Fume Generation and Melting Rates of Shielded Metal Arc Welding Electrodes

Electronically controlled welding apparatus is used to determine the fume generation rates and melting rates of some hardfacing and HSLA steel SMAW electrodes

BY R. K. TANDON, J. ELLIS, P. T. CRISP, AND R. S. BAKER

ABSTRACT. An electronically-controlled welding apparatus with a fume collection system was used for shielded metal arc welding (AC and DC) of three hardfacing and two high-strength, low-alloy steel electrodes at optimum current settings for each electrode.

At each current setting, fume generation rates (FGR's, *i.e.*, g fume/kg electrode melted) varied by a factor of 1.5 to 2.0 while acceptable arc length was maintained. FGR's increased almost linearly with voltage and with power, and decreased almost linearly with current. AC welding gave FGR's which ranged from 50% greater (hardfacing high-manganese electrode) to 30% less (hardfacing medium-chromium electrode) than DC welding at the same current. No difference was found in FGR's between DCEN or DCEP welding* with a hardfacing high-manganese electrode.

Electrode melting rates (EMR's, kg electrode melted/h) increased almost linearly with current, and decreased almost linearly with voltage and power. For the same current with a hardfacing high-manganese electrode, EMR's varied as follows: AC < DCEP < DCEN.

The processes responsible for the observed variations are discussed, and the need for study of metal arc physics is emphasized.

**AC – alternating current; DCEP – direct current, electrode positive; DCEN – direct current, electrode negative.*

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Introduction

A large proportion of the electrodes currently produced are of the hardfacing and high-strength-low-alloy (HSLA) steel types. Special shielded metal arc welding (SMAW) electrodes are extensively used for hardfacing in agriculture, mining and engineering where resistance to abrasion, impact and erosion are essential weld requirements (Refs. 1, 2). HSLA steel SMAW electrodes have numerous industrial applications, such as the welding of tubes and vessels in chemical plants and steam generating equipment (Ref. 2).

Both types of electrodes contain varying amounts of chromium which, when released as chromium (VI) in fume, is suspected of causing lung cancers (Ref. 3), but this has not been established in welding health studies (Ref. 4). It is important, therefore, to study the formation rate and chemical composition of the fume emitted from such electrodes.

In this paper, data are presented for three hardfacing-SMAW and two HSLA steel SMAW electrodes in order to show the effect of electrical variables on fume generation rates and electrode melting rates. Both welding and fume collection were carried out under precisely controlled and reproducible conditions. This study is the first phase of a project in which it is planned to carry out physical, chemical and biological investigations of fume particles from hardfacing SMAW and HSLA steel SMAW electrodes.

Experimental Procedure

The equipment and method used for generating and collecting welding fume have already been described by the authors (Ref. 5). A schematic diagram of the equipment is shown in Fig. 1.

An electronic controller maintains a constant preset welding voltage by adjusting the arc length via an electrode feeder mechanism. The electronic controller also operates the horizontal drive table and welding power supply while continuously displaying the welding current and voltage; both current and voltage can be continuously recorded. The electrode feeder mechanism comprises an insulated electrode holder mounted on a worm thread which is driven by a DC servo-motor. The horizontal table moves on rollers with a total movement of 500 mm (19.7 in.) at speeds adjustable from 100 to 700 mm/min (3.94 to 27.6 ipm).

For AC welding (Ref. 5), the low current range (open circuit = 78 V) was used for all electrodes except E11 (Table 1); for the E11 electrode, a high current range (open circuit = 55 V) was used. DC welding was performed with a Lincwelder DC 250 MK generator (open circuit = 60V).

For both AC and DC welding, the current on the power supply was set to the mid-point of the recommended operating range, and welding was performed at arc voltages between 20 and 35 V. The use of automatic welding apparatus simulated both practical welding conditions and unstable long-arc conditions. The latter were included in the study in order to probe the physical and chemical processes occurring in the welding arc.

