Introduction

The determination of fall voltages associated with welding arcs has been a great interest for researchers as these values lead to greater insight and comprehension of arc welding, including the effects of reversed/variable polarity. Numerous studies have measured or developed models relating plasmas and their respective fall voltages with results varying drastically between literature. Most research has explored looking at arc discharges between two pure metal electrodes (copper, tungsten, and graphite) with different types of plasmas (air, argon, or CO₂) (Refs. 1–7).

In relation to a welding system, this type of research is most similar to gas tungsten arc welding (GTAW), which involves a nonconsumable thermionic tungsten cathode, nonthermionic anode, and inert plasma/shielding gas. Knowing the magnitude of fall voltages in GTAW aids in understanding electrode wear and heat inputs typically seen in welding systems.

Despite the extensive work performed in the GTAW system, substantially less research has been made in the determination of fall voltages associated with gas metal arc welding (GMAW) (Ref. 8). The addition of a nonthermionic cathode in conjunction with a continuously feeding melting anode has led to increased challenges in experimentation (Ref. 9). Understanding arc phenomenon in GMAW has often proved challenging due to unpredictable and unstable behavior of the welding system during metal transfer. Models have been developed to assist in the comprehension of GMAW with many models related to metal transfer, droplet temperature, fume generation, efficiency, and heat distribution (Refs. 4, 9–13). These models often require a measurement of fall voltage and are frequently approximated with measurements found in GTAW due to their similarity (Refs. 3, 14). This similarity has led to reasonable approximations but is not necessarily accurate as the addition of a consumable anode, nonthermionic cathode, and different plasma/shielding gas composition in GMAW will lead to altering arc column properties and different fall voltages (Refs. 3, 4, 9, 12, 13, 15, 16).

This paper explains how measurements of voltage loss, thermal efficiency, droplet temperature, and droplet diameter were experimentally obtained with possible explanations for the results. The measurement of the various fall voltage regions was either directly measured or inferred based on experimental parameters and measurements. This is the first time all fall voltage regions have been simultaneously measured as a function of current. This was undertaken to get a complete understanding of the GMAW system for various welding parameters in a consistent manner. Experimental decisions and parameters were selected primarily for their relation to typical welding syst-
Background

When an electric discharge is present between two metallic electrodes, there is a large voltage loss associated very close to both the cathode and anode (Refs. 4, 15). The rapid reduction in temperature between the plasma and electrode surface results in insufficient thermal ionization and ion generation for proper electrical conductivity close to the anode/cathode (Ref. 9). A large potential is generated in these regions known as fall voltage regions or drop potential regions. These regions are in the order of 1–100 μm in thickness (Refs. 4, 8, 9, 17, 18).

Earliest measurements of cathode and anode fall voltages began with Stark who utilized a probe allowing electron temperature measurements very close to a cathode or anode in a plasma (Ref. 19). These temperature measurements allowed for derivation of current density and overall fall voltage measurements. Stark’s probe was greatly improved by Langmuir through the creation of the Langmuir probe allowing more accurate measurements (Refs. 20, 21). These probes were a fundamental basis for understanding plasmas as electron temperature, current density, and fall voltage could be determined. Further experiments were conducted utilizing Langmuir’s probe in different types of plasmas and electrodes (Refs. 22–25). Results varied as cathode fall measurements obtained were between 5 and 15 V. These early experiments were conducted to gain further understanding of plasmas and were not directly related to welding systems.

In relation to a typical welding system, the fall voltage regions are the primary contributing factor for heat inputs in both the cathode and anode (Ref. 3). With sufficient pressure, voltage, and current (typical of those found in a welding system), large heat inputs are obtained leading to subsequent melting of the cathode and anode. This is the fundamental basis for a successful welding system. In addition to the cathode and anode fall voltage, a typical welding system also has voltage loss associated with the contact tip, electrode, and arc column as shown in Fig. 1.

Fig. 1 — Typical GMAW system and fall voltage regions. A — Contact tip voltage loss; B — electrode extension voltage loss; C — overall anode fall voltage; D — overall arc column fall voltage; E — overall cathode fall voltage.

Various systems have been utilized to determine fall voltages in GTAW such as probe sweeping, energy balance, and Langmuir’s probe (Ref. 7). However, the addition of a consumable anode has led to increased difficulty in voltage potential measurements in GMAW. Other methods have been used to determine fall voltages for a GMAW system typically in the form of calorimeters, models, or arc analysis (Refs. 2–9, 26–28). Some methods are outlined below showing how voltage fall measurements were made at various regions in GMAW.

Cathode

The cathode fall region is the negative area of the GMAW system. To maintain a stable arc, multiple small cathode spots are created to generate a sufficient number of electrons. The cathode fall region in nonthermionic materials is less understood compared to thermionic materials. In thermionic cathodes, electrons are generated when the material reaches the thermal electron emission temperature (Ref. 15). These electrons are accelerated away from the cathode and ionize neutral atoms. These ions are then accelerated toward the cathode providing the cathode with heat from the ions’ kinetic and potential energy (Ref. 29).

