# Voltage and Electrical Power in Arc Welding

**MatE 481/681 Fundamentals of Welding Engineering**

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## Contents

# Summary

The voltage associated with the arc column, anode, and cathode are the most important in determining arc welding voltage; however, other components of voltage are necessary to understand the behavior of welding. Let's consider the most general case of a wire-based process, from which the voltage of all other types of welding can be derived.

In arc welding there are two types of voltage loss. One type can be approximated well as a resistive (Ohmic) voltage loss, and is associated with the leads, the sliding contact between the wire and the contact tip, and the electrode extension. The voltage loss in an Ohmic voltage loss in CC is

$$V = IR \tag{1}$$

where $I$ is the constant current and R is the resistance. For systems in which current varies, the instantaneous voltage and current follow the same relationship

$$v = iR \tag{2}$$

where $i$ and $v$ are the instantaneous values of current and ohmic voltage loss.

Another type is a voltage loss with weak dependence on current, which in this class we approximate as a constant voltage loss associated with the anode and cathode fall and the arc column.

When the current is not constant, for example with waveforms, electromagnetic effects can play a role. The electromagnetic effects were crucial in older types of welding machines in which physical inductance played a significant role in metal transfer. Modern inverter-type welding machines have such low physical inductance that most of their behavior is the result of software. Outside the welding machine, in most welding applications electromagnetic effects are significant only in the leads.

The components of voltage in arc welding imply the dissipation of electrical power in the form of generation of thermal power at different parts of the welding circuit. Some power is a useful contribution to the weld, such as plasma fall voltage on the work, and some power is dissipated as just losses, such as the in the welding leads.


# 1 Components of Welding Voltage

In addition to the voltages associated with the arc column and anode and cathode falls, there are additional voltages associated with arc welding.

Figure 1 illustrates the area of electrode and arc in a wire-base process such as GMAW, MCAW, FCAW, or SAW. This figure highlights important components of the welding voltage beyond the voltage components of the arc. A key element in this schematic is the electrode extension, frequently called the "electrode stickout." Another important concept is that of the contact tip to workpiece distance (CTWD).

The CTWD is the distance measured from the end of the contact tip to the surface of the component where the bead will be deposited. If the joint is a single pass, CTWD can be referenced to either the root (for deeper passes) or the surface (e.g. of the plate or pipe), and must be specified clearly. If the joint is multi-pass, CTWD refers to the surface of the previous pass.

The electrode is defined as the length of electrode from the point of electrical contact to the arc attachment. This definition is very general, and also applies to non-wire processes such as SMAW and GTAW. The definition of electrode differs in some sources; for example, in [1], the terms "electrode extension" and "electrode stickout" refer to the CTWD. The electrode is difficult to define with accuracy because neither the point of electrical contact or the point of arc attachment are clearly defined. First of all, both electrical contact and arc attachment are areas, not points. The point of electrical contact is typically considered as the end of the contact tip; however, the actual point of electrical contact can be inside the contact tip, depending on the wire cast and the relation between wire diameter and contact tip bore; using contact tips meant for wires of larger diameter can increase the variations in location of the point of electrical contact. In [2], the point of electrical contact for wires of 1.2 and 1.6 mm diameter was considered to be 1.25 mm into the contact tip from the exit hole.

The arc length is similarly difficult to define [3], since typically neither the electrode tip or the weld bead are flat and static.

In wire-based processes, there is a sliding electrical contact between the wire and the contact tip, which also has an associated voltage loss.

Finally, there is a voltage loss associated with the leads bringing electrical current from the power supply to the torch and workpiece and back.

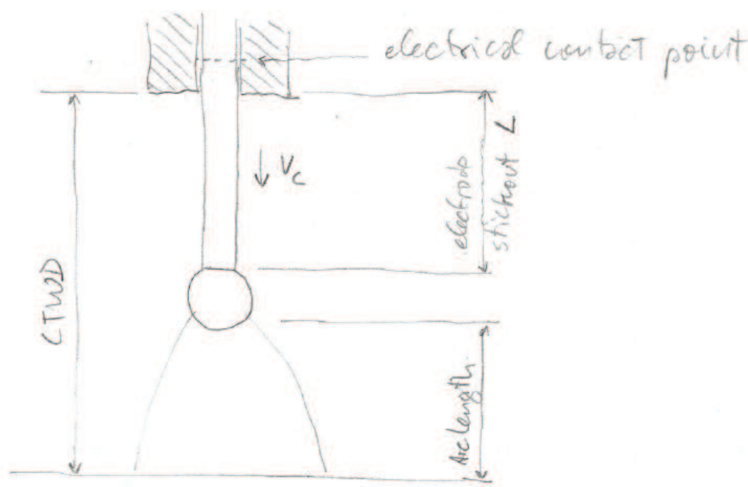


Figure 1: Electrode and arc area in wire-based processes highlighting the electrode extension and arc length. CTWD is the contact tip to workpiece distance

# 2 Sources of Electrical Power Dissipation

In welding, eectrical power is dissipated as heat. As current circulates through a welding circuit, the power associated with each voltage will be

$$q = IV \tag{3}$$

which for the case of resistive losses can also be expressed as

$$q = I^2 R \tag{4}$$

# 3 The Arc Column

Our understanding of the arc indicates that the arc column voltage $V_{\mathrm{AC}}$ under practical conditions is approximately independent of current, and proportional to the arc length as

$$V_{\mathrm{AC}} = K_{\mathrm{V_{AC}}} L_{\mathrm{AC}} \tag{5}$$

where $L_{\mathrm{AC}}$ is the arc length, and $K_{\mathrm{V_{AC}}}$ is the proportionality constant, approximately 0.8 V mm$^{-1}$ in GMAW and 1 V mm$^{-1}$ in GTAW.

The electrical power dissipated in the arc column is

$$q_{\mathrm{c}} = IV_{\mathrm{c}} \tag{6}$$

Most of this power is lost as radiation to the environment. Some of it is captured by the welding work, and a small fraction is captured by the electrode.

