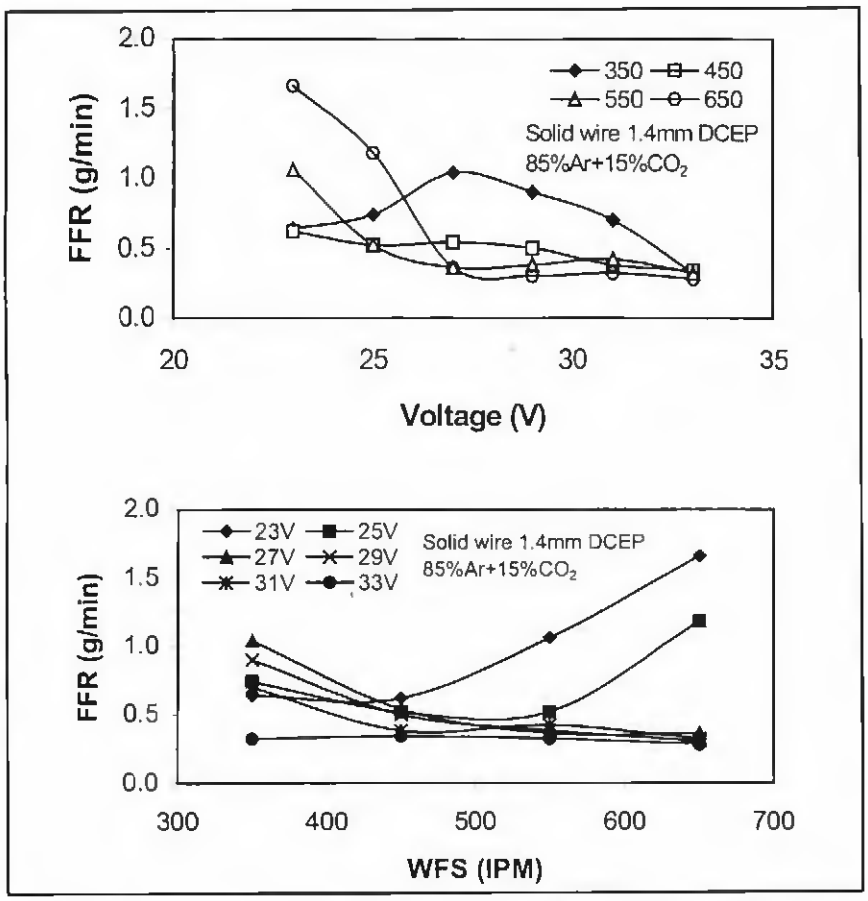

Fig. 1 — Fume formation rate (FFR) values produced during direct current electrode positive gas metal arc welding using 1.4-mm solid wire.

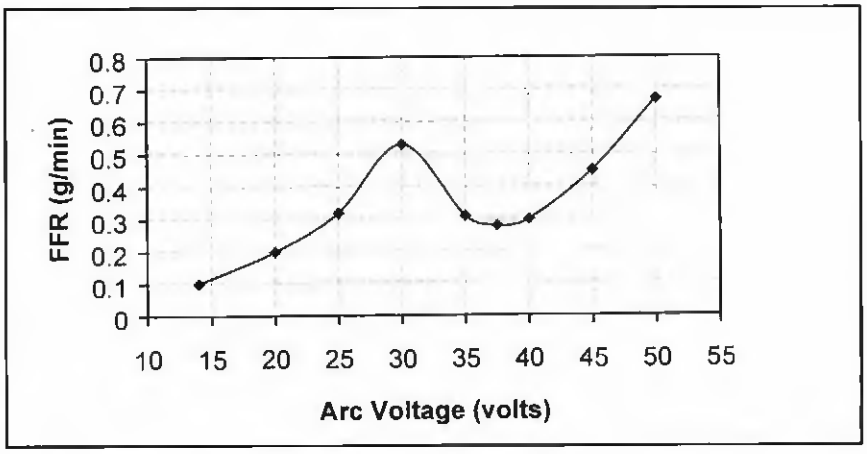

Fig. 2 — Predicted cusp-shaped relation between the fume formation rate and arc voltage.

argon/CO_2 shielding gas mixtures are replaced by 100% CO_2 shielding gas (Refs. 4, 6, 7, 10 and 13).

Heile and Hill (Ref. 3) and Gray, et. *al.* (Ref. 4), highlighted the critical connection between fume generation and the metal transfer mode when they investigated gas metal arc welding. The amount of fume increased when the metal transfer mode changed from short circuiting to globular and decreased when spray transfer occurred. The highest FFR values were produced immediately prior to the transition from globular to spray metal transfer. Gray, et. *al.*, also introduced the terms fractionated and unfractionated fume to explain why collected fumes were preferentially enriched in volatile elements such as chromium, manganese and iron. Fractionated fume contains higher contents of volatile elements. Unfractionated fume is produced by combustion of spatter droplets expelled from the arc envelope.

The spatial relationship between the molten weld pool surface and the arc envelope strongly affects fume generation. Levchenko, et. *al.* (Ref. 6), measured the fume generation rate when the arc current and voltage were increased simultaneously (when the input power increased during welding) and noted the fume formation rate decreased dramatically when the arc became buried in the molten weld pool. Preferential absorption of metal vapor by the surrounding weld metal occurred when the arc buried in the molten weld pool. For example, when welding using 1.2-mm-diameter electrode wire, an increase in the arc current from 400 to 430 A decreased the FFR value by 50% and the FGR value by about 70%. Golvatchuk, *et. al.* (Ref. 7), extended this approach and related FFR and FGR values with the intensity of fume formation (β_a = g/kW h) and the specific generation rate (γ_a = g(kW kg)) during welding, namely,

$$\beta_a = 6\times10^4 \frac{(FFR)}{I_{arc}V_{arc}} \qquad (1)$$

$$\gamma_a = 10^3 \frac{G_a}{I_{arc}V_{arc}} \qquad (2)$$

where I_{arc} is the arc current, V_{arc} is the arc voltage and G_a is the fume formation rate (FFR) divided by the deposition rate.

The β_a and γ_a parameters were a convenient means of connecting melting and evaporation of electrode material and input power during welding. β_a values found experimentally using a testing matrix where the arc current and voltage were simultaneously varied enabled calculation of the fume generation rate for a wide range of welding parameter settings.

The present paper examines fume generation during GMA welding using solid-wire and metal-cored welding consumables. Divergent results have been reported concerning fume generation during GMA welding using metal-cored electrodes. For example, Jones and Moreton (Ref. 16) found the fume generation responses of metal-cored wires compared very favorably with those of solid wire. However, Hilton and Plumridge (Ref. 13) found higher FFR values were produced when using metal-cored