In nonthermionic materials, electron generation may be a result of oxide dissociation or reactions as cathode attachment spots are preferentially located at oxides (Ref. 15). Experiments have shown that a material free of any oxide material cannot sustain a stable arc (Ref. 15). Industrial welding systems will have the addition of O₂ or CO₂ in the shielding/plasma gas to avoid unstable arcing behavior. The CO₂ addition generates an oxide layer in the weld pool that reduces the cathode work function and promotes increased stability (Ref. 18). Additionally, the higher arc plasma temperature, higher thermal conductivity of CO₂, and the reactions between the CO₂ and molten weld pool all contribute to more heat being contributed to the weld pool (Ref. 18).

Literature has placed the overall cathode fall voltage in GMAW to be somewhere between 10 and 20 V (Refs. 4, 8, 28, 30). Lancaster estimated the overall cathode fall voltage to be approximately 10–20 V and estimated the overall cathode fall voltage to be ~15 V for a welding current of 118 A (Ref. 4). Jonsson theoretically derived the sum of the overall cathode and anode fall voltages to range between 13.32 and...
14.93 V. At the time, Jonsson believed that the anode sheath voltage was very small or negative possibly due to the work of Pfender (Refs. 8, 26). Hajossy determined the overall cathode fall voltage of a GMAW system in different shielding gases by comparing the heat input, melting rate, and instantaneous resistance during short-circuit in direct current electrode negative (DCEN) (Ref. 28). The calculation used by Hajossy did not appear to consider overheating at the electrode surface. Utilizing Ar, CO₂, and air shielding gases, Hajossy found the overall cathode fall voltage of the GMAW system to be 13.9, 14.5, and 16.4 V, respectively (Ref. 28). Huismann calculated deposition rates in DCEN with a cathode fall voltage of 11 V and found similar deposition rates as those from empirical values (Ref. 31).

Anode

The anode fall region is the positive area that attracts electrons. Electrons transfer their kinetic and thermal energy to the anode during condensation resulting in heating of the anode (Ref. 9). Anode fall voltage is often calculated using an energy balance around the GMAW electrode as shown below (Refs. 4, 9, 10, 27):

\[
(1 + m)q = \left( \frac{3kT}{2e} + V_A \right)I
\]

where \( q \) is the overall energy transferred to the electrode from the arc, \( m \) is the portion of the anode heat lost by radiation, \( \phi_m \) is the work function of the anode material, \( k \) is Boltzmann’s constant, \( T \) is the temperature of the electrons, \( e \) is the electron charge, \( V_A \) is the anode sheath voltage, and \( I \) is the current (Ref. 4). Typical values of \( m \) are smaller than 1% (Ref. 4). \( 3kT/2e \) describes the thermal energy of electrons. Almost all literature reports the overall anode fall voltage as shown below:

\[
V_{an} = \frac{q_m}{I} - V_{elec} - V_{cont} = \phi_m + \frac{3kT}{2e} + V_A
\]

where \( V_{an} \) is the overall anode fall voltage, \( q_m \) is the total anode heat input, \( V_{elec} \) is the electrode voltage loss, and \( V_{cont} \) is the contact tip voltage loss. This equation assumes \( m \) is negligible. The value of \( V_{an} \) typically varies from 4–9 V depending on welding parameters (Refs. 8, 9, 26–28). Lancaster has reported that the value of overall anode fall voltage may vary as much as 1–12 V but is calculated to be approximately 5.5 V (Ref. 4). Lancaster stated that the overall anode fall voltage does not vary with arc current below a critical value. Above this critical value, it is stated that the overall anode fall voltage will decrease (Ref. 4). In contrast, Nemchinsky calculated overall anode fall for aluminum and steel in GMAW and compared it with experimental values obtained by Wawzink (Refs. 9, 27). Both Nemchinsky and Wawzink found that the overall anode fall voltage increased with increasing current. Nemchinsky derived the overall anode fall voltage to be 8–9 V between 200 and 300 A (Refs. 9, 32). Huismann calculated deposition rates in direct current electrode positive (DCEP) with an anode fall voltage of 5.5 V and found similar deposition rates as those determined with empirical findings (Ref. 31). Hajossy determined the overall anode fall voltage of a GMAW system in different shielding gases by comparing the overall heat input, deposition rate, and instantaneous resistance during short-circuit in DCEP. Hajossy found that the overall anode fall voltage was 7.0 V in an argon arc and 4.9 V in a CO₂ arc (Ref. 28).

Contact Tip

There is a voltage loss associated between the contact tip of the welding torch and the consumable electrode from the electrical contact resistance between the surfaces. This voltage loss
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will contribute to heating of the welding torch and electrode. A typical GMAW system will have a constant contact resistance between the contact tip and consumable electrode when metal transfer is stable (Ref. 33). Literature has found the contact tip voltage drop by measuring the voltage difference between the contact tip and a tungsten probe pressed up against the moving electrode directly after leaving the contact tip (Refs. 8, 32, 34). This method was used by Waszink who measured a voltage drop of 0.1–0.3 V for currents of 100–250 A in a 1.2-mm- (3⁄64-in.) diameter coppered steel electrode (Ref. 32). Jonsson found a slightly higher value of 1.3–1.7 V for currents of 200–325 A (Ref. 8). By extrapolation of Wilson’s results, a contact tip drop of approximately 0.5 and 3.0 V for an electrode extension of 1–7 in. (25.4–177.8 mm) in a 0.3125-in.- (7.94-mm-) diameter electrode was found (Ref. 33).

