Gas Metal Arc Welding

Product and Procedure Selection

Gas Metal Arc Welding

The gas metal arc process is dominant today as a joining process among the world's welding fabricators. Despite its sixty years of history, research and development continue to provide improvements to this process, and the effort has been rewarded with high quality results.

This publication's purpose is to provide the reader with the basic concepts of the gas metal arc welding (GMAW) process, and then provide an examination of more recent process developments. Additionally, the reader will find technical data and direction, providing the opportunity to optimize the operation of the GMAW process and all of its variants.

Process Definition

Gas Metal Arc Welding (GMAW), by definition, is an arc welding process which produces the coalescence of metals by heating them with an arc between a continuously fed filler metal electrode and the work. The process uses shielding from an externally supplied gas to protect the molten weld pool. The application of GMAW generally requires DC+ (reverse) polarity to the electrode.

In non-standard terminology, GMAW is commonly known as MIG (Metal Inert Gas) welding and it is less commonly known as MAG (Metal Active Gas) welding. In either case, the GMAW process lends itself to weld a wide range of both solid carbon steel and tubular metal-cored electrodes. The alloy material range for GMAW includes: carbon steel, stainless steel, aluminum, magnesium, copper, nickel, silicon bronze and tubular metal-cored surfacing alloys. The GMAW process lends itself to semiautomatic, robotic automation and hard automation welding applications.

Advantages of GMAW

The GMAW process enjoys widespread use because of its ability to provide high quality welds, for a wide range of ferrous and non-ferrous alloys, at a low price. GMAW also has the following advantages:

- The ability to join a wide range of material types and thicknesses.
- Simple equipment components are readily available and affordable.
- GMAW has higher electrode efficiencies, usually between 93% and 98%, when compared to other welding processes.
- Higher welder efficiencies and operator factor, when compared to other open arc welding processes.
- GMAW is easily adapted for high-speed robotic, hard automation and semiautomatic welding applications.
- All-position welding capability.
- Excellent weld bead appearance.
- Lower hydrogen weld deposit — generally less than 5 mL/100 g of weld metal.
- Lower heat input when compared to other welding processes.
- A minimum of weld spatter and slag makes weld clean up fast and easy.
- Less welding fumes when compared to SMAW (Shielded Metal Arc Welding) and FCAW (Flux-Cored Arc Welding) processes.

Benefits of GMAW

- Generally, lower cost per length of weld metal deposited when compared to other open arc welding processes.
- Lower cost electrode.
- Less distortion with GMAW-P (Pulsed Spray Transfer Mode), GMAW-S (Short-Circuit Transfer Mode) and STT™ (Surface Tension Transfer™).
- Handles poor fit-up with GMAW-S and STT modes.
- Reduced welding fume generation.
- Minimal post-weld cleanup.

Limitations of GMAW

- The lower heat input characteristic of the short-circuiting mode of metal transfer restricts its use to thin materials.
- The higher heat input axial spray transfer generally restricts its use to thicker base materials.
- The higher heat input mode of axial spray is restricted to flat or horizontal welding positions.
- The use of argon based shielding gas for axial spray and pulsed spray transfer modes is more expensive than 100% carbon dioxide (CO_2).

Gas Metal Arc Welding Guidelines

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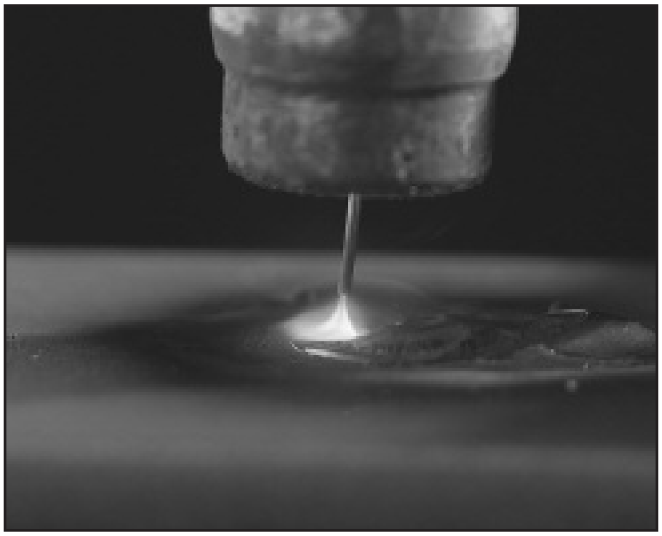

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History of Gas Metal Arc Welding

The history of GMAW, gas metal arc welding, had its industrial introduction in the late 1940's. The site was the Battelle Memorial Institute, and it was there that Hobart and Devers, sponsored by the Air Reduction Company, researched and developed the first use of a continuously fed aluminum wire electrode, shielded with 100% argon gas.

Axial spray transfer for aluminum was the earliest metal transfer mode for the process. This eventually led to the use of argon plus small additions of oxygen. The oxygen improved arc stability and finally permitted the use of axial spray transfer on ferrous materials. The process was limited because of the high energy level of axial spray transfer to plate thickness material.

In the early 1950's, the work of Lyubavshkii and Novoshilov initiated the development of the GMAW process to include the use of large diameters of steel electrode shielded with carbon dioxide, a reactive gas. The process development at this stage was high in weld spatter, and the level of heat generated by the arc made the process uninviting to welders.

In the late 1950's improvements in power source technology and the interface of small diameter electrodes, in the 0.035" - 0.062" (0.9 - 1.6 mm) diameter range, permitted the implementation of the discrete mode known as short-circuiting transfer. This development permitted the use of lower heat input welding on thin sections of base material, and it provided the opportunity for all-position welding.

In the early 1960's, power source research and development led to the introduction of pulsed spray in the GMAW mode. The idea for pulsed spray transfer, GMAW-P, occurred in the 1950's and it conceptually involved the use of a high-speed transition between a high-energy peak current to a low background current. The motivation behind the idea was the need to decrease spatter and eliminate incomplete fusion defects. The pulsed arc process incorporated the benefits of axial spray transfer — clean, spatter-free welds having excellent fusion, with lower heat input. The lower average current provided by GMAW-P allowed for out-of-position welding capability with improved weld quality, when compared with short-circuit transfer.

The 1970's introduced power source technology, which further enhanced the development of the GMAW process and GMAW-P in particular. This period saw the incorporation of the earliest thyristor power sources for pulsed GMAW. The Welding Institute of the United Kingdom is largely responsible for determining the linear relationship between pulsed frequency and wire feed speed. The algorithm for this mathematical relationship permitted a fundamental base for subsequent synergic transistor controlled power sources. The new high speed electronic controls improved the interface between welding sophistication and the welding shop floor. The new descriptor for this development was the word "Synergic." As it relates, synergy means: one knob control – as the welder increases or decreases wire feed speed, a predetermined pulsed energy is automatically applied to the arc. Synergic power sources made it easier to use GMAW-P.

In the 1990's, research and development in welding power source technology continued to evolve. The Lincoln Electric Company took the lead in developing a wide range of power source platforms designed with the optimized arc in mind. Widely recognized as Waveform Control Technology™ the Lincoln Electric welding systems incorporate an inverter based transformer design with a high speed, computerized control circuit. Software developed programs provide an expansive array of synergic and non-synergic optimized arc welding programs for the following welding processes:

GMAW — Gas Metal Arc Welding
FCAW — Flux-Cored Arc Welding
GTAW — Gas Tungsten Arc Welding
SMAW — Shielded Metal Arc Welding
CAC-A — Carbon Arc Cutting Process

Among the newer advanced Waveform Control Technology™ processes is Surface Tension Transfer™, or STT™. STT is a low heat input mode of weld metal transfer, which incorporates a high-speed reactive power source to meet the instantaneous needs of the arc. The power source is a waveform generator, which is therefore neither a constant current nor constant voltage power source.

Unique to STT, is the application of applying welding current independent of the wire feed speed. This feature has the benefit of increasing or decreasing the welding current to increase or decrease heat input. Fundamentally, STT provides an answer for controlling the welding conditions, that can produce incomplete fusion. The STT welding mode has the dual benefit of increasing productivity, and improving overall weld quality. See *Advanced Welding Processes for GMAW* on page 18.

The GMAW process is flexible in its ability to provide sound welds for a very wide base material type and thickness range. Central to the application of GMAW is a basic understanding of the interplay between several essential variables:

- The thickness range of the base material to be welded will dictate the electrode diameter, and the useable current range.
- The shielding gas selection will influence the selection of the mode of metal transfer, and will have a definite effect on the finished weld profile.

Modes of Metal Transfer

Short-Circuit Metal Transfer

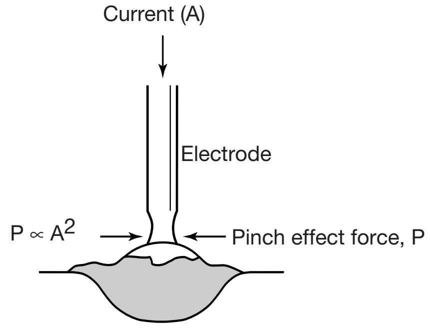


FIGURE 1: Pinch Effect During Short-Circuiting Transfer

Short-circuiting metal transfer, known by the acronym GMAW-S, is a mode of metal transfer, whereby a continuously fed solid or metal-cored wire electrode is deposited during repeated electrical short-circuits.

The short-circuiting metal transfer mode is the low heat input mode of metal transfer for GMAW. All of the metal transfer occurs when the electrode is electrically shorted (in physical contact) with the base material or molten puddle. Central to the successful operation of short-circuiting transfer is the diameter of electrode, the shielding gas type and the welding procedure employed. This mode of metal transfer typically supports the use of 0.025” - 0.045” (0.6 - 1.1 mm) diameter electrodes shielded with either 100% CO_2 or a mixture of 75-80% argon, plus 25-20% CO_2. The low heat input attribute makes it ideal for sheet metal thickness materials. The useable base material thickness range for short-circuiting transfer is typically considered to be 0.024” – 0.20” (0.6 – 5.0 mm) material. Other names commonly applied to short-circuiting transfer include short arc microwire welding, fine wire welding, and dip transfer.

Advantages of Short-Circuiting Transfer

- All-position capability, including flat, horizontal, vertical-up, vertical-down and overhead.
- Handles poor fit-up extremely well, and is capable of root pass work on pipe applications.
- Lower heat input reduces weldment distortion.
- Higher operator appeal and ease of use.
- Higher electrode efficiencies, 93% or more.

Limitations of Short-Circuiting Transfer

- Restricted to sheet metal thickness range and open roots of groove joints on heavier sections of base material.
- Poor welding procedure control can result in incomplete fusion. Cold lap and cold shut are additional terms that serve to describe incomplete fusion defects.
- Poor procedure control can result in excessive spatter, and will increase weldment cleanup cost.
- To prevent the loss of shielding gas to the wind, welding outdoors may require the use of a windscreen(s).

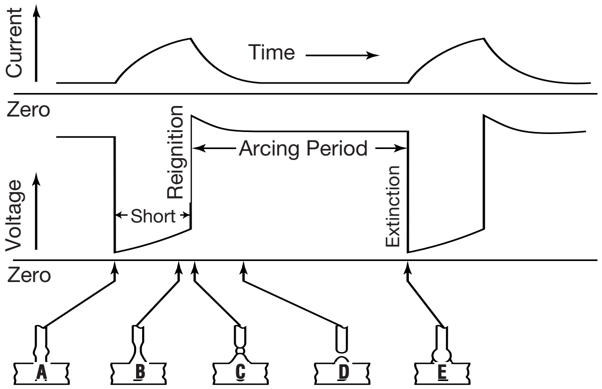
Description of Short-Circuiting Transfer

The transfer of a single molten droplet of electrode occurs during the shorting phase of the transfer cycle (See Figure 2). Physical contact of the electrode occurs with the molten weld pool, and the number of short-circuiting events can occur up to 200 times per second. The current delivered by the welding power supply rises, and the rise in current accompanies an increase in the magnetic force applied to the end of the electrode. The electromagnetic field, which surrounds the electrode, provides the force, which squeezes (more commonly known as pinch) the molten droplet from the end of the electrode.

Because of the low-heat input associated with short-circuiting transfer, it is more commonly applied to sheet metal thickness material. However, it has frequently found use for welding the root pass in thicker sections of material in open groove joints. The short-circuiting mode lends itself to root pass applications on heavier plate groove welds or pipe.

Solid wire electrodes for short-circuiting transfer range from 0.025” - 0.045” (0.6 –1.1 mm). The shielding gas selection includes 100% CO_2, and binary blends of argon + CO_2 or argon + O_2. Occasionally ternary blends, (three part mixes), of argon + CO_2 + oxygen are sometimes employed to meet the needs of a particular application.

FIGURE 2: Oscillograms and Sketches of Short Circuiting Transfer



A The solid or metal-cored electrode makes physical contact with the molten puddle. The arc voltage approaches zero, and the current level increases. The rate of rise to the peak current is affected by the amount of applied inductance.

B This point demonstrates the effect of electromagnetic forces that are applied uniformly around the electrode. The application of this force necks or pinches the electrode. The voltage very slowly begins to climb through the period before detachment, and the current continues to climb to a peak value.

C This is the point where the molten droplet is forced from the tip of the electrode. The current reaches its maximum peak at this point. Jet forces are applied to the molten puddle and their action prevents the molten puddle from rebounding and reattaching itself to the electrode.

D This is the tail-out region of the short-circuit waveform, and it is during this downward excursion toward the background current when the molten droplet reforms.

E The electrode at this point is, once again, making contact with the molten puddle, preparing for the transfer of another droplet. The frequency of this varies between 20 and 200 times per second. The frequency of the short-circuit events is influenced by the amount of inductance and the type of shielding gas. Additions of argon increase the frequency of short-circuits and it reduces the size of the molten droplet.

Inductance Control

Keywords:

Rate of Current Rise

Henries

Variable Inductance

Fixed Inductance

The application of an inductance control feature is typical for most GMAW power sources. Inductance has effects **only** in the short-circuit transfer mode. Usually, inductance is either fixed or variable; and this depends upon the design of the power source. A fixed inductance power source indicates that an optimum level of inductance is built into the power source, and variable inductance indicates that the amount of inductance applied to the arc is adjustable. Inductance controls the rate of current rise following the short-circuit condition. Consequently, its use is beneficial because its adjustment facilitates adding or decreasing energy to the short-circuit condition. Inductance plays a role in the frequency of droplet transfer per unit of time: as the inductance increases, the frequency of short-circuit metal transfer decreases. Each droplet contains more energy and toe wetting improves. As the inductance decreases, the short-circuit events increase, and the size of the molten droplet decreases. The objective for the variable inductance control feature, on any given power source, is to transfer the smallest molten droplet possible with the least amount of spatter, and with sufficient energy to ensure good fusion. Additions of inductance will provide the essential energy to improve toe wetting.

Inductance is measured in Henries, and in a variable inductance power source it is the resulting arc performance characteristic that results from the interplay of a combination of electrical components. These components typically include the choke filter, capacitors, and power resistors.

Globular Transfer

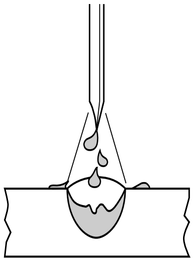


FIGURE 3: Globular Weld Metal Transfer Characteristics

Globular metal transfer is a GMAW mode of metal transfer, whereby a continuously fed solid or metal-cored wire electrode is deposited in a combination of short-circuits and gravity-assisted large drops. The larger droplets are irregularly shaped.

During the use of all metal-cored or solid wire electrodes for GMAW, there is a transition where short-circuiting transfer ends and globular transfer begins. Globular transfer characteristically gives the appearance of large irregularly shaped molten droplets that are larger than the diameter of the electrode. The irregularly shaped molten droplets do not follow an axial detachment from the electrode, instead they can fall out of the path of the weld or move towards the contact tip. Cathode jet forces, that move upwards from the work-piece, are responsible for the irregular shape and the upward spinning motion of the molten droplets.

The process at this current level is difficult to control, and spatter is severe. Gravity is instrumental in the transfer of the large molten droplets, with occasional short-circuits.

During the 1960's and 1970's, globular transfer was a popular mode of metal transfer for high production sheet metal fabrication. The transfer mode is associated with the use of 100% CO_2 shielding, but it has also seen heavy use with argon/CO_2 blends. For general fabrication on carbon steel, it provides a mode of transfer, just below the transition to axial spray transfer, which has lent itself to higher speed welding.

The use of globular transfer in high production settings is being replaced with advanced forms of GMAW. The change is being made to GMAW-P, which results in lower fume levels, lower or absent spatter levels, and elimination of incomplete fusion defects.

Advantages of Globular Transfer

- Uses inexpensive CO_2 shielding gas, but is frequently used with argon/CO_2 blends.
- Is capable of making welds at very high travel speeds.
- Inexpensive solid or metal-cored electrodes.
- Welding equipment is inexpensive.

Limitations of Globular Transfer:

- Higher spatter levels result in costly cleanup.
- Reduced operator appeal.
- Prone to cold lap or cold shut incomplete fusion defects, which results in costly repairs.
- Weld bead shape is convex, and welds exhibit poor wetting at the toes.
- High spatter level reduces electrode efficiency to a range of 87 – 93%.

Axial Spray Transfer

Keywords:

Globular to Axial Spray Transition Current

Weld Interface

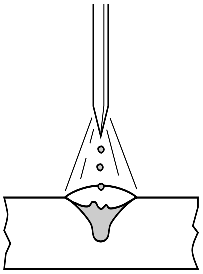


FIGURE 4: Axial Spray Weld Metal Transfer Characteristics

Axial spray metal transfer is the higher energy mode of metal transfer, whereby a continuously fed solid or metal-cored wire electrode is deposited at a higher energy level, resulting in a stream of small molten droplets. The droplets are propelled axially across the arc.

Axial spray transfer is the higher energy form of GMAW metal transfer. To achieve axial spray transfer, binary blends containing argon + 1-5 % oxygen or argon + CO_2, where the CO_2 levels are 18% or less. Axial spray transfer is supported by either the use of solid wire or metal-cored electrodes. Axial spray transfer may be used with all of the common alloys including: aluminum, magnesium, carbon steel, stainless steel, nickel alloys, and copper alloys.

For most of the diameters of filler metal alloys, the change to axial spray transfer takes place at the globular to spray transition current. A stream of fine metal droplets that travel axially from the end of the electrode characterizes the axial spray mode of metal transfer. The high puddle fluidity restricts its use to the horizontal and flat welding positions.

For carbon steel, axial spray transfer is applied to heavier section thickness material for fillets and for use in groove type weld joints. The use of argon shielding gas compositions of 95%, with a balance of oxygen, creates a deep finger-like penetration profile, while shielding gas mixes that contain more than 10% CO_2 reduce the finger-like penetration profile and provide a more rounded type of penetration.

The selection of axial spray metal transfer is dependent upon the thickness of base material and the ability to position the weld joint into the horizontal or flat welding positions. Finished weld bead appearance is excellent, and operator appeal is very high. Axial spray transfer provides its best results when the weld joint is free of oil, dirt, rust, and millscale.

Advantages of Axial Spray Transfer

- High deposition rates.
- High electrode efficiency of 98% or more.
- Employs a wide range of filler metal types in an equally wide range of electrode diameters.
- Excellent weld bead appearance.
- High operator appeal and ease of use.
- Requires little post weld cleanup.
- Absence of weld spatter.
- Excellent weld fusion.
- Lends itself to semiautomatic, robotic, and hard automation applications.

Limitations of Axial Spray Transfer

- Restricted to the flat and horizontal welding positions.
- Welding fume generation is higher.
- The higher-radiated heat and the generation of a very bright arc require extra welder and bystander protection.
- The use of axial spray transfer outdoors requires the use of a windscreen(s).
- The shielding used to support axial spray transfer costs more than 100% CO_2.

TABLE 1 — Transition Currents for Axial Spray Transfer

GMAW Axial Spray Transition Currents for Solid and Composite Carbon Steel Electrodes and Stainless Steel Solid Wire Electrodes

Filler Metal Type	Electrode Diameter Inches (mm)	Shielding Gas	Approximate Current (Amps)
Carbon and Low Alloy Solid Steel	0.030 (0.8)	90% Argon, 10% CO_2	155 - 165
	0.035 (0.9)	90% Argon, 10% CO_2	175 - 185
	0.045 (1.2)	90% Argon, 10% CO_2	215 - 225
	0.052 (1.3)	90% Argon, 10% CO_2	265 - 275
	0.062 (1.6)	90% Argon, 10% CO_2	280 - 290
	0.035 (0.9)	98% Argon, 2% O_2	130 - 140
	0.045 (1.2)	98% Argon, 2% O_2	205 - 215
	0.052 (1.3)	98% Argon, 2% O_2	240 - 250
	0.062 (1.6)	98% Argon, 2% O_2	265 - 275
Carbon and Low Alloy Composite Steel	0.040 (1.0)	90% Argon, 10% CO_2	140 - 150
	0.045 (1.2)	90% Argon, 10% CO_2	160 - 170
	0.052 (1.3)	90% Argon, 10% CO_2	170 - 180
	0.062 (1.6)	90% Argon, 10% CO_2	220 - 230
Stainless Steel	0.030 (0.8)	98% Argon, 2% O_2	120 - 130
	0.035 (0.9)	98% Argon, 2% O_2	140 - 150
	0.045 (1.2)	98% Argon, 2% O_2	185 - 195
	0.062 (1.6)	98% Argon, 2% O_2	250 - 260
	0.030 (0.8)	98% Argon, 2% CO_2	130 - 140
	0.035 (0.9)	98% Argon, 2% CO_2	200 - 210
	0.045 (1.2)	98% Argon, 2% CO_2	145 - 155
	0.062 (1.6)	98% Argon, 2% CO_2	255 - 265

Pulsed Spray Transfer

Keywords:

Period

Peak Current

Background Current

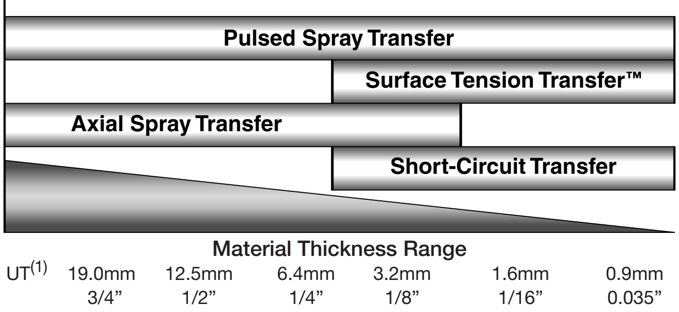
Frequency

Pulsed spray metal transfer, known by the acronym GMAW-P, is a highly controlled variant of axial spray transfer, in which the welding current is cycled between a high peak current level to a low background current level. Metal transfer occurs during the high energy peak level in the form of a single molten droplet.

GMAW-P was developed for two demanding reasons: control of weld spatter and the elimination of incomplete fusion defects common to globular and short-circuiting transfer. Its earliest application included the welding of high strength low alloy base material for out-of-position ship hull fabrication. The advantages that it brought to the shipbuilding industry included: higher efficiency electrodes than FCAW, and the ability to deliver lower hydrogen weld deposits. The mode employs electrode diameters from 0.030” – 1/16” (0.8 – 1.6 mm) solid wire electrodes and metal-cored electrodes from 0.045” – 5/64” (1.1 – 2.0 mm) diameter. It is used for welding a wide range of material types. Argon based shielding gas selection with a maximum of 18% CO_2 supports the use of pulsed spray metal transfer with carbon steels.

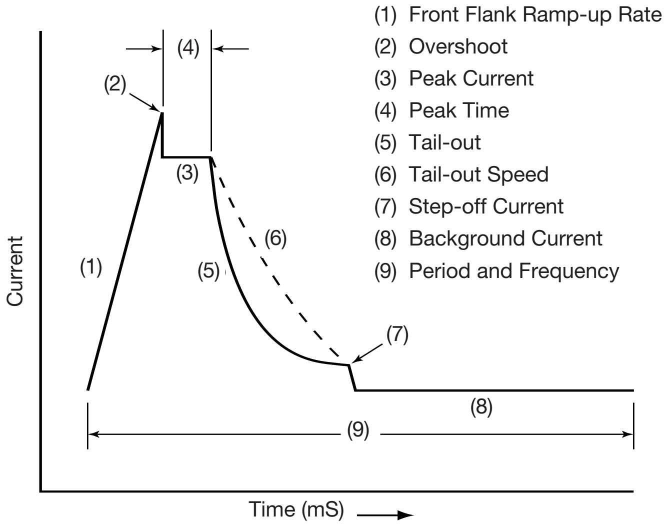
The welding current alternates between a peak current and a lower background current, and this controlled dynamic of the current results in a lower average current than is found with axial spray transfer. The time, which includes the peak current and the background current, is a period, and the period is known as a cycle (Hz). The high current excursion exceeds the globular to spray transition current, and the low current is reduced to a value lower than is seen with short-circuiting transfer. Ideally, during the peak current, the high point of the period, a single droplet of molten metal is detached and transferred across the arc. The descent to the lower current, known as the background current, provides arc stability and is largely responsible for the overall heat input into the weld. The frequency is the number of times the period occurs per second, or cycles per second. The frequency of the period increases in proportion to the wire feed speed. Taken together they produce an average current, which leverages its use in a wide material thickness range.

GMAW Mode of Metal Transfer Selector



(1) UT = Unlimited Base Material Thickness.

FIGURE 5: A Single Pulsed Event



Advantages of Pulsed Spray Transfer

- Absent or very low levels of spatter.
- More resistant to lack of fusion defects than other modes of GMAW metal transfer.
- Excellent weld bead appearance.
- High operator appeal.
- Offers an engineered solution for the control of weld fume generation.
- Reduced levels of heat induced distortion.
- Ability to weld out-of-position.
- Lower hydrogen deposit.
- Reduces the tendency for arc blow.
- Handles poor fit-up.
- When compared to FCAW, SMAW, and GMAW-S, pulsed spray transfer provides a low cost high-electrode efficiency of 98%.
- Lends itself to robotic and hard automation applications.
- Is combined for use with Tandem GMAW Twinarc™ or other multiple arc scenarios.
- Capable of arc travel speeds greater than 50 inches per minute (1.2 M/min.).