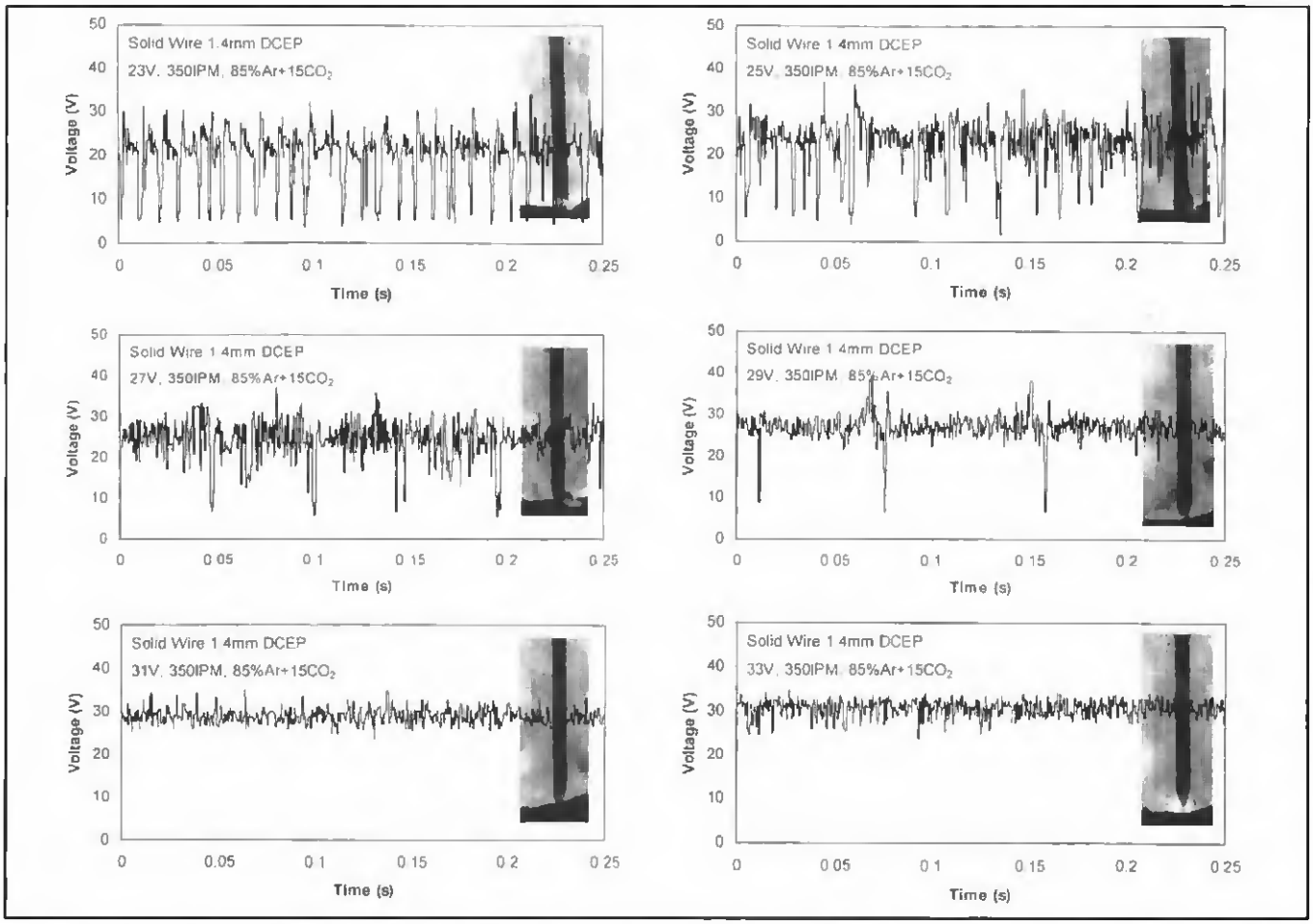

Fig. 3 — Voltage waveform and high-speed image during direct current electrode positive (DCEP) gas metal arc welding using 1.4-mm solid wire at a voltage range of 25–31 V and 350 in./min wire feed speed.

welding consumables. With this in mind, this paper compares fume formation during GMA welding using solid-wire and metal-cored welding consumables in tests involving a wide range of welding parameter settings. Since fume generation depends markedly on the metal transfer mode during arc welding, the results produced when using direct current electrode positive and direct current electrode negative polarities are of particular interest.

The effects of welding parameter changes on the metal transfer modes produced during gas metal arc welding using solid-wire welding consumables have been well documented (Ref. 17). Knowledge of this type provided the essential foundation when the critical relationship between fume generation and metal transfer mode during gas metal arc welding was established. However, the metal transfer modes when using metal-core electrodes are quite different from those produced during solid-wire welding. With this in mind, the present study examines the relationship between fume generation and the metal transfer mode

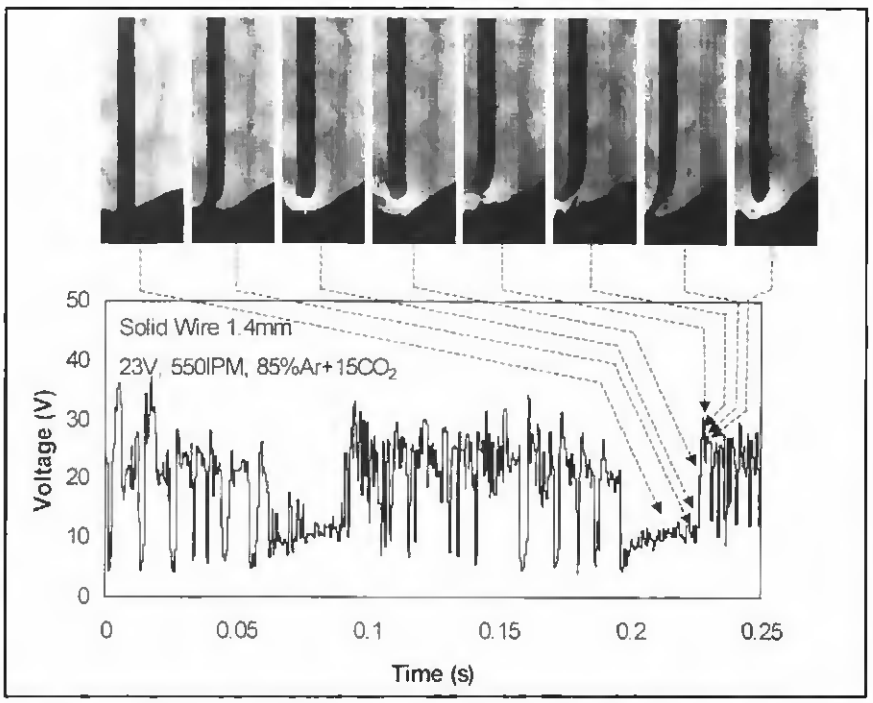

Fig. 4 — Voltage waveform and metal transfer during DCEP gas metal arc welding using 1.4-mm solid wire.

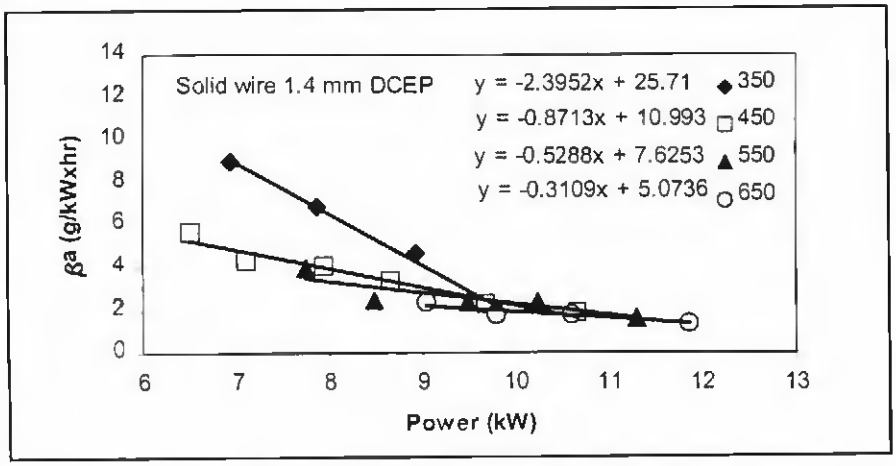

Fig. 5 — Relation between the intensity of fume generation (ßa = g/kWxh) and power input during DCEP gas metal arc welding using solid wire.