Electrode Extension

With current flowing through the consumable electrode in GMAW, ohmic heating must be considered. The wire will have an associated voltage loss resulting in joule heating proportional to the electrode extension. Many models have been developed to understand the effects of resistive heating in GMAW (Refs. 14, 27, 32, 34–37). The potential of ohmic heating will vary depending on wire composition and many of these models attempt to be applicable to a wide range of materials.

Luijendijk’s calculations found an average voltage loss of 0.5 V for a welding current of 250 A (Ref. 33).

Arc Column

The plasma column is the region between the cathode and anode fall regions. This region is seen as the current-carrying section of the arc and reaches temperatures of approximately 5000–25,000 K (8540–44,540°F) (Refs. 4, 12, 13, 15, 40). These high temperatures result in large radiative energy losses in the arc column (Ref. 9). This heat loss is balanced by resistive heating in the arc to maintain the proper temperature and ionization. The continuous nature of the arc column has led researchers to approximate this region with a linear voltage drop as a function of arc length (Refs. 4, 9, 15).

The arc column is often seen as being very similar in GTAW and GMAW as similar plasma/shielding gases are used (Ref. 9). The primary difference is the metallic vaporization associated with GMAW. The addition of a consumable anode increases metal vapors in the plasma leading to a change in the plasma’s temperature, pressure, and composition (Refs. 3, 10). Typical GTAW plasma temperatures are app-
proximately 15,000–25,000 K (17,540–44,540°F) with GMAW plasma temperature being cooler at 5000–15,000 K (8540–26,540°F) (Refs. 4, 12, 13, 40). This will change overall conductivity properties and arcing behavior in the plasma, making comparisons between GTAW and GMAW difficult.

Halmoy predicted the arc column voltage in GMAW by welding at a constant current and wire feed speed, changing the contact tip to work distance, and then measuring the change in arc length and electrode extension. Halmoy’s findings showed that the arc fall voltage was a function of arc length. Above 200 A, the electric field in the arc column had a drop potential of 0.6 V/mm (Ref. 36). For a welding current of 200 A and arc length of 0, Halmoy measured the total voltage drop to be approximately 19 V (Ref. 36). With a zero arc length, this total voltage drop is the cumulative overall cathode and anode fall voltage.

### Experimental Setup

The experimental setup is identical to that used by Scott and Chapuis as seen in Fig. 2 (Refs. 41–43). The setup is broken up into several different components including a solid-state calorimeter, water-cooled copper cathode, custom contact tip, and synchronized high-speed videography with data acquisition. Cathode and anode heat inputs are measured independently. The experimental setup is limited to free-flight metal transfer modes with no capability of performing short-circuit waveforms.

### Welding Equipment

Welding was performed with a Lincoln Power Wave S500 and a Lincoln 84 Dual Feeder (program 5 weld set reference: Z153615). All welds were done in constant voltage (CV) mode in direct current electrode positive polarity (DCEP). A Tregaskiss Tough Gun I.C.E. water-cooled robotic GMAW torch was used with a 0.045-in.- (1.143-mm-) diameter ER70S-6 carbon steel electrode. Shielding gas was mixed to 35 standard cubic feet per hour (16.52 L/min) using an OMEGA FL-6GP-40ST-40ST-40ST gas proportioning rotameter. One hundred percent Ar and 95% Ar–5% CO2 shielding gas blends were used for experimentation.

### Copper Cathode

The purpose of the water-cooled copper cathode was to maintain an arc during experimentation. The copper cathode was designed to allow passage of liquid droplets from the electrode to the calorimeter as shown in Fig. 2. Water is capable of flowing through the copper cathode without interference. Water flow rate was monitored with a Kings 7520 7C-02 flow meter with typical flow rates of 0.33 ± 0.02 U.S. gal/min (1.25 ± 0.076 L/min). Omega GKQSS-18G-12 K-type thermocouples were used to measure the temperature change of the water inlet and outlet temperatures reaching ~75°C (167°F). Welding was maintained for approximately 30 s to ensure steady state was reached.

### Overall cathode fall voltage and heat input were determined using

\[
V_{\text{cat}} = \frac{q_{\text{cat}}}{I} = \frac{(T_\text{out} - T_\text{in})mC_w}{I} \tag{3}
\]

where \(V_{\text{cat}}\) is the overall cathode fall voltage, \(q_{\text{cat}}\) is the total cathode heat input, \(T_\text{out}\) is outlet temperature, \(T_\text{in}\) is the inlet temperature, \(m\) is the water mass flow rate, \(C_w\) is the specific heat capacity of water, and \(I\) is the current (Ref. 44).