Limitations of Pulsed Spray Transfer

- Equipment to support the process is more expensive than traditional systems.
- Blends of argon based shielding gas are more expensive than carbon dioxide.
- Higher arc energy requires the use of additional safety protection for welders and bystanders.
- Adds complexity to welding.
- Requires the use of windscreens outdoors.

Components of the Welding Arc

Keywords:
Anode Region
Cathode Region
Arc Plasma Region
Electromagnetic Forces
Gravity – Droplet Weight
Surface Tension Forces
Jet Forces

The area of the welding arc is a region of high complexity that is comprised of physical forces and chemical reactions. The interaction of the components of the arc affects metal transfer and the quality of the finished weld. The behavior of the arc is influenced by:

- The type and diameter of the filler metal.
- The base metal conditions — clean or millscale.
- The shielding gas.
- The welding parameters — voltage and current.
- The interaction of physical forces — gravity, surface tension, jet forces, and electromagnetic force.

The character of the mode of metal transfer, the penetration profile, and the bead shape are influenced by the forces applied to the metal as it moves from the electrode end to the work-piece.

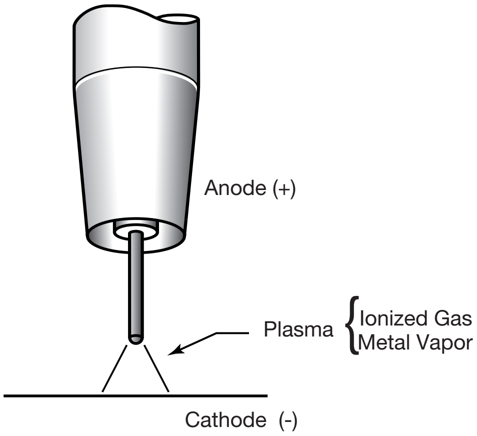


FIGURE 6: Cross Section of a GMAW Arc

Electromagnetic Forces

When current flows through a conductor, a magnetic field builds and surrounds the conductor. In GMAW the electro-magnetic forces, which are mathematically proportional to the square of the applied current, affect the mode of metal transfer. The most common term applied to the electromagnetic force is the pinch effect. As the molten drop forms, it is uniformly squeezed from the electrode anode end by the electromagnetic force. The size of the droplet transferred depends upon this force, the applied welding current, and the shielding gas.

Surface Tension Forces

Surface tension forces are those forces, which are normal to the surface of a molten droplet. They act on both the interior and the exterior surface of the droplet. Together they serve to support the form of a molten droplet. There is always an inward pull of the forces applied to the surface.

Jet Forces

In the short-circuiting mode of metal transfer, during the shorting portion of the metal transfer cycle, higher currents cause the electrode to heat to the point of melting. The high current drives an increase in the electromagnetic force, which causes the molten metal to detach from the electrode. As the droplet meets the weld pool, the surface tension forces supporting the molten droplet release and the molten droplet then adds itself to the molten weld pool.

In the globular transfer mode, a large molten droplet develops. Surface tension forces support the formation of the molten droplet, and jet forces push against the large droplet. The jet forces are responsible for supporting, spinning, and pushing the large droplet in an irregular fashion within the arc. The transfer occurs by the occasional shorting of the large droplet to the weld pool and the force of gravity. Once the droplet contacts the molten pool or work-piece, the surface tension forces in the droplet collapse, and the volume of weld metal is absorbed by the puddle.

The shielding gas employed in a welding application has an effect on the surface tension forces. If the energy level within the arc is high, as is the case with a 100% argon gas employed with a carbon steel electrode, then the bead shape will be extremely convex. If the surface tension value is low, because of the addition of carbon dioxide or oxygen, then the bead shape will be less convex, and more acceptable. So the addition of active gas components will result in improved weld bead and overall arc performance with carbon steel electrodes.

Shielding Gases for GMAW

The selection of the correct shielding gas for a given application is critical to the quality of the finished weld. The criteria used to make the selection includes, but is not restricted to, the following:

- Alloy of wire electrode.
- Desired mechanical properties of the deposited weld metal.
- Material thickness and joint design.
- Material condition – the presence of millscale, corrosion, resistant coatings, or oil.
- The mode of GMAW metal transfer.
- The welding position.
- Fit-up conditions.
- Desired penetration profile.
- Desired final weld bead appearance.
- Cost.

Under the heat of the arc, shielding gases respond in different ways. The flow of current in the arc, and its magnitude, has a profound effect on the behavior of the molten droplet. In some cases, a given shielding gas will optimally lend itself to one transfer mode, but will be incapable of meeting the needs of another. Three basic criteria are useful in understanding the properties of shielding gas:

- Ionization potential of the gas components
- Thermal conductivity of the shielding gas components
- The chemical reactivity of the shielding gas with the molten weld puddle

The following discussion details the arc physics associated with specific shielding gases, and permits the selection of the best shielding gas for the application.

Shielding Gases

Argon and helium are the two inert shielding gases used for protecting the molten weld pool. The inert classification indicates that neither argon nor helium will react chemically with the molten weld pool. However, in order to become a conductive gas, that is, a plasma, the gas must be ionized. Different gases require different amounts of energy to ionize, and this is measured in terms of the ionization energy. For argon, the ionization energy is 15.7 eV. Helium, on the other hand, has an ionization energy of 24.5 eV. Thus, it is easier to ionize argon than helium. For this reason argon facilitates better arc starting than helium.

The thermal conductivity, or the ability of the gas to transfer thermal energy, is the most important consideration for selecting a shielding gas. High thermal conductivity levels result in more conduction of the thermal energy into the workpiece. The thermal conductivity also affects the shape of the arc and the temperature distribution within the region. Argon has a lower thermal conductivity rate — about 10% of the level for both helium and hydrogen. The high thermal conductivity of helium will provide a broader penetration pattern and will reduce the depth of penetration. Gas mixtures with high percentages of argon will result in a penetration profile with a finger-like projection into the base material, and this is due to the lower thermal conductivity of argon.

Inert Shielding Gases

Argon is the most commonly used inert gas. Compared to helium its thermal conductivity is low. Its energy required to give up an electron, ionization energy, is low, and this results in the finger-like penetration profile associated with its use. Argon supports axial spray transfer. Nickel, copper, aluminum, titanium, and magnesium alloyed base materials use 100% argon shielding. Argon, because of its lower ionization energy, assists with arc starting. It is the main component gas used in binary (two-part) or ternary (three-part) mixes for GMAW welding. It also increases the molten droplet transfer rate.

Helium is commonly added to the gas mix for stainless and aluminum applications. Its thermal conductivity is very high, resulting in the broad but less deep penetration profile. When in use, arc stability will require additions of arc voltage. Helium additions to argon are effective in reducing the dilution of base material in corrosion resistant applications. Helium/argon blends are commonly used for welding aluminum greater than 1" (25 mm) thick.

Reactive Shielding Gases

Oxygen, hydrogen, nitrogen, and carbon dioxide (CO_2) are reactive gases. Reactive gases combine chemically with the weld pool to produce a desirable effect.

Carbon Dioxide (CO_2) is inert at room temperature. In the presence of the arc plasma and the molten weld puddle it is reactive. In the high energy of the arc plasma the CO_2 molecule breaks apart in a process known as dissociation. In this process, free carbon, carbon monoxide, and oxygen release from the CO_2 molecule. This occurs at the DC+ anode region of the arc. At the DC- cathode region, which is invariably the work piece for GMAW, the released elements of the CO_2 molecule undergo the process of recombination. During recombination higher energy levels exist and are responsible for the deep and broad penetration profile that characterizes the use of carbon dioxide.

Dissociation and Recombination

During the process of dissociation, the free elements of the CO_2 molecule (carbon, carbon monoxide, and oxygen) mix with the molten weld pool or recombine at the colder cathode region of the arc to form, once again, carbon dioxide. The free oxygen combines chemically with the silicon, manganese, and iron to form oxides of silicon, manganese and iron. Formed oxides, commonly referred to as silica islands, float to the surface of the weld pool, then solidify into islands on the surface of the finished weld or collect at the toes of a weld. Higher levels of carbon dioxide (higher oxidation potential) increases the amount of slag formed on the surface of the weld. Lower levels of carbon dioxide (lower oxidation potential) increase the amount of alloy, silicon and manganese retained in the weld. As a result, lower carbon dioxide levels, in a binary or ternary shielding gas blend, increase the yield and ultimate tensile strength of a finished weld (see Shielding Gas section on page 12).

Oxygen (O_2) is an oxidizer that reacts with components in the molten puddle to form oxides. In small additions (1-5%), with a balance of argon, it provides good arc stability and excellent weld bead appearance. The use of deoxidizers within the chemistry of filler alloys compensates for the oxidizing effect of oxygen. Silicon and manganese combine with oxygen to form oxides. The oxides float to the surface of the weld bead to form small islands, and are more abundant under CO_2 shielding than with blends of argon and oxygen gas.

Hydrogen (H_2) in small percentages (1-5%), is added to argon for shielding stainless steel and nickel alloys. Its higher thermal conductivity produces a fluid puddle, which promotes improved toe wetting and permits the use of faster travel speeds.

Binary Shielding Gas Blends

Two-part shielding gas blends are the most common and they are typically made up of either argon + helium, argon + CO_2, or argon + oxygen.

Argon + Helium

Argon/helium binary blends are useful for welding nickel based alloys and aluminum. The mode of metal transfer used is either axial spray transfer or pulsed spray transfer. The addition of helium provides more puddle fluidity and flatter bead shape. Helium promotes higher travel speeds. For aluminum GMAW, helium reduces the finger-like projection found with pure argon. Helium is also linked to reducing the appearance of hydrogen pores in welds that are made using aluminum magnesium fillers with 5XXX series base alloys. The argon component provides excellent arc starting and promotes cleaning action on aluminum.

Common Argon + Helium Blends

75% Argon + 25% Helium — this binary blend is frequently applied to improve the penetration profile for aluminum, copper, and nickel applications. The puddle is more fluid than with 100% argon.

75% Helium + 25% Argon — the higher helium content increases the thermal conductivity and puddle fluidity. The penetration profile is broad, and it exhibits excellent sidewall penetration.

Argon + CO_2

The most commonly found binary gas blends are those used for carbon steel GMAW welding. All four traditional modes of GMAW metal transfer are used with argon/CO_2 binary blends. They have also enjoyed success in pulsed GMAW applications on stainless steel where the CO_2 does not exceed 4%.

Axial spray transfer requires CO_2 contents less than 18%. Argon/CO_2 combinations are preferred where millscale is an unavoidable welding condition. As the CO_2 percentage increases, so does the tendency to increase heat input and risk burn-through. Argon/CO_2 blends up to 18% CO_2 support pulsed spray transfer.

Short-circuiting transfer is a low heat input mode of metal transfer that can use argon/CO_2 combinations. Optimally, these modes benefit from CO_2 levels greater than or equal to 20%. Use caution with higher levels of argon with short-circuit metal transfer.

FIGURE 7: Bead contour and penetration patterns for various shielding gases

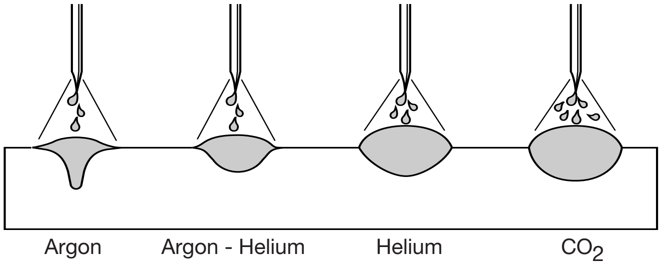
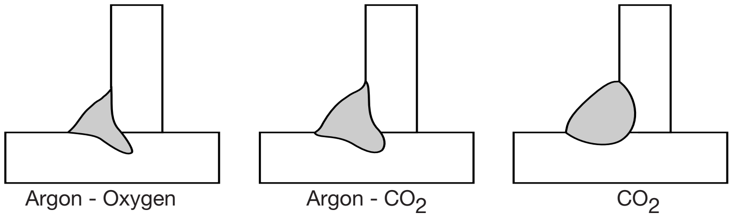


FIGURE 8: Relative effect of Oxygen versus CO_2 additions to the argon shield



Common Short-Circuiting Transfer Shielding Gas Blends

75% Argon + 25% CO_2 — reduces spatter and improves weld bead appearance on carbon steel applications.

80% Argon + 20% CO_2 — another popular blend, which further reduces spatter and enhances weld bead appearance on carbon steel applications.

Common Axial Spray Transfer shielding gas blends

98% Argon + 2% CO_2 — for axial or pulsed spray with stainless steel electrodes and carbon steel electrodes. This blend has seen repeated success on high-speed sheet metal applications. There is excellent puddle fluidity and fast travel speeds associated with this shielding gas blend.

95% Argon + 5% CO_2 — for pulsed spray with carbon steel electrodes. The addition of 5% CO_2 provides for additional puddle fluidity, and it lends itself to heavier fabrication than blends with 2% CO_2.

92% Argon + 8% CO_2 — for both axial and pulsed spray applications on carbon steel. Higher energy in axial spray transfer increases puddle fluidity.

90% Argon + 10% CO_2 — for either axial spray or GMAW-P applications on carbon steel. The penetration is broader and it reduces the depth of the finger-like penetration exhibited by argon + oxygen mixes.

85% Argon + 15% CO_2 — the higher CO_2 level in axial or pulsed spray transfer increases sidewall fusion on sheet metal or plate thickness material. Generally produces improved toe wetting on carbon steel with low levels of millscale. In GMAW-S, short circuiting transfer, the lower CO_2 level translates to less heat for welding parts with less risk of burnthrough.

82% Argon + 18% CO_2 — the effective limit for axial spray with CO_2. Popular European blend used for a wide range of welding thicknesses. Broad arc enhances penetration profile along the weld interface. Also lends itself well for use in short-circuiting transfer or STT applications.

Argon + Oxygen

Argon/oxygen blends attain axial spray transfer at lower currents than argon/CO_2 blends. The droplet sizes are smaller, and the weld pool is more fluid. The use of argon + oxygen has historically been associated with high travel speed welding on thin materials. Both stainless steel and carbon steel benefit from the use of argon/oxygen blends.

99% Argon + 1% Oxygen — used for stainless steel applications. The use of oxygen as an arc stabilizer enhances the fine droplet transfer and maintains the puddle fluidity for this gas blend. Stainless steel welds will appear gray because of the oxidizing effect on the weld pool.

98% Argon + 2% Oxygen — used as a shielding gas for either carbon or stainless steel applications. The earliest use of argon/oxygen blends for axial spray transfer on carbon steel employed 2% oxygen level. It is typically applied to applications that require high travel speed on sheet metal. Applied with either axial spray or pulsed spray transfer modes. Stainless deposits are dull gray in appearance. This blend is often used when superior mechanical properties are required from low alloy carbon steel electrodes.

95% Argon + 5% Oxygen — general purpose axial spray or pulsed spray transfer shielding gas applied to heavier sections of carbon steel. The base material is usually required to be free of contaminants with a low level of millscale.

Ternary Gas Shielding Blends

Three-part shielding gas blends continue to be popular for carbon steel, stainless steel, and, in restricted cases, nickel alloys. For short-circuiting transfer on carbon steel the addition of 40% helium, to argon and CO_2, as a third component to the shielding gas blend, provides a broader penetration profile. Helium provides greater thermal conductivity for short-circuiting transfer applications on carbon steel and stainless steel base materials. The broader penetration profile and increased sidewall fusion reduces the tendency for incomplete fusion.

For stainless steel applications, three-part mixes are quite common. Helium additions of 55% to 90% are added to argon and 2.5% CO_2 for short-circuiting transfer. They are favored for reducing spatter, improving puddle fluidity, and for providing a flatter weld bead shape.

Common Ternary Gas Shielding Blends

90% Helium + 7.5% Argon + 2.5% CO_2 — is the most popular of the short-circuiting blends for stainless steel applications. The high thermal conductivity of helium provides a flat bead shape and excellent fusion. This blend has also been adapted for use in pulsed spray transfer applications, but it is limited to stainless or nickel base materials greater than .062" (1.6 mm) thick. It is associated with high travel speeds on stainless steel applications.

55% Helium + 42.5% Argon + 2.5% CO_2 — although less popular than the 90% helium mix discussed above, this blend features a cooler arc for pulsed spray transfer. It also lends itself very well to the short-circuiting mode of metal transfer for stainless and nickel alloy applications. The lower helium concentration permits its use with axial spray transfer.

38% Helium + 65% Argon + 7% CO_2 — this ternary blend is for use with short-circuiting transfer on mild and low alloy steel applications. It can also be used on pipe for open root welding. The high thermal conductivity broadens the penetration profile and reduces the tendency to cold lap.

90% Argon + 8% CO_2 + 2% Oxygen — this ternary mix is applied to short-circuiting, pulsed spray, and axial spray modes of metal transfer on carbon steel applications. The high inert gas component reduces spatter.

GMAW SHIELDING GAS SELECTION GUIDE

Base Material	Electrode Type	Lincoln GMAW Product Name	Mode of Metal Transfer	Shielding Gas Blends
Carbon Steel	ER70S-3 ER70S-4 ER70S-6 or E70C-6M	SuperArc® SuperGlide® Metalshield®	GMAW-S or STT	100% CO_2 75-90% Argon + 10-25% CO_2
			Axial Spray or GMAW-P	82-98% Argon + 2-18% CO_2 95-98% Argon + 2-5% Oxygen 90% Argon + 7.5% CO_2 + 2.5% Oxygen
Low Alloy Steel	ER80S-Ni1 ER80S-D2 ER100S-G ER110S-G E90C-G E110C-G	SuperArc and Metalshield	GMAW-S or STT	100% CO_2 75-80% Argon + 20-25% CO_2
			Axial Spray or GMAW-P	95% Argon + 5% CO_2 95-98% Argon + 2-5% Oxygen
Aluminum	ER1100 ER4043, ER4047 ER5183, ER5356 ER5554, ER5556	SuperGlaze®	Axial Spray or GMAW-P (No GMAW-S)	100% Argon 75% Helium + 25% Argon 75% Argon + 25% Helium 100% Helium
Austenitic Stainless Steel	ER308LSi ER309LSi ER316LSi	Blue Max®	GMAW-S or STT	98-99% Argon + 1-2% Oxygen 90% Helium + 7.5% Argon + 2.5% CO_2 55% Helium + 42.5% Argon + 2.5 CO_2
			Axial Spray or GMAW-P	98-99% Argon + 1-2% Oxygen 98% Argon + 2% CO_2 97-99% Argon + 1-3% Hydrogen 55% Helium + 42.5% Argon + 2.5% CO_2
Nickel Alloys	ERNiCr-3 ERNiCrMo-4 ERNiCrMo-3 ERNiCrMo-10 ERNiCrMo-14 ERNiCrMo-17	Blue Max	GMAW-S or STT	90% Helium + 7.5% Argon + 2.5% CO_2 89% Argon + 10.5% Helium + .5% CO_2 66.1% Argon + 33% Helium + .9% CO_2 75% Argon + 25% Helium 75% Helium + 25% Argon
			Axial Spray or GMAW-P	100% Argon 89% Argon + 10.5% helium + .5% CO_2 66.1% Argon + 33% Helium + .9% CO_2 75% Helium + 25% Argon 75% Argon + 25% Helium 97-99% Argon + 1-3% Hydrogen
Duplex Stainless Steel (Second Generation)	2209 2304	Blue Max	GMAW-S or STT	66.1% Argon + 33% Helium + .9% CO_2 90% Helium + 7.5% Argon + 2.5% CO_2 98-99% Argon + 1-2% Oxygen 98% Argon + 2% CO_2
			Axial Spray or GMAW-P	75% Argon + 25% Helium 75% Helium + 25% Argon 100% Argon 100% Helium 66.1% Argon + 33% helium + .9% CO_2
90/10 Copper Nickel Alloys	ERCuNi Type 70/30		Axial Spray or GMAW-P (No GMAW-S)	100% Argon 75% Argon + 25% Helium 75% Helium + 25% Argon
Copper Alloys	ERCu (Deoxidized)		Axial Spray or GMAW-P	100% Argon 75% Argon + 25% Helium 75% Helium + 25% Argon
Silicon Bronze and Brasses	ERCuSi		GMAW-S, STT, Axial Spray or GMAW-P	100% Argon
Aluminum Bronze	ERCuAl-A1 ERCuAl-A2 ERCuAl-A3		Axial Spray or GMAW-P Limited GMAW-S	100% Argon

Effects of Variables

Current Density

Keywords:

Current Density

Cross-Sectional Area

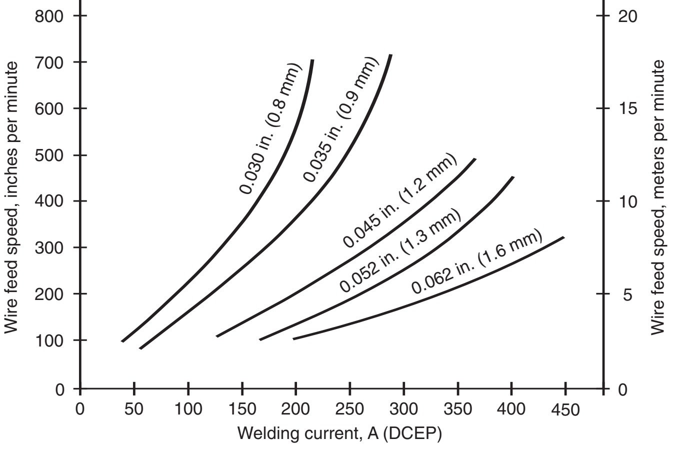
Saturated

Current density is defined as the current employed with a particular electrode diameter divided by its current carrying cross-sectional area. If the wire feed speed is low, then the current density will be low, and vice versa. From this you can determine that:

- Lower current density applied to a given electrode is associated with the short-circuit mode of metal transfer.
- Higher current density is associated with the higher energy modes of metal transfer: globular, axial spray transfer or the more advanced pulsed spray metal transfer.

The current for a given GMAW solid or metal-cored electrode will reach a maximum density level. Once this level of current density is attained, no additional current can be carried by the electrode. In other words, the electrode has reached its maximum current density. In particular, Figure 9 demonstrates this phenomenon for 0.035” (0.9 mm) diameter solid wire. It can be seen that the current is relatively linear to approximately 200 ampere, but as the current reaches just beyond 210 ampere, the rise in current becomes exponential. At approximately 280 ampere [720 ipm (18.3 M/min.) wire feed speed], the electrode reaches its maximum current density. The electrode at this point becomes saturated with current and no more current can be added to the electrode. Therefore, the maximum current density for a given electrode diameter is synonymous with the concept of current saturation. So it can be speculated that this phenomenon occurs for all diameters and material types of electrodes used for GMAW.

FIGURE 9: Typical Welding Currents vs. Wire Feed Speeds



It is important to note that once the electrode reaches its maximum current density, the saturation point, any added wire feed speed will provide a higher deposition rate with no increase in current.

Electrode Efficiencies

Electrode efficiency is a term that is applied to the percentage of electrode that actually ends up in the weld deposit. Spatter levels, smoke, and slag formers affect the electrode efficiency in GMAW. The electrode efficiency is a numeric value that is assigned to the particular mode of metal transfer:

- GMAW-S, short-circuit transfer, shielded with an argon + CO_2 gas blend, will typically operate with an electrode efficiency equal to or greater than 93%. Shielded by 100% CO_2, the electrode efficiency will range from 90 to 93%. Typically, CO_2 increases spatter levels to some extent, and argon blends are typically useful in reducing, but not completely eliminating, spatter.
- STT™, a dynamically controlled form of GMAW-S, will attain electrode efficiencies of 98% .
- Globular transfer is associated with higher spatter levels that profoundly impact electrode efficiency. The efficiency of globular transfer can vary from 85 to 88%, when shielded with 100% CO_2. Under argon blends the efficiency may vary from 88 to 90%.
- Axial spray has a higher electrode efficiency. This higher energy mode of metal transfer is associated with electrode efficiencies of 98%.
- The electrode efficiency for GMAW-P varies depending upon the welding application and the sophistication of the power source. Generally, the efficiency factor applied for GMAW-P is 98%, like that for axial spray, but there may be the need for a higher travel speed application that requires shorter arc lengths. High speed pulsed spray transfer types of applications generally introduce higher spatter levels. This necessarily reduces the electrode efficiency to some lower value.

All of this is related to the amount of electrode that actually ends up in the weld. If 100 lbs. (45 kg) of 0.035” (0.9 mm) diameter electrode is purchased for use on a particular project, and the project calls for the use of GMAW-S, then the effective amount of electrode that will be expected to end up in the welds will be:

EE x (lbs. Electrode)
= 0.93 x 100 lbs.
= 93 lbs.

NOTE: The calculation assumes no loss of material due to wire clipping.

Deposition Rate

Keywords:

Deposition Rate

Melt-off Rate

The melt-off rate for a particular electrode does not include consideration for the efficiency of the mode of metal transfer or the process. Its interest is in how much electrode is being melted.

Deposition rate is applied to the amount of electrode, measured in wire feed speed per unit of time, that is fed into the molten puddle. Importantly, its value reflects the use of the factor for electrode efficiency.

Depending upon the mode of metal transfer, as indicated in the Electrode Efficiency section on page 16, the factor for the particular mode of metal transfer employed is applied to the melt-off rate.

To determine the deposition rate for a given diameter of solid carbon or low alloy steel wire electrode the following mathematical formula will be useful:

$$13.1\,(D^2)(WFS)(EE)$$

where: D = electrode diameter
WFS = wire feed speed (inches per minute)
EE = electrode efficiency
13.1 = is a constant that is based upon the density of steel and its cross-sectional area.