All measurements were made at a welding speed of 150 mm/min (5.9 ipm), with the electrode feeder mechanism set at an angle of 45 deg to the table. All welding was done on 8 mm (0.31 in.) thick mild steel plates. Voltage measurements were made between the top of the electrode and the work table and between points 50 mm (1.97 in.) apart near the top of each electrode; current

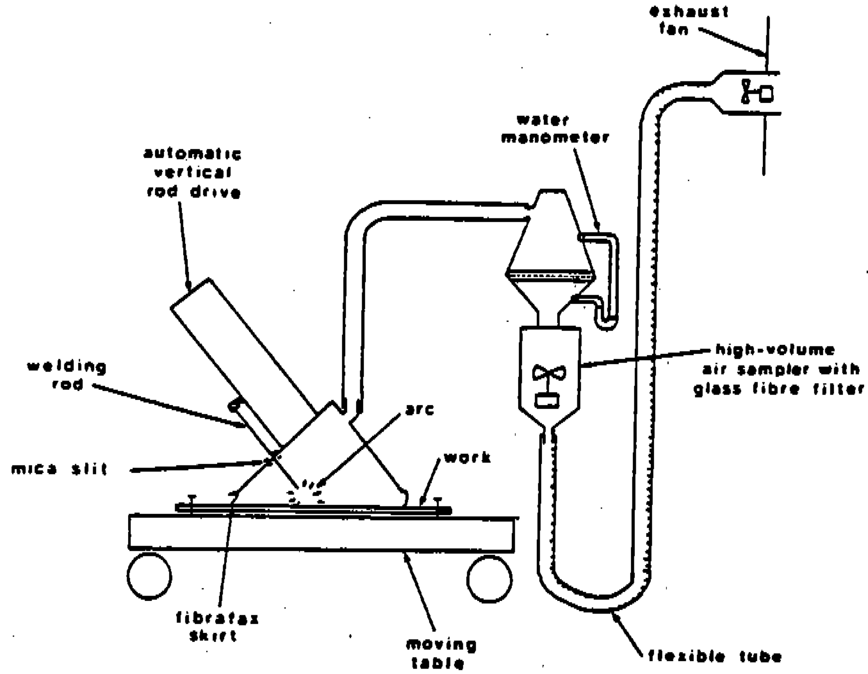

Fig. 1—Schematic of the welding and fume collection equipment. Reproduced from Australian Welding Journal *with permission (Ref. 5)*

was determined by measuring the voltage drop across a shunt of known resistance. Dynamic properties of the arc (Ref. 6) and phase angle were measured using a cathode-ray oscilloscope.

Fume collection was carried out following the procedures described by the American Welding Society (Ref. 7) and the Australian Welding Research Association (Ref. 8). An air flow rate of approximately 16 L/s (2034 cfh) was used; this is within the range of fume-plume conditions in practical welding.

Results

The electrodes used in the study and their recommended operating conditions are given in Table 1. The relationships between the electrical variables—current, voltage and power—are shown in Fig. 2, and the variations in fume generation rate and electrode melting rate with current are shown in Figs. 3 and 4.

It must be borne in mind that both fume generation rates and electrode melting rates relate to a situation where power (V · A) is increasing as voltage (V) is increasing and current (A) is decreasing (see Fig. 2). We are thus working along points on the voltage-current curve at constant current setting on the power supply. The experiments were not designed to make comparisons of fume generation rates at equivalent power levels (power (kW) = current (A) × voltage (V) ÷ 1000). However, in all instances where equivalent power levels were obtained, higher fume generation rates were found with higher arc voltages.

Values for average current, fume generation rate, and electrode melting rate were reproducible within ±5% using the same voltage setting on the electronic controller and electrodes of the same production batch. During welding, voltage and current fluctuated within ±1 V, ±1 A with electrode E11 and within ±2.5 V, ±5 A for the other electrodes.

Resistive heating of the unused portion of electrode was small, since the voltage drop along the electrode was 20–50 mV/cm (≅ 51–127 mV/in.), corresponding to ≈ 1 V along a full rod. Current and arc voltage were in phase (phase angle <3 deg), confirming the absence of significant capacitance or inductance in the arc. All electrodes formed a gun barrel tip during use, and the welded seams were generally flat and uniform. Electrodes E11 and E12 formed considerably less slag than the other electrodes.

No leakage of fume around the collecting hood was visible during welding, and loss of fume due to deposition in the steel tubing and hood was <5%. The glass-fiber filter collects particles below 0.3 μm with decreasing efficiency, but such particles constitute only a small percentage of the total mass collected on the filter (Ref. 9).

Discussion

The fume generation rates (FGR's) for each electrode varied by a factor of approximately two while acceptable arc length was maintained using the recommended nominal current settings on the power supplies. FGR's increased almost linearly with voltage and with power, and decreased almost linearly with current—Figs. 3 and 4.