### Calorimeter and Anode

A solid-state, high-purity copper calorimeter was used to measure anode heat input. Calorimeter dimensions were height of 35 mm (1.38 in.), diameter of 50.8 mm (2 in.), and positioned 127 mm (5 in.) below the water-cooled copper cathode. A solid-state calorimeter was more desired than a water-based calorimeter as there is no error associated with water evaporation (Ref. 42). Ten Omega GKQSS-18G-12 K-type thermocouples were used to measure the temperature change of the calorimeter. Droplets that fell onto the calorimeter were weighed using an Adam PGW 4502e scale to an accuracy of ± 0.01 g (0.0022 lb). Properties of pure copper and pure iron were used for the calorimeter and wire, respectively, when determining anode heat input and droplet temperature (Refs. 45, 46). Molten tin calibration tests have shown that the accuracy of the enthalpy measurements varied by ± 1.1% when the final calorimeter temperature was kept below 187°C (368.6°F). Overall anode fall voltage was then determined using Equation 2.
Electrode Extension

A known electrode extension allows for proper calculation of resistive heating into the wire electrode. Normal industrial contact tips can have a small variance in the measured electrode extension distance as it is unclear where the last point of contact is (Refs. 33, 42). A custom contact tip was used that ensured a known contact point as shown in Fig. 3 (Ref. 42). A tungsten indicator was set to the desired electrode extension distance as shown in Fig. 3. Voltage settings were adjusted during welding until the desired electrode extension was visually verified using the tungsten indicator and high-speed camera. Current was controlled by varying wire feed speed (WFS) with a resolution of 1 in./min (0.0254 m/min). Voltage settings changed with WFS and were selected to maintain a consistent arc length between experiments. All tests done in this research had an electrode extension of approximately 12.5 mm (0.5 in.) and arc length of approximately 12.5 mm (0.5 in.).

A known electrode extension allows for easier repetition and is used to calculate the resistance and voltage loss with a scaling analysis produced by Lehnhoff and Mendez (Ref. 37). The voltage drop in the electrode extension can be determined using an energy balance:

\[ V_{\text{elec}} = H_{\text{f}} U A \]  

where \( H_{\text{f}} \) is the amount of joule heating gained by the electrode, \( U \) is the WFS, and \( A \) is the cross-sectional area of the wire. Following Lehnhoff, \( H_{\text{f}} \) can be calculated as (Ref. 37)

\[ H_{\text{f}} = H_{\text{i}} H_{\text{e}} \]  

where \( H_{\text{i}} \) is the enthalpy variation between room temperature and just before melting of the electrode. \( H_{\text{e}} ^{H_{\text{2}}} \) can be determined as

\[ \Delta H_{\text{e}} = 2 \left( \frac{d}{e^{M_{1}} - 1} \right) \left( \frac{d}{1 - e^{M_{1}}} + d \left( 1 + \frac{d}{M_{1}} \right) \right) \]  

where \( \rho \) is the electrical resistivity, \( \Delta \) is the maximum change in \( \rho \) from \( H_{\text{0}} \) to \( H_{\text{m}} \), \( \Delta \) is the relative curvature in \( \rho \) (H), \( M_{1} \) is the enthalpy in the wire material, and \( L \) is the electrode extension (Ref. 37). Resistivity properties of ER70S-6 were obtained and used for calculations as shown in Table 1 (Ref. 38).

Contact Tip

Contact voltage loss from the resistance at the contact tip and electrode was measured directly. A second tungsten bar maintained sliding contact with the steel electrode immediately after leaving the contact tip as shown in Fig. 3. A torsional spring was attached to a tungsten electrode to ensure constant contact with the steel electrode. This approach is similar to the technique used by Wilson and Waszink (Refs. 32, 34).

High-Speed Videography

High-speed video taken at 5000 frames per second was used to confirm that the desired metal transfer mode and electrode extension were achieved. A Phantom V210 high-speed camera was utilized with a 850-nm-long wave pass filter. Data acquisition was captured in synchronization with the high-speed videography to determine welding parameters. An LEM LV 25-P voltage transducer and LEM HTA 600-S current transducer were used to capture total voltage and current with an accuracy of ±0.9% and ±1.0%, respectively. Total voltage measurements were performed between the welding torch and cathode. Voltage loss through the welding torch cable were not included in measurements. Analog signals from the transducers were captured with a National Instruments USB 6351 X series data acquisition unit at 50,000 Hz. The frequency of detachment was measured by counting 100 droplet detachments in its respective time frame for each test. Droplet diameter was determined through a volumetric balance by using the follow formula:

\[ d_{\text{d}} = \left( \frac{3U (d_{\text{w}})^{2}}{2f_{\text{d}}} \right) ^{\frac{1}{3}} \]  

where \( d_{\text{d}} \) is the droplet diameter, \( d_{\text{w}} \) is the wire diameter, and \( f_{\text{d}} \) is the frequency of detachment.

Arc Column

The combination of the water-cooled cathode, calorimeter, and data acquisition system were used to calculate voltage loss of the arc column. Arc column voltage loss was determined using

\[ V_{\text{ail}} = V_{\text{tot}} - V_{\text{cat}} - V_{\text{an}} - V_{\text{elec}} - V_{\text{cont}} \]  

where \( V_{\text{ail}} \) is the arc column voltage loss, and \( V_{\text{tot}} \) is the total welding voltage.