If the melt off rate is all that is required, then use the same formula and remove the factor for EE.

Aluminum is approximately 33% the density of carbon steel, and its constant will be 13.1 x .33, or 4.32. Stainless steel, typically, is only slightly greater in density than carbon steel, 0.284 lbs/in^3 versus 0.283 lbs/in.^{3}, and therefore the 13.1 constant is sufficient.

Electrode Extension and Contact Tip to Work Distance

Keywords:

Electrode Extension
Electrical Stickout (ESO)
Contact Tip to Work Distance (CTWD)

The electrode extended from the end of the contact tip to the arc is properly known as electrode extension. The popular non-standard term is electrical stickout (ESO). In GMAW, this is the amount of electrode that is visible to the welder. The electrode extension includes only the length of the electrode, not the extension plus the length of the arc. The use of the term electrode extension is more commonly applied for semiautomatic welding than it is for robotic or mechanized welding operations. Contact tip to work distance (CTWD) is the standard term used in the latter.

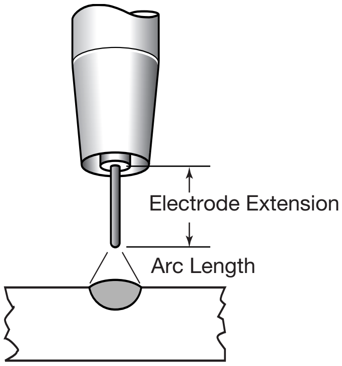


FIGURE 10: Electrical Stickout (ESO)

Contact tip to work distance (CTWD) is a term that lends itself well to the electrode extension for mechanized or robotic welding applications. It is measured from the end of the contact tip to the work piece.

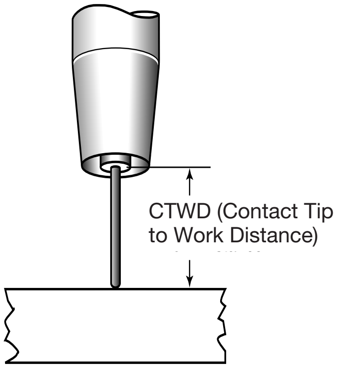


FIGURE 11: Contact Tip to Work Distance (CTWD)

In a non-adaptive constant voltage (CV) system the electrode extension or the CTWD acts as a resistor. Varying the length of the electrode affects the current applied to the arc:

- Increasing electrode extension increases the resistance to the flow of current in the electrode, and the current in the arc is decreased.
- Decreasing the electrode extension decreases the resistance to the flow of current in the electrode, and the current in the arc increases.

Because the current can vary with an increase or decrease in extension, the consistency of the extension is important to the consistency of weld penetration. It is important to maintain a very steady hand during semiautomatic welding. It is equally as important to establish and maintain the correct CTWD for mechanized or robotic welding.

For short-circuiting metal transfer or GMAW-S, semiautomatic welding, the electrode extension should be held between 3/8”-1/2” (10 – 12 mm). For either axial spray or GMAW-P, pulsed spray metal transfer, the electrode extension should be held between 3/4” – 1” (19 – 25 mm). Maintaining the correct electrode extension is important to the uniformity of the penetration profile along the length of a weld, and it is considered to be an important variable for any GMAW procedure.

Advanced Welding Processes for GMAW

Keywords:
Waveform Control Technology™
Output Modulation
Waveform Control
Adaptive Control
Synergic Control
Real-Time

Waveform Control Technology

The inverter power source in the early 1980's introduced a new era in the development of arc welding power sources. They affected the development of the full range of welding processes, but in the specific areas of GMAW the results from intense research and development are staggering.

The unique concept of Waveform Control Technology™ features an inverter transformer power supply and a central processing unit. The welding power output is produced by a high speed amplifier. The software developed to drive the output is enhanced to provide superior optimized welding output for a variety of GMAW modes of metal transfer. The most notable of these developments is the Surface Tension Transfer™, (STT™), Constant Power™, and a variety of special pulsed spray transfer modes of metal transfer.

The newer power sources feature the ability of the power source to interact with the end-user and permit the worker to create their own GMAW-P welding software program. Wave Designer 2000™ software is a commercially available Windows® software program that provides real-time output control of the power source. RS232 connectivity to the power source establishes a communication link with the computer. For pulsed spray transfer, short-circuiting transfer and STT, the output is modulated in response to changes made to the components of the waveform.

The use of waveform control software allows further optimization for a given mode of metal transfer. Templates for pulsed spray transfer, short-circuiting transfer and STT are available for adjustment to meet critical weld requirements. The objective for the development may be to improve toe wetting action, reduce dilution levels or to improve high travel speed performance of a pulsed waveform. In any case, the interaction between the arc performance and the adaptable output are central to the success of Waveform Control Technology.

Data acquisition tools that are an important part of the software allow the further ability to monitor the waveform during its development. The information collected permits alteration and or final documentation of the suitability of the waveform for the application.

Synergic control is designed to support all GMAW modes of metal transfer. One knob control permits the welder to select the wire feed speed, and then the voltage/trim value automatically follows. For all of the synergic modes of metal transfer the concept of synergy eases the use of higher technology on the shop floor.

The adaptive arc is an arc that quickly adjusts to changes in the electrode extension to maintain the same arc length. The objective for adaptive control is to improve arc performance and maintain finished weld quality.

Components of GMAW-P Waveform

Keywords:
Front Flank Ramp-up Rate
Percent Overshoot
Peak Current
Peak Time
Tail-out
Tail-out Speed
Step-off Current
Background Current
Pulse Frequency

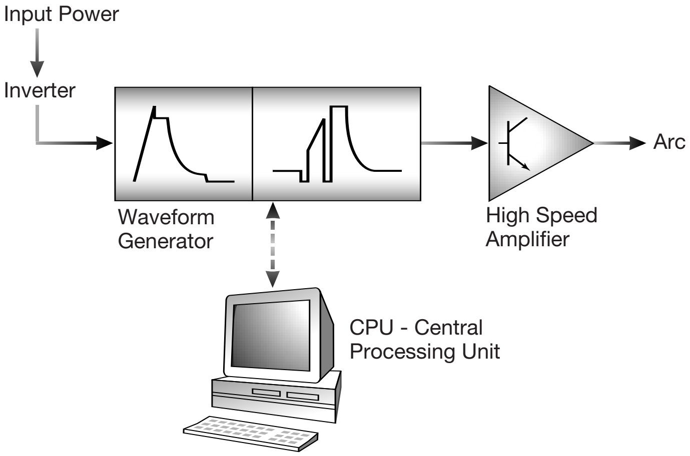


FIGURE 12: Wave Designer 2000 Pulse Editor

Nine essential components are useful for manipulating the output character of the GMAW-P waveform. The interaction of the components determines the specific outcome character of the waveform. Important in this basic understanding is the effect that shielding gas (see shielding gases for GMAW on page 12), electrode diameter, and electrode type have on the finished weld.

The Wave Designer 2000™ graphical user interface provides a visual image for the theoretical waveform. It is plotted on a "Current vs. Time" grid which reproduces changes made to the waveform. The changes made to a given pulsed waveform either add to, or subtract from, the area under the waveform. As the area under the waveform increases, there will be an increase in energy to the arc. The reverse is also true, when the area under the waveform decreases, the energy to the arc decreases.

GMAW-P Waveform Components

Front Flank Ramp-up Rate (1)

The ramp-up rate determines how rapidly the current will increase from the background current to the peak current. The ramp-up rate assists in the formation of the molten droplet at the end of the electrode. The rate is measured in terms of amps/millisecond. The rate of rise can reach 1000 amps/millisecond. As the slope of the ramp-up rate increases, the stiffness of the arc also increases. A fast ramp-up rate is associated with arc stiffness and louder arc noise. Decreasing the rate of rise contributes to a softer sounding arc.

Overshoot (2)

Overshoot describes the condition where the front flank increases to a predetermined level beyond the level of the peak current. It is expressed in units of percent. Increasing overshoot is associated with a more rigid arc that is less prone to deflection. Overshoot adds to the pinch current and it increases the electromagnetic pinch force applied to the molten droplet.

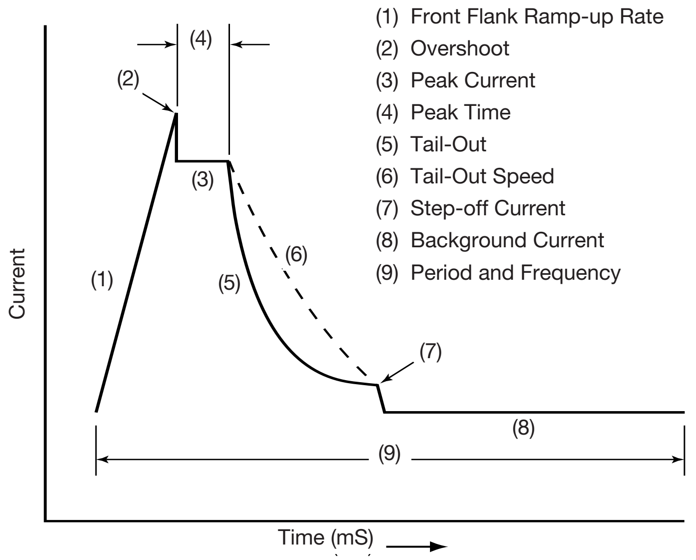


FIGURE 13: Waveform Development Editor

Peak Current (3)

Peak current is the nominal current for the high energy pulse. It is adjusted to a level that is set consistently above the globular to spray transition current. Peak current is expressed in units of ampere. During the time when the peak current is delivered, the molten droplet detaches from the electrode. An increase in peak current increases the average welding current and the weld penetration.

Peak Current Time (4)

Peak current time describes the length of time that the current is at its peak. It is associated with droplet size. Peak time is expressed in terms of milliseconds. As the peak time increases, the droplets decrease in size. As the peak time decreases, the droplet size increases. The traditional expectation is that a single molten droplet is transferred with each pulse peak. The effective time at peak can range from less than 1 millisecond to 3 or more milliseconds. An increase in peak time increases average current, and it also increases weld penetration.

Tail-out (5)

Tail-out is associated with current decay from the peak to the background current. It generally follows an exponential path to the background current. The increase in tail-out time increases the average current and marginally increases penetration. Tail-out time is increased to provide an increase in droplet fluidity. This results in improved toe wetting, a softer arc sound, and increased puddle fluidity.

Tail-out Speed (6)

Tail-out speed defines the rate at which the waveform moves from the peak current to either the step-off current or the background current. Manipulation of this portion of the waveform increases or decreases the exponential fall to the background current.

Step-off Current (7)

Step-off current defines the current level at the portion of the waveform where tail-out ends. It can add to, or take away from, the area under the waveform. It is associated with stabilizing the arc with stainless or nickel alloy filler metals.

Background Current (8)

Background current refers to the lower nominal current of the output. The unit of measure for the background current is ampere. Increases in background current will increase penetration.

Pulse Frequency (9)

Pulse frequency is responsible for how often the pulse cycle occurs in one second. As the frequency increases, the arc narrows, the average current increases, and the molten droplets become smaller. As the frequency decreases, the weld bead and the arc become wider. Frequency is generally proportional to the wire feed speed.

The Adaptive Loop

Keywords:

Scale Factor
Adaptive Loop
Arc Length Regulation
Constant Current

In a constant current scenario, as the CTWD is increased, the arc length also increases. As the CTWD decreases, the arc length also decreases. To control the length of the arc despite changes in CTWD, an adaptive control is necessary. The adaptive control will add energy to the arc as the CTWD decreases, and it will take energy out of the waveform as the CTWD is increased. This provides stability to the arc length, and increases the overall usability of the waveform.

Frequency, background current, peak time, and peak current are the typical components of the waveform used to regulate the arc length. Scale factor is the term attached to arc length regulation, and percentage is the term applied for its relative magnitude. If the background current is set to a value of 100 amps and the corresponding scale factor is expressed as 10%, then as the CTWD decreases, 10% more background current will be added to the present level for background current. If the CTWD increases, then up to 10% background current will decrease from the original 100 amps. This is how the arc length regulation operates, and it is coordinated to include the values for the other scale factor components detailed above. The regulation of the arc length occurs automatically, and it is functional within limits of the CTWD. The effective CTWD range for the adaptive loop is 0.50” – 1.25” (12 – 30 mm).

The adjustment of trim relates directly to the scale factors employed in the adaptive loop. As the trim decreases from a nominal value of 1.00, then the scale factors apply themselves together to decrease the arc length. As the trim is increased to a value greater than 1.00, then the scale factors work together to increase the arc length. Additionally, the "arc control" feature in the GMAW-P mode is directly tied to the adaptive loop. As the arc control is moved to +1 through +10, then frequency increases while background current decreases. The result is that the arc column narrows. If the "arc control" feature is moved to –1 through –10, then the result is a wider arc column and a wider finished weld.

The absence of the use of scale factors assumes that the arc is stable for a given wire feed speed or for a wide range of wire feed speeds. Arc stability means that the arc will not vary in length with a consistent CTWD. In this scenario, the welding program is non-adaptive, and only by adjusting the length of the CTWD, will there be a variance in arc length. When using a true non-adaptive program, trim and arc control will produce no changes in arc performance or level of arc energy.

Advanced Waveform Control Technology

Surface Tension Transfer™ (STT™)

Keywords:

Peak Current
Background Current
Tail-Out Current
Reactive Power Source
Sensing Lead

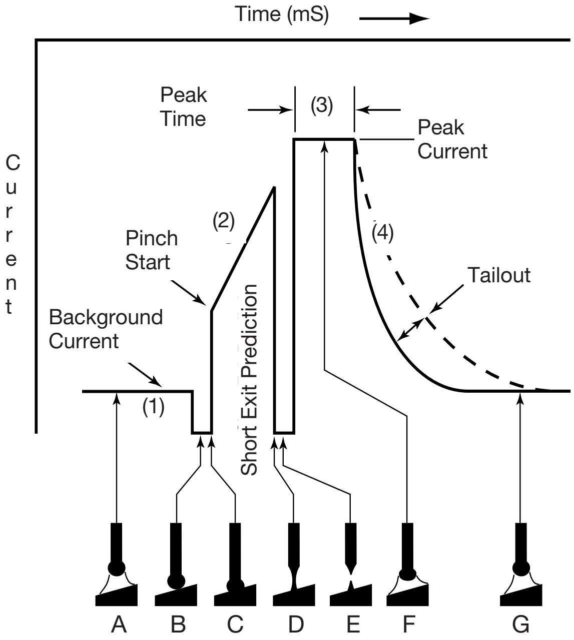
The Surface Tension Transfer (STT) welding mode of metal transfer is a low heat input welding mode. It specializes in its ability to provide smooth even rippled weld beads, free of weld spatter, and with consistently good fusion. It is ideal for sheet metal applications requiring excellent weld bead appearance and it is successfully applied for root pass welding of open root pipe joints.

The STT welding mode is reactive. The power source monitors the arc and responds instantaneously to the changes in the arc dynamics. A sensing lead attaches to the work piece to provide feedback information to the power source. Uniquely, the STT power source provides current to the electrode independent of the wire feed speed. This feature permits the ability to add or reduce current to meet application requirements.

The power source that supports STT is neither constant current nor constant voltage. It provides controls for the essential components of the STT waveform. Among these are controls for peak current, background current, and tail-out current. See Figure 14 on page 21.

Surface Tension Transfer™ (STT™)

FIGURE 14: Typical Waveform for STT



A. The molten tip of the electrode makes physical contact with the molten pool at the background current level.

B. The background current is reduced to a lower level to prevent the occurrence of a premature molten droplet detachment.

C. The current then ramps up quickly to a point where the pinch force associated with the rise in current (electromagnetic force) starts to neck down the molten column of the electrode. The power source at this point begins to monitor the changes in voltage over time as it relates to the necking of the molten droplet. The molten metal is still in contact with the molten weld pool. Via the sensing lead, the power source references the observed voltage, and continuously compares the new voltage value to the previous voltage value.

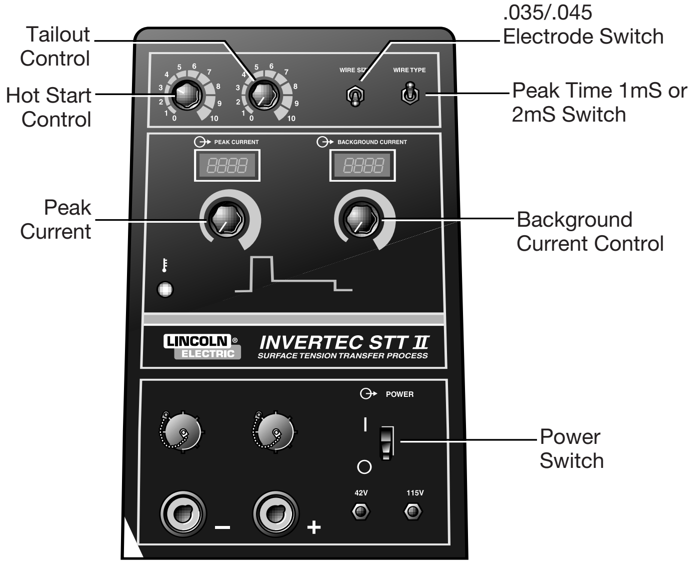
D. At the point where the molten metal is about to disconnect from the end of the electrode, the power source reduces the current to a lower than background current level. At this point in the waveform, surface tension forces collapse and the molten droplet transfers to the weld pool. This controlled detachment of the molten droplet is free of spatter.

E. The power source then rises to the peak current level where a new droplet begins to form. Anode jet forces depress the molten weld puddle to prevent it from reattaching to the electrode. On its descent to the background current, the tail-out current provides the molten droplet with additional energy. The added energy increases puddle fluidity, and the result is improved wetting at the toes of the weld.

F. A plasma boost is applied which provides the energy to re-establish the arc length, provide a new molten droplet, and force the molten puddle away from the molten droplet. The length of time is nominally 1 mS for carbon steel electrodes and 2 mS for both stainless and nickel alloyed filler metals.

G. The tail-out region is employed in applications where the energy added to the molten droplet provides faster travel speeds and improved finished weld wetting action at the toes. In most pipe root applications, this value is kept to a minimum.

STT Arc Controls



The **peak current** control is responsible for establishing the arc length, and it provides sufficient energy to preheat the work piece to insure good fusion. If it is set too high, the molten droplets will become too large. The molten droplet formed should be equal to 1-1/2 of the electrode diameter.

Background current is the essential component responsible for providing weld penetration into the base material, and it is largely responsible for the overall heat input into the weld. Manipulation of this component controls the level of weld penetration, and it effects the size of the molten droplet.

Tail-out current is responsible for adding energy to the molten droplet to provide increased droplet fluidity. It applies added energy without effecting droplet size. Increasing the tail-out current permits faster travel speeds and improves weld toe wetting action. The use of tail-out has proven to be a great value in increasing puddle fluidity, and this translates into higher arc travel speeds.

Tandem GMAW

Keywords:

High Deposition

Higher Travel Speed

The Tandem GMAW system was developed to take advantage of the potential for higher travel speeds and higher deposition rates when using two electrodes in the same molten puddle. The system employs two power sources, two wire drives, and a system control. It is adapted for either repetitive side-beam type applications or it is employed with a welding robot. This variant of the gas metal arc welding process is capable of higher travel speeds, 1-1/2 to 2 times the speed of a single electrode. Some travel speeds may exceed 150"/min. (3.81 m/min). Deposition rates to 42 lbs/hr (19.1 kg/hr) are achievable for heavier plate welding.

The arc components are broken into two parts: the lead arc and the trail arc. Generally, two electrodes of the same diameter are fed into the same puddle. Typical applications include the use of 0.035" – 1/16" (0.9 – 1.6 mm) diameter electrodes. The arcs are employed in a single barrel torch, and each electrode is fed through its own conductor tube. Similarly, there are two contact tips and two diffusers, see page 23.

Features of Tandem GMAW

- Capable of higher travel speeds on sheet metal than conventional single electrode GMAW.
- Lower hydrogen weld deposit.
- Lower spatter levels when compared to other processes and modes of metal transfer.
- Capable of high deposition welding for heavy plate fabrication.
- May be used for out-of-position welding.

Modes of Metal Transfer for Tandem GMAW

The modes of metal transfer used for the tandem GMAW variant are axial spray metal transfer or pulsed spray metal transfer. The combinations of the modes that are popularly employed include:

- **Spray + Pulse** — Axial spray transfer on the lead arc followed by pulsed spray transfer on the trail arc.
- **Pulse + Pulse** — Pulsed spray transfer on both the lead and the trail arc.
- **Spray + Spray** — Axial spray transfer on both the lead and the trail arc.

The software programs designed to support the **Pulse + Pulse** configuration require that the wire feed speed setting for each the lead and the trail are the same. Trim values can be adjusted to account for arc length requirements.

The higher energy **spray + spray** configuration is used for special heavy plate welding where deeper penetration is required. **Pulse + pulse** allows for heavy welding or high speed sheet metal welding.

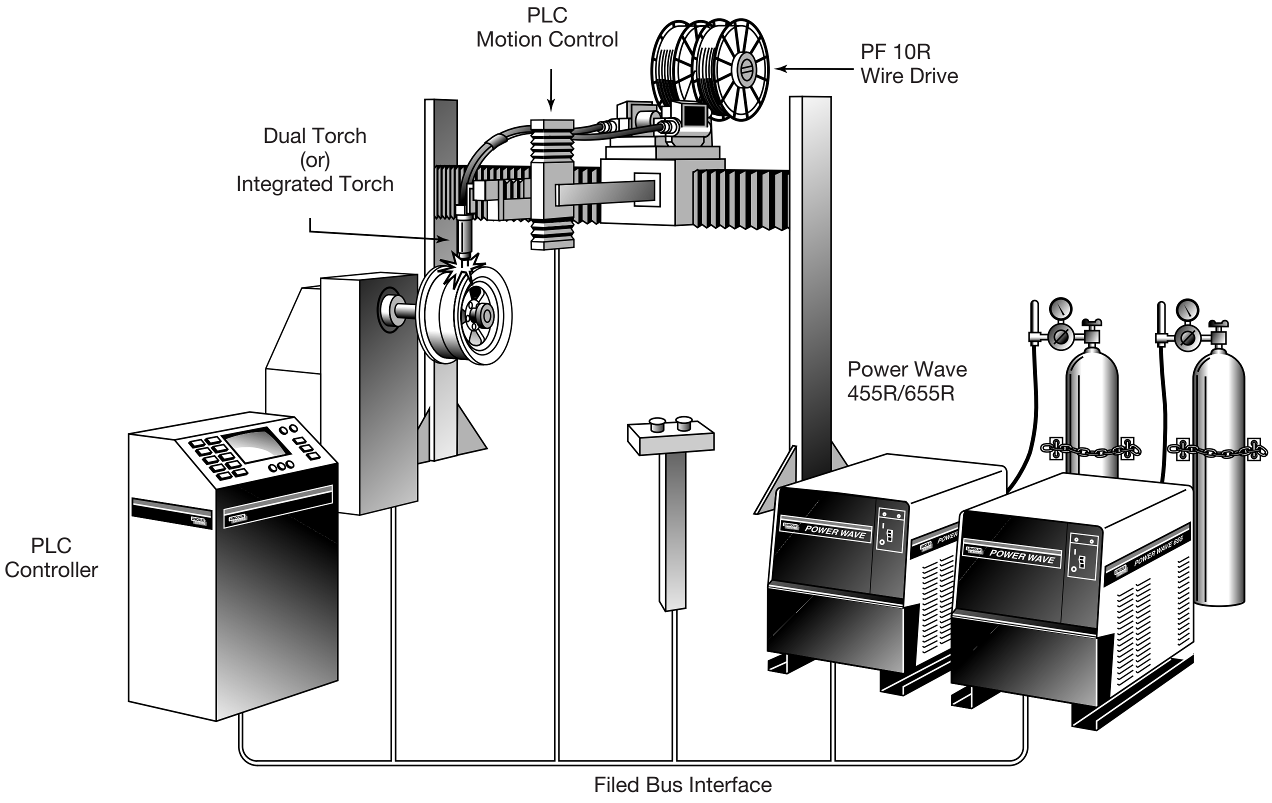


FIGURE 15: Tandem GMAW System

Tandem Torch Alignment and Contact Tip to Work Distance

Sheet Metal Applications

Central to the successful operation of tandem GMAW is an understanding of the set up of the special tandem GMAW welding torch. In all cases, the central axis of the torch should be normal to the weld joint. The lead arc has a built in 6° lagging electrode angle, and the trail has a built in 6° leading electrode angle.

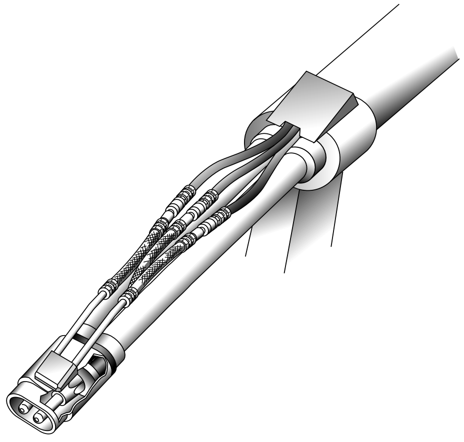


FIGURE 16: Tandem GMAW Torch Cutaway

The CTWD for higher speed sheet metal type applications should be set to 0.625” (16 mm). The electrode spacing is critical, and the shorter CTWD establishes the correct spacing. When the CTWD is held to this position the two arcs become more distinct from one another, and shorter arc lengths are used to provide higher travel speeds.

Heavy Plate Fabrication

The use of tandem GMAW for heavy plate fabrication requires a longer CTWD, 1” (25 mm). The longer CTWD provides the correct spacing between the two arcs, and in this scenario, the arcs tend to move very closely together. When held to the longer CTWD the arcs lend themselves for use with much higher wire feed speeds.