## 3.1 Arc length

Arc length in GMAW (with different metal transfer mechanisms), FCAW, MCAW, GTAW, SAW, SMAW (with different fluxes: cellulosic, iron powder)

# 4 The Anode and the Cathode

Our understanding of the arc indicates that the anode fall voltage $V_{\mathrm{a}}$ and the cathode fall voltage $V_{\mathrm{k}}$under practical conditions are approximately independent of current, with $V_{\mathrm{a}} \approx$ 4.8 V for steel and 4.2 V for aluminum alloys, $V_{\mathrm{k}} \approx 1$ V for thermionic cathodes (such as the GTAW electrode), and $V_{\mathrm{k}} \approx 11$ V for pure Ar, and 13.8 V fo Ar-5% $CO_2$ for non-thermionic cathodes.

The thermal power generated at the anode and cathode are associated with the anode and cathode voltages $V_{\mathrm{a}}$ and $V_{\mathrm{k}}$. The distribution of this power between the plasma and the associated metal surface requires deeper understanding of the physics of plasmas. In this class we will assume that 100% of the thermal power generated is absorbed by the metal, and none of it is carried away by the plasma.

# 5 Voltage Drop at the Welding Leads

The welding leads are expected to not interfere with the welding process; however, their effect is often noticeable. The welding leads oppose the welding current in two ways: through resistance and through inductance. The combined effects of resistance and inductance is called "impedance"

The welding leads resistance causes a voltage loss proportional to the current and resistance of the leads. The inductance opposes changes in current, and thus is important because it can smooth out waveforms and pulses to an unacceptable level.

The expression for impedance of welding leads is:

$$Z_{\mathrm{WL}} = R_{\mathrm{WL}} + jX_{\mathrm{WL}} \tag{7}$$

where $Z_{\mathrm{WL}}$ is the impedance, $R_{\mathrm{WL}}$ is its resistance component, and $X_{\mathrm{WL}}$ is the inductance component. The symbol $j$ is the imaginary number (not called $i$ as usual to avoid confusion with current) which is used in electrical engineering for circuit calculations. We will not worry about complex algebra operations here.

## 5.1 Resistance of Welding Leads

The welding leads are conductors of constant cross section typically of nearly pure copper. Assuming the lead to the torch and return form the workpiece are made of the same conductor, the total resistance of leads can be calculated as

$$R_{\mathrm{WL}} = \frac{L_{\mathrm{WL}}\rho_{\mathrm{e,WL}}}{A_{\mathrm{WL}}} f_{\mathrm{R_{WL}}} \tag{8}$$

where $L_{\mathrm{WL}}$ is the total length of leads (to torch plus return from workpiece), $\rho_{\mathrm{e,WL}}$ is the electrical resistivity of welding leads, $A_{\mathrm{EE}}$ is the conductive cross-section of the leads, and $f_{R_{\mathrm{WL}}}$ is a correction factor for skin effect [4] (typically equal to 1).

$$f_{R_{\mathrm{WL}}} = 1 + \frac{a}{192 + 0.8a} \tag{9}$$

with

$$a = \left(\frac{8\pi\, 10^{-7} f}{R_{\mathrm{WL}}}\right)^2 \tag{10}$$

where $f$ is the frequency of the harmonic considered. This equation is accurate for round solid leads and values of $f_{R_{\mathrm{WL}}}$ between 1 and 1.25.

Equation 8 can be easily generalized for combinations of different conductors such as arrangements using leads in parallel or series. These arrangements are relevant when multiple leads are used in parallel for high currents, or when the electrode cable is thinner than the work cable (not "ground" cable) to facilitate handling of the torch or electrode holder.

The resistivity of electrical copper depends on temperature, and can be estimated as suggested in [5]:

$$\rho_{\mathrm{e,Cu}}(T) = \rho_{\mathrm{e,Cu,20}}\,[1 + C\,(T - 20°\mathrm{C})] \tag{11}$$

with $\rho_{\mathrm{e,Cu,20}}$ =1.68 $10^{-8}$ Ω m, and $C$ =0.00404 Ω m $\mathrm{K}^{-1}$.

The size of welding leads can be determined based on rated output of the power source, length of leads, and duty cycle as suggested in Table 1. Typical cross sections of electrical conductors are listed in Table 2 as American Wire Gage (AWG) according to [6]. For power sources of the same rating, lower duty cycle implies smaller cable because less energy needs to be dissipated. Longer cables are thicker not because of issues of energy dissipation, but to avoid excessive resistive voltage losses in the leads.

The rated output of the power source is the maximum current the machine is designed to deliver in normal use. Like most electrical equipment, it is often possible to exceed the rated current for a short time, during which little extra heat is accumulated (e.g. the temperature in the windings does not exceed the thermal limit). The rated output level is often part of the power source name, for example Power Wave 455 (Lincoln Electric), or Dynasty 600 (Miller Electric). The duty cycle is defined as the percentage of a ten minute period that the power source can operate at a given output current before heat accumulation exceeds the machines temperature limit. Machines with overload protection will shut down automatically.

XXX Calculate resistance, reactance (60 Hz(line frequency, and approx CMT freq, 120 Hz (approx globular and STT freq), 600 Hz (sharp features of waveforms, 5th harmonic of 120 Hz) , and resistive voltage loss in welding leads from Table 1 accounting for current of machine rating, maximum combined length in a given range, cross section of cables as indicated in Table 2, and maximum temperature of 75°C.

**Example 5.1 Resistance of welding leads**

[XXX redo example with correct numbers for resistivity of copper] For 400 A at 60% duty cycle and a total length of leads of 31 m (100 ft), it is recommended to use a 2/0 conductor of 67.4 mm$^2$. What are the resistance, voltage loss, and power loss in the leads at 400 A if the leads are at 30°C?

$$R_{\mathrm{WL}} = \frac{31\,\mathrm{m} \times 1.724\,10^{-8}\,[1 + 0.004 \times (30°\mathrm{C} - 20°\mathrm{C})]}{67.4\,10^{-6}\,\mathrm{m}^2} = 0.0082\ \Omega \tag{12}$$

$$V_{\mathrm{WL}} = I R_{\mathrm{WL}} = 400\,\mathrm{A} \times 0.0082\ \Omega = 3.3\ \ \mathrm{V} \tag{13}$$

$$q_{\mathrm{WL}} = I V_{\mathrm{WL}} = 400\ \ \mathrm{A} \times 3.3\ \ \mathrm{V} = 1320\ \ \mathrm{W} \tag{14}$$

XXX Calculate resistive power loss in welding leads from Table 3 accounting for current of machine rating, maximum combined length in a given range, cross section of cables as indicated in Table 2, and maximum temperature of 75°C.