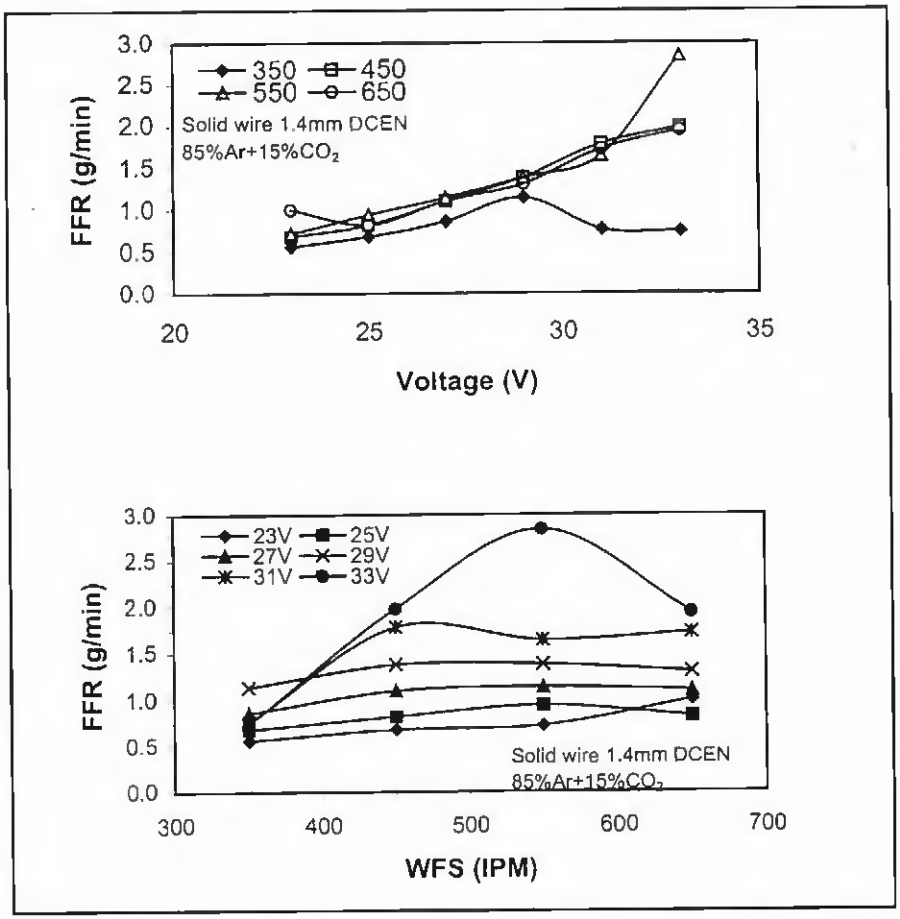

Fig. 6 — Fume formation rate (FFR) values produced during DCEN gas metal arc welding using solid wire.

when welding with metal-cored wire.

Although arc instability, inferior metal transfer and poor weld deposit profiles are typical of solid-wire welding using DCEN polarity, this is not the case when metal-cored welding consumables are employed. The operating characteristics of metal-cored electrodes can be markedly improved through additions of flux and arc stabilizers in the core. Therefore, the higher deposition rate capability of DCEN welding is accessible. As a result, fume generation during DCEN metal-cored-wire welding is of particular interest.

Experimental Procedure

All fume-generation testing was carried out according to the ANSI/AWS F1.2 standard. The standard fume-measuring chamber enabled rapid determination of fume generation (in g/min and in g/kg of weld deposit) during gas metal arc welding using a range of welding parameter settings. During testing, the weight of fume collected on a fiberglass filter was measured and compared with the weight of the filter pad prior to the arc welding operation. Prior to fume testing, the chamber was calibrated following the recommendations of the ANSI/AWS F1.2 standard. Weld deposits were made using 1.2-mm-diameter, ER70S-3 solid wire using an arc current of 300 A, an arc voltage of 26 V and a travel speed of 14 in./min (6 mm/s). The test results produced during calibration testing were within 10% of the specified fume generation rate (0.55 g/min when using 100% CO_2 shielding gas).

During the experimental program, all welding tests were carried out using 1.4-mm-diameter proprietary solid wire and metal-cored wire. The shielding gas comprised 85 vol-% argon and 15 vol-% CO_2 throughout. Both direct current electrode positive and direct current electrode negative welding trials were investigated using a range of arc voltage and wire-feed-speed settings.

Arc current, arc voltage and wire-feed-speed data were collected using a high-speed data acquisition setup at a sampling rate of 40 kHz per channel. The data acquisition system was coupled with synchronous, high-speed imaging of metal transfer using a high-speed Kodak EKTAPRO CCD camera. Synchronous metal transfer imaging and electrical output, in combination with an advanced computer-based statistical analysis package, provided an extremely powerful tool for evaluating the influence of consumable type and/or welding parameter changes on arc stability and fume generation during arc welding.

Results and Discussion

Fume Generation Using Solid-Wire

Using Direct-Current Electrode Positive Polarity

Figure 1 shows the FFR values produced during DCEP solid-wire welding at a range of arc voltages (23 to 33 V) and wire feed speeds (350 to 650 in./min). The results produced when welding using a wire feed speed of 350 in./min were quite different from those found when using higher wire-feed-speed settings (450, 550

and 650 in./min). When using a wire feed speed of 350 in./min, the fume formation rate peaked at an arc voltage of 27 V and decreased when the arc voltage was further increased — Fig. 1. High fume formation rates were produced when combinations of high wire-feed-speed settings (550 and 650 in./min) and low arc voltages (23 and 25 V) were applied.

Gray, *et.al.* (Ref. 4), and Albert (Ref. 8) suggested the relation between the fume generation rate and arc voltage during DCEP solid-wire welding could be interpreted as a continuous cosp-shaped line (Fig. 2), with the highest FFR values being produced immediately prior to the transition from globular to spray transfer. The lowest fume generation rates were produced when welding using the spray transfer mode. When the arc voltage further increased, the amount of fume also increased since the metal-transfer mode changed from spray transfer to streaming transfer.

In the present study, a parabolic-shaped FFR/voltage relation was produced when welding using a wire feed speed of 350 in./min, with the highest fume formation rate occurring at a voltage of 27 V. Figure 3 shows the arc voltage waveforms and metal-transfer images produced using a wire feed speed of 350 in./min. Short-circuiting metal transfer occurred when the lowest voltage setting (23 V) was applied. The short-circuiting tendency decreased when the arc voltage increased from 25 to 29 V and spray metal transfer free of short circuiting was observed when an arc voltage of 31 V was applied. The highest fume generation rate occurred when the metal-transfer mode comprised a mixture of irregular short circuiting and spray transfer. Increasing the arc voltage above 27 V decreased the FFR value since the incidence of irregular short circuiting significantly decreased. The lowest FFR values coincided with the onset of stable spray transfer during arc welding.

Parabolic-shaped FGR/arc voltage profiles were not found when higher wire feed speed settings were employed — Fig. 1. Also, the metal-transfer modes observed when using higher wire feed speeds (450, 550 and 650 in./min) did not correspond with a short-circuiting/globular/spray/streaming metal transfer progression. In fact, the mode of metal transfer changed directly from unstable short circuiting to spray transfer when arc voltage was increased.

High FFR values were produced using a combination of low arc voltage and high wire-feed-speed settings (550 and 650 in./min) since the excessive wire-delivery rate created large numbers of unstable short circuits during the welding operation — Fig. 4. An unstable short circuiting transfer terminology is used here since the excessive wire delivery rate created an unstable welding situation where the filler metal was fed much too rapidly for the arc voltage setting. This produced cascades of short circuits that facilitated ejection of spatter and volatilized fume

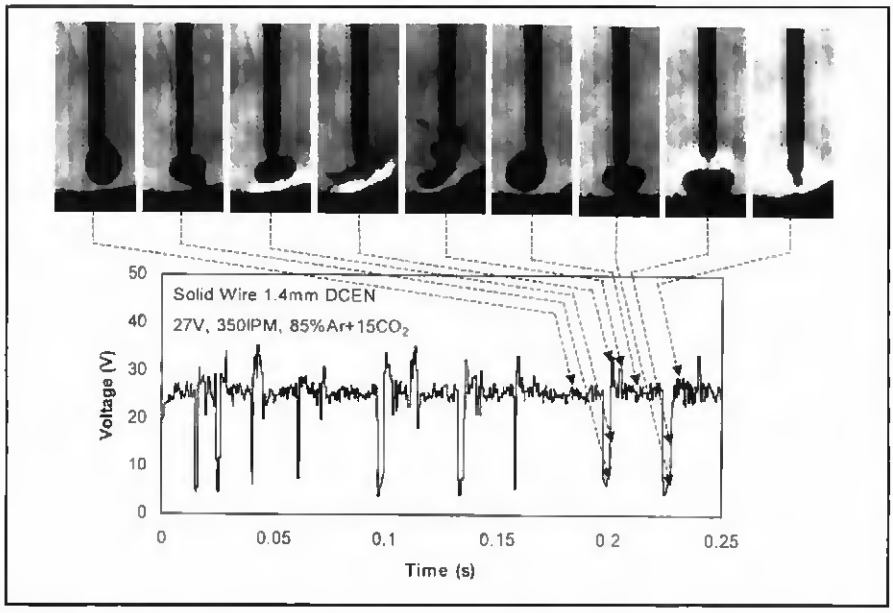

Fig. 7 — Voltage waveform and metal transfer during DCEN gas metal arc welding using 1.4-mm solid wire.