Equipment for GMAW

The basic design of an industrial, GMAW system includes four principle components:

1. Power source.
2. Wire drive and accessories (drive rolls, guide tubes,reel stand, etc.).
3. GMAW gun and cable assembly designed to deliver the shielding gas and the electrode to the arc.
4. Shielding gas apparatus and accessories.

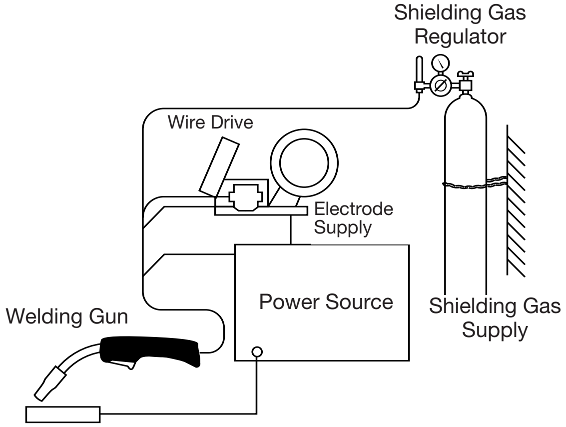


FIGURE 17: Basic GMAW System

There is a very wide range of GMAW components available from The Lincoln Electric Company. Each system's design provides optimum arc performance for the mode of metal transfer selected. The selection includes:

- Combination power sources and wire drives, which range in current capacity from 135 – 350 amp. The lower output range power source/wire feeder combinations are intended for limited sheet metal applications. For example, see Figure 18.

FIGURE 18: Power MIG 350MP System

- Constant voltage fixed power sources with a selection of wire drives and accessories for three-phase input power. They range from 250 – 655 amps of welding output. For example, see Figure 19.

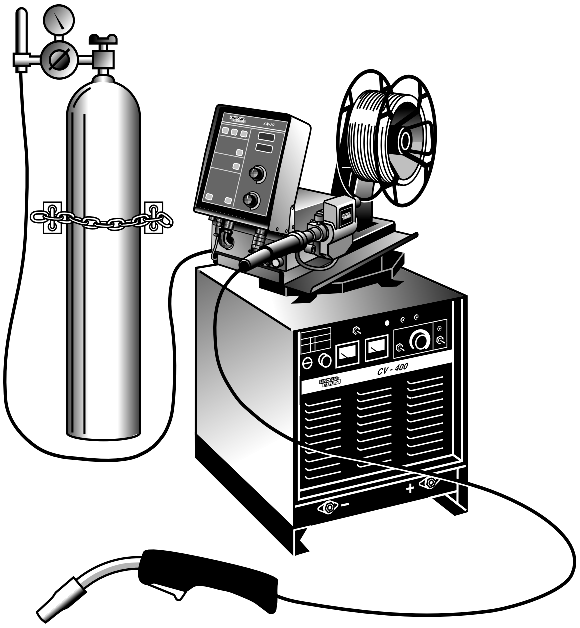


FIGURE 19: CV-400 with LN-10 GMAW System

- Multiprocess power sources capable of the full range of gas metal arc modes of transfer with additional process capabilities. These range from single-phase 300 amps to three-phase 655 amp systems. For example, see Figure 20.

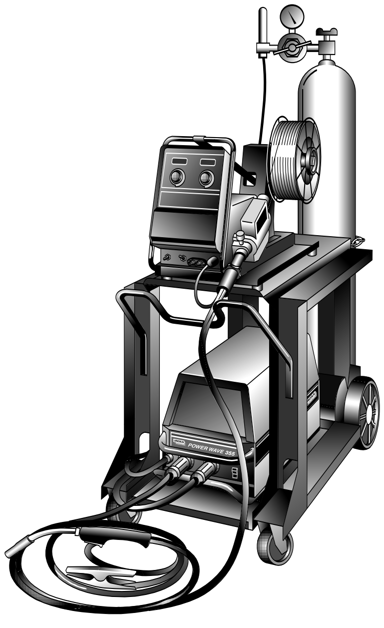


FIGURE 20: PowerWave™ 355M with Power Feed 10M GMAW System

- Advanced process power sources dedicated to Surface Tension Transfer™ and GMAW-P. They range in output from 225 - 655 amps, and all of these systems require three-phase input power. For example see Figure 21.
- Engine driven power sources that range from 200 - 600 amps of output. See page 31 for an example of a portable engine driven GMAW system.

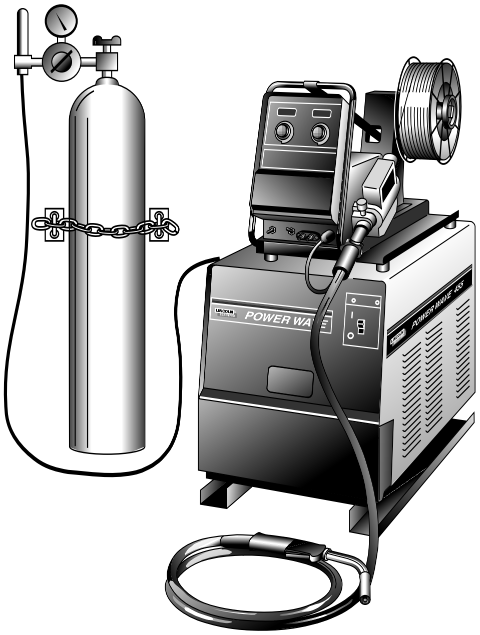


FIGURE 21: PowerWave® 455M/STT GMAW System with Power Feed 10M

The Power Source

Power sources incorporate output characteristics designed to optimize the arc performance for a given welding process. For GMAW, the output characteristics fall into two main categories:

- constant current
- constant voltage

Each of these two terms references the volt-ampere characteristics of the power source, and in each case, the volt-ampere relationship references the slope of the output. See Figures 22 and 23 for comparison output curves of CC (constant current) and CV (constant voltage).

Dedicated constant current power sources were more widely used in the early days of GMAW than they are today, but they see continued use in the welding of aluminum. The design uses a drooping output curve, see Figure 22. In constant current, the CTWD (contact tip to work distance) determines the arc length. As the CTWD increases the arc length increases, and as the CTWD decreases the arc length decreases. This presented a problem for semiautomatic welding because it is difficult to maintain the same CTWD. To compensate for this problem an arc voltage controlled wire feeder was designed to compensate for changes in arc length. In this scenario, as the CTWD decreases, the wire feed speed would increase; and as the CTWD increases, the wire feed speed would decrease.

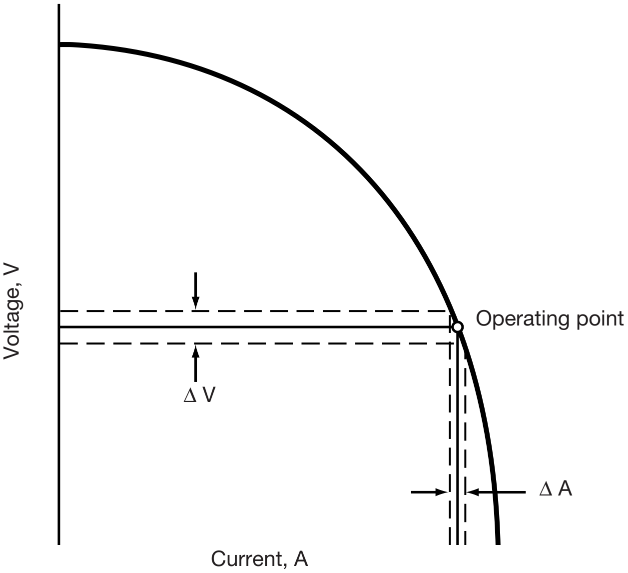


FIGURE 22: CC (Constant Current) Power Source Volt-Amp Characteristics

Typically, constant current applications were confined to large diameter/large weld puddle aluminum GMAW applications or large diameter/large weld puddle carbon steel applications.

Constant voltage power source designs provide a specific arc voltage for a given pre-selected wire feed speed. The volt-amp curve, or slope, is comparatively flat. As the CTWD increases with these types of power sources, there is a decrease in the welding current. As the CTWD decreases there is an increase in the welding current. The arc in this case becomes a series circuit, and the CTWD provides resistance to current. In either scenario, the voltage remains the same and the arc length remains the same, see Figure 24 on page 26.

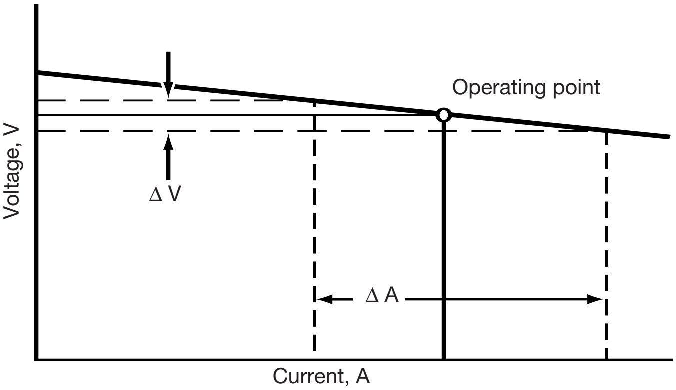
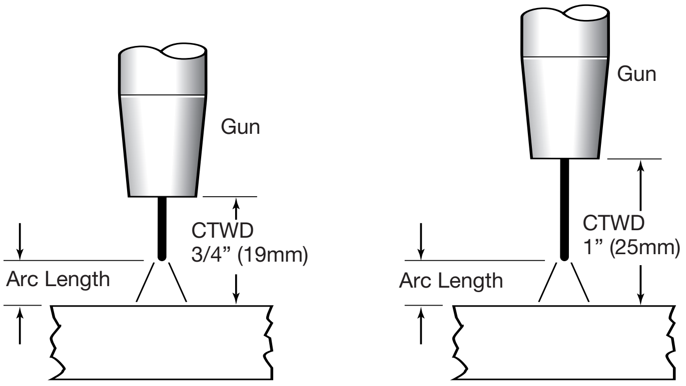


FIGURE 23: CV (Constant Voltage) Power Source Volt-Amp Characteristics

FIGURE 24: Unaffected Arc Length with Constant Voltage Power Sources



Power sources designed for GMAW require a feature for providing inductance. Inductance is a necessary component for short-circuiting transfer and low wire feed speed globular transfer. It is of little use for spray arc transfer and the advanced processes such as Surface Tension Transfer™ or GMAW-P.

A variable inductance control is important for short-circuiting transfer because it will permit fine-tuning of the arc to minimize spatter and improve weld toe wetting.

The traditional GMAW power source will provide either analog or digital meters used to quantify voltage and current. These are essential variables and their accuracy is central to the quality of a finished weld.

Developments in transformer design permit the use of smaller inverter transformers, which increases the portability and reduces the required space needed for the power source. This in turn provides relief for valuable manufacturing space. Inverter designs characteristically provide smooth efficient output to the arc. Many of the designs incorporate the use of welding software to drive the output and quality of the arc, see Waveform Control Technology™ section on page 18.

The Wire Drive and Accessories

GMAW wire drive designs provide for the use of a wide range of solid or metal-cored electrodes, 0.025" – 1/16" (0.6 – 1.6 mm). The wire feed speed may be pre-settable via a digital readout or a calibrated marking system on the wire feed speed control. The ability to provide a precise wire speed is important to good welding procedure control. Most standard wire drives for GMAW provide a permanent magnet motor, which in turn provides for fast starting and stopping of the feed system.

The effective range of wire feed speed is important, and most wires drives will provide a range of 70 – 800 ipm (inches per minute), (2 – 20 M/min.) of wire feed speed. Higher wire feed speed wire drives are available for applications requiring the delivery of wire feed speed up to 1200 ipm (30 M/min.).

Optional considerations for wire drive controls include timers for setting pre-flow and post-flow for the shielding gas. A burn-back control may be added to prevent the electrode from sticking to the crater at the end of the weld. Some wire drives may provide a cold inch control for safely inching wire electrode through a GMAW torch to the work. An optional purge control for the shielding gas system, provides gas flow in advance of the arc, and displaces the air that may have entered the system.

The wire drive system provides a gas solenoid, which activates when the GMAW torch trigger is depressed. Shielding gas pre-flow and post-flow conditions control the solenoid circuit and add gas before and after the arc is established. Optional water connections are available for use with water-cooled GMAW guns.

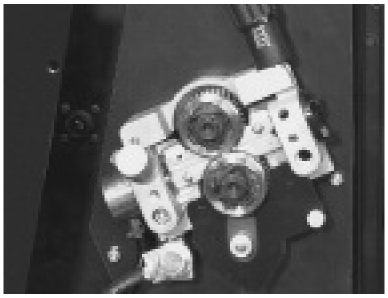
GMAW Wire Drives

LF-72 Series and LF-74

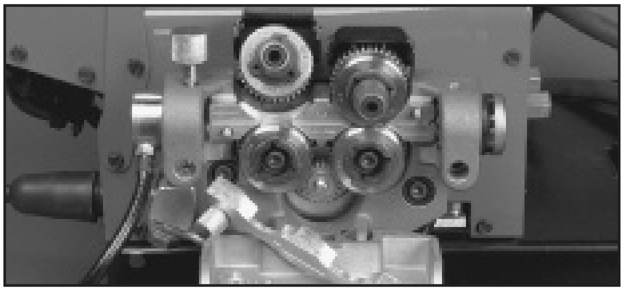
LN-10

LN-15

Two- or four-roll drive systems deliver the electrode to the welding torch. Two-roll systems are standard with smaller non-industrial systems, but the four-roll system is popular for industrial applications.



Two-Roll Drive System



Four-Roll Drive System

A mounting block for the power cable permanently fixes to the GMAW torch receiver of the wire drive.

The use of a wire straightening device incorporates the ability of the wire drive to provide three important features for the arc:

1. The straightening device reduces the cast of the spooled, coiled, or bulk electrode used for welding. This is especially important for nickel alloys.
2. Reducing the cast improves electrode placement of the arc in the weld joint.
3. Reducing the cast helps reduce drag in the liner (conduit) of the GMAW torch, and, therefore, will reduce premature wear.

Typical platform mount installations, where the wire drive is located on the top of the power source, will require the selection of a wire reel stand. There are a variety of enclosures designed to provide protection for the electrode in use. The spool mounting spindle design provides variable tension for the electrode package in use, and it incorporates a braking action to prevent unspooling of the electrode at the reel stand. A lift bale provides a mounting feature for extending the reach in a work cell using boom type arms.

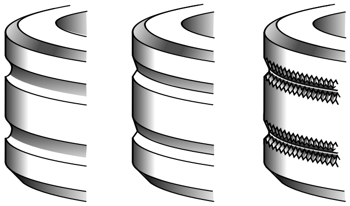
Accessories for Wire Drives

Four Roll Wire Drive Kit

Two Roll Wire Drive Kit

Wire Straightener

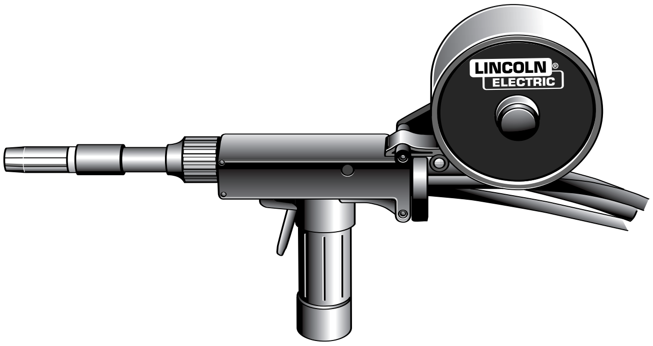
Drive Roll Kit for Cobramatic®



U-Groove, V-Groove and Knurled Rolls

Special Wire Feeding Considerations

Spool guns are designed to provide a means for delivering aluminum, and other small 1 and 2 lb. (0.45 and 0.90 kg) packages of electrode to the arc. The spool gun incorporates a wire drive motor, a wire feed speed control, and an electrode enclosure in a comfortable lightweight design.

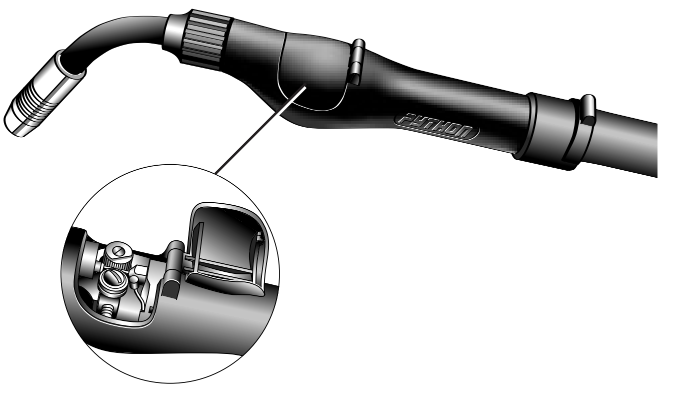


Spool Gun

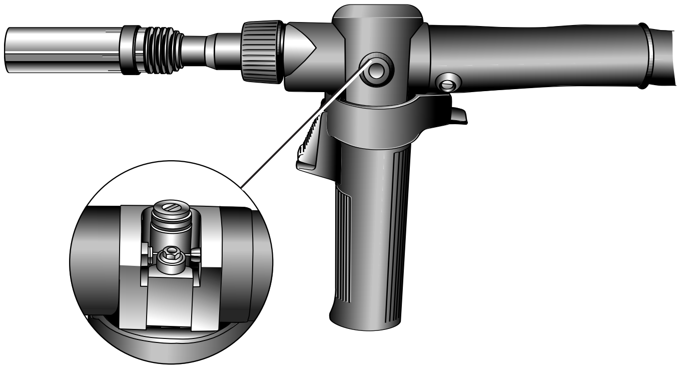
Aluminum fillers are characterized as softer than steel electrodes, and they have lower column strength (stiffness). The smaller the diameter of aluminum electrode, 0.030 - 0.047" (0.8 – 1.2 mm), the more difficult it is to feed. As a result of the softer and less stiff characteristics, they generally benefit from either a push-pull or a spool gun feeding system. A spool gun only has to push the electrode 8" - 10" (200 - 250 mm) to the arc, and a push-pull system is designed with the same principle in mind. In either case, these systems more reliably feed aluminum filler metals than a standard hand held GMAW gun.

Both robotic and hard automation applications benefit from push-pull systems. Reliable feeding is best accomplished with an assist type of system that reduces the distance that the electrode has to travel from the wire drive to the arc.

A standard GMAW gun will require the use of teflon or nylon gun liners to permit the delivery of the electrode to the work. The GMAW gun cable should be kept short, usually 10 ft. (3 m) to promote electrode delivery. Pushing aluminum through a GMAW gun is usually restricted to 5XXX type aluminum filler alloys 3/64" (1.2 mm) diameter or greater.



Python™ Push-Pull System



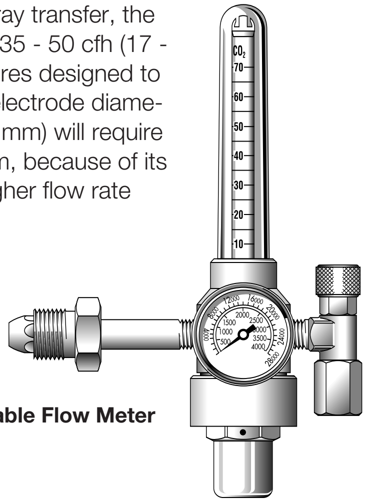
Binzel™ Push-Pull System for Aluminum Feeding

Shielding Gas Regulation

The delivery of a shielding gas to the arc is important to the quality of the finished weld. GMAW requires a regulator for measuring the flow rate of gas either from a manifold system, which incorporates several pressurized gas cylinders; a bulk inert gas distribution system, which is then piped to the welding work cells; or from a single gas cylinder. Flow meter regulator designs provide two readings to the welder: the first reading is from a meter that measures internal cylinder pressure, and it allows the welder to recognize how much gas remains in the cylinder. The second measures the rate of flow of the shielding gas as it exits the cylinder. The rate of gas flow is measured in either cubic feet per hour (cfh) or liters per minute (L/min). A hose connects the regulating device to the gas solenoid contained in the wire drive. A connecting hose extends from the front of the wire drive to a brass nipple located at the GMAW torch.

Bulk gas systems or manifold systems connected to piped-in mixes of shielding gas usually include a pressure regulator, which controls line pressure. An adjustable flow meter is then added as a separate item.

The rate of flow for short-circuiting transfer with either CO_2 or a mixed shielding gas is usually 25 - 30 cfh, (12-17 L/min). For globular transfer or axial spray transfer, the flow rate is nominally set at 35 - 50 cfh (17 - 21 L/min). Special procedures designed to meet the requirements for electrode diameters greater than 1/16" (1.6 mm) will require a higher rate of flow. Helium, because of its lower density, requires a higher flow rate than those indicated above.



Adjustable Flow Meter

Bulk Electrode Packaging

In order to minimize the electrode packaging changes, GMAW welding stations may incorporate bulk electrode dispensing systems. In general, there are four types of packages:

- Vertical Reels
- Horizontal Reels (fixed or moving)
- Drums
- Boxes

Each bulk package requires the use of an electrode conduit, orbital arm or other mechanical dispensing device(s) to get the electrode to the wire drive.

Vertical Reels depend on a mechanical delivery system designed, through a system of pulleys, to ease the delivery of the electrode from the vertically mounted reel. When long conduit distances are involved, the use of a system of pulleys and or an assist motor will ease the burden placed on the wire drive. Vertical reels are available in 600 lb. (272 kg) packaging.

Horizontal Reels - Fixed Reel Type depend on an orbiting arm, which rotates around the top of the reel, to deliver the electrode to the wire drive. Longer feeding distances sometimes require an assist motor. Horizontal reels are available in 600 lb. (272 kg) and 1000 lb. (454 kg) packaging.

Horizontal Reels - Moving Reel Type are used with reels of electrode that require the rotation of the entire spool. The mechanical advantage of this type of dispensing system allows reduced pulling of the electrode from the reel to the wire drive. Longer feeding distances sometimes require an assist motor.

Accu-Trak® and Speed-Feed® Drums of electrode are increasingly popular for use in either semiautomatic or automatic welding applications. They are available in 250 lb. (113 kg), 500 lb. (227 kg), 600 lb. (272 kg) and 1000 lb. (454 kg) packages for use with semiautomatic or full automatic applications. The accurate placement of the electrode into the weld joint is a principal objective of their design. The electrode feeds through a cone or hat that sits on top of the drum, which connects to the conduit. Longer feeding distances sometimes require an assist motor.

Accu-Pak® Boxes of electrode are similar to the Accu-Trak drums and they are available in 500 lb. (227 kg) and 1000 lb. (454 kg) packaging The box provides easier transport from weld station to weld station. A cone or hat sits on top of the box and the electrode passes through the top center of the cone. The conduit connects to the top of the cone or hat and it then connects to the wire drive.

Accu-Pak Box

- Wire protection — completely enclosed package.
- Recyclable
- Ease of Lifting (Lifting Straps).
- Vapor Barrier (Plastic Bag Surrounds Wire).
- Excellent Wire Placement.

Accu-Pak Box shown with a K2175 Payoff Kit

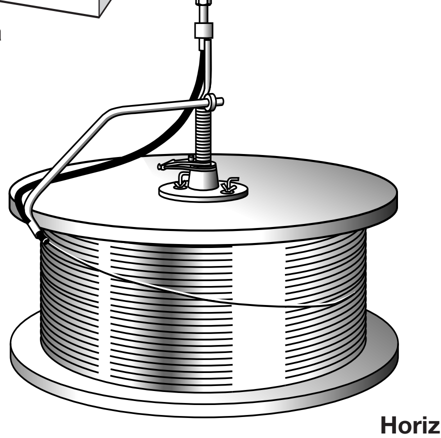
Accu-Trak Drum

- Wire protection — completely enclosed package.
- Ease of Handling — Handling Devices Commercially Available.
- Excellent Wire Placement.

Accu-Trak Drum shown with a K884 Payoff Kit

Accu-Trak Reels

- Lower Cost Bulk Package Solution.
- Excellent Wire Placement.
- Reel Cover Protection Commercially Available.