## 5.2 Reactance of Welding Leads

The conductor reactance is

$$X = 2\pi f L \tag{15}$$

Table 1: Recommended AWG Welding Cable Sizes-Rated 75°C [7]

| Machine rating (A) | Duty Cycle (%) | Combined Lengths of Electrode and Work Cables 0 to 50 ft. | 51-100 ft. | 101-150 ft. | 151-200 ft. | 201-250 ft. |
|---|---|---|---|---|---|---|
| 125 | 30 | 6 | 5 | 3 | 2 | 1 |
| 150 | 40 | 6 | 5 | 3 | 2 | 1 |
| 180 | 30 | 4 | 4 | 3 | 2 | 1 |
| 200 | 60 | 2 | 2 | 2 | 1 | 1/0 |
| 225 | 30 | 3 | 3 | 2 | 1 | 1/0 |
| 250 | 30 | 3 | 3 | 2 | 1 | 1/0 |
| 250 | 60 | 1 | 1 | 1 | 1 | 1/0 |
| 300 | 60 | 1 | 1 | 1 | 1/0 | 2/0 |
| 350 | 60 | 1/0 | 1/0 | 2/0 | 2/0 | 3/0 |
| 400 | 60 | 2/0 | 2/0 | 2/0 | 3/0 | 4/0 |
| 400 | 100 | 3/0 | 3/0 | 3/0 | 3/0 | 4/0 |
| 500 | 60 | 2/0 | 2/0 | 3/0 | 3/0 | 4/0 |
| 600 | 60 | 3/0 | 3/0 | 3/0 | 4/0 | 2 2/0 |
| 600 | 100 | 2 1/0 | 2 1/0 | 2 1/0 | 2 2/0 | 2 3/0 |
| 650 | 60 | 3/0 | 3/0 | 4/0 | 2 2/0 | 2 3/0 |
| 700 | 100 | 2 2/0 | 2 2/0 | 2 3/0 | 2 3/0 | 2 4/0 |
| 800 | 100 | 2 3/0 | 2 3/0 | 2 3/0 | 2 3/0 | 2 4/0 |
| 1000 | 100 | 3 3/0 | 3 3/0 | 3 3/0 | 3 3/0 | 3 3/0 |
| 1200 | 100 | 4 4/0 | 4 4/0 | 4 4/0 | 4 4/0 | 4 4/0 |
| 1500 | 100 | 5 4/0 | 5 4/0 | 5 4/0 | 5 4/0 | 5 4/0 |

Values are for operation at ambient temperatures of 40°C and below. Applications above 40°C may require cables larger than recommended, or rated higher than 75°C.

Table 2: Conducting area of welding leads

| AWG | Diameter mm | $A_{\mathrm{WL}}$ mm$^2$ |
|---|---|---|
| 0000 (4/0) | 11.684 | 107 |
| 000 (3/0) | 10.405 | 85.0 |
| 00(2/0) | 9.266 | 67.4 |
| 0 (1/0) | 8.251 | 53.5 |
| 1 | 7.348 | 42.4 |
| 2 | 6.544 | 33.6 |
| 3 | 5.827 | 26.7 |
| 4 | 5.189 | 21.2 |
| 5 | 4.621 | 16.8 |
| 6 | 4.115 | 13.3 |

Note: Wire sizes with "0," e.g. 000 or 3/0 are called "three aught"

where $f$ is a frequency, and $L$ is the inductance of the conductor. The reactance increases with the frequency. Following B. S. Sokolov (Izmeritel'naya Tekhnika, No. 3, pp. 51-53, March, 1970), the inductance has two components: $L_e$ the external inductance, and $L_i$, the internal inductance due to skin effect.

The external inductance can be estimated as

$$L_e = \frac{\mu_0 L_{\mathrm{WL}}}{2\pi} \left( \ln \frac{4L_{\mathrm{WL}}}{d} - 1 \right) \tag{16}$$

where $\mu_0$ is the magnetic permeability of vacuum ($\mu_0$=4$\pi$e−7 N/A$^2$ or H/m or VA$^{-1}$s m$^{-1}$, and $d$ is the diameter of the conductor. The internal inductance $L_i$ for copper conductors is best read from the graph in Figure 5.2.

Waveforms in welding are approximately periodical, and can be interpreted using Fourier series as a superposition of sine waves of the base ("fundamental") frequency, two times the fundamental, three times, the fundamental, and so on.

Figure 5.2 illustrates the fundamental frequency and first four harmonics of a sawtooth wave. We see how the "sharpness" of the waveform is associated with the higher order harmonics. Inductance does not dissipate energy, however, its effect is to attenuate the higher harmonics of waveforms.

The loss of sharpness of waveforms can be a problem for processes with sharp waveforms such as controlled short-circuit and some free-flight pulsing. Because inductance is proportional to the length of the conductors, when using sophisticated pulses, the welding leads should be as short as practically possible.

Table 3: Estimated power loss in welding leads using recommended AWG Welding Cable Sizes

| Machine rating (A) | Duty Cycle (%) | Combined Lengths of Electrode and Work Cables 0 to 50 ft. | 51-100 ft. | 101-150 ft. | 151-200 ft. | 201-250 ft. |
|---|---|---|---|---|---|---|
| 125 | 30 | 6 | 5 | 3 | 2 | 1 |
| 150 | 40 | 6 | 5 | 3 | 2 | 1 |
| 180 | 30 | 4 | 4 | 3 | 2 | 1 |
| 200 | 60 | 2 | 2 | 2 | 1 | 1/0 |
| 225 | 30 | 3 | 3 | 2 | 1 | 1/0 |
| 250 | 30 | 3 | 3 | 2 | 1 | 1/0 |
| 250 | 60 | 1 | 1 | 1 | 1 | 1/0 |
| 300 | 60 | 1 | 1 | 1 | 1/0 | 2/0 |
| 350 | 60 | 1/0 | 1/0 | 2/0 | 2/0 | 3/0 |
| 400 | 60 | 2/0 | 2/0 | 2/0 | 3/0 | 4/0 |
| 400 | 100 | 3/0 | 3/0 | 3/0 | 3/0 | 4/0 |
| 500 | 60 | 2/0 | 2/0 | 3/0 | 3/0 | 4/0 |
| 600 | 60 | 3/0 | 3/0 | 3/0 | 4/0 | 2 2/0 |
| 600 | 100 | 2 1/0 | 2 1/0 | 2 1/0 | 2 2/0 | 2 3/0 |
| 650 | 60 | 3/0 | 3/0 | 4/0 | 2 2/0 | 2 3/0 |
| 700 | 100 | 2 2/0 | 2 2/0 | 2 3/0 | 2 3/0 | 2 4/0 |
| 800 | 100 | 2 3/0 | 2 3/0 | 2 3/0 | 2 3/0 | 2 4/0 |
| 1000 | 100 | 3 3/0 | 3 3/0 | 3 3/0 | 3 3/0 | 3 3/0 |
| 1200 | 100 | 4 4/0 | 4 4/0 | 4 4/0 | 4 4/0 | 4 4/0 |
| 1500 | 100 | 5 4/0 | 5 4/0 | 5 4/0 | 5 4/0 | 5 4/0 |

Values are for operation at ambient temperatures of 40°C.