It is likely that the power of the arc is the principal factor determining the FGR's (Refs. 5, 10), since an increase in the rate of heat input to the arc should lead to greater evaporation and sputtering of molten metal and molten flux. The arc voltage may also be important since it

Table 1—Description of the Hardfacing and High-Strength, Low-Alloy Steel Electrodes Used

Code[a]	Type	Diameter, mm	Recommended operation and current, A	Nominal weld deposit analysis, wt-%
E01	Hardfacing, medium-chromium	3.25	AC : 90-135 DCEP: 90-135	Cr:7, C:0.4, Mo:0.5, Mn:0.3, V:0.5
E04	High-strength, low-alloy steel	3.25	AC :105-150 DCEP:105-150	Ni:1.6, C:0.07, Mn:1.0, Si:0.04, Mo:0.3
E05	High-strength, low-alloy steel	3.25	DCEP: 75-130	Cr:2.12, C:0.045, Mo:0.95, P:0.022, Mn:0.72, S:0.019, Si:0.38
E11	Hardfacing, high-manganese	4.0	AC :125-230 DCEP:125-210 DCEN:125-210	Mn:14.5, Si:0.14, Ni:3.2, P: ≤ 0.05, Mo:0.75, S:0.01, C:0.65
E12	Hardfacing, high-chromium	6.0	AC :120 DCEP:120	Cr:30-35, Mn:3-3.5, C:4-5

(a) AWRA system of classification corresponding to code designations: E01 – 1855A4; E04 – E9018G; E05 – E9015B3; E11 – 1215A4; E12 – 2355A1.

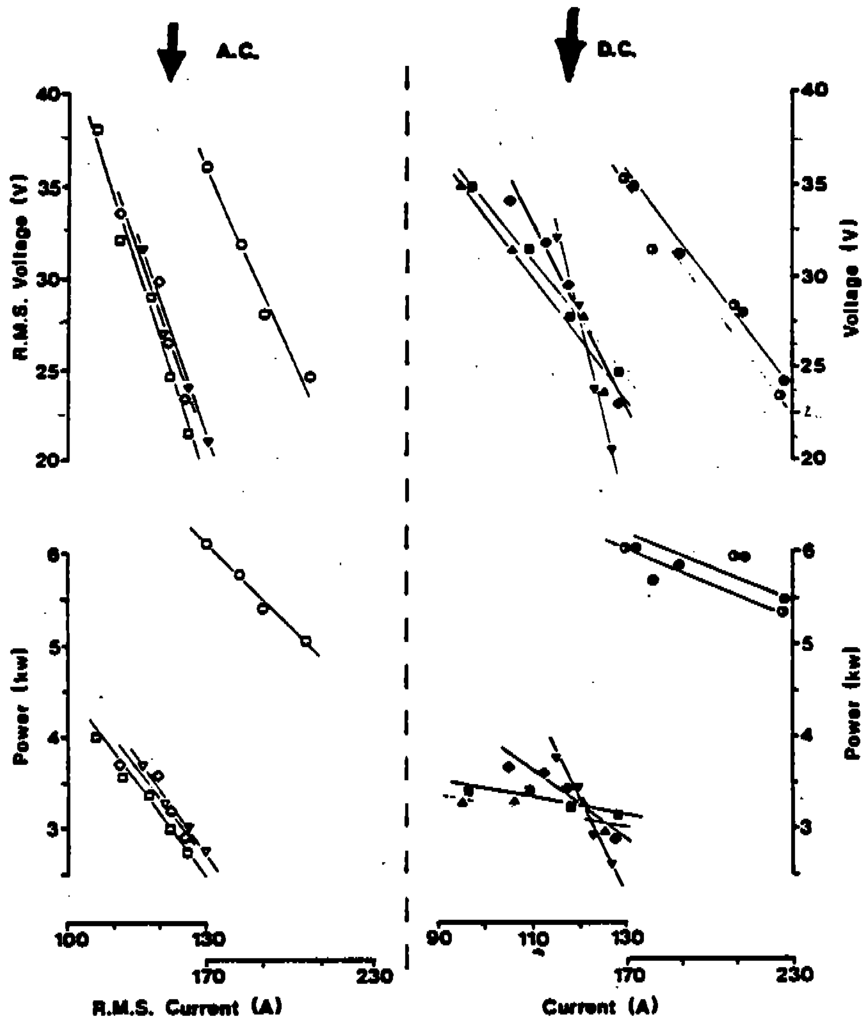

Fig. 2 — Effect of current on arc voltage and power using specific electrodes by code designation (see Table 1): E01 with AC — ▽, with DCEP — ▼; E04 with AC — □, with DCEP — ■; E05 with DCEP — ▲; E11 with AC — O, with DCEP — ●, with DCEN — ◐; E12 with AC — ◇, with DCEP — ◆

determines the arc length (Ref. 1) and, thus, the following:

1. The surface area of the plasma column through which material can escape.
2. The time the material spends in the plasma (Ref. 5).