Horizontal Reel shown with a K895-2 Rotary Wire Dispenser

FIGURE 25: Automatic GMAW System

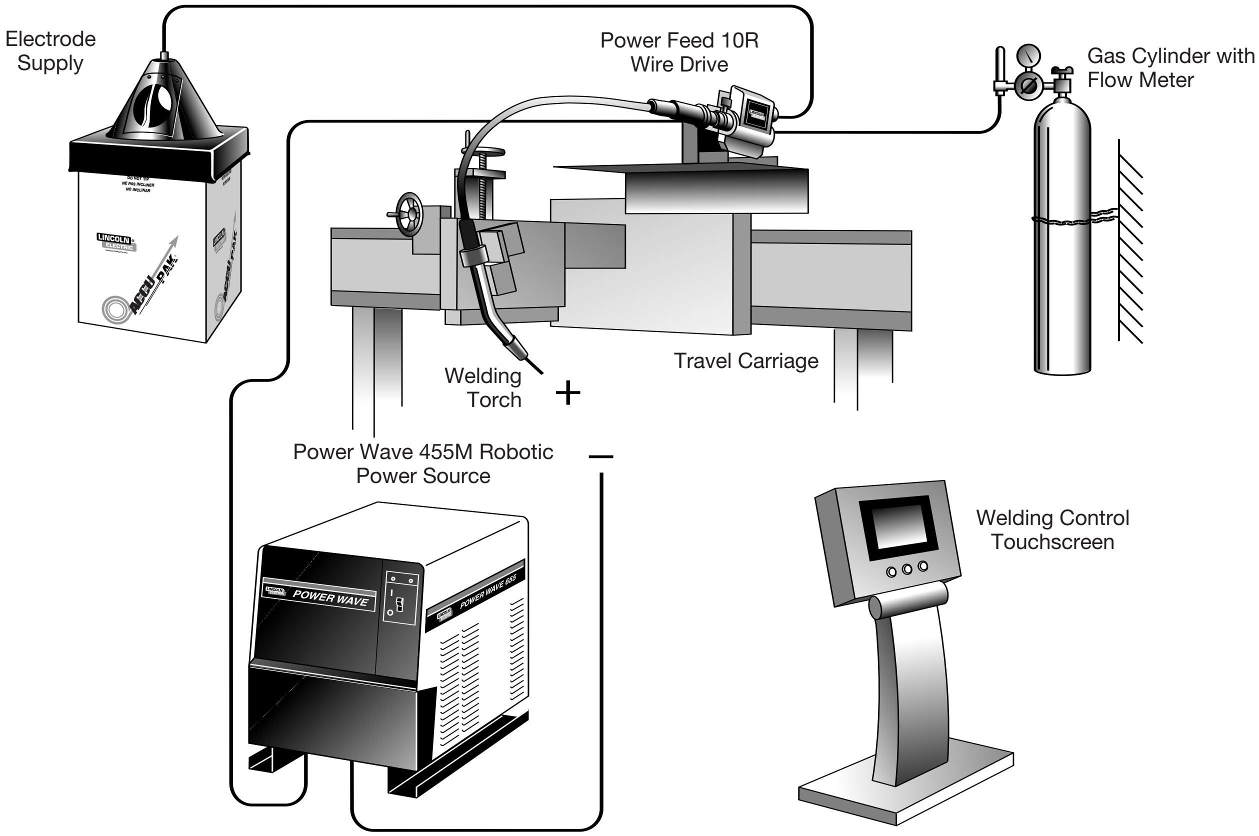


FIGURE 26: Semiautomatic GMAW System

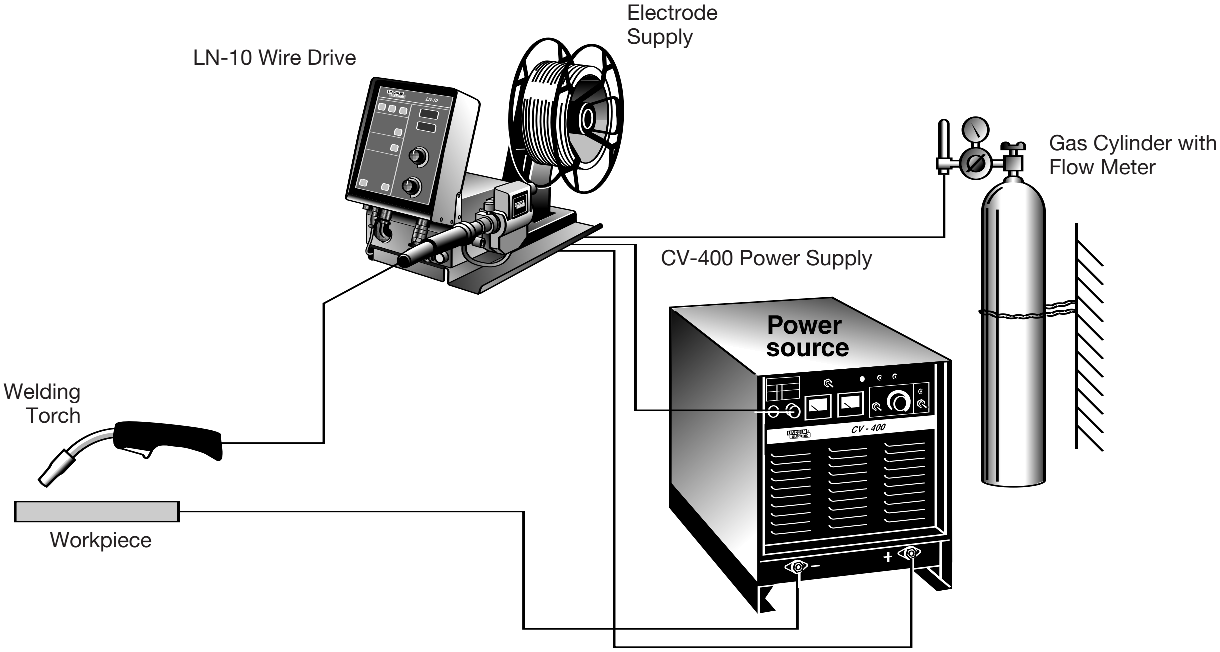
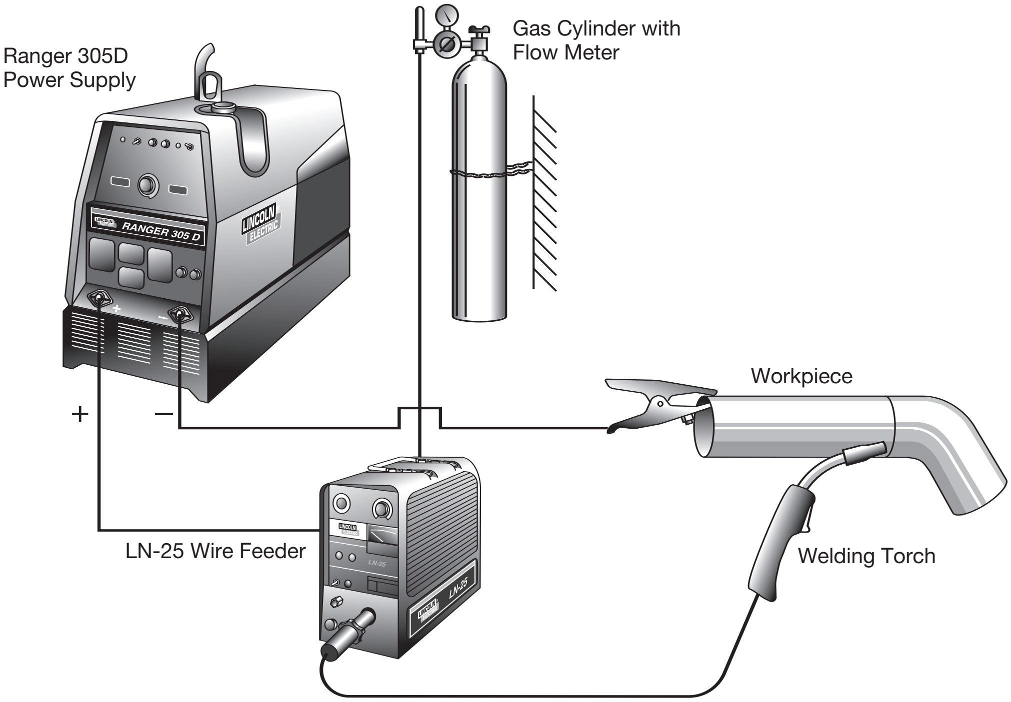


FIGURE 27: Portable Engine Driven GMAW System



GMAW Torches

Keywords*:*

Torch Nozzle	*Water-Cooled Torch*
Contact Tip	*Air-Cooled Torch*
Torch Barrel	*Water Cooler*
Gas Diffuser	*Torch Duty Cycle*
Torch Liner	

The selection of the proper GMAW torch, commonly called a MIG gun, depends upon the following factors:

- Type of welding: semiautomatic, hard automation or robotic automation.
- Level of current (amps) required by the welding application and capacity of the torch.
- Shielding gas selected.
- Duty cycle of the torch.
- Preference of an air-cooled or water-cooled torch.

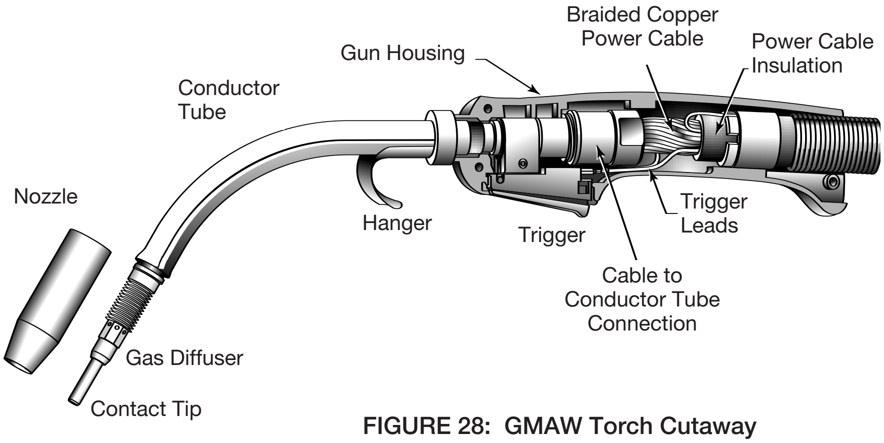


FIGURE 28: GMAW Torch Cutaway

Semiautomatic GMAW Welding

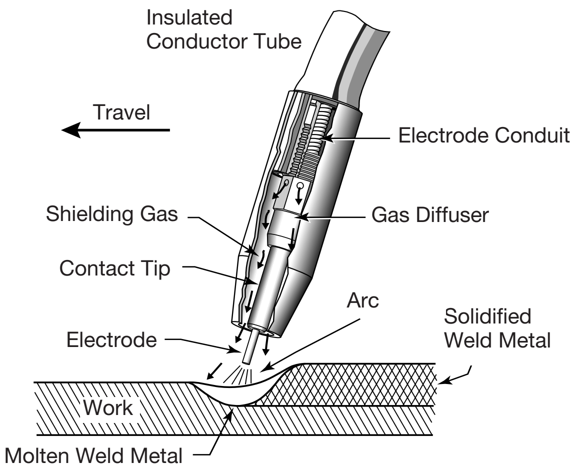
The GMAW torch provides a conduit for the welding current, the shielding gas, and the electrode. The welding current is picked up at the torch power block located on the wire drive. Current transfers from the welding cable to the electrode through the contact tip. Contact tips are available in a range of sizes designed to accommodate the electrode diameter in use, and they usually attach to the gas diffuser via a threaded connection.

The electrode is fed through an internal liner usually located internal to the power cable. The shielding gas connections are located at the welding gun mounting block on the wire drive.

They connect to the output side of the gas solenoid. The gas flows to the gas diffuser, which uniformly delivers the gas to the arc. The nozzle size is selected depending on the electrode diameter and the shielding gas rate of flow.

Most of the welding with the GMAW process requires a selection of a torch that will meet the anticipated comfort level of the welder and simultaneously meet the wear requirement imposed by the welding operation. The welding current used in the application is primary to the selection, and the durability of the torch under conditions of the arc dictates the appropriate GMAW torch size.

FIGURE 29: GMAW Torch Cutaway



All GMAW torches for semiautomatic welding provide a duty cycle rating. The heat generated and transferred to the torch handle needs to be considered. The duty cycle of the GMAW torch selected relates to the shielding gas and the maximum current that is specific to the welding application. Most air-cooled torches are rated at a 60% duty cycle for a specific current, and their operation is based upon the use of 100% CO_2 shielding. If argon based blends are indicated, then the torch duty cycle should be reduced by 50%.

Most GMAW torches come in lengths of 10 - 25 ft. (3 – 8 m) and the length selected should provide no compromise for delivery of the shielding gas and the electrode to the arc.

TABLE 2: Magnum® Air-Cooled Torch Ratings and Diameter Ranges

MAGNUM GUNS

Magnum Gun	Rating (Amps)	Diameter Range Inches (mm)	Duty Cycle
Magnum 200	200	0.025 - 0.045 (0.6 - 1.1)	60
Magnum 300	300	0.035 - 5/64 (0.9 - 2.0)	60
Magnum 400	400	0.035 - 5/64 (0.9 - 2.0)	60
Magnum 550	550	0.035 - 1/8 (0.9 - 3.2)	60

The selection of a water-cooled torch for GMAW has several advantages. They are rated 100% duty cycle for their given capacity. They increase the life of the consumable components of the torch by approximately 50%. Water–cooled torches have operator appeal because they reduce the heat transferred to the GMAW torch handle. The downside of a water-cooled torch is that they tend to require more maintenance. Additionally, the use of a water-cooled torch requires the purchase of a water cooler, see photo below. Implementation of a water-cooled GMAW torch depends largely upon the size of the electrode used, the amount of time a welder spends at the arc, and the projected cost of welding torch consumables.

Magnum® Cool-Arc Water Cooler

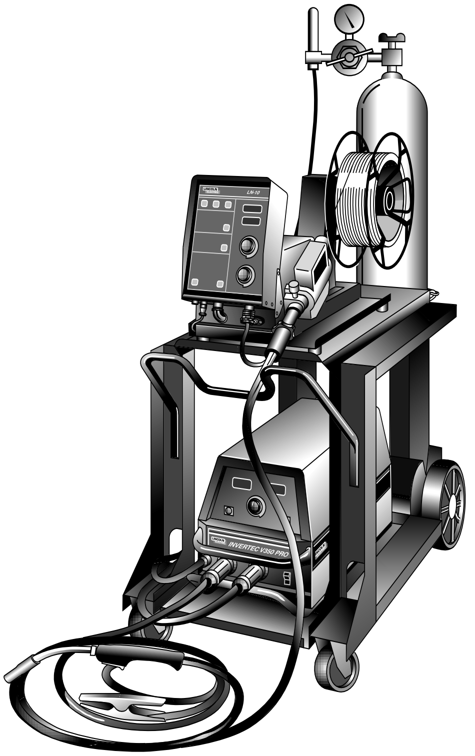
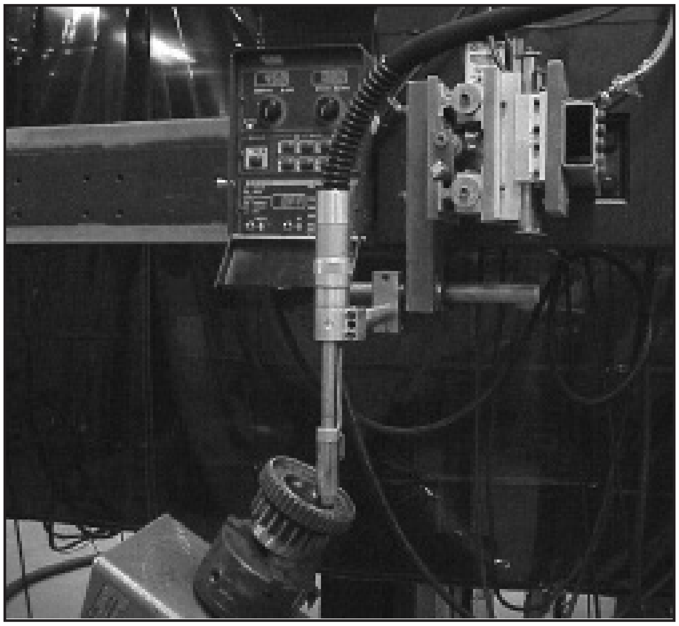


FIGURE 30: Semiautomatic GMAW Welding System

GMAW Torches for Hard Automation



Fixed Length Automatic Torch for Hard Automation

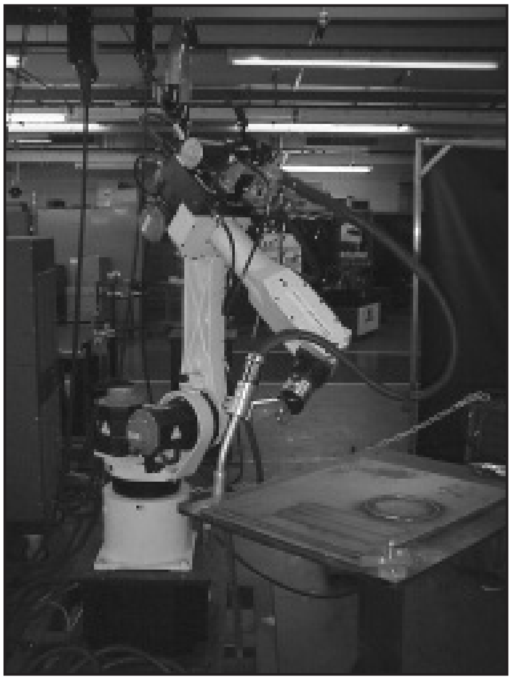
Hard automation requires the torches meet the demands of high productivity. The choice of water-cooled torches versus an air-cooled torch depends on the same criteria applied to the selection of a torch for semiautomatic welding. Most hard automation systems incorporate a system design that provides the need for a torch no longer than 3 ft. (1 m). This aids in feeding, and reduces maintenance time and cost.

Data should be collected regarding appropriate maintenance levels for guns. Maintaining the performance on an arc welding system requires changing the GMAW consumable parts. Torch liners, torch barrels, diffusers, nozzles, and contact tips, require replacement and they are essential to maintaining weld quality. The information collected can provide a schedule for preventive maintenance.

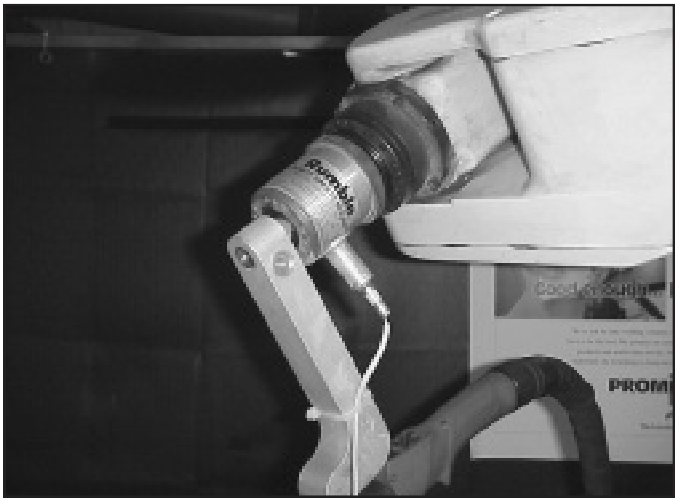
GMAW Torches for Robotic Automation

The criteria for selecting GMAW torches employed for robotic applications follow the same pattern as used for both semi-automatic and hard automation. The torch must be of a physical size to move between tooling, holding clamps, and it must also be flexible enough to access hard to reach locations. To meet the demanding needs of robotic applications, a number of torch configurations are available that incorporate long torch barrels, small diameter nozzles, and torch exchange systems.

Whether or not to proceed with a water-cooled or air-cooled torch depends, again, on the demands of productivity, and the preventive maintenance program employed. A collision sensor and a breakaway mounting to the end of the robot arm are standard for all robotic applications. Each of these two components are designed to limit damage to a system in the event of a crash.



Robotic Automation GMAW Welding System



Collision Sensor

GMAW of Carbon and Low Alloy Steels

Selecting Carbon and Low Alloy Steel Electrodes

Selecting the proper filler metal for use with GMAW is similar to the process that must be employed when determining the applicable electrode for any welding process:

- The electrode must deposit welds that will have the mechanical and chemical properties needed for the proper performance of the welded connection.
- The electrode must be suitable to address the unique circumstances associated with the particular application.
- The electrode must meet the welder's expectations in terms of arc action and puddle control.
- The selected electrode should result in the total overall lowest cost of welding. This is not to say that the lowest cost electrode will always lead to the total overall lowest cost; in many cases, a higher purchase priced electrode will result in decreased overall costs.

A Two Component System

GMAW is a two-component welding process, in terms of the consumables that will be used: both a gas and an electrode are required. The electrode selection process cannot be made separate from consideration of the type of shielding gas that will be used. The most efficient means of selection of the proper filler metal for GMAW is to consider electrode/gas combinations when making comparisons. For example, a more expensive shielding gas, with a less expensive electrode, may or may not be more economical than a low cost gas and more expensive electrode. Thus, the electrode/gas combination must be considered.

The gas selection can have an effect on mechanical properties as well. Changes in shielding gas may increase or decrease Charpy V-Notch properties of the deposit, for example. The effect of shielding gas on weld properties is more significant for the higher strength, and more alloyed, filler metals.

Electrode Diameter

As with other processes, the diameter of the electrode used with GMAW is an important decision. Considerations have to be made for the various welding positions, the material thickness and the selected mode of metal transfer.

Production Conditions

The type of conditions that are encountered in production welding influences the electrode selection. A key factor is material cleanliness: the more oxide on the base metal surface, the higher the need for deoxidizers in the electrode.

Electrode Selection Checklist

The following are suggestions for selecting the proper GMAW steel electrode for a given application:

A. Determine the required mechanical property requirement

The primary mechanical properties of interest are the yield and tensile strength, and Charpy V-Notch. For most steels with a tensile strength of 70 ksi or less, matching strength filler metal will be used for all welds. For higher strength steels, and especially when the tensile strength exceeds 100 ksi, under matching filler metal may be selected for fillet and partial joint penetration groove welds.

The Charpy V-Notch (CVN) properties may be specified in contract documents, or in applicable codes.

When the mechanical property requirements have been determined, available filler metals can be compared to requirements. Typically, the AWS classification properties are compared to the application requirements.

Tables 3 and 4 on page 36 can be helpful in determining the suitable electrodes for matching tensile strength requirements.

B. Determine the weld deposit chemistry requirements

Under some conditions, it is important for the deposited weld metal to have a specific chemistry in order to meet service conditions. For example, when the weld is to have atmospheric corrosion resistance similar to "weathering" steels (such as A588), the weld is typically required to have a nickel content of 1%.

C. Evaluate the production conditions

The surface condition is a key condition to consider. Mill scale, rust, and other surface contaminants may justify the use of an electrode with a higher level of deoxidizers.

D. Determine final weld appearance requirements

Where toe wetting, flat weld faces, low levels of spatter and other visual criteria are important, higher levels of silicon in the electrode may be helpful.

E. Determine the appropriate electrode diameter

Before the electrode diameter can be determined, a basic understanding of the welding procedure variables must be known. Larger diameter electrodes usually cost less, feed better, and can carry more current. Smaller diameters are appropriate for minimizing melt through on thinner materials, as well as to maximize deposition rates per amp of output.

Types of Carbon and Low Alloy Steel Electrodes

Keywords:

AWS A5.18

AWS A5.28

Deoxidizers

GMAW solid carbon steel wire electrodes are also known as fine wires or microwires because they tend to be smaller in diameter when compared to electrodes used in other arc welding processes. GMAW wire is defined as a solid or composite metal-cored electrode ranging in wire diameter from 0.023" - 1/16" (0.6 - 1.6 mm). They are also defined according to their AWS (American Welding Society) classification, AWS A5.18, Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding, and AWS A5.28, Specification for Low Alloy Steel Filler Metals for Gas Shielded Arc Welding. The general requirements applied to GMAW consumables are:

- Chemical composition
- Mechanical properties
- Solid wire diameters
- Packaging requirements

The first classifications discussed pertain to solid carbon steel electrode wires with differing deoxidizing alloy levels. The remaining classifications pertain to composite metal-cored electrodes classified under the GMAW process.

The American Welding Society uses an alphanumerical system for GMAW wire classification. For example, a solid wire electrode may have the AWS classification ER70S-3, sometimes referred to as an S-3 wire. Each letter and number represents a specific defining characteristic. The "E" stands for electrode, the current carrying device. The "R" stands for rod, meaning that the electrode can also be used as a filler rod for GTAW applications. The number "70" indicates the minimum as-welded tensile strength measure in thousands of pounds per square inch (ksi). The "S" refers to a solid electrode wire. The "3" refers to the level of specific alloy, deoxidizer(s) that makes up the carbon steel electrodes chemical composition.

A deoxidizer is an element in the wire that helps to remove oxygen and nitrogen from the weld, thus reducing the occurrence of weld metal porosity. Typically for carbon steel, the deoxidizers include manganese and silicon. Other deoxidizers, although rare, may include aluminum, zirconium, and titanium. Generally, the higher the silicon deoxidizer level the more fluid the molten puddle becomes – this enhances toe wetting and finished weld bead appearance.

Tables 5 and 6 on page 37 show the AWS chemical composition requirements for solid electrodes per AWS A5.18 and A5.28.

GMAW Carbon Steel Solid Wire Classifications

AWS A5.18 GMAW Carbon Steel Electrodes

ER70S-2

The ER70S-2 carbon steel electrode is a triple deoxidized product. It contains high silicon and manganese levels, but also contains deoxidizers such as aluminum, titanium and zirconium. This GMAW electrode is used for both single and multiple pass welding, and historically, for root pass welds on carbon steel pipe. Due to the deoxidizers, the ER70S-2 is indicated for use on steels with moderate levels of mill scale. The use of this electrode has decreased in recent years, and it is replaced, typically, by either ER70S-3 or ER70S-6 carbon steel electrode.

ER70S-3 (SuperArc® L-50)

The ER70S-3 GMAW electrode contains medium levels of silicon and manganese. It is popularly employed in both single and multiple pass welding applications. It is the most popular GMAW electrode. Lincoln Electric's premium GMAW wire electrodes conforming to this classification include **SuperArc™ L-50**, a copper coated wire, and **SuperGlide™ S3**, a non-copper coated wire.

ER70S-4 (SuperArc® L-54)

The ER70S-4 GMAW electrode has higher levels of silicon and manganese than an ER70S-3. Its intended use is for those applications requiring higher deoxidizer levels than an ER70S-3. It is used for both single and multiple pass welding. The ER70S-4 classification does not require Charpy impact conformance testing. Lincoln Electric's premium GMAW wire electrode conforming to this classification is **SuperArc L-54**.

ER70S-6 (SuperArc® L-56)

The ER70S-6 carbon steel GMAW electrode contains high levels of silicon and manganese deoxidizers, and is best suited for welding on base materials with moderate to high levels of mill scale. It can be used in both single and multiple pass welding applications. Also, due to the higher silicon level, the puddle fluidity increases and results in a flat weld bead with excellent weld toe wetting. Lincoln Electric's premium GMAW wire electrodes conforming to this classification include **SuperArc L-56**, a copper coated wire, and **SuperGlide S6**, a non-copper coated wire electrode.

ER70S-7

The ER70S-7 GMAW electrode has higher levels of manganese than an ER70S-6 electrode, but it has lower levels of silicon. The silicon levels, however, are higher than an ER70S-3 electrode. It can be used with argon/CO_2 binary gas mixtures as well. Due to chemical composition, this electrode also has intermediate hardness levels between an ER70S-3 and an ER70S-6 electrode.