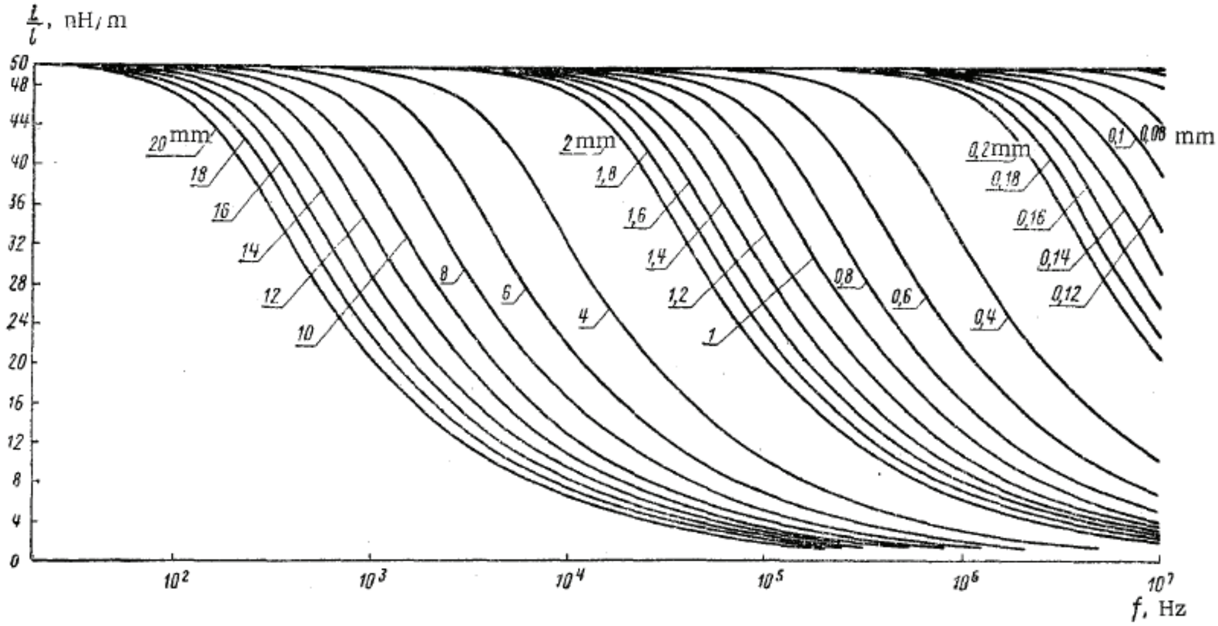


Figure 2:

**Example 5.2 Reactance of welding leads**
For leads with a total length of 31 m (100 ft), a 2/0 conductor has a diameter of 9.266 mm. What are the inductance and reactance in the leads at 400 A and frequency of 100 Hz, 1000 Hz and 10,000 Hz?

$$L = L_e + L_i \tag{17}$$

$$L_e = \frac{4\pi\text{e}{-7}\ \text{VA}^{-1}\text{s m}^{-1} \times 31\ \text{m}}{2\pi}\left(\ln\frac{4 \times 31\ \text{m}}{0.009266\ \text{m}} - 1\right) = 52.7\mu\text{H} \tag{18}$$

For ≈9.266 mm, the graph indicates $L_i/l$ as 49 nH/m at 100 Hz, 20 nH/m at 1000 Hz, and 7 nH/m at 10,000 Hz. Therefore, $L_i$ is 1.52$\mu$H at 100 Hz, 0.62$\mu$H at 1000 Hz,and 0.21$\mu$H at 10,000 Hz. Thus the total inductance is 54.2$\mu$H at 100 Hz, 53.3$\mu$H at 1000 Hz,and 52.9 $\mu$H at 10,000 Hz. We see that the skin effect is very secondary.

The total reactance is 0.034 VA$^{-1}$ at 100 Hz, 0.33 VA$^{-1}$ at 1000 Hz,and 3.32 VA$^{-1}$ at 10,000 Hz. In all cases, much larger than the electrical resistance.

# 6 The Contact Tip

In semi-automatic processes such as those with wire feeding or in strip cladding, there is a sliding contact between the contact tip (or its equivalent) and the consumable. This sliding contact results in a non-negligible resistance.

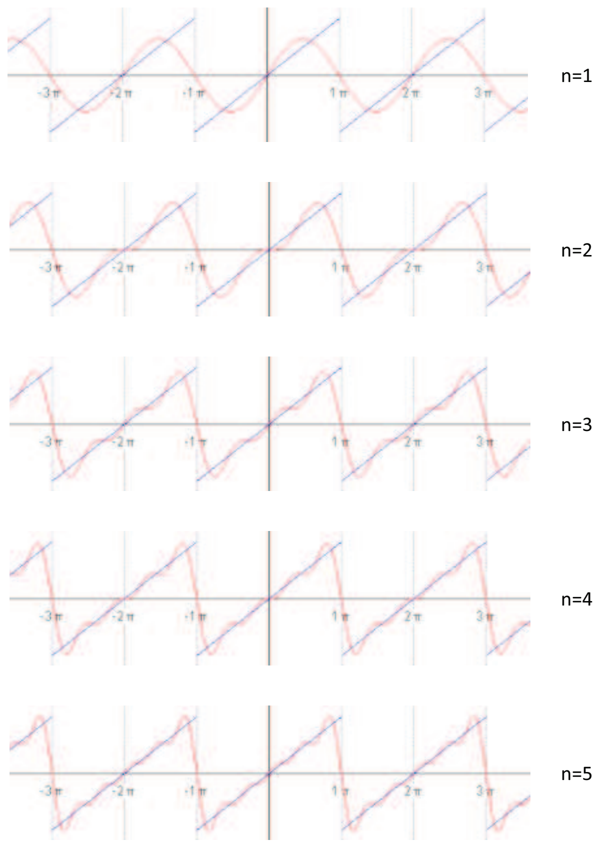


Figure 3: Fundamental frequency and first four harmonics of a sawtooth wave.