Results

Results are summarized in Tables 2 and 3 and Figs. 4–7. All average values presented are given with their standard deviation.

Cathode

Average overall cathode fall volt-
<table>
<thead>
<tr>
<th>Gas Type</th>
<th>Average Voltage (V)</th>
<th>Average Current (A)</th>
<th>Wire Feed Speed (in./min)</th>
<th>Frequency of Droplet Detachment (Hz)</th>
<th>Droplet Diameter (mm)</th>
<th>Droplet Temperature (K)</th>
<th>Cathode Fall Voltage (V)</th>
<th>Anode Fall Voltage (V)</th>
<th>Contact Tip Voltage Loss (V)</th>
<th>Electrode Extension Voltage Loss (V)</th>
<th>Arc Column Voltage Loss (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Ar</td>
<td>28.1</td>
<td>185.2</td>
<td>240</td>
<td>49</td>
<td>1.59</td>
<td>76.6</td>
<td>2448</td>
<td>13.98</td>
<td>5.66</td>
<td>0.40</td>
<td>1.50</td>
</tr>
<tr>
<td>100% Ar</td>
<td>28.1</td>
<td>192.3</td>
<td>240</td>
<td>77</td>
<td>1.37</td>
<td>72.0</td>
<td>2595</td>
<td>12.41</td>
<td>5.77</td>
<td>0.42</td>
<td>1.63</td>
</tr>
<tr>
<td>5% CO2</td>
<td>29.6</td>
<td>254.9</td>
<td>260</td>
<td>71</td>
<td>0.95</td>
<td>66.2</td>
<td>2631</td>
<td>12.17</td>
<td>4.71</td>
<td>0.49</td>
<td>2.25</td>
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<tr>
<td>5% CO2</td>
<td>30.2</td>
<td>231.4</td>
<td>270</td>
<td>71</td>
<td>0.92</td>
<td>69.1</td>
<td>2714</td>
<td>13.02</td>
<td>4.56</td>
<td>0.51</td>
<td>2.46</td>
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<td>247.3</td>
<td>280</td>
<td>434</td>
<td>0.81</td>
<td>65.5</td>
<td>2706</td>
<td>12.95</td>
<td>4.22</td>
<td>0.53</td>
<td>2.66</td>
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<td>256.8</td>
<td>290</td>
<td>477</td>
<td>0.80</td>
<td>64.2</td>
<td>2755</td>
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<td>266.2</td>
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<td>511</td>
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<td>63.7</td>
<td>2655</td>
<td>13.27</td>
<td>3.65</td>
<td>0.58</td>
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</tr>
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<td>32.5</td>
<td>214.1</td>
<td>245</td>
<td>128</td>
<td>1.17</td>
<td>62.3</td>
<td>2312</td>
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<td>78.0</td>
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<td>226.3</td>
<td>265</td>
<td>259</td>
<td>0.95</td>
<td>70.8</td>
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<td>4.08</td>
<td>0.49</td>
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<td>229.5</td>
<td>265</td>
<td>236</td>
<td>0.98</td>
<td>66.5</td>
<td>2573</td>
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<td>33.8</td>
<td>232.2</td>
<td>255</td>
<td>259</td>
<td>0.93</td>
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<td>265</td>
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<td>236.3</td>
<td>275</td>
<td>397</td>
<td>0.83</td>
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<td>275</td>
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<td>74.7</td>
<td>2757</td>
<td>16.62</td>
<td>4.71</td>
<td>0.52</td>
<td>2.43</td>
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<tr>
<td>95% Ar - 5% CO2</td>
<td>32.6</td>
<td>239.4</td>
<td>270</td>
<td>439</td>
<td>0.80</td>
<td>68.3</td>
<td>2801</td>
<td>14.60</td>
<td>4.71</td>
<td>0.52</td>
<td>2.46</td>
</tr>
<tr>
<td>95% Ar - 5% CO2</td>
<td>32.8</td>
<td>240.9</td>
<td>275</td>
<td>466</td>
<td>0.79</td>
<td>68.0</td>
<td>2691</td>
<td>14.85</td>
<td>4.47</td>
<td>0.52</td>
<td>2.46</td>
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<td>95% Ar - 5% CO2</td>
<td>32.9</td>
<td>241.6</td>
<td>275</td>
<td>471</td>
<td>0.79</td>
<td>64.5</td>
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<td>4.67</td>
<td>0.52</td>
<td>2.48</td>
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<tr>
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<td>295</td>
<td>458</td>
<td>0.81</td>
<td>70.9</td>
<td>2786</td>
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<td>4.70</td>
<td>0.54</td>
<td>2.58</td>
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<tr>
<td>95% Ar - 5% CO2</td>
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<td>255.1</td>
<td>305</td>
<td>546</td>
<td>0.77</td>
<td>69.1</td>
<td>2788</td>
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<td>4.81</td>
<td>0.55</td>
<td>2.63</td>
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<tr>
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<td>262.3</td>
<td>315</td>
<td>655</td>
<td>0.74</td>
<td>71.4</td>
<td>2989</td>
<td>15.97</td>
<td>5.30</td>
<td>0.57</td>
<td>2.75</td>
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</table>
Average overall cathode fall voltage was 12.7 ± 0.9 V and 15.5 ± 1.3 V for 100% Ar and 95% Ar–5% CO₂, respectively, as shown in Fig. 6 and Table 3. Large experimental uncertainties were found in the overall cathode fall voltage due to the precision of the flow meter. The trend in the 100% Ar tests indicate that overall cathode fall voltage is independent from current. This trend was similarly proposed by literature but was never experimentally verified (Refs. 9, 47, 48).