ER70S-G

The ER70S-G AWS classification for solid wire electrodes having a "G" indicates it is of a general classification. This classification does not have AWS chemical composition, testing, or mechanical property requirements. This is not to say, however, that these electrodes do not meet nor exceed the properties of otherwise AWS classified electrodes. Weld chemistries or testing results for application of the ER70S-G electrode should be obtained by the manufacturer prior to use.

AWS A5.18 GMAW-C Carbon Steel Composite Electrodes

E70C-6M (Metalshield® MC-6 and Metalshield MC-706)

The E70C-6M electrode has high levels of deoxidizers in silicon and manganese and is an excellent choice for welding on base materials with high levels of mill scale. It is better suited for this application than solid wires due to its composite design. This electrode is also a preferred choice for welding on automated thin base material at fast travel speeds and has fantastic operator appeal due to ease of use, puddle fluidity and good wash in.

AWS A5.28 GMAW Low Alloy Solid Steel Wires

ER80S-Ni1 (SuperArc® LA-75)

The ER80S-Ni1 AWS classification is a high silicon, high manganese low alloy steel GMAW electrode containing 1% nickel. This wire also contains small levels of chromium, molybdenum, and vanadium. These elements combine to provide higher strength levels, higher impact properties, and the 1% nickel provides corrosion resistance for ASTM A588 weathering steels. ER80S-Ni1 welds must exhibit a CVN value of 20 ft-lbs @ -50°F (27J @ -29°C). Lincoln Electric's premium ER80S-Ni1 GMAW low alloy electrode is SuperArc LA-75.

ER80S-D2 (SuperArc® LA-90)

An ER80S-D2 GMAW wire electrode is higher silicon, higher manganese low alloy product containing a 0.50% level of molybdenum. Molybdenum strengthens the weld metal and improves toughness. Lincoln Electric's premium ER80S-D2 product is SuperArc LA-90 and also satisfies requirements for classification as an ER90S-D2 and an ER90S-G, providing an as-welded tensile strength in excess of 90 ksi.

ER100S-1 and ER100S-G (SuperArc® LA-100)

As the "G" suffix indicates, the ER100S-G AWS classification of GMAW wire electrode is used for single and multiple pass welding, and it is a general classification. There are no AWS chemical compositions or mechanical property requirements. Lincoln Electric's SuperArc LA-100 premium GMAW wire electrode meets the ER100S-G, ER110S-G, and the Military Specification MIL-100S-1 classification requirements. This electrode meets a minimum tensile strength of 100 ksi and minimum yield strengths of 82 ksi. It contains 0.5% molybdenum and 1-2% nickel, making it an excellent choice for welding HY-80 and ASTM A514 steels.

AWS A5.28 GMAW-C Low Alloy Composite Electrodes

E90C-G (Metalshield® MC-900)

E90C-G electrodes are high silicon, high manganese electrodes well suited to weld over high levels of mill scale on base materials. The high alloy in this wire is suited to weld on HSLA, HY80, ASTM A710 and other high strength steels. Expect high deposition rates with little slag and spatter from these electrodes.

E110C-G (Metalshield® MC-1100)

E110C-G electrodes are high silicon, high manganese electrodes well suited to weld over high levels of mill scale on base materials. The alloy balance and high strength of these electrodes are designed to weld on many HSLA steels such as ASTM A514, HY-100 and "T-1" steels as well as other high alloy steels. High deposition rates with little slag and spatter can be expected.

TABLE 3 — Mechanical Properties Requirements for AWS A5.18 GMAW Carbon Solid and Composite Steel Electrodes

MECHANICAL PROPERTIES REQUIREMENTS

AWS Classification	Tensile Strength ksi (MPa)	Yield Strength ksi (MPa)	Elongation (%)	Charpy V-Notch, ft-lbs (J) @ 0°F (-18°C)	Charpy V-Notch, ft-lbs (J) @-20°F (-29°C)
ER70S-2	70 (480)	58 (400)	22	Not Required	20 (27)
ER70S-3	70 (480)	58 (400)	22	20 (27)	Not Required
ER70S-4	70 (480)	58 (400)	22	Not Required	Not Required
ER70S-6	70 (480)	58 (400)	22	Not Required	20 (27)
ER70S-7	70 (480)	58 (400)	22	Not Required	20 (27)
ER70S-G	70 (480)	58 (400)	22	Not Required	Not Required
E70C-3X	70 (480)	58 (400)	22	20 (27)	Not Required
E70C-6X	70 (480)	58 (400)	22	Not Required	20 (27)

NOTE: Mechanical properties as determined from an all-weld metal specimen. Single values are minimum levels.

TABLE 4 — Mechanical Properties Requirements for AWS A5.28 GMAW Low Alloy Solid and Composite Steel Electrodes

MECHANICAL PROPERTIES REQUIREMENTS

AWS Classification	Tensile Strength ksi (MPa)	Yield Strength ksi (MPa)	Elongation (%)	Charpy V-Notch, ft-lbs (J) @-20°F (-29°C)	Charpy V-Notch, ft-lbs (J) @-50°F (-46°C)	Charpy V-Notch, ft-lbs (J) @-60°F (-51°C)
ER80S-Ni1	80 (550)	68 (470)	24	Not Required	20 (27)	Not Required
ER80S-D2	80 (550)	68 (470)	17	20 (27)	Not Required	Not Required
ER100S-1	100 (690)	88 (610)	16	Not Required	Not Required	50 (68)
ER90S-D2	90 (620)	78 (540)	17	20 (27)	Not Required	Not Required
E90C-G	90 (620)	Not Specified	Not Specified	Not Required	Not Required	Not Required
E110C-G	110 (760)	Not Specified	Not Specified	Not Required	Not Required	Not Required

NOTE: Mechanical properties as determined from an all-weld metal specimen. Single values are minimum levels.

Solid & Composite Steel Wire Electrode Chemical Composition

Carbon (C) – Carbon is a critical element found in GMAW solid wire electrodes. It is added in precise amounts to provide strength and ductility in the weldment.

Manganese (Mn) – Manganese is another element that adds strength to the weld. It is added to GMAW electrodes to act as a deoxidizer, removing oxygen from the weld, and reducing the chance of weld metal porosity.

Silicon (Si) – Silicon is also added to GMAW electrodes to act as a deoxidizer, removing oxygen from the weld, and reducing the chance of weld metal porosity. In general, the higher the level of silicon in the metal, the more fluid the weld puddle. Additions of silicon increase tensile and yield strength.

Phosphorus (P) – AWS restricts the level of phosphorus in a GMAW wire electrode, as it is generally undesirable to the weld deposit. It can contribute to weld cracking

Sulfur (S) – AWS restricts the level of sulfur in GMAW electrodes as it is generally undesirable for weldability and can contribute to weld cracking. However, in limited amounts, it improves fluidity and wetting.

Copper (Cu) – Copper is found in solid wire electrodes, however, the majority of the copper comes from the coating of the wire electrode (if copper-coated). AWS limits surface copper as well as total copper in the finished product. Benefits of copper coating include better conductivity, and therefore, better arc starts, and longer contact tip life.

Titanium (Ti) – Titanium is found in ER70S-2 mild steel GMAW wire electrode and is added as a deoxidizer. ER70S-2 GMAW electrodes are often referred to as "triple deoxidized" due to the addition of three other deoxidizers in addition to silicon and manganese. Some deoxidizers aid in removing both oxygen and nitrogen from the weld, reducing the occurrence of weld metal porosity.

Zirconium (Zr), Aluminum (Al), Nickel (Ni) – Zirconium, aluminum and nickel are found in ER70S-2 mild steel GMAW electrodes and are added as deoxidizers. ER70S-2 GMAW electrodes are often referred to as "triple deoxidized" due to the addition of 3 other deoxidizers in addition to silicon and manganese. Deoxidizers aid in removing oxygen and nitrogen from the weld, reducing the occurrence of weld metal porosity.

Molybdenum (Mo) – Molybdenum is also found in many low alloy GMAW wire electrodes. It is added for strength and improved impact properties, even when the weld is subject to stress relieving post-weld heat treatment.

Chromium (Cr) – Chromium is added to some low alloy GMAW wire electrodes for corrosion resistance. It is also a primary element found in stainless steel wire electrodes.

TABLE 5 — Chemical Composition Requirements for AWS A5.18 GMAW Carbon Solid Steel and Composite Electrodes

CHEMICAL COMPOSITION REQUIREMENTS

AWS Classification	%C	%Mn	%Si	%S	%P	%Cu	%Ti	%Zr	%Al
ER70S-2	0.07	0.90 - 1.40	0.40 - 0.70	0.025	0.035	0.50	0.05 - 0.15	0.02 - 0.12	0.05 - 0.15
ER70S-3	0.06 - 0.15	0.90 - 1.40	0.45 - 0.70	0.025	0.035	0.50	—	—	—
ER70S-4	0.07 - 0.15	1.00 - 1.50	0.65 - 0.85	0.025	0.035	0.50	—	—	—
ER70S-6	0.07 - 0.15	1.40 - 1.85	0.80 - 1.15	0.025	0.035	0.50	—	—	—
ER70S-7	0.07 - 0.15	1.50 - 2.00(1)	0.50 - 0.80	—	—	—	—	—	—
E70C-3X	0.12	1.75	0.90	0.03	0.03	0.50	—	—	—
E70C-6X	0.12	1.75	0.90	0.03	0.03	0.50	—	—	—

(1) Maximum Mn may exceed 2.0%. If it does, the maximum C must be reduced 0.01% for each 0.05% increase in Mn or part thereof.
(2) All solid electrode classifications have the following maximum requirements: Ni- 0.15, Cr- 0.15, Mo- 0.15, V- 0.03.
(3) All composite electrodes have the following maximum requirements: Ni- 0.50, Cr- 0.20, Mo- 0.30, V- 0.08.
(4) All composite electrode chemical compositions refer to weld metal compositions.

TABLE 6 — Chemical Composition Requirements for AWS A5.28 GMAW Low Alloy Solid Steel and Composite Electrodes

CHEMICAL COMPOSITION REQUIREMENTS

AWS Classification	%C	%Mn	%Si	%P	%S	%Ni	%Cr	%Mo	%V	%Ti	%Zr	%Al	%Cu	(1)
ER80S-Ni1	0.12	1.25	0.40-0.80	0.025	0.025	0.80-1.10	0.15	0.35	0.05	—	—	—	0.35	0.50
ER80S-D2,(2) **ER90S-D2**	0.07-0.12	1.60-2.10	0.50-0.80	0.025	0.025	0.15	—	0.40-0.60	—	—	—	—	0.50	0.50
ER100S-1	0.08	1.25-1.80	0.20-0.55	0.010	0.010	1.40-2.10	0.30	0.25-0.55	0.05	0.10	0.10	0.10	0.25	0.50
E90C-G, **E110C-G**	Not Specified	(In order to meet the requirements of the "G" classification the electrode must have a mimimum of one or more of the following: 0.50% Ni, 0.30% Cr, 0.20% Mo.)												

(1) Total of other elements. Other elements, if intentionally added, shall be reported.
(2) This composition was formerly classified E70S-1B in AWS Specification A5.18-69.

AWS Specifications for Manufacturing GMAW Wires

Keywords:

Cast
Helix
Heat or Lot

The American Welding Society has manufacturing specifications and acceptance standards for GMAW electrodes. In addition to chemical composition and mechanical property requirements, AWS also has specifications for:

- Method of manufacture
- Wire electrode diameter
- Electrode surface finish
- Packaging
- Winding requirements

Carbon steel wire electrode diameter tolerances are:

.045” (1.1 mm) and smaller diameters	±.001”
.052” (1.4 mm) diameter	±.002”
.062” (1.6 mm) diameter	±.002”

AWS specifies the surface finish of GMAW wire electrodes to be smooth, uniform, free of scratches, scales, and any depressions that could adversely affect the welding characteristics of the wire electrode and/or the properties of the deposited weld metal. Also, the wire on the spool (or other packaging) must be from one "heat" or "lot" of raw material. This helps to minimize changes in chemical composition within a spool.

There is also a specification on standard welding electrode packaging and the identification used on packaging. AWS identifies standard packaging for GMAW wire electrodes as coils with supports, coils without supports, spools and drums. Sizes and dimensions of these packages are specified to help manufacturers design equipment with wire holding devices that are appropriately sized. The next page shows various packages. Each package of wire electrode must have the appropriate product information easily identified along with the required warnings and precautionary information. Each spool, coil, reel or drum must be individually identified along with the outer packaging.

Finally, AWS specifies winding requirements for GMAW solid wire electrodes. Cast and helix are two key requirements. Figure 31 shows a graphic depiction of cast and helix in a GMAW wire electrode. To measure cast and helix, a sample of wire electrode should be taken from the spool large enough to form a loop when it is cut from the package, and then left unrestrained on the floor. Cast is essentially the diameter of the loop (if the shape is an oval, it is the largest diameter circle that will fit within the oval). AWS requires the cast to be not less than 15” for 0.035” (0.9 mm) and larger diameter electrodes and not less than 12” for 0.030” (0.8 mm) and smaller diameters on all spool packaging larger than a 4” spool, [1 lb. and 2 lb. (0.5 and 0.9 kg) spools]. Helix is the rise of the wire electrode off of a flat surface. AWS specifies that the helix be less than 1” (25 mm) at any location.

Specific bulk packages, such as Accu-Trak® and Accu-Pak® utilize a unique winding technique that elastically twists the wire to provide consistent twist-free "straight" wire. Wire from these packages will not form a loop when cut and therefore, standard cast and helix measurements can not take place. Individual manufacturers shall inspect this product to meet customer requirements.

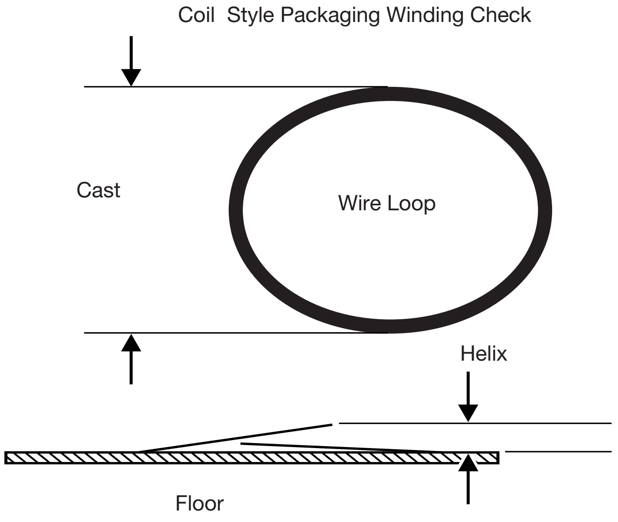


FIGURE 31: Cast and Helix in a GMAW Wire Electrode

GMAW Wire Package Selection Guidelines

When choosing a GMAW wire electrode for a welding application, there are many factors to consider, such as mechanical properties of the base material, chemistry of the base material, surface condition of the base material, and packaging requirements.

Once the mechanical properties and chemical makeup of the base material are known, it is fairly easy to choose a GMAW solid wire electrode. The tensile strength of the wire should, at minimum, match the tensile strength of the base material in order to get the full strength of the weld joint.

Alloyed base materials are generally higher strength steels and therefore not only are mechanical properties a consideration but also the chemistry of the electrode. Many of these requirements have already been discussed when defining each individual AWS classification of GMAW wire electrodes.

Package selection, however, can be based upon user preference, welding application, volume consumption, floor space and cost. The photo on page 39 shows a variety of GMAW solid wire packages from 2 lb. (0.9 kg) spools through 1000 lb. (450 kg) drums and reels. Lincoln Electric’s SuperArc® and SuperGlide® GMAW wire can be found in a full range of these packages to suit a wide variety of requirements.

A 2 lb. (0.9 kg) spool of solid GMAW wire electrode is a four inch diameter package that is generally used for self-contained small wire feed welders, such as Lincoln Electric’s SP-135T or in spool guns. They are generally used for occasional use for hobbyists, tack welding, or for applications where weld joints are restricted and the spool gun is the preferred option.

The next size spool is an eight inch diameter spool that holds ten lbs. (5 kg) through 12.5 lbs. (6 kg) of GMAW solid wire electrode. This package is also primarily used on self-contained wire feeder welders, but due to the increase in consumable weight, it has also found use in industrial applications. It is an excellent choice for use with the Lincoln's LN-15 across-the-arc portable wire feeder.

The most commonly used packaging of GMAW wire electrodes is the 12" (305 mm) spool that contains 30 lbs. (13.6 kg) through 44 lbs. (20 kg) of filler electrode. This packaging is used in a wide range of welding applications, but is usually confined to sheet metal or thin plate welding.

Most spool packages readily have a 2" (50 mm) inside diameter center hole for mounting on to a wire mounting platform. Other packages, such as the steel spool, features a basket which contains 30 lbs (14 kg) of filler electrode. It requires a permanent centering adapter for mounting the wire electrode basket.

A 14" (355 mm) inside diameter package generally referred to as a coil usually holds 60 lbs. (27 kg) of solid wire filler. It is found in higher productivity semiautomatic welding applications. This package requires a centering wire reel basket for mounting to a wire feeder. Coils of GMAW electrode are a good transition package from 30 lb. (14 kg) spools. They frequently lead to bulk packaged solid wire electrode such as speed feed reels, drums, or boxes. Request publication C4.10 for more information on SuperArc and SuperGlide premium GMAW wires.

CARBON AND LOW ALLOY PRODUCT SELECTION GUIDE

Carbon Steel		Low Alloy Steel	
AWS Classification	**Lincoln Product Name**	**AWS Classification**	**Lincoln Product Name**
ER70S-3	SuperArc® L-50 SuperGlide® S3	ER80S-Ni1	SuperArc LA-75
ER70S-4	SuperArc L-54	ER80S-D2 ER90S-D2	SuperArc LA-90
ER70S-6	SuperArc L-56 SuperGlide S6	ER100S-G ER110S-G	SuperArc LA-100
E70C-6M	Metalshield® MC-6 Metalshield MC-710XL Metalshield MC-715	E90C-G	Metalshield MC-900
		E110C-G	Metalshield MC-110

Request publication C4.10 for more information on SuperArc and SuperGlide premium GMAW electrode wires.

Lincoln's Premium GMAW Electrode Wire

GMAW of Stainless Steels

Stainless steels are defined as iron base alloys which contain at least 10.5% chromium. The thin but dense chromium oxide film which forms on the surface of a stainless steel provides corrosion resistance and prevents further oxidation. There are five types of stainless steels depending on the other alloying additions present, and they range from fully austenitic to fully ferritic types.

Type of Stainless Steels

Austenitic stainless steels include the 200 and 300 series of which type 304 is the most common. The primary alloying additions are chromium and nickel. **Ferritic stainless steels** are non-hardenable Fe-Cr alloys. Types 405, 409, 430, 422 and 446 are representative of this group. **Martensitic stainless steels** are similar in composition to the ferritic group but contain higher carbon and lower chromium to permit hardening by heat treatment. Types 403, 410, 416 and 420 are representative of this group. **Duplex stainless steels** are supplied with a microstructure of approximately equal amounts of ferrite and austenite. They contain roughly 24% chromium and 5% nickel. Their numbering system is not included in the 200, 300 or 400 groups. **Precipitation hardening stainless steels** contain alloying additions such as aluminum which allow them to be hardened by a solution and aging heat treatment. They are further classified into sub groups as martensitic, semiaustenitic and austenitic precipitation hardening stainless steels. They are identified as the 600-series of stainless steels (e.g., 630, 631, 660).

Special Alloying Elements

The alloying elements which appear in stainless steels are classed as **ferrite promoters** and **austenite promoters** and are listed below:

Ferrite Promoters

<u>Chromium</u> – provides basic corrosion resistance.

<u>Molybdenum</u> – provides high temperature strength and increases corrosion resistance.

<u>Niobium (Columbium), Titanium</u> – strong carbide formers.

Austenite Promoters

<u>Nickel</u> – provides high temperature strength and ductility.

<u>Carbon</u> – carbide former, strengthener.

<u>Nitrogen</u> – increases strength, reduces toughness.

Neutral Effect

Regarding Austenite & Ferrite.

<u>Manganese</u> – sulfide former.

<u>Silicon</u> – wetting agent.

<u>Sulfur and Selenium</u> – improve machinability, but may cause hot cracking in welds.

Weldability of Stainless Steels

Most stainless steels are considered to have good weldability and may be welded by several welding processes including the arc welding processes, resistance welding, electron and laser beam welding, friction welding and brazing. For any of these processes, joint surfaces and any filler metal must be clean.

The coefficient of thermal expansion for the austenitic types is 50% greater than that of carbon steel and this must be considered to minimize distortion. The low thermal and electrical conductivity of austenitic stainless steel is generally helpful. Less welding heat is required to make a weld because the heat is not conducted away from a joint as rapidly as in carbon steel. In resistance welding, lower current can be used because resistivity is higher. Stainless steels which require special welding procedures are discussed in later sections.

Ferritic Stainless Steels

The ferritic stainless steels contain 10.5 to 30% Cr, up to 0.20% C and sometimes ferrite promoters Al, Nb (Cb), Ti and Mo. They are ferritic at all temperatures and, therefore, do not transform to austenite and are not hardenable by heat treatment. This group includes the more common types 405, 409, 430, 442 and 446. Table 7 lists the nominal composition of a number of standard and several non-standard ferritic stainless steels. They are characterized by weld and heat affected zoned (HAZ) grain growth which can result in low toughness of welds.

To weld the ferritic stainless steels, filler metals should be used which match or exceed the chromium level of the base alloy. Type 409 is available as metal cored wire and Type 430 is available in all forms. Austenitic Types 309 and 312 may be used for dissimilar joints. To minimize grain growth, weld heat input should be minimized, preheat should be limited to 300 - 450°F (149 - 232°C) and used only for the higher carbon ferritic stainless steels (e.g., 430, 434, 442 and 446). Many of the highly alloyed ferritic stainless steels are only available in sheet and tube forms and are usually welded by GTAW (Gas Tungsten Arc Welding) or TIG welding without filler metal.

Martensitic Stainless Steels

The martensitic stainless steels contain 11 to 18% Cr, up to 1.20% C and small amounts of Mn and Ni and, sometimes, Mo. These steels will transform to austenite on heating and, therefore, can be hardened by formation of martensite on cooling. This group includes Types 403, 410, 414, 416, 420, 422, 431 and 440. Both standard and non-standard martensitic stainless steels are listed in Table 8. They have a tendency toward weld cracking on cooling when hard brittle martensite is formed.

Chromium and carbon content of the filler metal should generally match these elements in the base metal. Type 410 filler is available as covered electrode, solid wire and cored wire and can be used to weld types 402, 410, 414 and 420 steels. Type 410 NiMo filler metal can also be used. When it is necessary to match the carbon in Type 420 steel, Type 420 filler, which is available as solid wire and cored wire, should be used. Types 308, 309 and 310 austenitic filler metals can be used to weld the martensitic steels to themselves or to other steels where as-deposited toughness is required.

Preheating and interpass temperatures in the 400 - 600°F (204 - 316°C) range is recommended for most martensitic stainless steels. Steels with over 0.20% carbon often require a post weld heat treatment to soften and toughen the weld.

TABLE 7 — Nominal Compositions of Ferritic Stainless Steels

NOMINAL COMPOSITIONS

	UNS	Composition - Percent *							
Type	**Number**	**C**	**Mn**	**Si**	**Cr**	**Ni**	**P**	**S**	**Other**
405	S40500	0.08	1.00	1.00	11.5-14.5		0.04	0.03	0.10-0.30 Al
409	S40900	0.08	1.00	1.00	10.5-11.75		0.045	0.045	6 x %C min. TI
429	S42900	0.12	1.00	1.00	14.0-16.0		0.04	0.03	
430	S43000	0.12	1.00	1.00	16.0-18.0		0.04	0.03	
430F**	S43020	0.12	1.25	1.00	16.0-18.0		0.06	0.15 min.	0.06 Mo
430FSe**	S43023	0.12	1.25	1.00	16.0-18.0		0.06	0.06	0.15 min. Se
430Ti	S43036	0.10	1.00	1.00	16.0-19.5	0.75	0.04	0.03	5 x %C - Ti min.
434	S43400	0.12	1.00	1.00	16.0-18.0		0.04	0.03	0.75-1.25 Mo
436	S43600	0.12	1.00	1.00	16.0-18.0		0.04	0.03	0.75-1.25 Mo; 5 x %C min. Nb(Cb) + Ta
442	S44200	0.20	1.00	1.00	18.0-23.0		0.04	0.03	
444	S44400	0.025	1.00	1.00	17.5-19.5	1.00	0.04	0.03	1.75-2.5 Mo, 0.035 N 0.2 + 4 (%C + %N); (Ti +Nb(Cb))
446	S44600	0.20	1.50	1.00	23.0-27.0		0.04	0.03	0.25 N
18-2FM**	S18200	0.08	2.50	1.00	17.5-19.5		0.04	0.15 min.	
18SR		0.04	0.3	1.00	18.0				2.0 Al; 0.4 Ti
26-1 (E-Brite)	S44625	0.01	0.40	0.40	25.0-27.5	0.50	0.02	0.02	0.75-1.5 Mo; 0.015N; 0.2 Cu; 0.5 (Ni+Cu)
26-1Ti	S44626	0.06	0.75	0.75	25.0-27.0	0.5	0.04	0.02	0.75-1.5 Mo; 0.04 N; 0.2 Cu; 0.2-1.0 Ti
29-4	S44700	0.01	0.30	0.20	28.0-30.0	0.15	0.025	0.02	3.5-4.2 Mo
29-4-2	S44800	0.01	0.30	0.20	28.0-30.0	2.0-2.5	0.025	0.02	3.5-4.2 Mo
Monit	S44635	0.25	1.00	0.75	24.5-26.0	3.5-4.5	0.04	0.03	3.5-4.5 Mo; 0.3-0.6 (Ti + Nb(Cb))
Sea-cure/ Sc-1	S44660	0.025	1.00	0.75	25.0-27.0	1.5-3.5	0.04	0.03	2.5-3.5 Mo; 0.2 + 4 (%C + %N) (Ti + Nb(Cb))

*Single values are maximum values.