Typical values of contact tip resistance $R_{\mathrm{CT}}$ in GMAW vary between 0.1 m$\Omega$ and 1 m$\Omega$. The contact tip resistance decreases significantly with pressure at the point of contact and slightly with current. The surface finish of the electrode can also affect contact tip resistance significantly. In [8] the contact tip resistance was measured as 2.16 m$\Omega$ for 0.045 in. steel wires between 185 A and 260 A, and in [9] as 2.85 m$\Omega$ for aluminum wires of 1.2 mm with pulsed currents spanning a range of instant currents between 50 A and 350 A.

The sliding electrical contact between the consumable and the contact tip generates the following rate of heat

$$q_{\mathrm{CT}} = I^2 R_{\mathrm{CT}} \tag{19}$$

The thermal power generated can be very high, especially in pulsed processes in which the current reaches high peaks. During the short duration of the pulse, the heat might not dissipate fast enough, in some cases causing local melting of the point of contact, with the end result of fast contact tip wear and metal transfer instabilities.

In this class we will assume that all the heat generated at the sliding contact goes into the consumable. This is not exact, and further work should be done to determine the split of heat between the contact tip and the consumable. Form the point of view of overall voltage or thermal power generation, the contribution of the sliding contact is relatively small.

# 7 Voltage Drop at the Electrode Extension

For solid wires in constant current conditions, the voltage drop at the electrode extension depends on the electrical resistance of the electrode extension

$$V_{\mathrm{EE}} = I R_{\mathrm{EE}} \tag{20}$$

Because the electrical resistivity shows large variations with temperature, the calculation of total resistance requires special considerations, analyzed in detail in [10]. The electrical resistance of the electrode extension for solid electrodes can be calculated as

$$R_{\mathrm{EE}} = \frac{\Delta i_{0\mathrm{m}} U_{\mathrm{c}} A_{\mathrm{EE}} \rho_{\mathrm{EE}}}{I^2} \left[ 2 \frac{e^{\frac{d}{M_1}} - 1}{b\left(1 - e^{\frac{d}{M_1}}\right) + d\left(1 + e^{\frac{d}{M_1}}\right)} \right] \tag{21}$$

where $\Delta i_{0\mathrm{m}}$ is the difference in enthalpy per unit mass of consumable between the initial temperature of the wire and melting temperature, $\dot{m}_\mathrm{c}$ is the mass rate of consumable being consumed ("burnoff"), $I$ is the welding current and

$$d = \sqrt{b^2 - 4a} \tag{22}$$

$$b = M_2 + 4M_3 = \frac{\Delta\rho_{\mathrm{e1}}}{\rho_{\mathrm{e0}}} + 4\frac{\Delta\rho_{\mathrm{e2}}}{\rho_{\mathrm{e0}}} \tag{23}$$

$$a = -4M_3 = -4\frac{\Delta\rho_{\mathrm{e2}}}{\rho_{\mathrm{e0}}} \tag{24}$$

$$M_1 = \frac{U_\mathrm{c}\rho_{\mathrm{EE}}\Delta i_{0\mathrm{m}}A_{\mathrm{EE}}^2}{L_{\mathrm{EE}}\rho_{\mathrm{e0}}I^2} \tag{25}$$

$$\Delta\rho_{\mathrm{e1}} = \rho_{\mathrm{em}} - \rho_{\mathrm{e0}}$$

$$\Delta\rho_{\mathrm{e2}} = \begin{cases} \max\left\{\rho_\mathrm{e} - \left[\rho_{\mathrm{e0}} + \frac{\Delta\rho_{\mathrm{e1}}}{\Delta i_{0\mathrm{m}}}\left(i - i_0\right)\right]\right\} & \text{or} \\ \\ \min\left\{\rho_\mathrm{e} - \left[\rho_{\mathrm{e0}} + \frac{\Delta\rho_{\mathrm{e1}}}{\Delta i_{0\mathrm{m}}}\left(i - i_0\right)\right]\right\} & \text{whichever is greater in magnitude} \end{cases}$$

where $\rho_{\mathrm{e0}}$ is the resistivity of the electrode at the starting temperature; typically room temperature, $\rho_{\mathrm{em}}$ is the resistivity of the electrode at the melting temperature. Measurements of resistivity of welding wires of several materials are in [11].

Figure 7 illustrates the resistivity of ER70S-6 wire as a function of temperature. From this image we can infer that for this wire: $\rho_{\mathrm{e},0} = 0.336\ \mu\Omega\mathrm{m}$, $\rho_{\mathrm{e,m}} = 1.57\ \mu\Omega\mathrm{m}$ ($T_\mathrm{m} \approx 1500°\mathrm{C}$, $\Delta\rho_{\mathrm{e},1} = 1.24\ \mu\Omega\mathrm{m}$), $\Delta\rho_{\mathrm{e},2} = 0.373\ \mu\Omega\mathrm{m}$.

An overall effective electrical resistivity for the electrode extension can be defined as

$$\rho_{\mathrm{eEE}} = \frac{R_{\mathrm{EE}}A_{\mathrm{EE}}}{L_{\mathrm{EE}}} \tag{26}$$

The value of effective electrical resistivity depends slightly on process parameters such as current, wire feed speed, and electrode extension. Typical values for steel and aluminum in GMAW are displayed in Table 4.