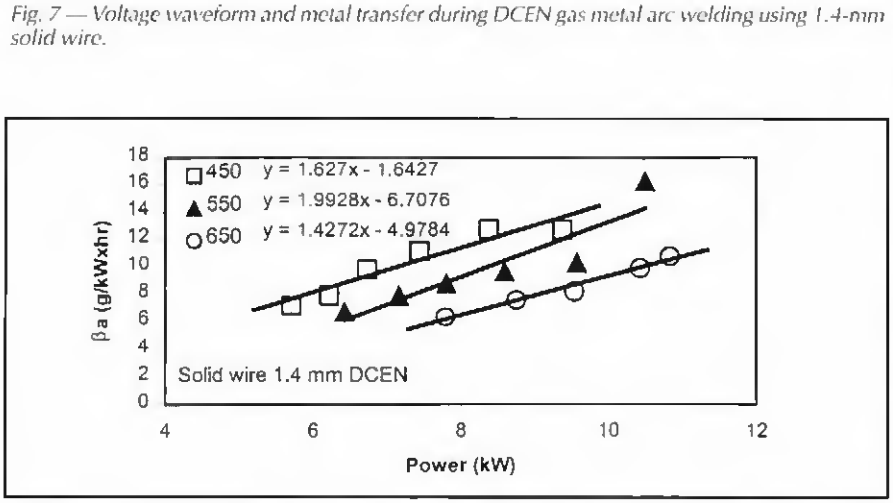

Fig. 8 — Relation between the intensity of fume generation (ßa = g/kWxh) and the power input during DCEN gas metal arc welding using solid wire.

Table 1 — Regression Equations Enabling the Calculation of FFR Values during Solid Wire and Metal-Cored Wire Welding

Welding Condition	Wire Feed Speed (in./min)	Regression Equation
DCEP solid wire	350	y = –2.3953 x + 25.71
	450	y = –0.8713 x + 10.99
	550	y = –0.5288 x +7.63
	650	y = –0.3109 x +5.07
DCEN solid wire	450	y = 1.63 x –1.64
	550	y = 1.99 x –6.71
	650	y = 1.43 x –4.98
DCEP metal-cored wire	400	y = –0.34 x + 6.63
	(500/600/700)	y = –0.245 x + 4.38

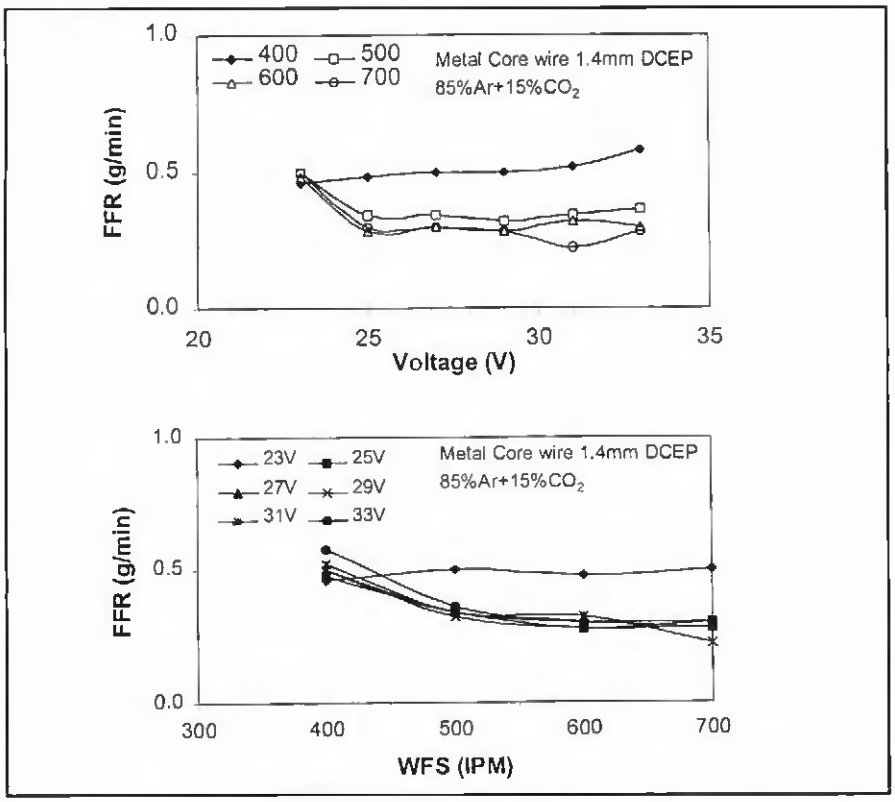

Fig. 9 — Fume formation rate (FFR) values produced during DCEP gas metal arc welding using 1.4-mm metal-cored wire.

from the arc envelope. It has already been confirmed ejected spatter is a major source of welding fume (Ref. 4).

Figure 5 shows the relation between the intensity of fume generation β_a and power input (kW) for the different wire feed speed settings. At each wire-feed-speed setting, the intensity of fume formation β_a was linearly related with power input. The regression equations for the different wire-feed-speed settings are indicated in Table 1. These regression equations can be used to calculate the FFR values produced when welding using any given set of welding parameters. For example, the calculated FFR value is 0.93 g/min when a wire feed speed of 350 in./min, an arc current of 285 A and voltage of 27 V are assumed. This compares with a measured FFR value of 1.04 g/min during arc welding using an arc current of 285 A, a wire feed speed of 350 in./min A and an arc voltage of 27 V.

It is apparent from Fig. 5 increasing power input beyond 9.5 kW during gas metal arc welding had a negligible effect on the amount of fume generation. These results, therefore, support the assertion the fume generation rate can be decreased markedly when a critical power input level is exceeded during gas metal arc welding using solid wire (Ref. 6). This is important; the selection of solid-wire