No trend was apparent in 95% Ar–5% CO₂ experiments as these tests appeared to have a higher variance when compared to 100% Ar. The addition of CO₂ shielding gas increased spatter causing metal droplets to occasionally touch the cathode. At CO₂ concentrations ≥ 10%, steady state could not be reached as the cathode hole would become plugged or liquid metal would begin falling onto the calorimeter after contacting the cathode. This invalidated cathode and anode heat input results before steady state could be completed. Spatter with 95% Ar–5% CO₂ shielding gas persisted but was much less influential compared to concentrations ≥ 10% CO₂. 95% Ar–5% CO₂ experiments were deemed acceptable as steady state could be reached, no cathode hole plugging occurred, no droplets appeared to contact the cathode before reaching the calorimeter, and the overall anode fall voltage measurements were consistent with those found in 100% Ar.

**Anode**

Average overall anode fall voltage was 4.7 ± 0.6 V and 4.5 ± 0.5 V for 100% Ar and 95% Ar–5% CO₂, respectively, as shown in Fig. 7 and Table 3. Observing the results of 100% Ar and 95% Ar–5% CO₂ simultaneously, overall anode fall voltage appears to be constant with current. The transition through globular, project spray, and streaming spray did not have a clear effect on overall anode fall voltage as shown in Fig. 7. The change in metal transfer mode between globular and projected spray was determined by comparing the wire diameter of 1.143 mm (0.045 in.) to the droplet diameter calculated using Equation 8. If the droplet was larger than the wire diameter, metal transfer mode was globular. Significantly less experiments were performed in the globular regime due to the increased spatter associated with this metal transfer. The change between projected spray and streaming spray was apparent in the high-speed videography.

Utilizing Equation 2, an electron temperature of 6000 K (10,340°F), and work function of 4.81 V for iron, overall anode fall voltage can be compared to the anode sheath voltage as shown in Fig. 7 (Refs. 4, 12, 13, 40, 49). Average anode sheath voltage was determined to be on the order of –0.98 V. It was assumed that plasma temperature would not change with welding parameters.

**Thermal Efficiency**

Comparing the cathode and anode heat inputs with the overall heat input, thermal efficiency can be calculated. Typical thermal efficiencies range between 68 and 88%, is dependent on welding parameters, and dependent on joint configuration (Refs. 11, 50–56). Average thermal efficiency in experimentation was 69%. No apparent trend was found between efficiencies of different metal transfer modes. Comparing

![Fig. 7 — Anode fall voltage utilizing 100% Ar (left) and 95% Ar–5% CO₂ (right) shielding gas blends. Transitions between metal transfer modes are shown. Metal transfer modes were distinguished using droplet diameter, wire diameter, and high-speed videography.](image)
were selected so the average electrode ±0.5–1.0 mm. Welding parameters sion variations of approximately during welding with electrode exten-

sion was at the referenced 12.5 mm (0.5 in.) tungsten probe. Actual values of WFS and current were used in Equation 4 to calculate voltage loss. The continuous change in electrode extension altered the instantaneous welding voltage and current leading to some variation in measurements.

**Arc Column**

Average arc column voltage loss was 9.5 ± 1.5 V and 9.9 ± 1.7 V for 100% Ar and 95% Ar–5% CO₂, respectively. Arc column voltage loss was calculated using Equation 9 with an arc length of 12.5 mm (0.5 in.). Arc column potential ranged between 0.52 and 1.05 V/mm with an average of 0.77 ± 0.12 V/mm. Arc column voltage loss appeared to linearly increase with current when using 100% Ar, as shown in Fig. 4. It could not be determined what trend was apparent when using 95% Ar–5% CO₂ as variations were within experimental error.

**Discussion**

Results indicated that cathode, anode, and arc column are the dominant voltage loss regions with contact tip and electrode extension voltage loss being less significant. All results are comparable with those found in literature, as summarized in Table 4.

**Cathode**

Steel cathodes were used in experimentation to reproduce typical industrial cathode materials. Experimentation with steel cathodes could not be completed as insufficient thermal conductivity resulted in premature melting of the cathode prior to steady state. The similarity in work functions between copper and steel has led to comparable measurements as the differences in work function will have a minimal effect (Refs. 11, 41, 42, 48–62). Work function has a slight variation with crystalline orientation. Considering the (111) plane orientation, the work function for copper and steel are 4.94 and 4.81 V, respectively (Ref. 49). It would be expected that overall cathode fall voltage values would differ by 0.13 V between copper and steel. This difference is within experimental error and will likely have a minimal effect on results.