Table 4: Typical values of effective electrical resistivity for GMAW

| wire | | $\rho_{\mathrm{eEE}}$ $\Omega$ m |
|---|---|---|
| steel | ER70S | $7.2\,10^{-7}$ |
| aluminum | 4043 | $5.1\,10^{-8}$ |
| aluminum | 5356 | $7.0\,10^{-8}$ |

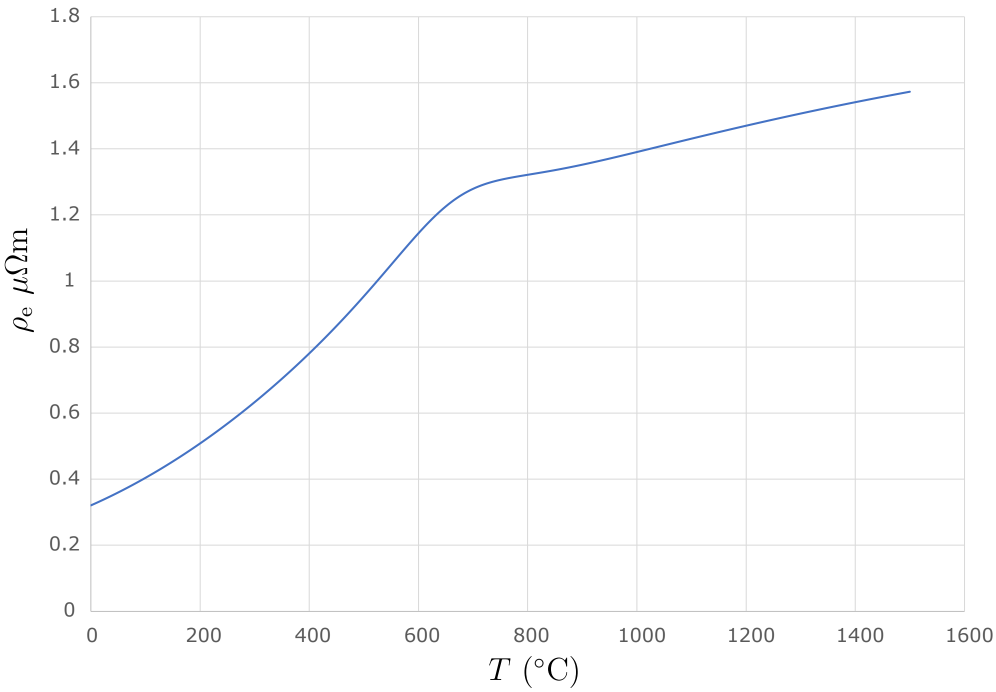


Figure 4: Resistivity of ER70S-6 wire [11]

In the GMAW of steel, for a given consumable size, a range of currents is possible within consumable design limits. The maximum design current of a consumable increases with its diameter, such that roughly, when all common GMAW procedures are considered, the current density of the steel consumable in GMAW is of the order of $2.2\,10^8$ Am$^{-2}$. Considering an electrical resistivity of the order of $7.2\,10^{-7}\Omega$m, results in

$$V_{\mathrm{EE}} = 0.16 \text{ V/mm } L_{\mathrm{EE}}(\mathrm{mm}) = 4 \text{ V/in } L_{\mathrm{EE}}(\mathrm{in})$$

For an electrode extension of the order of 0.5 in (12.7 mm), we obtain approximately 2 V.

Under constant current conditions, the thermal power generated at the electrode extension is

$$q_{\mathrm{EE}} = I^2 R_{\mathrm{EE}} \tag{27}$$

This amount of power plays an important role in the regulation of GMAW with steel consumables, enabling closed-loop torch standoff control systems based only on welding current and voltage measurements. With aluminum wires, however, the electrode extension resistance is too small to play a role in welding machine regulation, and standoff controls require additional sensors.

# 8 Considerations Beyond Constant Current

The expressions presented above can also be used for conditions beyond constant current by making appropriate considerations.

Resistive loads dissipate power proportionally to the square of the instantaneous current. These loads are the welding leads, the contact tip resistance, and the electrode extension. In these cases, the thermal power generation can be calculated using the constant current expressions with a constant current value equal to the RMS (root mean square) value of the varying current.

$$I_{\mathrm{RMS}} = \sqrt{\frac{1}{\tau}\int_{\tau} i^2 dt} \tag{28}$$

where $\tau$ is a long enough sampling time, and $i$ is the instantaneous value of the welding current. For the electrode extension, this approximation is valid when the frequency of variations is above the critical value for distribution of heat in the electrode extension.

The arc voltages (cathode, anode, and column) are only mildly dependent on current, and are best approximated as constant voltages. For variable current without change of polarity, a good estimate of thermal power generation is obtained from the formulae for constant current using the average current

$$I_{\mathrm{AVE}} = \frac{1}{\tau}\int_{\tau} i dt \tag{29}$$

For the case of variable polarity, the thermal power generated in the arc column can be calculated approximately using the arc column voltage and the average of the absolute value of the current

$$I_{\mathrm{AVE,ABS}} = \frac{1}{\tau}\int_{\tau} |i| dt \tag{30}$$

The case of variable polarity at the electrode or the work needs to account for the fact that as polarity changes, the cathode and anode switch between the electrode and the plate. In this case, the average thermal power generated can be estimated using the average of the absolute value of the current, and a time averaged voltage for the related surface:

$$q_{\mathrm{surface}} = I_{\mathrm{AVE,ABS}} V_{\mathrm{AVE}} \tag{31}$$

where

$$V_{\mathrm{AVE}} = f_{\mathrm{a}} V_{\mathrm{a}} + f_{\mathrm{k}} V_{\mathrm{k}} \tag{32}$$

where $f_{\mathrm{a}}$ and $f_{\mathrm{k}}$ are the the time fraction in which the surface acts as an anode (positive) or as a cathode (negative), and $V_{\mathrm{a}}$ and $V_{\mathrm{k}}$ are the voltages associated with the anode and the cathode.

For a sinusoidal wave:

$$I_{\mathrm{RMS}} = \frac{i_{\max}}{\sqrt{2}} \approx 0.7071 i_{\max} \tag{33}$$

$$I_{\mathrm{AVE,ABS}} = \frac{2\sqrt{2}}{\pi} I_{\mathrm{RMS}} \approx 0.9003 I_{\mathrm{RMS}} \tag{34}$$

For a rectangular pulse of constant polarity with peak of current $I_\mathrm{p}$ and duration $t_\mathrm{p}$ and a background of current $I_\mathrm{b}$ and duration $t_\mathrm{b}$:

$$I_\mathrm{RMS} = \sqrt{f_\mathrm{p} {I_\mathrm{p}}^2 + f_\mathrm{b} {I_\mathrm{b}}^2} \tag{35}$$

$$I_\mathrm{AVE} = f_\mathrm{p} I_\mathrm{p} + f_\mathrm{b} + I_\mathrm{b} \tag{36}$$

$$I_\mathrm{AVE,ABS} = I_\mathrm{AVE} \tag{37}$$

$$f_\mathrm{p} = \frac{t_\mathrm{p}}{t_\mathrm{p} + t_\mathrm{b}} \tag{38}$$

$$f_\mathrm{b} = \frac{t_\mathrm{b}}{t_\mathrm{p} + t_\mathrm{b}} \tag{39}$$

## 8.1 Electrode Extension Beyond Constant Current

Welding situations beyond constant current include short circuit transfer, pulsed transfer, and variable polarity, among others. In all cases, the current variations are approximately periodic. When the fundamental frequency is high enough, the effect of current is averaged out. For the case of resistive heating, the amount of heat generated is proportional to the square of the instantaneous current, and the appropriate average in this case is the "root mean square" (RMS) of the current ($I_\mathrm{RMS}$).