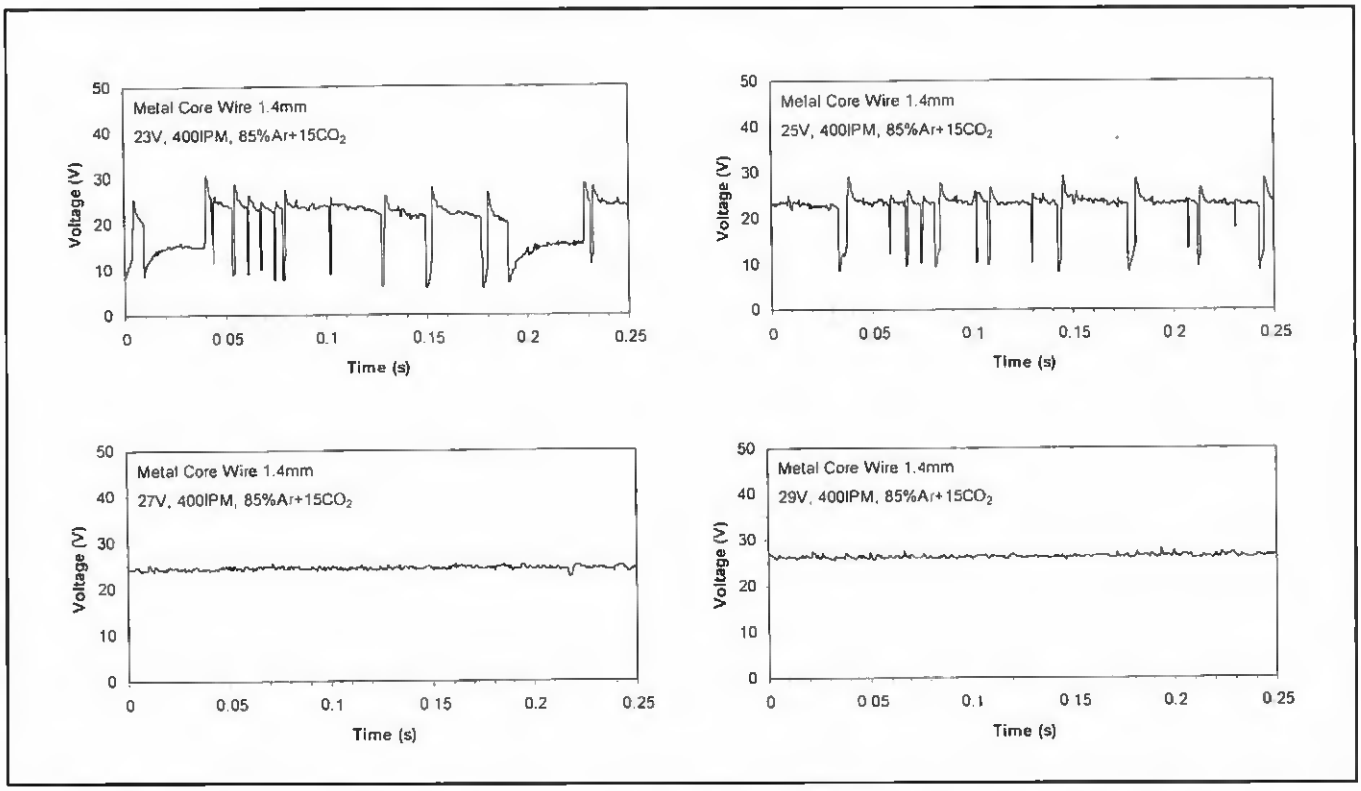

Fig. 10 — Voltage waveform and high-speed image during DCEP gas metal arc welding using 1.4-mm metal-cored wire at a voltage range of 23–29 V and 400 in./min wire feed speed.

welding conditions that produce the highest deposition rates are also those that provide the minimum fume generation tendency.

Using Direct-Current Electrode Negative Polarity

The fume formation rates produced during DCEN welding using solid wire are shown in Fig. 6. A parabolic-shaped FFR/arc-voltage relation was produced when welding using a wire feed speed of 350 in./min. A similar-shaped FFR/voltage relation was found during DCEP welding using solid wire. However, much larger diameter droplets were formed on the electrode tip during the DCEN welding operation. Figure 7 illustrates the different short-circuiting metal transfer processes that occurred when welding using a wire feed speed of 350 in./min. Large droplets forming on the electrode tip shorted with the weld pool but were not transferred. Instead, they were repelled and the arc was reestablished between the droplet and welding pool. The other short-circuiting process resulted in metal transfer with an arc forming between the electrode tip and the upper surface of the droplet as it was enveloped in the weld pool — Fig. 7. The highest fume formation rate occurred when an arc voltage of 29 V was used. Spray transfer, accompanied by occasional short circuiting, was observed when the voltage was increased to 31 V; this welding parameter setting produced the lowest fume formation rate — Fig. 6.

Parabolic-shaped FFR/voltage relations were not found when welding using higher wire-feed-speed settings (from 450 to 650 in./min), and the fume generation rate markedly increased at high arc voltages. For example, the fume generation rate was 2.8 g/min when an arc voltage of 33 V and a wire feed speed of 550 in./min were employed. This FFR value is almost nine times higher than that found during DCEP welding using similar wire-feed-speed and arc voltage settings (0.32 g/min). When the arc voltage increased from 23 to 33 V, the mode of metal transfer changed from short circuiting to the formation of very large diameter droplets that had long residence times on the electrode tip prior to transferring into the weld pool. The increased surface area available for evaporation of these large diameter droplets readily explains the high FFR values found during fume testing — Fig. 6.

In contrast, the fume formation rate during DCEN welding markedly increased when higher power levels were employed for all wire-feed-speed settings except 350 in./min. The relation between the intensity of fume generation (ßa) and input power (kW) were linear during DCEN welding using wire feed speeds ranging from 450 to 650 in./min — Fig. 8. However, unlike DCEP solid wire welding, higher, not lower, ßa values were found when the power input increased. The regression equations found during DCEN welding (Fig. 8) are presented in Table 1. As pointed out earlier, these relations can be used to calculate the fume generation rate for any given set of welding parameters during gas metal arc welding.

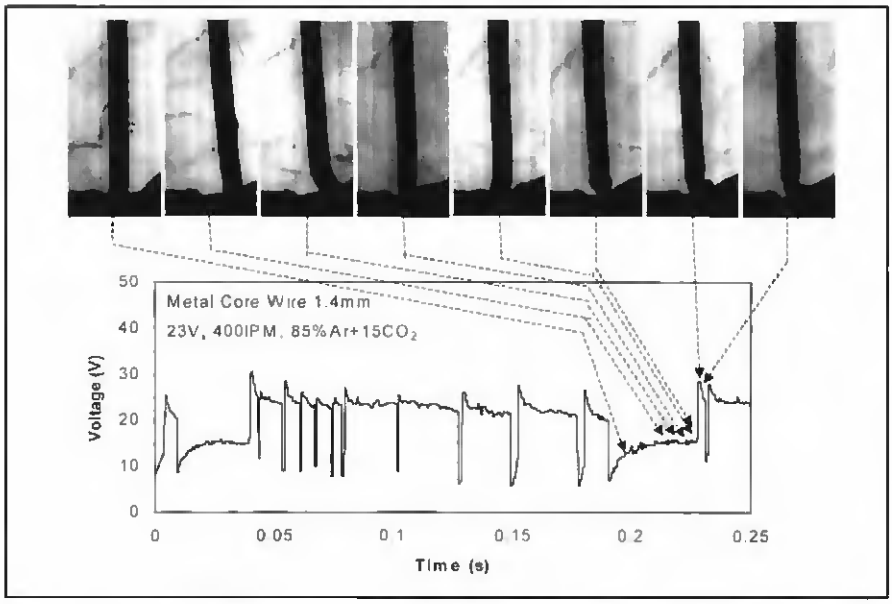

Fig. 11 — Voltage waveform and metal transfer during DCEP gas metal arc welding using 1.4-mm metal-cored wire.

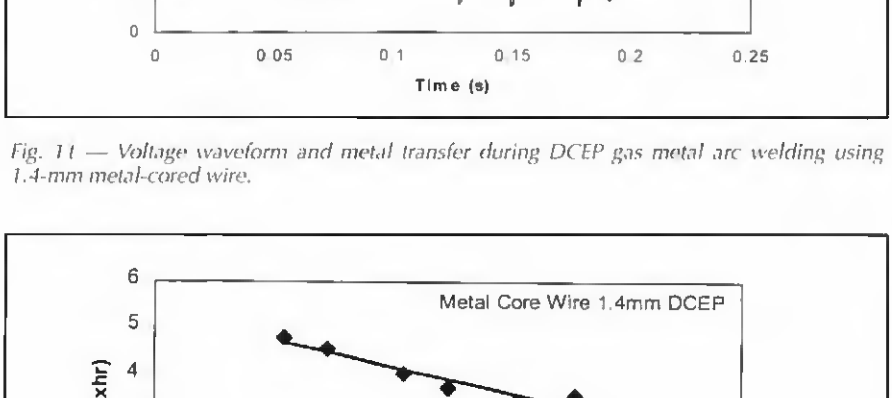

Fig. 12 — Relation between the intensity of fume generation (ßa = g/kWxh) and the power input during DCEP gas metal arc welding using 1.4-mm metal-cored wire.

Fume Generation Using Metal-Cored Wire

Using Direct-Current Electrode Positive Polarity

Figure 9 shows the FFR values produced during DCEP welding using metal-cored wire. The FFR values found using the lowest wire feed speed (400 in./min) were much higher than those produced when using higher wire-feed-speed settings (500 to 700 in./min). When the wire-feed-speed was 400 in./min, the amount of fume generation only marginally increased when the arc voltage increased from 23 to 33 V.

The voltage waveforms and metal transfer images in Fig. 10 show the incidence of irregular short circuiting when low voltages (23 and 25 V) were used and the onset of stable spray transfer when the arc voltage exceeded 27 V. Similar results were observed when higher wire-feed-speed settings (500, 600 and 700 in./min) were employed during welding.