Overall cathode fall voltage was higher in experiments with 95% Ar–5% CO₂ shielding gas as small amounts of spatter needed to be re-

moved from the cathode. This small amount of spatter will inadvertently and artificially increase the cathode heat input. If the spatter had been collected at the time of experimentation, the increase in overall cathode fall voltage could be determined. It is estimated that for a 30-s test, 1–3 g of spatter was collected on the cathode. If the spatter has the same heat content as the droplets collected, the spatter would increase overall cathode fall voltage by approximately 0.5–1.5 V. If the excess spatter that landed on the cathode had been collected, the additional heat input could have been more accurately predicted.

The large differences in overall cathode fall voltage between 100% Ar and 95% Ar–5% CO₂ shielding gas blends in-

<table>
<thead>
<tr>
<th>Author</th>
<th>Cathode Vₚₑₙ (V)</th>
<th>Anode Vₚₑₙ (V)</th>
<th>Contact Tip Vₚₑₙ (V)</th>
<th>Electrode Extension Vₚₑₙ (V)</th>
<th>Arc Column Potential Vₚₑₙ (V/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lancaster</td>
<td>15</td>
<td>1–12</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Jonsson (100% Ar)</td>
<td>13.32–14.93</td>
<td>Very Small</td>
<td>1.3–1.7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hajossy (100% CO₂)</td>
<td>14.5</td>
<td>4.9</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Waszink</td>
<td>—</td>
<td>7–7.5</td>
<td>0.1–0.3</td>
<td>2.5</td>
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<td>Nemchinsky</td>
<td>—</td>
<td>8–9</td>
<td>—</td>
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<td>Wilson</td>
<td>—</td>
<td>0.3–0.6</td>
<td>—</td>
<td>0.5–3.0</td>
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<td>Halmoy</td>
<td>12.72</td>
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<td>0.46</td>
<td>0.68</td>
<td>0.7</td>
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<tr>
<td>McIntosh (100% Ar)</td>
<td>15.48</td>
<td>7.39</td>
<td>0.51</td>
<td>0.74</td>
<td>0.7</td>
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<tr>
<td>McIntosh (95% Ar–5% CO₂)</td>
<td>15.48</td>
<td>7.39</td>
<td>0.51</td>
<td>0.74</td>
<td>0.7</td>
</tr>
</tbody>
</table>
WELDING RESEARCH

dicates that shielding gas may be affecting the cathode fall voltage region. However, the spatter associated with the 95% Ar–5% CO₂ shielding gas tests made conclusions difficult as it is unclear how much overall cathode fall voltage was increased.

Radiative heat from the arc column is lost and will contribute to heating of the cathode. This radiative heat will lead to slightly higher overall cathode fall voltages in all experiments. It is currently unclear how much of this radiative heat was captured by the cathode.

Anode

It is currently unclear if the distance from the electrode tip to the top of the calorimeter is altering measurements (Refs. 11, 58–60). Previous work suggests this free-flight distance does not affect measurements significantly but requires further investigation (Refs. 11, 42, 43). Energy measurements obtained were used to estimate droplet temperature. Droplet temperatures found were comparable with other nonintrusive methods such as pyrometry (Refs. 11, 42, 56, 61–65).

Accurately determining voltage losses in the electrode extension and contact tip will directly influence overall anode fall voltage as shown in Equation 2. Heat generated at the contact tip will be unevenly distributed between the contact tip and electrode. It was assumed that all heat generated at the contact tip will contribute to anode heating as the amount of heat distribution could not be determined. This will lead to a slightly low value of overall anode fall voltage.

Equation 2 does not account for evaporation. Droplet surface temperatures have been shown to be at or above boiling point (Ref. 63). Fumes from an ER70S-6 electrode have shown to be primarily composed of iron and manganese (Ref. 11). Using the enthalpy of vaporization of iron and manganese with fume formation rates, evaporation was calculated to increase overall anode fall voltage by approximately 0.05–0.45 V depending on welding parameters (Refs. 66, 67). Further investigation is still required to properly determine the extent of energy lost during experimentation. If evaporation and contact tip heat distribution were properly determined and incorporated, average overall anode fall voltage is believed to be closer to 5.1–5.5 V and will be more comparable with some literature (Refs. 4, 31).

As shown in Fig. 7, the values of thermal energy and work function were used to determine the anode sheath voltage of ~0.98 V. This value is similar to Pfender’s value of anode sheath voltage (Ref. 26). The work function of (111) pure iron and polycrystalline pure manganese are 4.81 and 4.1 V, respectively (Ref. 49). Although the electrode is primarily composed of iron, the low concentration of Mn in the ER70S-6 electrode can lower the anode work function. Cathode and anode spots have been shown to preferentially form at locations with a lower ionization potential as these locations are easier to emit and condense electrons (Ref. 4). This difference in work function could increase calculated anode sheath voltage by 0.71 V. If evaporation and contact tip heat distribution are also considered, anode sheath voltage will be substantially closer to 0. This is why some researchers do not consider anode sheath voltage in Equation 2 (Refs. 9, 27).