A rule of thumb to determine a minimum frequency for using the RMS concept is to consider that the thermal effect of the cycle has to dissipate in the residence time of the electrode extension. The thermal effect of the cycle has a size given by $U_\mathrm{c} f$, and the residence time is $L_\mathrm{EE}/U_\mathrm{c}$. To dissipate the inhomogeneity, the heat needs to travel half the size of the thermal effect in each direction during the residence time. An approximate estimate of distance travelled by the heat is given by $\sqrt{\alpha_\mathrm{c} L_\mathrm{EE}/U_\mathrm{c}}$. This results in a minimum frequency for using the RMS approach of

$$f \gtrsim \frac{1}{3}\sqrt{\frac{U_\mathrm{c}^3}{\alpha_\mathrm{c} L_\mathrm{EE}}} \tag{40}$$

For a typical wire feed speed of 6 min/min (236 in/min, 0.1 m/s), and a 10 mm electrode extension (0.39 in), the behavior of steel wire with a thermal diffusivity of approximately $15\,10^{-6}$ m$^2$s$^{-1}$ can be approximated as that of a constant current of the value of the RMS for frequencies far above 27 Hz. Most pulsed, short circuit, and variable polarity processes operate a frequencies similar or higher than this. For frequencies far below this, the behavior of the electrode extension can be considered as in "quasi-equilibrium," in which the electrode extension behaves at each time the way it would behave under a constant current of that instantaneous value.

## 8.2 Considerations for Tubular Consumables and Rods

The cross section of electrical conduction of electrode is the cross sectional area of metal in processes involving solid electrodes such as GMAW or SMAW. For tubular electrodes such as FCAW or MCAW, the cross sectional area corresponds to the sheath, since the powders inside have negligible conductivity compared to the sheath, even in the case of metallic powders. Some conditions might require especial considerations, for example the case in which the powders might melt before the sheath melt, because the molten powders can then start carrying a non-negligible amount of current.

For the case of rods, such as in SMAW, Equation 21 might likely apply, since the temperature profile established by Joule heating is likely in quasi-equilibrium, and the temperature profile induced by conduction at the tip is not signifficantly affected by the changing length of the electrode.

# 9 Examples

**Example 9.1 Voltage distribution in GMAW**
Estimate the distribution of voltage in GMAW welding with steel wire of .035 in (0.9 mm) at 200 A DCEP and a wire feed speed of 350 ipm (8.89 m/min). The shielding gas is C5 (Ar-5 vol% $CO_2$, the CTWD is 15 mm, and the electrode stickout is 10 mm. The welding machine is rated for 350 A, with a duty of 60%, and the welding leads measure 12 ft. (3.658 m) in total.

**Welding leads:** For the configuration described, the recommended cable is 1/0 (Table 1), with a cross section of 53.5 mm$^2$ (Table 2). Assuming that the leads are at 50°C (hot to the touch with bare hands, cannot be held for long, but do not cause irreversible damage from touching), the resistivity of the copper is obtained from Equation 11:

$$\rho_{\mathrm{e,Cu}}(T) = 1.68\,10^{-8}\,\Omega\,\mathrm{m}\left[1 + .00404\,\mathrm{K}^{-1}\,(50°\mathrm{C} - 20°\mathrm{C})\right] = 1.884\,10^{-8}\,\Omega\,\mathrm{m} \tag{41}$$

With this value of resistivity we can now calculate the resistance associated with the leads using Equation 8

$$R_{\mathrm{WL}} = \frac{1.884\,10^{-8}\,\Omega\,\mathrm{m}\;3.658\,\mathrm{m}}{53.5\,10^{-6}\,\mathrm{m}^2}\,1 = 1.288\,10^{-3}\,\Omega \tag{42}$$

where $f_{\mathrm{R_{WL}}}$ =1 because the system is operating in DC. Similarly, because in DC the only current variations are noise, there's no meaningful reactance.

The voltage fall in the leads is then (Equation 1):

$$V_{\mathrm{WL}} = 200\,\mathrm{A}\;1.288\,10^{-3}\,\Omega = 0.2576\,\mathrm{V} \tag{43}$$

$$\begin{aligned} q_{\mathrm{WL}} &= V_{\mathrm{WL}} I \\ &= 0.2576\,\mathrm{V}\;200\,\mathrm{A} = 51.52\,\mathrm{W} \end{aligned}$$

**Contact tip:** Using the value of $R_{\mathrm{CT}}$=2.16 m$\Omega$ from Section 6 and Equation 1, the voltage loss at the sliding contact between the contact tip and the wire is

$$V_{\mathrm{CT}} = 200\,\mathrm{A}\ 2.16\,\mathrm{m}\Omega = 0.432\,\mathrm{V} \tag{44}$$

$$\begin{aligned} q_{\mathrm{CT}} &= V_{\mathrm{CT}} I \\ &= 0.4320\,\mathrm{V}\ 200\,\mathrm{A} = 86.40\,\mathrm{W} \end{aligned}$$

Not all this power goes into the wire, but because this is a relatively small fraction of the total power, the error involved is small. (use Muzychka paper to calculate fraction going into wire and contact tip)