Preferential melting of metal powder in the core facilitated spray transfer dur-

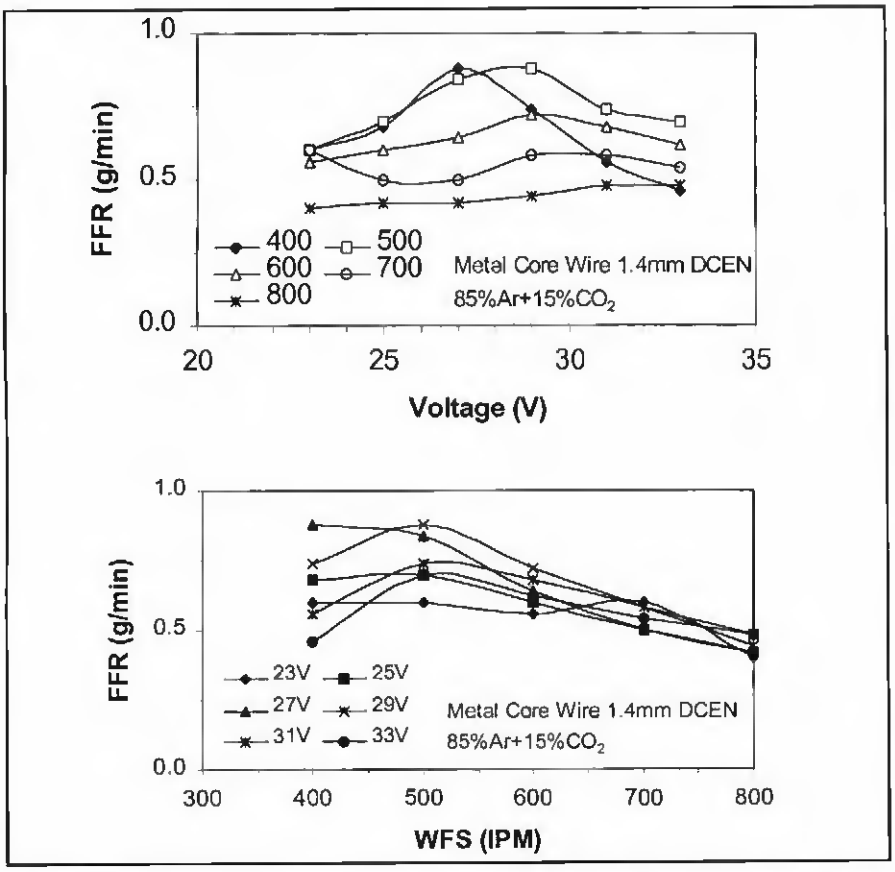

Fig. 13 — Fume formation rate (FFR) values produced during DCEN gas metal arc welding using 1.4-mm metal-cored wire.

ing metal-cored welding. In this connection, the metal-transfer mode when using metal-cored wire was similar to that observed during flux cored arc welding operations — Ref. 18.

Figure 11 shows the arc-voltage waveforms and metal-transfer images produced during welding using low voltage (23 V) and a wire feed speed of 400 in./min. The excessive wire delivery rate created cascades of short circuits that produced sudden expulsions of spatter and fume from the arc envelope as melted electrode material transferred into the weld pool. The increased arc instability explained the high FFR values found when using low arc voltages and wire feed speeds from 400 to 700 in./min.

The fume generation rate was largely unaffected by an increase in arc voltage from 25 to 33 V when using wire feed speeds of 500–700 in./min — Fig. 9. Lower fume generation rates were found when welding using higher wire feed speed settings (500–700 in./min) and were associated with reduction in the width of the arc gap.

Figure 12 shows the relation between the intensity of fume generation β_a and the input power during DCEP metal-cored wire welding. Linear relations were found for the 400 in./min wire-feed-speed test results and for the combined output produced using wire feed

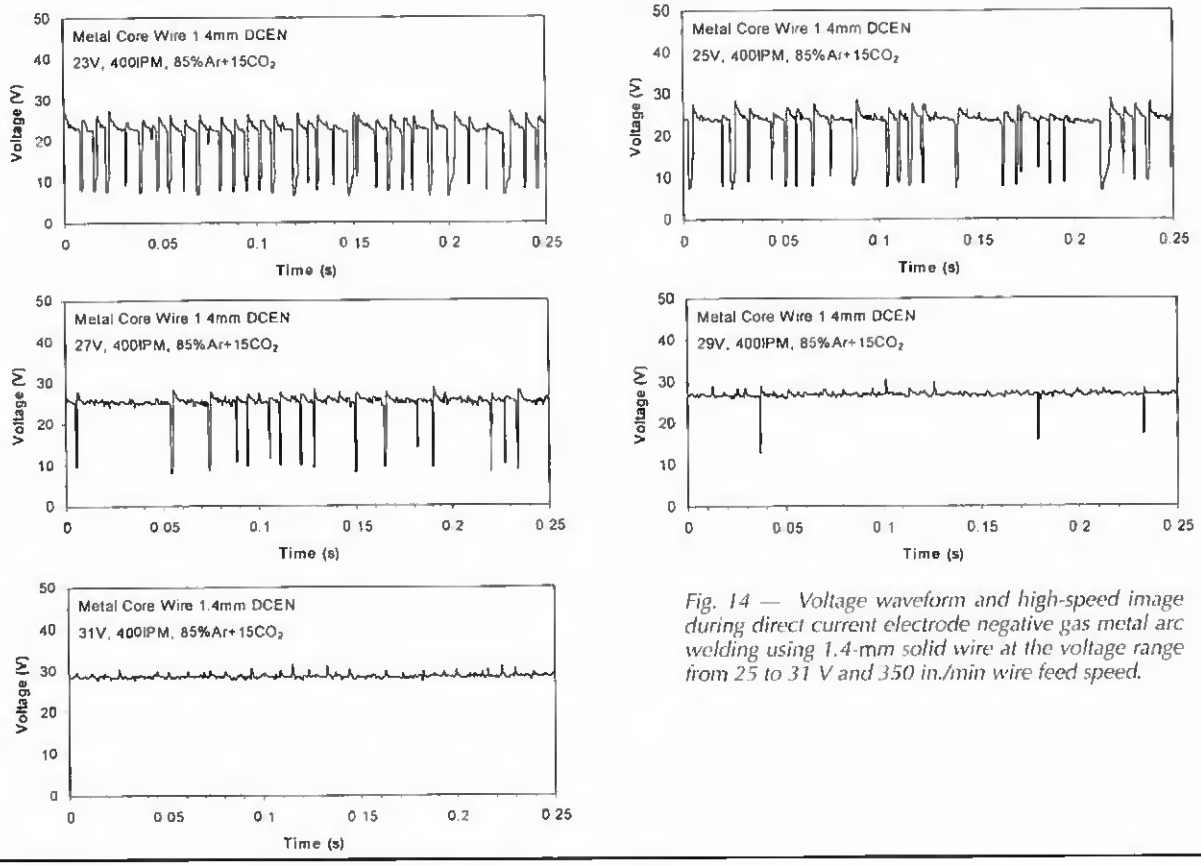

Fig. 14 — Voltage waveform and high-speed image during direct current electrode negative gas metal arc welding using 1.4-mm solid wire at the voltage range from 25 to 31 V and 350 in./min wire feed speed.

speeds from 500 to 700 in./min. Table 1 shows the regression equations relating the intensity of fume generation β_a with the input power and, as previously noted, can be used to calculate the fume formation rate for any given set of welding parameters.

Using Direct-Current Electrode Negative Polarity

The highest FFR values during DCEN welding using metal-cored wire were produced when using wire feed speeds of 400 and 500 in./min and arc voltages of 27 and 29 V, respectively —Fig. 13. The voltage waveforms produced when welding using a wire feed speed of 400 in./min show short circuiting occurred for all voltage settings up to 31 V — Fig. 14.

The highest fume generation rate occurred immediately prior to the transition from short circuiting to spray metal transfer. This situation is quite different from that of DCEP metal-cored welding, where short-circuit transfer was apparent only when welding using an arc voltage less than 25 V — Fig. 10.