Thermal Efficiency

A thermal efficiency of 69% was found in experimentation and is slightly low compared to previous measurements of thermal efficiency (Refs. 50–56). These previous measurements were primarily performed by welding directly on a plate calorimeter giving no capability of separating between cathode and anode heat inputs. The higher surface area of a plate calorimeter will yield a higher thermal efficiency as the larger surface area can absorb more radiative heat from the arc column. The small surface area of the cathode in this study does not permit large amounts of radiative absorption leading to a lower overall thermal efficiency. Models of the energy distribution in GMAW indicates that thermal efficiency is 68% when the cathode and anode do not receive radiative energy from the arc (Ref. 16).

Contact Tip

Contact tip voltage loss will lead to heating of the welding torch and electrode. Temperature measurements in the water-cooled torch were not used to determine heat inputs into the welding torch. Radiative heat from the arc will contribute to heating of the welding torch leading to an overestimation of heat input. The use of the custom contact tip and tungsten probe allowed for greater precision in contact tip voltage loss and overall anode fall voltage calculations. When the tungsten voltage probe was farther away from the contact point, contact tip voltage measurements were shown to increase slightly due to electrode extension voltage loss.

Electrode Extension

Average voltage loss by resistivity in the electrode extension was 2.27 ± 0.34 V and is comparable with other literature that utilized similar currents, wire diameter, and electrode extensions, as shown in Table 4. Lehnhoff’s model was greatly dependent on resistivity properties of the electrode. Resistivity properties of ER70S-6 were used over pure iron as the alloying elements will cause the resistance to be substantially higher (Refs. 37, 38). Any overestimation in the resistivity properties will greatly change electrode extension voltage loss.

Arc Column

The average arc column fall potential was measured to be 0.77 ± 0.12 V/mm. Equipment resolution, unwanted spatter, and propagation of errors resulted in experimental error being higher than desired. It was expected that the fall voltage of the 95% Ar–5% CO₂ tests would be higher than 100% Ar as the dissociation of CO₂ requires additional energy. However, this conclusion could not be determined as arc column fall voltage variations were within experimental error.

As shown in Fig. 4, arc column voltage loss appears to linearly increase with current. The increasing anode evaporation will decrease arc column temperatures and electrode conduction (Refs. 12, 13, 16). Further amounts of energy will be required for proper ionization and temperatures resulting in an increasing voltage loss. Radiative heat from the arc column is lost and will contribute to heating of...
the cathode, anode, and welding torch. Approximately 13–33% of the total arc column energy is lost as radiative heat depending on welding parameters and arc length (Refs. 4, 54, 56). It is unclear how much of this heat was distributed to the cathode and anode. Arc column voltage was obtained by the difference in total voltage and the other voltage loss regions, as shown in Equation 9. This methodology will lead to a slight underestimation of the arc column fall voltage as the overall cathode fall voltage is overestimated and the overall anode fall voltage is underestimated.

Conclusions

A solid-state calorimeter and a water-cooled cathode were used to infer fall voltages in GMAW using a ER70S-6 carbon steel electrode with 100% Ar and 95% Ar–5% CO2, shielding gas blends. Experimental current ranged between 185 and 266 A and extended through globular, projected spray, and streaming spray metal transfer modes. Arc length and electrode extension were both constant at approximately 12.5 mm (0.5 in.). The cathode, anode, contact tip, electrode extension, and arc column voltage losses measured were comparable with those found in literature.

The dominant voltage loss came from the cathode, anode, and arc column with the contact tip and electrode extension being less significant. Average overall cathode fall voltage was 12.7 ± 0.9 V and 15.5 ± 1.3 V for 100% Ar and 95% Ar–5% CO2, respectively. Overall cathode fall voltage was independent of current and is the first time to be experimentally verified. Average overall anode fall voltage was 4.7 ± 0.6 V and 4.5 ± 0.4 V for 100% Ar and 95% Ar–5% CO2, respectively. Overall anode fall voltage was independent of current and metal transfer mode and is slightly underestimated as evaporation was not measured. Droplet temperature measurements are comparable with other nonintrusive measuring methods helping the validity of calorimeter measurements.

Contact tip voltage loss was assumed to have a constant resistance across all welding parameters. Utilizing a tungsten probe, average contact tip voltage loss and resistance was measured to be 0.49 ± 0.04 V and 2.16 ± 0.5 mΩ, respectively. Based on the work of Lehnhoff, average electrode extension voltage loss was 2.27 ± 0.34 V. Arc column fall voltage potential was 0.77 ± 0.12 V/mm and is the first time to be measured with this technique.

The experiments performed in this study gave consistent measurements when spatter was not an issue. Welding parameters were representative of a typical GMAW system and gave nearly all voltage loss measurements allowing a more comprehensive understanding of a GMAW arc. The results found in this study will assist various models giving greater insight in metal transfer, droplet temperature, fume formation, and heat distribution in the GMAW system.

Acknowledgments

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References


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