**Electrode extension:** From Figure 7, for ER70S-6 wire: $\rho_{\mathrm{e},0} = 0.336\ \mu\Omega\mathrm{m}$, $\rho_{\mathrm{e,m}} = 1.57\ \mu\Omega\mathrm{m}$ ($T_{\mathrm{m}} \approx 1500$°C, $\Delta\rho_{\mathrm{e},1} = 1.24\ \mu\Omega\mathrm{m}$), $\Delta\rho_{\mathrm{e},2} = 0.373\ \mu\Omega\mathrm{m}$. The density of ER70S-6 at 20°C is $\rho_{\mathrm{c}}$ =7860 kg m$^{-3}$. The enthalpy gain between 20°C and melting temperature (1500°C) is $i_{0\mathrm{m}}$ =989.8 kJ mol$^{-1}$. The cross sectional area of the electrode is

$$A_{\mathrm{EE}} = \pi \frac{d_{\mathrm{c}}^2}{4} = \pi \frac{(0.889\,10^{-3}\,\mathrm{m})^2}{4} = 6.207\,10^{-7}\,\mathrm{m}^2 \tag{45}$$

Replacing these values into equations 22 to 25 we obtain $a$ =-4.440, $b$ =8.113, $d$ =9.142, and $M_1$ =3.305. Equation 21 then yields $R_{\mathrm{EE}}$ =15.86 m$\Omega$, with an associated effective resistivity of the electrode extension $\rho_{\mathrm{EE}}$ =9.843 $10^{-7}$ $\Omega$m. The voltage drop at the electrode extension is then:

$$V_{\mathrm{EE}} = 200\,\mathrm{A}\ 15.86\,\mathrm{m}\Omega = 3.171\ \ \mathrm{V} \tag{46}$$

$$\begin{aligned} q_{\mathrm{EE}} &= V_{\mathrm{EE}} I \\ &= 3.171\,\mathrm{V}\ 200\,\mathrm{A} = 634.2\,\mathrm{W} \end{aligned}$$

This is a significant amount of power that is very sensitive to the electrode extension, in addition to current.

**Anode fall:** For steel:

$$V_{\mathrm{a}} = 4.8\,\mathrm{V} \tag{47}$$

$$\begin{aligned} q_{\mathrm{a}} &= V_{\mathrm{a}} I \\ &= 4.8\,\mathrm{V}\ 200\,\mathrm{A} = 960\,\mathrm{W} \end{aligned}$$

This is the largest component dominating deposition rate.

**Arc column:** Arc length:

$$L_{\mathrm{AC}} = L_{\mathrm{CTWD}} - L_{\mathrm{EE}} \tag{48}$$
$$L_{\mathrm{AC}} = 15\,\mathrm{mm} - 10\,\mathrm{mm} = 5\,\mathrm{mm}$$

For GMAW:

$$V_{\mathrm{AC}} = 0.8\,\mathrm{V\ mm^{-1}} L_{\mathrm{AC}} = 0.8\,\mathrm{V\ mm^{-1}} 5\,\mathrm{mm} = 8\,\mathrm{V} \tag{49}$$

$$\begin{aligned} q_{\mathrm{AC}} &= V_{\mathrm{AC}} I \\ &= 8 equnV\ 200\,\mathrm{A} = 1600\,\mathrm{W} \end{aligned}$$

This is amount of heat is higher than the heat generated at the anode, but has only a small influence in deposition rate or penetration. Most of this heat is lost to the environment in the form of radiation and advection of hot gas and metal vapors.

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**Cathode fall:** For steel with Ar 5% $\mathrm{C)_2}$:

$$V_{\mathrm{k}} = 13.8\,\mathrm{V} \tag{50}$$

**Total voltage** The voltage readout, accounts for all voltages described above:

$$V = V_{\mathrm{WL}} + V_{\mathrm{CT}} + V_{\mathrm{EE}} + V_{\mathrm{a}} + V_{\mathrm{AC}} + V_{\mathrm{k}} \tag{51}$$
$$V = 0.2576\,\mathrm{V} + 0.4320\,\mathrm{V} + 3.171\,\mathrm{V} + 4.8\,\mathrm{V} + 4\,\mathrm{V} + 13.8\,\mathrm{V} = 26.5\,\mathrm{V}$$

The Millermatic Calculator suggests 24 V to 25 V under these circumstances, our calculation seems quite reasonable.

**Example 9.2 Voltage distribution in SMAW**

**Example 9.3 Voltage distribution in SAW**

XXXXX

# A Notation XXX add charge of electron, mu0, epsilon0, and other properties etc

| Variable | Unit | Description |
|---|---|---|
| $c$ | $\mathrm{J\,kg^{-1}\,K^{-1}}$ | Specific heat of the substrate |
| $i$ | $\mathrm{J\ kg^{-1}}$ | Enthalpy of substrate |
| $k$ | $\mathrm{W\ m^{-1}\ K^{-1}}$ | Thermal conductivity of the substrate |
| $L$ | m | Length of beam spot in direction of motion |
| $q$ | W | Power absorbed by substrate |
| $q''$ | $\mathrm{W\ m^{-2}}$ | Heat flux absorbed by substrate |
| $t$ | s | Time |
| $t_{\mathrm{R}}$ | s | Beam residence time |
| $T$ | °C | Temperature |
| $T_0$ | °C | Initial temperature (preheat or interpass temperature) |
| $T_{\mathrm{c}}$ | °C | Temperature of interest for calculations |
| $\bar{\dot{T}}_{\mathrm{f}}$ | $\mathrm{°C\ s^{-1}}$ | Average heating rate under the beam |
| $\dot{T}_{\mathrm{b}}$ | $\mathrm{°C\ s^{-1}}$ | Cooling rate behind the beam |
| $T_{\mathrm{max}}$ | °C | Maximum temperature at a given depth |
| $T_{\mathrm{max,\ s}}$ | °C | Maximum temperature at surface plane |
| $U$ | $\mathrm{m\,s^{-1}}$ | Travel speed of the moving heat source |
| $w_{\mathrm{HAZ}}$ | m | Width of HAZ |
| $w_{\mathrm{melt}}$ | m | Width of incipient melt track |
| $w_{\mathrm{spot}}$ | m | Width of laser spot |
| $x, y, z$ | m | Cartesian coordinates |
| **Greek** | | |
| $\alpha$ | $\mathrm{m^2\ s^{-1}}$ | Thermal diffusivity of the substrate |
| $\eta$ | - | Thermal efficiency |
| $\rho$ | $\mathrm{kg\ m^{-3}}$ | Density of the substrate |
| **Superscripts** | | |
| $^*$ | | Dimensionless value |
| **Subscripts** | | |
| $_{\mathrm{eff}}$ | | Effective value |
| **Acronyms** | | |
| HAZ | | Heat affected zone |

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