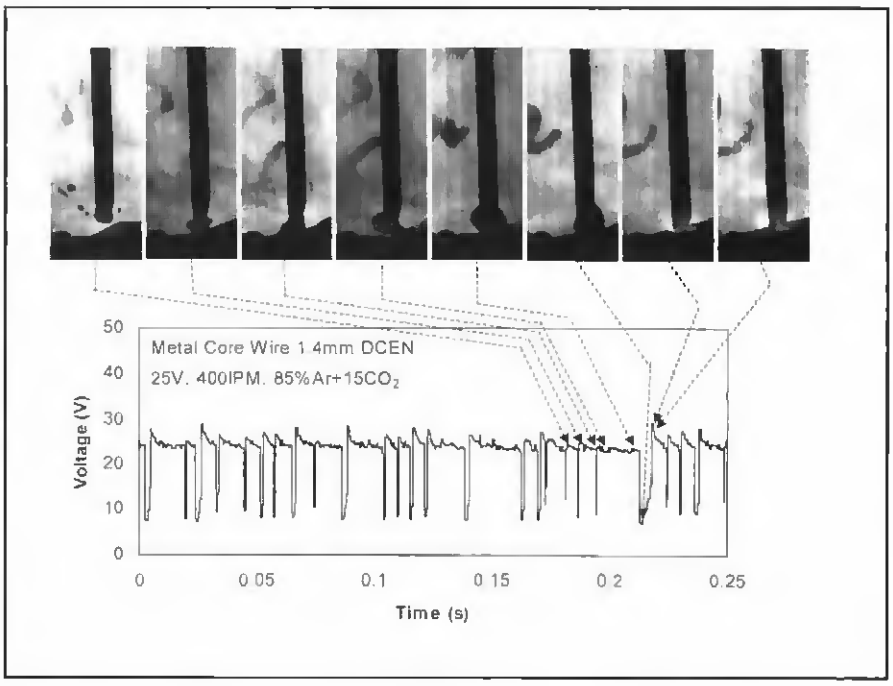

Fig. 15 — Voltage waveform and metal transfer during DCEN gas metal arc welding using 1.4-mm metal-cored wire.

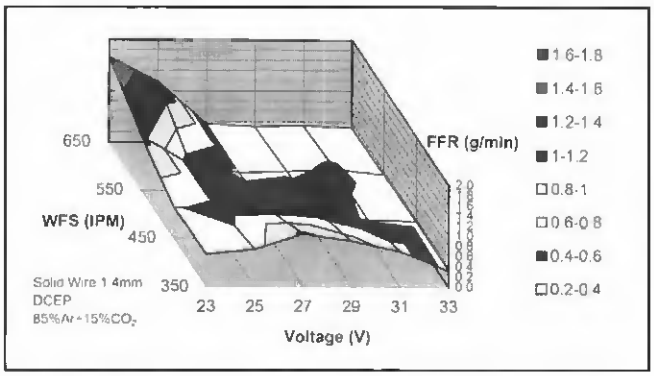

Fig. 16 — FFR values during DCEP solid-wire welding using a range of arc voltage and wire-feed-speed settings.

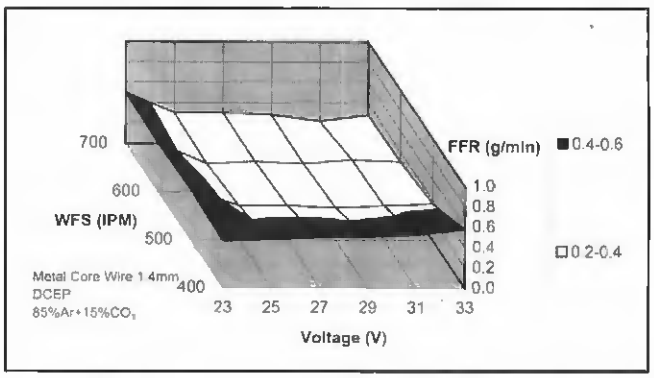

Fig. 17 — FFR values during DCEP metal-cored-wire welding for a range of arc voltages and wire-feed-speed settings.

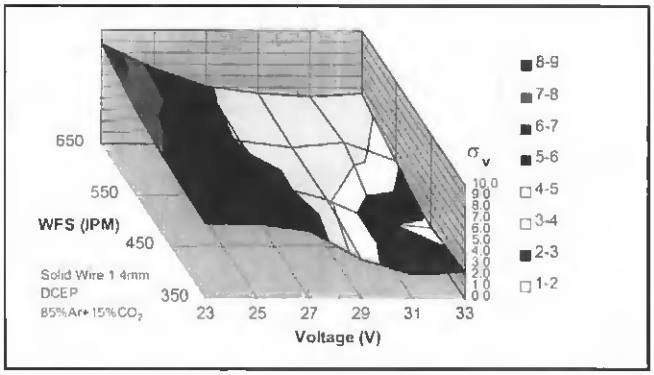

Fig. 18 — Standard deviation of arc voltage during DCEP solid-wire welding using a range of arc voltage and wire-feed-speed settings.

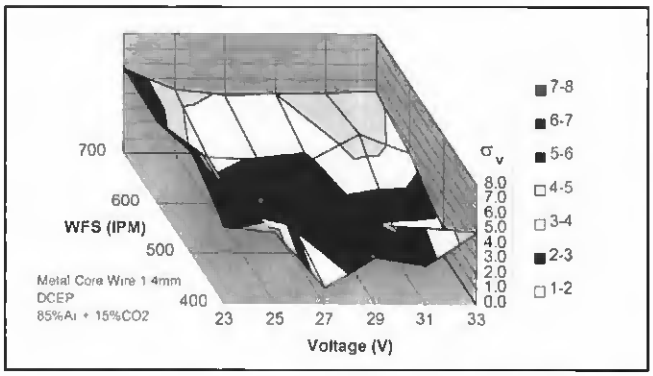

Fig. 19 — Standard deviation of arc voltage during DCEP metal-cored-wire welding for a range of arc voltage and wire-feed-speed settings.

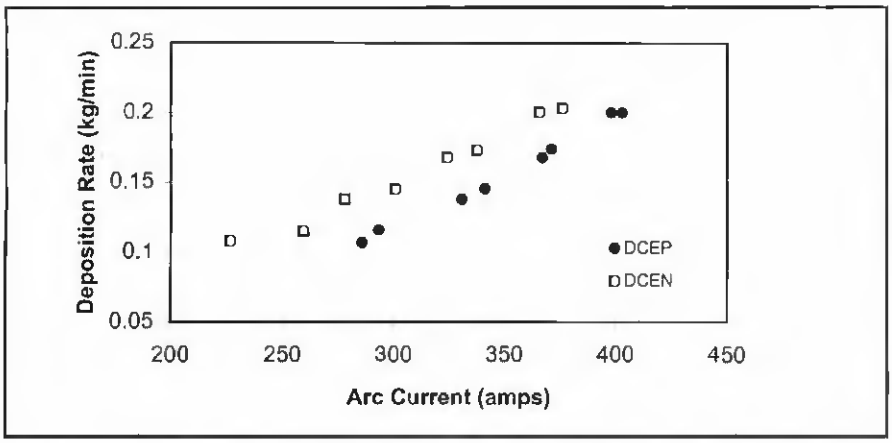

Fig. 20 — Deposition rates during DCEP-DCEN welding using 1.4-mm-diameter solid- and metal-cored wire at 27 V.