**These grades are generally considered to be unweldable.

(From *ASM Metals Handbook*, Ninth Edition, Volume 3)

TABLE 8 — Nominal Compositions of Martensitic Stainless Steels

NOMINAL COMPOSITIONS

	UNS	Composition - Percent *							
Type	**Number**	**C**	**Mn**	**Si**	**Cr**	**Ni**	**P**	**S**	**Other**
403	S40300	0.15	1.00	0.50	11.5-13.0		0.04	0.03	
410	S41000	0.15	1.00	1.00	11.5-13.0		0.04	0.03	
410Cb	S41040	0.18	1.00	1.00	11.5-13.5		0.04	0.03	0.05-0.3 Nb(Cb)
410S	S41008	0.08	1.00	1.00	11.5-13.5	0.6	0.04	0.03	
414	S41400	0.15	1.00	1.00	11.5-13.5	1.25-2.50	0.04	0.03	
414L		0.06	0.50	0.15	12.5-13.0	2.5-3.0	0.04	0.03	0.5 Mo; 0.03 Al
416	S41600	0.15	1.25	1.00	12.0-14.0		0.04	0.03	0.6 Mo
416Se**	S41623	0.15	1.25	1.00	12.0-14.0		0.06	0.06	0.15 min. Se
416 Plus X**	S41610	0.15	1.5-2.5	1.00	12.0-14.0		0.06	0.15 min.	0.6 Mo
420	S42000	0.15 min.	1.00	1.00	12.0-14.0		0.04	0.03	
420F**	S42020	0.15 min.	1.25	1.00	12.0-14.0		0.06	0.15 min.	0.6 Mo
422	S42200	0.20-0.25	1.00	0.75	11.0-13.0	0.5-1.0	0.025	0.025	0.75-1.25 Mo; 0.75-1.25 W; 0.15-0.3 V
431	S43100	0.20	1.00	1.00	15.0-17.0	1.25-2.50	0.04	0.03	
440A	S44002	0.60-0.75	1.00	1.00	16.0-18.0		0.04	0.03	0.75 Mo
440B	S44003	0.75-0.95	1.00	1.00	16.0-18.0		0.04	0.03	0.75 Mo
440C	S44004	0.95-1.20	1.00	1.00	16.0-18.0		0.04	0.03	0.75 Mo

*Single values are maximum values.

**These grades are generally considered to be unweldable.

(From *ASM Metals Handbook*, Ninth Edition, Volume 3)

Austenitic Stainless Steels

The austenitic stainless steels contain 16 - 26% Cr, 8 - 24% Ni + Mn, up to 0.40% C and small amounts of a few other elements such as Mo, Ti, Nb (Cb) and Ta. The balance between the Cr and Ni + Mn is normally adjusted to provide a microstructure of 90 - 100% austenite. These alloys are characterized by good strength and high toughness over a wide temperature range and oxidation resistance to over 1000°F (538°C). This group includes Types 302, 304, 310, 316, 321 and 347. Nominal composition of these and other austenitic stainless steels are listed in Table 9. Filler metals for these alloys should generally match the base metal but for most alloys, provide a microstructure with some ferrite to avoid hot cracking as will be discussed further. To achieve this, Type 308 is used for Type 302 and 304 and Type 347 for Type 321. The others should be welded with matching filler. Type 347 can also be welded with Type 308H filler. These filler materials are available as coated electrodes, solid bare wire and cored wire. Type 321 is available on a limited basis as solid and cored wire.

TABLE 9 — Nominal Compositions of Austenitic Stainless Steels

NOMINAL COMPOSITIONS

Type	UNS Number	Composition - Percent *							Other
		C	Mn	Si	Cr	Ni	P	S	
201	S20100	0.15	5.5-7.5	1.00	16.0-18.0	3.5-5.5	0.06	0.03	0.25 N
202	S20200	0.15	7.5-10.0	1.00	17.0-19.0	4.0-6.0	0.06	0.03	0.25 N
205	S20500	0.12-0.25	14.0-15.5	1.00	16.5-18.0	1.0-1.75	0.06	0.03	0.32-0.40 N
216	S21600	0.08	7.5-9.0	1.00	17.5-22.0	5.0-7.0	0.045	0.03	2.0-3.0 Mo; 0.25-0.5 N
301	S30100	0.15	2.00	1.00	16.0-18.0	6.0-8.0	0.045	0.03	
302	S30200	0.15	2.00	1.00	17.0-19.0	8.0-10.0	0.045	0.03	
302B	S30215	0.15	2.00	2.0-3.0	17.0-19.0	8.0-10.0	0.045	0.03	
303**	S30300	0.15	2.00	1.00	17.0-19.0	8.0-10.0	0.20	0.15 min.	0.6 Mo
303Se**	S30323	0.15	2.00	1.00	17.0-19.0	8.0-10.0	0.20	0.06	0.15 min. Se
304	S30400	0.08	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	
304H	S30409	0.04-0.10	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	
304L	S30403	0.03	2.00	1.00	18.0-20.0	8.0-12.0	0.045	0.03	
304LN	S30453	0.03	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	0.10-0.15 N
S30430	S30430	0.08	2.00	1.00	17.0-19.0	8.0-10.0	0.045	0.03	3.0-4.0 Cu
304N	S30451	0.08	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	0.10-0.16 N
304HN	S30452	0.04-0.10	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	0.10-0.16 N
305	S30500	0.12	2.00	1.00	17.0-19.0	10.5-13.0	0.045	0.03	
308	S30800	0.08	2.00	1.00	19.0-21.0	10.0-12.0	0.045	0.03	
308L		0.03	2.00	1.00	19.0-21.0	10.0-12.0	0.045	0.03	
309	S30900	0.20	2.00	1.00	22.0-24.0	12.0-15.0	0.045	0.03	
309S	S30908	0.08	2.00	1.00	22.0-24.0	12.0-15.0	0.045	0.03	
309S Cb	S30940	0.08	2.00	1.00	22.0-24.0	12.0-15.0	0.045	0.03	8 x %C - Nb(Cb)
309 Cb + Ta		0.08	2.00	1.00	22.0-24.0	12.0-15.0	0.045	0.03	8 x %C (Nb(Cb) + Ta)
310	S31000	0.25	2.00	1.50	24.0-26.0	19.0-22.0	0.045	0.03	
310S	S31008	0.08	2.00	1.50	24.0-26.0	19.0-22.0	0.045	0.03	
312		0.15	2.00	1.00	30.0 nom.	9.0 nom.	0.045	0.03	
254SMo	S31254	0.020	1.00	0.80	19.5-20.5	17.50-18.5	0.03	0.010	6.00-6.50Mo; 0.18-0.22N; Cu=0.5-1.00
314	S31400	0.25	2.00	1.5-3.0	23.0-26.0	19.0-22.0	0.045	0.03	
316	S31600	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
316F**	S31620	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.20	0.10 min.	1.75-2.5 Mo
316H	S31609	0.04-0.10	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
316L	S31603	0.03	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
316LN	S31653	0.03	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo; 0.10-0.30 N
316N	S31651	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo; 0.10-0.16 N
317	S31700	0.08	2.00	1.00	18.0-20.0	11.0-15.0	0.045	0.03	3.0-4.0 Mo
317L	S31703	0.03	2.00	1.00	18.0-20.0	11.0-15.0	0.045	0.03	3.0-4.0 Mo
317M	S31725	0.03	2.00	1.00	18.0-20.0	12.0-16.0	0.045	0.03	4.0-5.0 Mo
321	S32100	0.08	2.00	1.00	17.0-19.0	9.0-12.0	0.045	0.03	5 x %C min. Ti
321H	S32109	0.04-0.10	2.00	1.00	17.0-19.0	9.0-12.0	0.045	0.03	5 x %C min. Ti
329	S32900	0.10	2.00	1.00	25.0-30.0	3.0-6.0	0.045	0.03	1.0-2.0 Mo
330	N08330	0.08	2.00	0.75-1.5	17.0-20.0	34.0-37.0	0.04	0.03	
AL6-XN	N80367	0.030	2.00	1.00	20.0-22.0	23.5-25.5	0.04	0.03	6.00-7.00Mo; 0.18-0.25N; Cu=0.75
330HC		0.40	1.50	1.25	19.0 nom.	35.0 nom.			
332		0.04	1.00	0.50	21.5 nom.	32.0 nom.	0.045	0.03	
347	S34700	0.08	2.00	1.00	17.0-19.0	9.0-13.0	0.045	0.03	10 x %C min. Nb(Cb) +Ta
347H	S34709	0.04-0.10	2.00	1.00	17.0-19.0	9.0-13.0	0.045	0.03	10 x %C min. Nb(Cb) + Ta
348	S34800	0.08	2.00	1.00	17.0-19.0	9.0-13.0	0.045	0.03	0.2 Cu; 10 x %C min. Nb(Cb) + Ta(c)
348H	S34809	0.04-0.10	2.00	1.00	17.0-19.0	9.0-13.0	0.045	0.03	0.2 Cu; 10 x %C min. Nb(Cb) + Ta
384	S38400	0.08	2.00	1.00	15.0-17.0	17.0-19.0	0.045	0.03	
Nitronic 32	S24100	0.10	12.0	0.50	18.0	1.6			0.35 N
Nitronic 33	S24000	0.06	13.0	0.5	18.0	3.0			0.30 N
Nitronic 40	S21900	0.08	8.0-10.0	1.00	18.0-20.0	5.0-7.0	0.06	0.03	0.15-0.40 N
Nitronic 50	S20910	0.06	4.0-6.0	1.00	20.5-23.5	11.5-13.5	0.04	0.03	1.5-3.0 Mo; 0.2-0.4 N; 0.1-0.3 Cb; 0.1-0.3 V
Nitronic 60	S21800	0.10	7.0-9.0	3.5-4.5	16.0-18.0	8.0-9.0	0.04	0.03	1.5-3.0 Mo; 0.2-0.4 N;

* Single values are maximum. ** These values are general considered to be unweldable.
Information from AWS Metals Handbook, Ninth Edition, Volume 3

Sensitization

Two problems are associated with welds in the austenitic stainless steels: 1) sensitization of the weld heat affected zone, and 2) hot cracking of weld metal.

Sensitization leads to intergranular corrosion in the heat affected zone as shown in Figure 32. Sensitization is caused by chromium carbide formation and precipitation at grain boundaries in the heat affected zone when heated in the 800 - 1600°F (427 - 871°C) temperature range. Since most carbon is found near grain boundaries, chromium carbide formation removes some chromium from solution near the grain boundaries, thereby reducing the corrosion resistance of these local areas. This problem can be remedied by using low carbon base material and filler material to reduce the amount of carbon available to combine with chromium. Welds should be made without preheat and with minimum heat input to shorten the time in the sensitization temperature range.

The degree of carbide precipitation increases with:

1. Higher carbon content (for example, because 301 and 302 grades have a maximum carbon content of 0.15% they are more susceptible to carbon precipitation than grade 304 which has a maximum carbon content of only 0.08%).

2. Time at the critical mid-range temperatures – a few seconds at 1200°F (649°C) can do more damage than several minutes at 850°F (454°C) or 1450°F (788°C).

Welding naturally produces a temperature gradient in the steel. It ranges from melting temperature at the weld to room temperature some distance from the weld. A narrow zone on each side of the weld remains in the sensitizing temperature range for sufficient time for precipitation to occur. If used in severely corrosive conditions, lines of damaging corrosion appear alongside each weld.

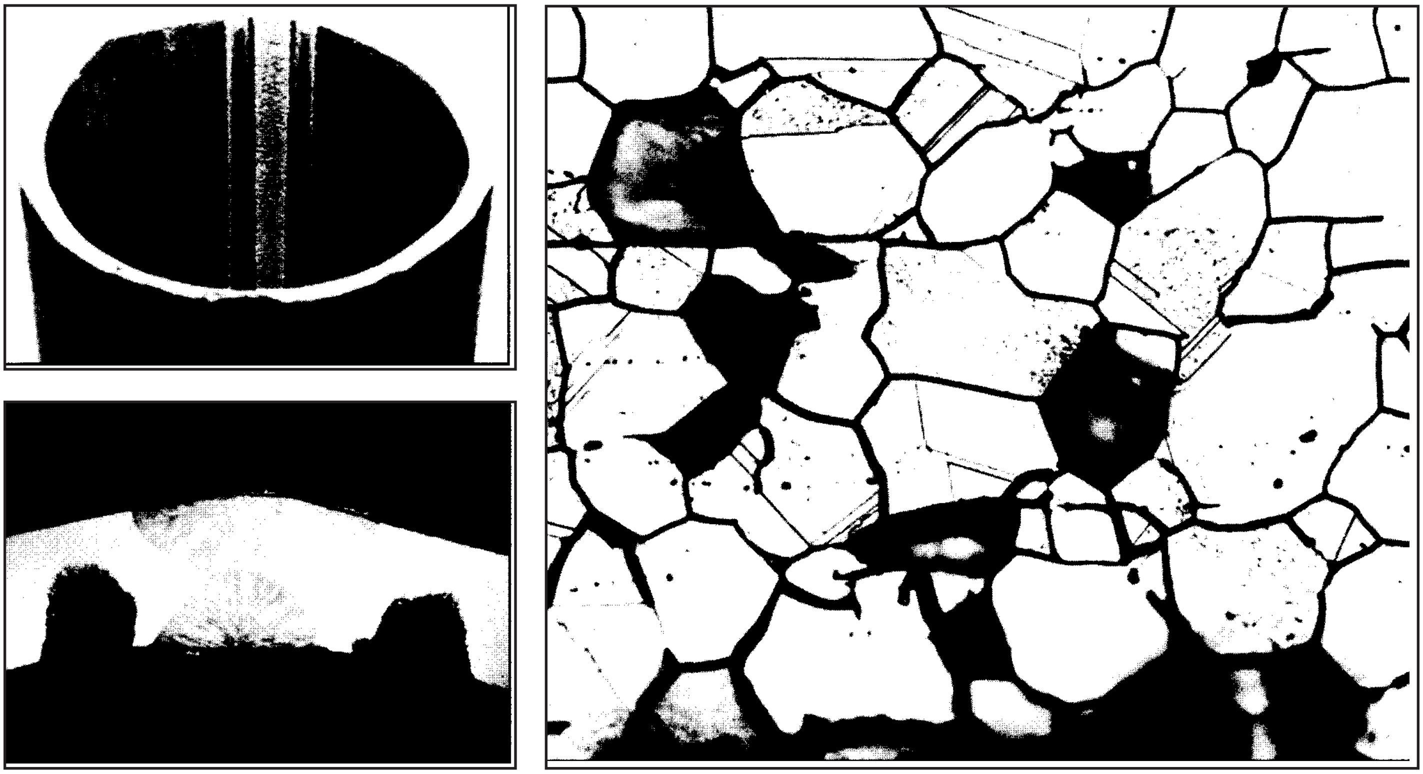


FIGURE 32: Intergranular Corrosion in the Heat Affected Zone

Control of Carbide Precipitation

The amount of carbide precipitation is reduced by promoting rapid cooling. Fortunately, copper chill bars, skip welding and other techniques needed to control distortion in sheet metal help reduce carbide precipitation. Annealing the weldment at 1900°F (1038°C) or higher, followed by water quench, eliminates carbide precipitation, but this is an expensive and often impractical procedure. Therefore, when weldments operate in severe corrosive applications or within the sensitizing temperature range, either ELC (extra low carbon) or stabilized grades are needed.

ELC – Extra Low Carbon – Grades (304L, 308L)

The 0.04% maximum carbon content of ELC grades helps eliminate damaging carbide precipitation caused by welding. These grades are most often used for weldments which operate in severe corrosive conditions at temperatures under 800°F (427°C).

ELC steels are generally welded with ELC electrode, e.g., AWS E308L-XX. Although the stabilized electrodes AWS E347-XX produce welds of equal resistance to carbide precipitation and similar mechanical properties, the ELC electrode welds tend to be less crack sensitive on heavy sections and have better low temperature notch toughness.

The low carbon content in ELC grades leaves more chromium to provide resistance to intergranular corrosion.

Stabilized Grades (321, 347, 348)
Another remedy is to use stabilized stainless steel base metal and filler materials which contain elements that will react with carbon, leaving all the chromium in solution to provide corrosion resistance. Stabilized grades contain small amounts of titanium (321), niobium (columbium) (347), or a combination of niobium and tantalum (347, 348). These elements have a stronger affinity for carbon then does chromium, so they combine with the carbon leaving the chromium to provide corrosion resistance.

These grades are most often used in severe corrosive conditions when service temperatures reach the sensitizing range. They are welded with the niobium stabilized electrodes, i.e., AWS E347-XX.

Type 321 electrodes are not generally made because titanium is lost in the arc. AWS E347-XX is usually quite satisfactory for joining type 321 base metal.

Molybdenum Grades (316, 316L, 317, 317L, D319)
Molybdenum in stainless steel increases the localized corrosion resistance to many chemicals. These steels are particularly effective in combatting pitting corrosion. Their most frequent use is in industrial processing equipment. Types 316 and 316L are welded with AWS E316L-XX electrodes.

The 316L and 317L are ELC grades that must be welded with ELC type electrodes to maintain resistance to carbide precipitation. Both 317 and 317L are generally welded with E317 or E317L electrodes respectively. They can be welded with AWS E316-XX electrode, but the welds are slightly lower in molybdenum content than the base metal with a corresponding lower corrosion resistance.

When hot oxidizing acids are encountered in service, E316, E316L, E317 or E317L welds may have poor corrosion resistance in the as-welded condition. In such cases, E309 or E309Cb electrodes may be better. As an alternative, the following heat treatment will restore corrosion resistance to the weld:

1. For 316 or 317 – full anneal at 1950 - 2050°F (1066 - 1121°C).
2. For 316L and 317L – stress relieve at 1600°F (871°C).

High Temperature Grades (302B, 304H, 309, 309S, 310, 310S)
These high alloy grades maintain strength at high temperatures and have good scaling resistance. They are primarily used in industrial equipment at high service temperatures – sometimes over 2000°F (1093°C).

AWS E310-XX electrodes are needed to match the high temperature properties and scaling resistance of grades 310 and 310S.

Both 302B and 309 grades are generally welded with E309-XX electrodes. 304H is generally welded with E308H-XX electrodes. E310-XX electrodes can be used on light plate. E310-XX welds on heavy plate tend to be more crack sensitive than E309-XX weld metals.

Free Machining Grades (303, 303Se)
Production welding of these grades **is not recommended** because the sulfur or selenium and phosphorus cause severe porosity and hot short cracking. If welding is necessary, special E312-XX or E309-XX electrodes are recommended because their high ferrite reduces cracking tendencies. Use techniques that reduce admixture of base metal into the weld metal and produce convex bead shapes.

Hot Cracking

Hot cracking is caused by low melting materials such as metallic compounds of sulfur and phosphorous which tend to penetrate grain boundaries. When these compounds are present in the weld or heat affected zone, they will penetrate grain boundaries and cracks will appear as the weld cools and shrinkage stress develops.

Hot cracking can be prevented by adjusting the composition of the base material and filler material to obtain a microstructure with a small amount of ferrite in the austenite matrix. The ferrite provides ferrite-austenite grain boundaries which are able to control the sulfur and phosphorous compounds so they do not permit hot cracking. This problem could be avoided by reducing the sulfur and phosphorus to very low amounts, but this would increase significantly the cost of making the steel.

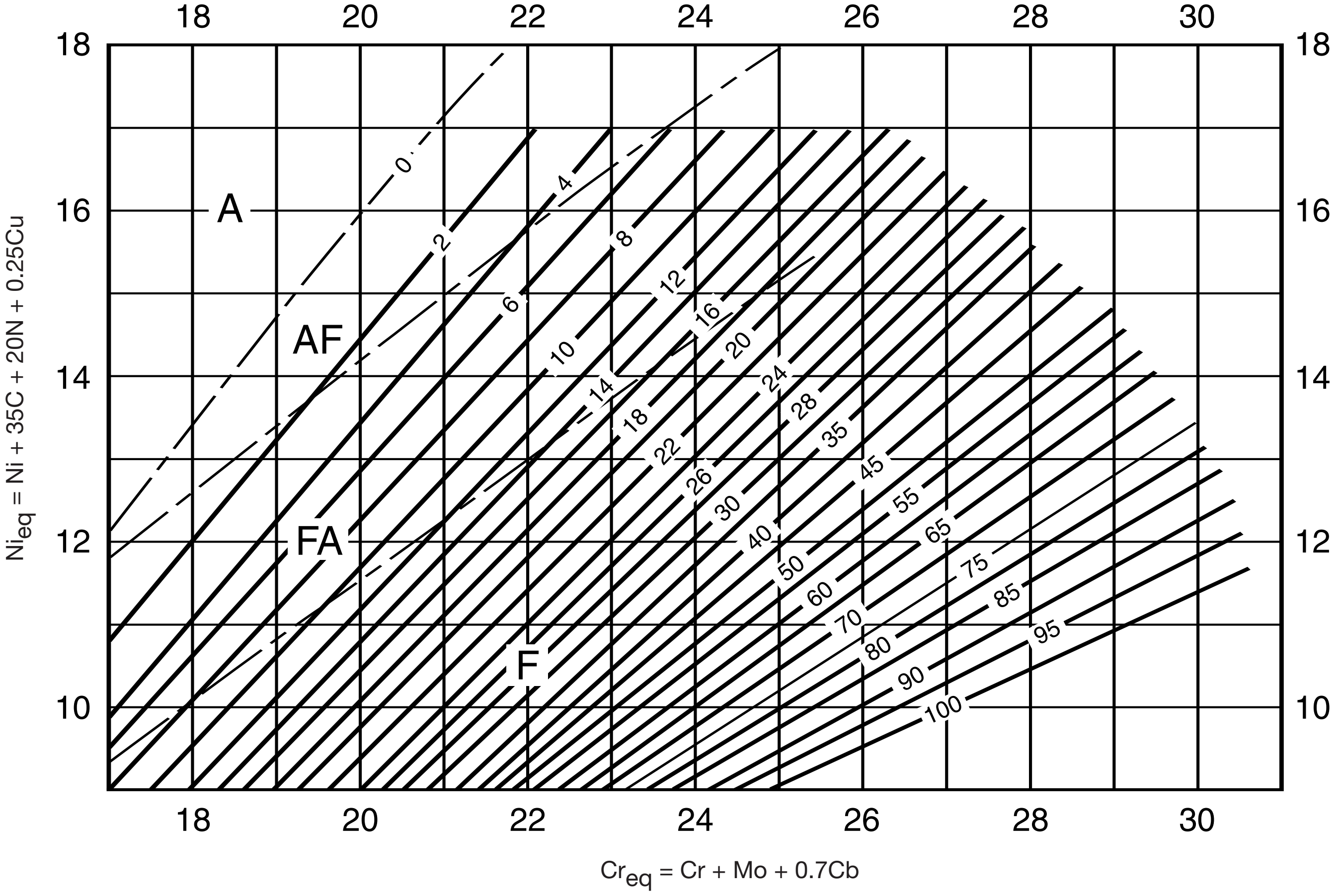
Normally, a ferrite level of 4 FN minimum is recommended to avoid hot cracking. Ferrite is best determined by measurement with a magnetic instrument calibrated to AWS A4.2 or ISO 8249. It can also be estimated from the composition of the base material and filler material with the use of any of several constitution diagrams. The oldest of these is the 1948 Schaeffler Diagram. The Cr equivalent (%Cr + %Mo + 1.5 x % Si + 0.5 x %Cb) is plotted on the horizontal axis and the nickel equivalent (%Ni + 30 x %C + 0.5 x %Mn) on the vertical axis. Despite long use, the Schaeffler Diagram is now outdated because it does not consider nitrogen effects and because it has not proven possible to establish agreement among several measurers as to the ferrite percent in a given weld metal.

An improvement on the Schaeffler Diagram is the 1973 WRC-DeLong Diagram, which can be used to estimate ferrite level. The main differences are that the DeLong Diagram includes nitrogen (N) in the Ni equivalent (%Ni + 30 x %C x 30 x %N + 0.5 x %Mn) and shows Ferrite Numbers in addition to "percent ferrite." Ferrite Numbers at low levels may approximate "percent ferrite." The most recent diagram, the WRC-1992 Diagram, Figure 33 on page 45, is considered to be the most accurate predicting diagram at present. The WRC-1992 Diagram has replaced the WRC-DeLong Diagram in the ASME Code with publication of the 1994-95 Winter Addendum. Its Ni equivalent (%Ni + 35 x %C + 20 x %N + 0.25 Cu) and chromium equivalent (%Cr + %Mo + 0.7 x %Cb) differ from those of Schaeffler and WRC-DeLong.

Ferrite Number may be estimated by drawing a horizontal line across the diagram from the nickel equivalent number and a vertical line from the chromium equivalent number. The Ferrite Number is indicated by the diagonal line which passes through the intersection of the horizontal and vertical lines.

FIGURE 33 — New 1992 WRC diagram including solidification mode boundaries.

Updated from T.A. Siewert, C.N. McCowan and D.L. Olson – Welding Journal, December 1988 by D.J. Kotecki and T.A. Siewert - Welding Journal, May 1992.



Predictions by the WRC-1992 and WRC-DeLong diagrams for common grades like 308 are similar, but the WRC-1992 diagram generally is more accurate for higher alloy and less common grades like high manganese austenitic or duplex ferritic-austenitic stainless steels.