No systematic difference was observed in FGR's with AC compared with DC welding. The results obtained here do not agree with the findings of Eichhorn *et al.* (Ref. 11) that AC welding generally produces less fume than DC welding.

The mechanism of metal transfer during SMAW welding is difficult to establish but under optimum conditions consists of a showery spray of metal and slap droplets (Ref. 1). Gray *et al.* (Ref. 12) proposed that, during spray transfer, the bulk of the fume formation occurs in the arc plasma by evaporation of droplets in the plasma jet rather than by processes at the cathode or anode. This proposal explains the similar FGR's obtained with DCEN and DCEP welding for electrode E11; it also explains the generally similar fume generation rates obtained with AC and DC welding at the same power — Fig. 4.

The electrode melting rates (EMR's) displayed opposite behavior to the FGR's in their variation with the electrical conditions. EMR's increased almost linearly with current and decreased almost linearly with voltage and power. EMR's obtained using AC and DCEP were generally similar, but the EMR for electrode E11 using DCEN was approximately 40% greater than that using DCEP.

The high melting rates obtainable with DCEN arcs are well known (Refs. 1, 13). The transfer of metal is globular and spattery, unless trace constituents such as metal oxides and calcium salts are included in the flux to make the cathode more thermionic; if this is done, spray transfer of metal predominates and the melting rate decreases (Ref. 1). It appears, therefore, that the differences in EMR's with different DC polarities arise from differences in the proportions of globular transfer (fast) and spray transfer (slow).

We suggest that globular transfer occurs when there are relatively few arc roots releasing heat ("plasma emission," Ref. 13) and that spray transfer occurs when the arc roots are relatively numerous ("field emission," Ref. 13). The

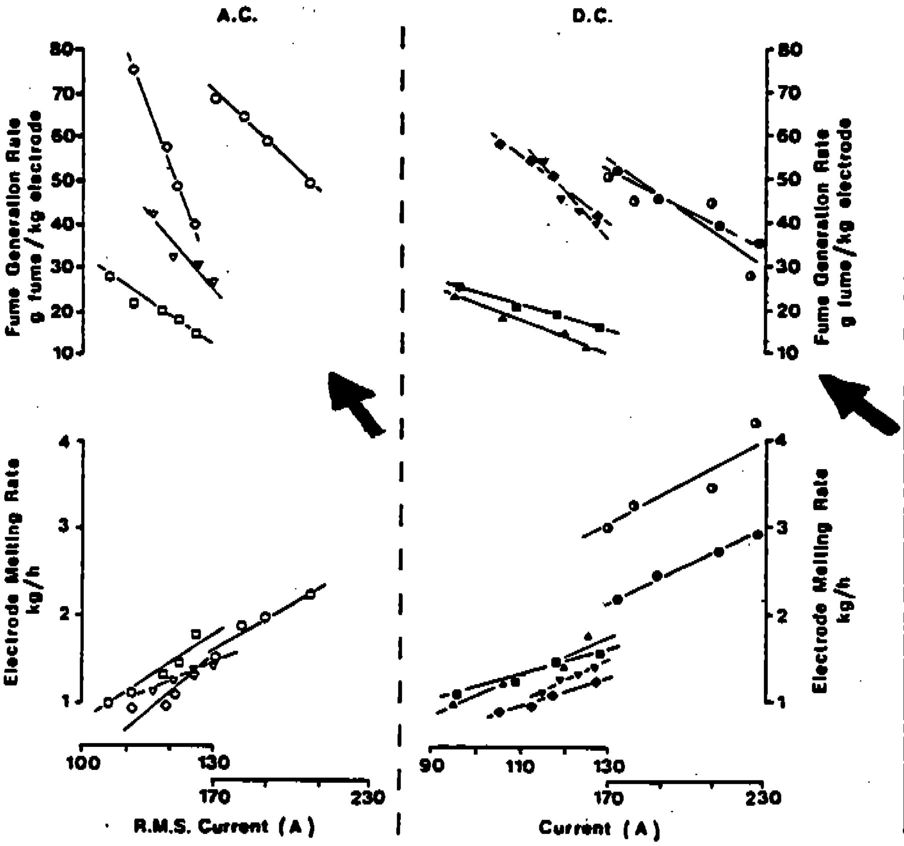

Fig. 3 — Effect of current on the fume generation rate and electrode melting rate (see Fig. 2 caption for symbols corresponding to electrode code designations)

increase in EMR's with increasing current may be due to the increasing frequency of charge-transfer processes per unit area of the electrode surface, resulting in a greater rate of heat dissipation.