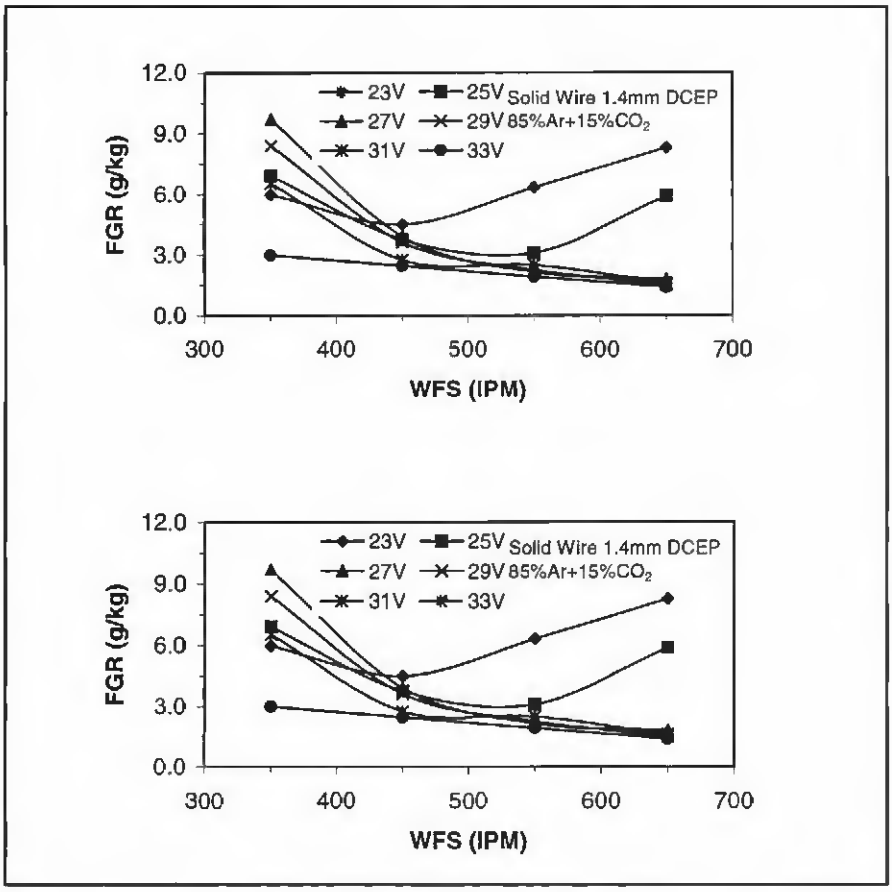

Fig. 21 — FGR values produced during DCEP gas metal arc welding using 1.4-mm-diameter solid wire.

The arc gap was much larger during DCEN metal-cored-wire welding and large-diameter metal droplets formed on the electrode tip prior to transfer into the weld pool — Fig. 15. This mode of metal transfer was particularly evident during welding using high arc voltage settings.

The arc gap and fume formation rate markedly decreased when the wire feed speed increased from 400 to 700 in./min. Finally, there was no observable relation between the intensity of fume generation (β_a) and the power input during DCEN welding using metal-cored wire.

Operating Envelopes for Fume Generation

Figures 16 and 17 show the combined effects of arc voltage and wire-feed-speed changes on fume generation during DCEP solid-wire and metal-cored-wire welding. Although DCEP metal-cored wire welding produced similar FFR values, the operating range producing the lowest fume generation rates was substantially increased.

Gray, *et. al.* (Ref. 4), indicated the lowest fume generation rates were produced when short-circuit transfer occurred during GMA welding — Fig. 2. The results produced during solid-wire and metal-cored-wire welding using low arc voltages and wire feed speeds from 400 to 750 in./min appear to contradict the suggestions of Gray, *et. al.* However, it is important to differentiate between short-circuiting metal transfer and increased arc instability when welding using low arc voltage settings. When the welding operation is carried out and the short-circuit transfer frequency is optimized via careful welding parameter selection and power source control, low fume generation rates are produced. This occurs because the temperature of the melted droplets is less and material is transferred directly into the weld pool (Ref. 8). However, if the wire-feed-speed setting is excessively high, the arcing process becomes unstable and spatter and fume are ejected from the arc envelope. Therefore, it is not short-circuiting metal transfer, *per se*, but arc instability that promotes increased fume generation. Extending this argument, a mixed metal transfer mode involving a combination of short-circuit and spray transfer will produce more fume generation than welding conditions that produce stable spray transfer during the welding operation. The fume-generating tendency will be decreased when the arc stability during welding is optimized. In this connection, DCEP metal-cored-wire welding provides improved arc stability over a larger operating range than solid wire — Figs. 18 and 19.

The fume generating performance of DCEP solid-wire and DCEN metal-cored welding consumables are of particular interest since higher deposition rates are possible during DCEN welding operations — Fig. 20. Figures 21 and 22 show the FGR (g/kg) values found during DCEP solid-wire and DCEN metal-cored-wire welding. It was pointed out earlier the amount of fume generation was least during DCEP solid-wire welding when using power inputs ≥9.5 kW. Figures 13 and 22 show the amount of fume generated during DCEN metal-cored-wire welding decreased substantially when the wire feed speed increased from 400 to 800 in./min.

It is apparent from Fig. 22 that DCEN metal-cored-wire welding using a high wire feed speed (800 in./min) produces FGR values similar to those found during DCEP solid-wire welding.

Conclusions

Fume generation during gas metal arc welding using solid-wire and metal-cored welding consumables was investigated in tests involving a wide range of arc voltage and wire-feed-speed settings. The following has been confirmed:

1) The fume generation rate during DCEP welding using 1.4-mm-diameter solid wire attained a minimum value when a critical power input of 9.5 kW was exceeded. The low fume generation rate produced during solid-wire welding using power levels ≥9.5 kW resulted from preferential absorption of metal vapor when the arc buried in the molten weld pool.

2) Although DCEP solid-wire and metal-cored-wire welding produced similar fume generation rates the operating range that provides the lowest fume generation rates and optimum arc stability was larger when using metal-cored wire.

3) The amount of fume generated during DCEN metal-cored-wire welding using a high wire feed speed (800 in./min) was similar to the best results produced during DCEP solid-wire welding. Therefore, the higher deposition rate capability of DCEN metal-cored-wire welding is accessible without increasing the fume formation tendency provided very high wire feed speeds are applied during the welding operation.

4) The fume generation rate can be readily calculated using simple relations involving the power input and the intensity of fume formation (β_a = g/kW h) during DCEP and DCEN solid-wire welding and DCEP metal-cored-wire welding. This approach could not be applied during DCEN welding using metal-cored wire.

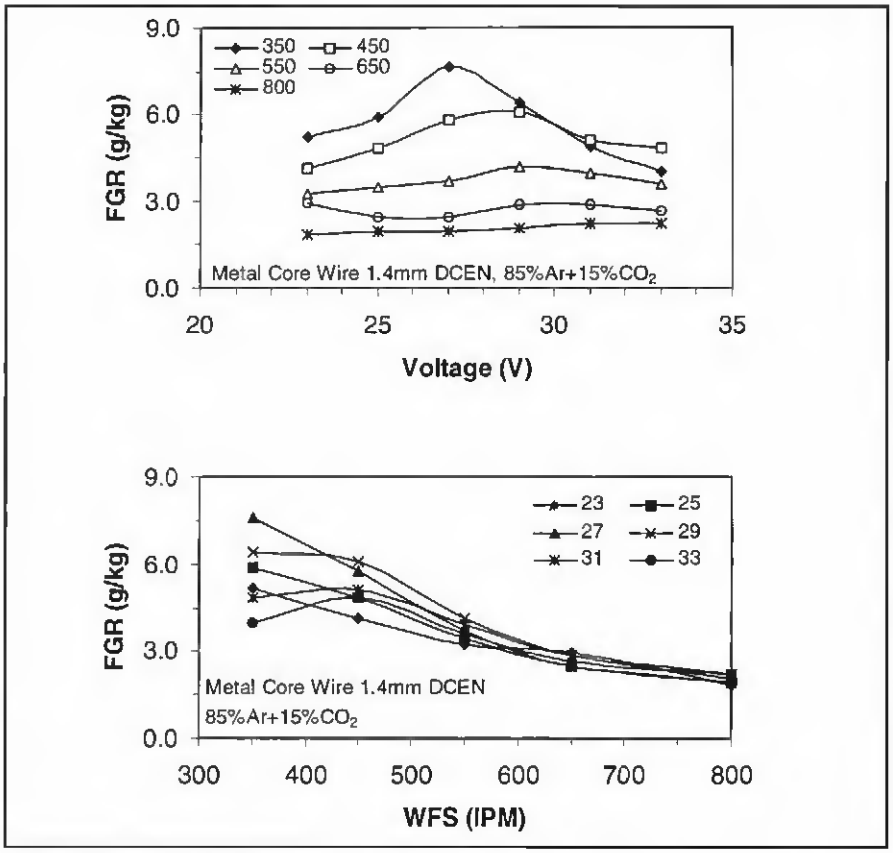

Fig. 22 — FGR values produced during DCEN gas metal arc welding using 1.4-mm-diameter metal-cored wire.

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