It is notable that EMR's increase with decreasing power. This is probably due to the relatively small amount of radiative heating of the electrode by the plasma or workpiece surface (Ref. 1); resistive heating of these components of the arc, therefore, has little bearing on events at the electrode surface.

Interpretation of fume-generation and electrode-melting data for covered electrodes is hindered by the limited information available on the physics of metal arcs. Processes occurring at the anode and cathode surfaces are poorly understood and, to date, studies of the arc plasma have concentrated on the simplest cases, *i.e.*, inert-gas shielding, nonconsumable electrode and cooled workpiece (Refs. 12, 14).

The flux coatings of covered electrodes provide additional charge carriers to the plasma (readily ionizable elements such as sodium, potassium and calcium); these modify the emissivity of the cathode and anode surfaces (metal oxide and ionizable atomic films) and probably affect most other arc variables. Further interpretations of fume-generation and electrode-melting data must wait until the chemical physics of flux coatings and electrode processes are better understood.

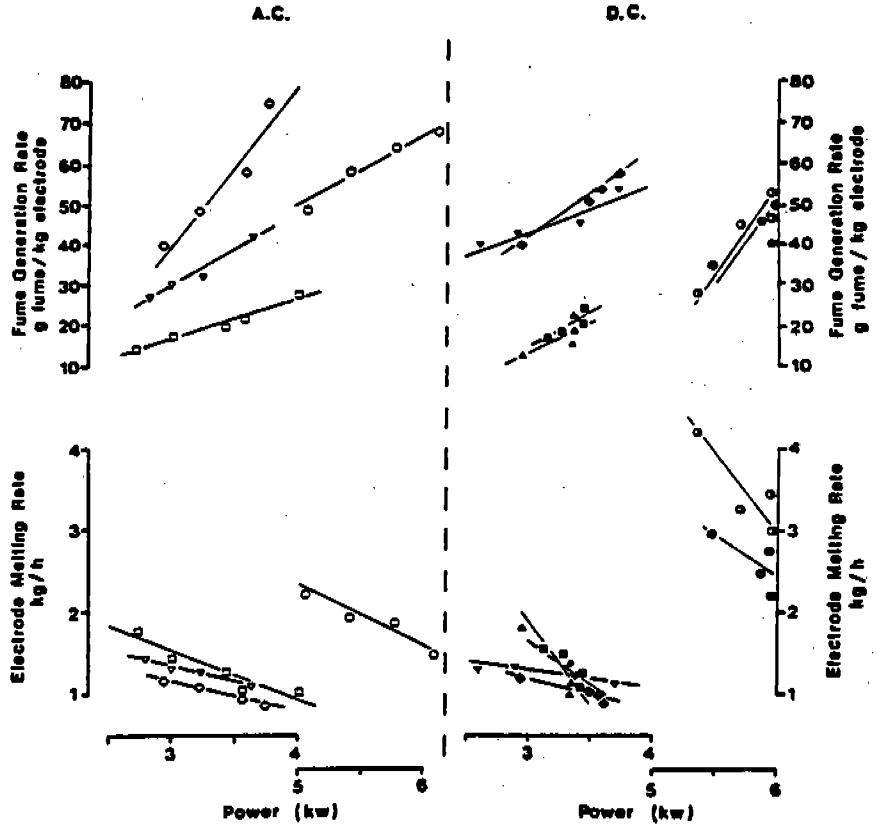

Fig. 4 – Effect of power in the fume generation rate and electrode melting rate (see Fig. 2 caption for symbols corresponding to electrode code designations)

Conclusion

Wide variations in fume generation rate occur with different electrodes and with the same electrode under different welding conditons. In particular, the highest fume generation rates were observed with a high-chromium hardfacing electrode; this result may be important due to the present concern about chromium (VI) toxicity.

Variations in fume generation rates are important for determining the precautions which should be taken during welding operations and must be known for chemical and biological studies of fume toxicity. In addition, fume generation rate data for welding processes under different conditions must be available so that hypotheses concerning electrode and plasma behavior may be tested.

Acknowledgments

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