Ferrite Number can be measured directly on weld deposits from the magnetic properties of the ferrite. Several instruments are available commercially, including the Magnet Gage, the Severn Gage, the Inspector Gage and the Ferritescope which can be calibrated to AWS A4.2 or ISO 8249 and provide readings in Ferrite Number.

The amount of ferrite normally should not be greater than necessary to prevent hot cracking with some margin of safety. The presence of ferrite can reduce corrosion resistance in certain media and excess ferrite can impair ductility and toughness.

Precipitation Hardening Stainless Steels

There are three categories of precipitation hardening stainless steels – martensitic, semiaustenitic and austenitic.

The martensitic stainless steels can be hardened by quenching from the austenitizing temperature [around 1900°F (1038°C)] then aging between 900 - 1150°F (482 - 621°C). Since these steels contain less than 0.07% carbon, the martensite is not very hard and the main hardening is obtained from the aging (precipitation) reaction. Examples of this group are 17-4PH, 15-5PH and PH13-8Mo. Nominal compositions of precipitation hardening stainless steels are listed in Table 10.

The semiaustenitic stainless steels will not transform to martensite when cooled from the austenitizing temperature because the martensite transformation temperature is below room temperature. These steels must be given a conditioning treatment which consists of heating in the range of 1350 to 1750°F (732 to 954°C) to precipitate carbon and/or alloy elements as carbides or intermetallic compounds. This removes alloy elements from solution, thereby destabilizing the austenite, which raises the martensite transformation temperature so that a martensite structure will be obtained on cooling to room temperature. Aging the steel between 850 - 1100°F (454 - 593°C) will stress relieve and temper the martensite to increase toughness, ductility, hardness and corrosion resistance. Examples of this group are 17-7PH, PH 15-7 Mo and AM 350.

The austenitic precipitation hardening stainless steels remain austenitic after quenching from the solutioning temperature even after substantial amounts of cold work. They are hardened only by the aging reaction. This would include solution treating between 1800 and 2050°F (982 to 1121°C), oil or water quenching and aging at 1300 to 1350°F (704 to 732°C) for up to 24 hours. Examples of these steels include A286 and 17-10P.

If maximum strength is required in martensitic and semi-austenitic precipitation hardening stainless steels, matching or nearly matching filler metal should be used and the component, before welding, should be in the annealed or solution annealed condition. Often, Type 630 filler metal, which is nearly identical with 17-4PH base metal, is used for martensitic and semi-austenitic PH stainlesses. After welding, a complete solution heat treatment plus an aging treatment is preferred. If the post weld solution treatment is not feasible, the components should be solution treated before welding then aged after welding. Thick sections of highly restrained parts are sometimes welded in the overaged condition. These would require a full heat treatment after welding to attain maximum strength.

The austenitic precipitation hardening stainless steels are the most difficult to weld because of hot cracking. Welding should preferably be done with the parts in the solution treated condition, under minimum restraint and with minimum heat input. Nickel base alloy filler metals of the NiCrFe type or conventional austenitic stainless steel type are often preferred.

TABLE 10 — Nominal Compositions of Precipitation Hardening and Duplex Stainless Steels

NOMINAL COMPOSITIONS

Type	UNS Number	Composition - Percent *							ASTM A GRADE	Other
		C	Mn	Si	Cr	Ni	P	S		
Precipitation-Hardening Types										
PH 13-8 Mo	S13800	0.05	0.10	0.10	12.25-13.25	7.5-8.5	0.01	0.008		2.0-2.5 Mo; 0.90-1.35 Al; 0.01 N
15-5 PH	S15500	0.07	1.00	1.00	14.0-15.5	3.5-5.5	0.04	0.03		2.5-4.5 Cu; 0.15-0.45 Nb(Cb) + Ta
17-4 PH	S17400	0.07	1.00	1.00	15.5-17.5	3.0-5.0	0.04	0.03	630	3.0-5.0 Cu; 0.15-0.45 Nb(Cb) + Ta
17-7 PH	S17700	0.09	1.00	1.00	16.0-18.0	6.5-7.75	0.04	0.03	631	0.75-1.15 Al
PH 15-7 Mo	S15700	0.09	1.00	1.00	14.0-16.0	6.5-7.75	0.04	0.03		2.0-3.0 Mo; 0.75-1.5 Al
17-10 P		0.07	0.75	0.50	17.0	10.5	0.28			
A286	S66286	0.08	2.00	1.00	13.5-16.0	24.0-27.0	0.040	0.030	660	1.0-1.5 Mo; 2 Ti; 0.3 V
AM350	S35000	0.07-0.11	0.5-1.25	0.50	16.0-17.0	4.0-5.0	0.04	0.03		2.5-3.25 Mo; 0.07-0.13 N
AM355	S35500	0.10-0.15	0.5-1.25	0.50	15.0-16.0	4.0-5.0	0.04	0.03		2.5-3.25 Mo
AM363		0.04	0.15	0.05	11.0	4.0				0.25 Ti
Custom 450	S45000	0.05	1.00	1.00	14.0-16.0	5.0-7.0	0.03	0.03		1.25-1.75 Cu; 0.5-1.0 Mo 8 x %C - Nb(Cb)
Custom 455	S45500	0.05	0.50	0.50	11.0-12.5	7.5-9.5	0.04	0.03		0.5 Mo; 1.5-2.5 Cu; 0.8-1.4 Ti; 0.1-0.5 Nb(Cb)
Stainless W	S17600	0.08	1.00	1.00	16.0-17.5	6.0-7.5	0.04	0.03		0.4 Al; 0.4-1.2 Ti
Duplex Types										
2205	S32205	0.03	2.0	1.0	22.0	5.5	0.03	0.02		3.0 Mo; 0.18 N
2304	S32304	0.03	2.5	1.0	23.0	4.0				0.1 N
255		0.04	1.5	1.0	25.5	5.5				3.0 Mo; 0.17 N; 2.0 Cu
NU744LN		0.067	1.7	0.44	21.6	4.9				2.4 Mo; 0.10 N; 0.2 Cu
2507	S32750	0.03	1.2	0.8	25	5.5	0.035	0.020		4 Mo; 0.28 N

*Single values are maximum values.

(From *ASM Metals Handbook*, Ninth Edition, Volume 3) and ASTM A638

Duplex Stainless Steels

Duplex Ferritic – Austenitic Stainless Steels

Duplex stainless steels solidify as 100% ferrite, but about half of the ferrite transforms to austenite during cooling through temperatures above approximately 1900°F (1040°C). This behavior is accomplished by increasing chromium and decreasing nickel as compared to austenitic grades. Nitrogen is deliberately added to speed up the rate of austenite formation during cooling. Duplex stainless steels are ferromagnetic. They combine both the higher strength and fabrication properties of austenitics with the resistance to chloride stress corrosion cracking of ferritic stainless steels. The most common grade is 2205 (UNS S32205), consisting of 22%Cr, 5%Ni, 3%Mo and 0.15% N.

Physical Properties

Average physical properties for each of the main groups of stainless steel are listed in Table 11. This includes elastic modulus, density, coefficient of thermal expansion, thermal conductivity, specific heat, electrical resistivity, magnetic permeability and melting range. These values should be close enough for most engineering purposes. If more precise data is required for a particular type of stainless steel, it can be found in the *ASM Metals Handbook*, Ninth Edition, Volume 3.

Mechanical Properties

Nominal mechanical properties of ferritic and austenitic stainless steels in the annealed condition are listed in Table 12 and Table 13 respectively. The austenitic stainless steels generally have higher tensile strengths and elongation than the ferritic stainless steels but lower yield strengths. Reduction in area is about the same for both groups. Nominal mechanical properties of martensitic stainless steels in both the annealed and tempered condition are listed in Table 14. The tempered condition involves heating to austenitize, cooling to form martensite and reheating to the indicated temperature to increase toughness. Table 15 lists the mechanical properties of the precipitation hardening stainless steels as solution annealed and after aging treatments at the temperature indicated. Properties of three duplex stainless steels are included.

TABLE 11 — Physical Properties of Groups of Stainless Steels

NOMINAL PHYSICAL PROPERTIES

Property	Austenitic Types	Ferritic Types	Martensitic Types	Precipitation Hardening Types
Elastic Modulus; 10^6 psi	28.3	29.0	29.0	29.0
GPa	195	200	200	200
Density; lb./in.^{3}	0.29	0.28	0.28	0.28
g/cm^3	8.0	7.8	7.8	7.8
Coefficiency of Thermal Expansion: µin./in. °F	9.2	5.8	5.7	6.0
µm/m °C	16.6	10.4	10.3	10.8
Thermal Conduct.; Btu/hrft. °F	9.1	14.5	14.0	12.9
w/mk	15.7	25.1	24.2	22.3
Specific Heat; Btu/lb. °F	0.12	0.11	0.11	0.11
J/k °K	500	460	460	460
Electrical Resistivity, µΩcm	74	61	61	80
Magnetic Permeability	1.02	600-1,100	700-1000	95
Melting Range °F	2,500-2,650	2,600-2,790	2,600-2,790	2,560-2,625
°C	1,375-1,450	1,425-1,530	1,425-1,530	1,400-1,440

TABLE 12 — Nominal Mechanical Properties of Ferritic Stainless Steels

NOMINAL MECHANICAL PROPERTIES

Type	Condition	Tensile Strength		0.2% Yield Strength		Elong.	R.A.	Hardness
		ksi	MPa	ksi	MPa	%	%	Rockwell
405	Anneal	70	480	40	275	30	60	B80
409	Anneal	65	450	35	240	25		B75M
429	Anneal	71	490	45	310	30	65	B88M
430	Anneal	75	515	45	310	30	60	B82
430F	Anneal	80	550	55	380	25	60	B86
430Ti	Anneal	75	515	45	310	30	65	
434	Anneal	77	530	53	365	23		B83M
436	Anneal	77	530	53	365	23		B83M
442	Anneal	80	550	45	310	25	50	B85
444	Anneal	60	415	40	275	20		B95M
446	Anneal	80	550	50	345	23	50	B86
26-1EBrite	Anneal	65	450	40	275	22		B90M
26-1Ti	Anneal	68	470	45	310	20		B95M
29-4	Anneal	80	550	60	415	20		B98M
29-4-2	Anneal	80	550	60	415	20		B98M
18SR	Anneal	90	620	65	450	25		B90
Monit	Anneal	94	650	80	550	20		B100M
Sea-cure/SC-1	Anneal	80	550	55	380	20		B100M

M = Maximum

(From *ASM Metals Handbook*, 8th Edition, Volume 1; and 9th Edition, Volume 3)

TABLE 13 — Properties of Austenitic Stainless Steels

NOMINAL MECHANICAL PROPERTIES

Type	Condition	Tensile Strength		0.2% Yield Strength		Elong.	R.A.	Hardness
		ksi	MPa	ksi	MPa	%	%	Rockwell
201	Anneal	115	793	55	379	55		B90
201	Full Hard	185	1275	140	965	4		C41
202	Anneal	105	724	55	379	55		B90
301	Anneal	110	758	40	276	60		B85
301	Full Hard	185	1275	140	965	8		C41
302	Anneal	90	620	37	255	55	65	B82
302B	Anneal	95	655	40	276	50	65	B85
303	Anneal	90	620	35	241	50	55	B84
304	Anneal	85	586	35	241	55	65	B80
304L	Anneal	80	552	30	207	55	65	B76
304N	Anneal	85	586	35	241	30		
304LN	Anneal	80	552	30	207			
305	Anneal	85	586	37	255	55	70	B82
308	Anneal	85	586	35	241	55	65	B80
308L	Anneal	80	551	30	207	55	65	B76
309	Anneal	90	620	40	276	45	65	B85
310	Anneal	95	655	40	276	45	65	B87
312	Anneal	95	655			20		
314	Anneal	100	689	50	345	45	60	B87
316	Anneal	85	586	35	241	55	70	B80
316L	Anneal	78	538	30	207	55	65	B76
316F	Anneal	85	586	35	241	55	70	B80
317	Anneal	90	620	40	276	50	55	B85
317L	Anneal	85	586	35	241	50	55	B80
321	Anneal	87	599	35	241	55	65	B80
347/348	Anneal	92	634	35	241	50	65	B84
329	Anneal	105	724	80	552	25	50	B98
330	Anneal	80	550	35	241	30		B80
330HC	Anneal	85	586	42	290	45	65	
332	Anneal	80	552	35	241	45	70	
384	Anneal	80	550					

(From *ASM Metals Handbook*, 8th Edition, Volume 1; and 9th Edition, Volume 3 and ASTM standards)

TABLE 14 — Nominal Mechanical Properties of Martensitic Stainless Steels

NOMINAL MECHANICAL PROPERTIES

Type	Condition	Tensile Strength		0.2% Yield Strength		Elong.	R.A.	Hardness
		ksi	MPa	ksi	MPa	%	%	Rockwell
403	Anneal	75	517	40	276	30	65	B82
403	*Temp. 800°F	195	1344	150	1034	17	55	C41
410	Anneal	75	517	40	276	30	65	B82
410	*Temp. 800°F	195	1344	150	1034	17	55	C41
410S	Anneal	60	414	30	207	22		B95M
410Cb	Anneal	70	483	40	276	13	45	
410Cb	*Temp. (Int.)	125	862	100	689	13	45	
414	Anneal	120	827	95	655	17	55	C22
414	*Temp. 800°F	200	1379	150	1034	16	58	C43
414L	Anneal	115	793	80	552	20	60	
416 Plus X	Anneal	75	517	40	276	30	60	
420	Anneal	95	655	50	345	25	55	B92
420	*Temp. 600°F	230	1586	195	1344	8	25	C50
422	Temp., Int.	140	965	110	758	13	30	
431	Anneal	125	862	95	655	20	60	C24
431	*Temp. 800°F	205	1413	155	1069	15	60	C43
440A	Anneal	105	724	60	414	20	45	B95
440A	*Temp. 600°F	260	1793	240	1655	5	20	C51
440B	Anneal	107	738	62	427	18	35	B96
440B	*Temp. 600°F	280	1931	270	1862	3	15	C55
440C	Anneal	110	758	65	448	13	25	B97
440C	*Temp. 600°F	285	1965	275	1896	2	10	C57

*Tempered after austentizing and cooling to room temperature. M = Maximum (600°F = 315°C), Int. = Intermediate temper hot finished (800°F = 427°C)

(From ASM Metals Handbook, 8th Edition, Volume 1; and 9th Edition, Volume 3)

TABLE 15 — Nominal Mechanical Properties of Precipitation Hardening and Duplex Stainless Steels

NOMINAL MECHANICAL PROPERTIES

Type	Condition	Tensile Strength		0.2% Yield Strength		Elong.	R.A.	Hardness
		ksi	MPa	ksi	MPa	%	%	Rockwell
Precipitation Hardening Types								
Ph13-8 Mo	H950	220	1517	205	1413	8	45	C45
15-5PH	H900	190	1310	170	1172	10	35	C44
15-5PH	H1150	135	931	105	724	16	50	C32
17-4PH	Sol. Ann.	150	1034	110	758	10	45	C33
17-4PH	H900	200	1379	178	1227	12	48	C44
17-7PH	Sol. Ann.	130	896	40	276	35		B85
17-7PH	RH950	235	1620	220	1517	6		C48
PH15-7 Mo	Sol. Ann.	130	896	55	379	35		B88
PH15-7 Mo	RH950	240	1655	225	1551	6	25	C48
17-10P	Sol. Ann.	89	613	37	255	70	76	B82
17-10P	H1300	143	986	98	676	20	32	C32
A286	H1350	130	896	85	586	15		
AM350	Sol. Ann.	160	1103	55	379	40		B95
AM350	DA	195	1344	155	1069	10.5		C41
AM355	Sol. Ann.	175	1207	65	448	30		B95
AM355	DA	195	1344	155	1069	10		C41
Custom 450	Anneal	125	862	95	655	10	40	C30
Custom 450	H900	180	1241	170	1172	10	40	C40
Custom 455	H900	235	1620	220	1517	8	30	C47
Stainless W	Sol. Ann.	120	827	75	517	7		C30
Stainless W	H950	195	1344	180	1241	7	25	C46
Duplex Types								
2205		120	827	65	448	25		
2304		110	758	60	414	25		
255		110	758	80	552	15		
2507		116	800	80	550	15		

From *ASM Metals Handbook*, 8th Edition, Volume 1; and 9th Edition, Volume 3

Selection of a Stainless Steel

The selection of a particular type stainless steel will depend on what is required by the application. In most cases the primary consideration is corrosion resistance, tarnish resistance or oxidation resistance at elevated temperature. In addition to these requirements, the selected stainless steel must have some minimum mechanical properties such as strength, toughness, ductility and fatigue strength. Several types and grades of stainless steel may provide the corrosion resistance and mechanical properties required. In this case, the final selection should be made on the basis of the lowest cost available alloy which will fulfill the service requirements. Generally, selection of the type of stainless steel is made by the designer of the equipment or component based on his knowledge, experience and data on corrosion behavior of various alloys in the environment of interest. The responsibility of the welding engineer normally does not include selection of the base alloy, only selection of the filler material, welding process and welding procedure.

If it becomes necessary for the welding engineer to select a base alloy, information should be gathered on the service environment, expected life of the part and extent of corrosion which is acceptable. To assist in this selection, Table 16, on page 50, lists corrosion resistance of several standard types of stainless steel to a number of corrosive media. This indicates that austenitic types and higher chromium types generally are more corrosion resistant than the martensitic and lower chromium ferritic types. A great deal of test data has been generated on the corrosion behavior of many metals and alloys in many kinds of corrosive media.

Other factors which must be considered in selecting a stainless steel are resistance to pitting, crevice corrosion and intergranular attack. Intergranular attack is caused by carbide precipitation in weld heat affected zones and methods of preventing this problem were discussed previously. If the application involves service at elevated temperature, then elevated temperature mechanical properties such as creep strength, stress rupture strength and oxidation resistance must be considered.

With the corrosion and oxidation test data derived from the handbooks and other references, a stainless steel or other alloy may be selected for a particular application. Once the stainless steel is selected, it is the welding engineer's responsibility to design the joints, select the weld filler metal, welding process and welding procedure.

TABLE 16 — Corrosion Resistance of Stainless Steel in Various Environments

CORROSION RESISTANCE

Type	Atmospheric							
Stainless Austenitic	Industrial	Marine	City	Rural	Fresh Water	Salt Water	Soil	Chemical
201	5	2	1	1	1		3	7
202	5	2	1	1	1		3	7
205	5	2	1	1	1		3	7
301	5	2	1	1	1		3	7
302	5	2	1	1	1		3	7
302B	5	2	1	1	1		3	7
303	5	2	1	1	1		3	7
303Se	5	2	1	1	1		3	7
304	5	2	1	1	1	3	3	7
304H	5	2	1	1	1	3	3	7
304L	5	2	1	1	1	3	3	7
304N	5	2	1	1	1	3	3	7
305	5	2	1	1	1		3	7
308	5	2	1	1	1		3	7
309	5	2	1	1	1	3	3	7
309S	5	2	1	1	1	3	3	7
310	5	2	1	1	1	3	3	7
310S	5	2	1	1	1	3	3	7
314	5	2	1	1	1			7
316	3	1	1	1	1	3	1	7
316F	3	1	1	1	1	3	1	7
316H	3	1	1	1	1	3	1	7
316L	3	1	1	1	1	3	1	7
316N	3	1	1	1	1	3	1	7
317	3	1	1	1	1	3	1	7
317L	3	1	1	1	1	3	1	7
321	5	2	1	1	1	3	3	7
321H	5	2	1	1	1	3	3	7
329	3	2	1	1	1	1	3	7
330	3	1	1	1	1		3	7
347	5	2	1	1	1	3	3	7
347H	5	2	1	1	1	3	3	7
348	5	2	1	1	1	3	3	7
348H	5	2	1	1	1	3	3	7
384		2	1	1	1		3	7
Ferritic Types								
405	6	4	2	1	3	6	6	7
409	6	4	2	1	3	6	6	7
429	3	4	2	1	1	6	6	7
430	3	4	1	1	1	6	6	7
430F	3	4	1	1	1	6	6	7
430FSe	3	4	1	1	1	6	6	7
434	3	4	1	1	1			7
436	3	4	1	1	1			7
442	3	2	1	1	1			7
446	3	2	1	1	1	3		7
Martensitic Types								
403	6	4	2	1	3	6	6	7
410	6	4	2	1	3	6	6	7
414	6	4	2	1	3	6	6	7
416	6	4	2	1	3	6	6	7
416Se	6	4	2	1	3	6	6	7
420	6	4	2	1	3	6	6	7

Code: 1 – No rust, staining or pitting,
2 – Light rust or stains, no pitting,
3 – Light rust or stains, light pitting,
4 – Rust covered or stained,
5 – Rust covered and pitted,
6 – Rust and severe pitting,
7 – Corrosion and pitting in chemical media varies widely with media, concentration, temperature and agitation. Consult literature and handbooks for data on specific application.

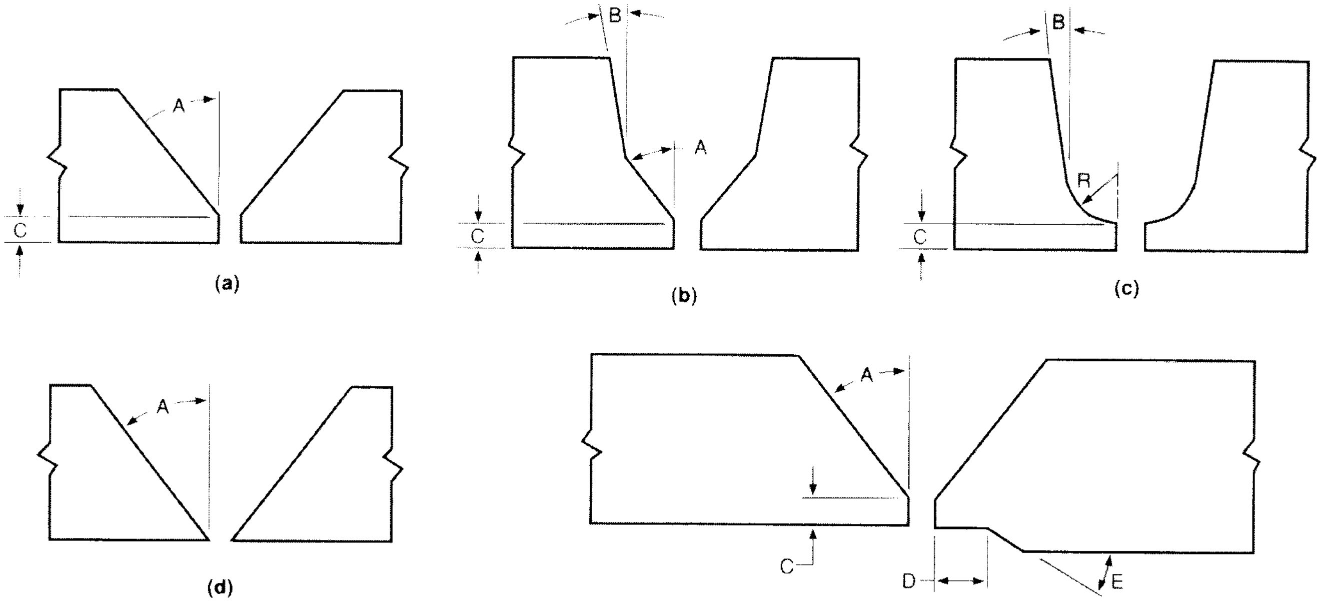
Design for Stainless Steels

Since the coefficient of thermal expansion for austenitic stainless steels is relatively high, the control of distortion must be considered in designing weldments of these alloys. The volume of weld metal in joints must be limited to the smallest size which will provide the necessary properties. In thick plate, a “U” groove, Figure 34(c), which gives a smaller volume than a “V” groove, should be used. If it is possible to weld from both sides of a joint, a double “U” or “V” groove joint preparation should be used. This not only reduces the volume of weld metal required but also helps to balance the shrinkage stresses. Accurate joint fitup and careful joint preparation which are necessary for high quality welds also help minimize distortion.

Joint location and weld sequence should be considered to minimize distortion.

Strong tooling and fixturing should be employed to hold parts in place and resist tendencies for components to move during welding. The tooling should also provide an inert gas backup to the root of the weld to prevent oxidation when the root pass is being made.

FIGURE 34 — Typical joint designs for welding austenitic stainless steel pipe.



A = 37-1/2°± 2-1/2°
B = 10° ± 1°
C = 1/16 in. ± 1/32 in. (1.6 mm ± 0.8 mm)

D = 2 times amount of offset
E = 30° max
R = 1/4 in. (6.4 mm)

From AWS D10.4

Selecting Solid and Metal-Cored Stainless Steel Electrodes for GMAW

TABLE 17 — Solid, Metal-Cored Wires for Welding Austenitic Stainless Steels

ELECTRODES

Base Stainless Steel		Recommended Solid, Metal-Cored Stainless Steel GMAW Wire
Wrought	**Cast**	
201		ER209, ER219, ER308, ER308S
202		ER209, ER219, ER308, ER308S
205		ER240
216		ER209
301		ER308, ER308S, ER308LSi
302	CF-20	ER308, ER308S, ER308LSi
304	CF-8	ER308, ER308S, ER308LSi, ER309, ER309S, ER309LSi
304H		ER308H
304L	CF-3	ER308L, ER308LS, ER347, ER308LSi
304LN		ER308L, ER308LS, ER347, ER308LSi
304N		ER308, ER308S, ER308LSi, ER309, ER309S, ER309LSi
304HN		ER308H
305		ER308, ER308S, ER308LSi, ER309, ER309S, ER309LSi
308		ER308, ER308S, ER308LSi, ER309, ER309S, ER309LSi
308L		ER308L, ER308LS, ER308LSi, ER347
309	CH-20	ER309, ER309S, ER309LSi, ER310
309S	CH-10	ER309L, ER309LS, ER309LSi
309SCb		
309CbTa		
310	CK-20	ER310
310S		ER310
312	CE-30	ER312
314		ER310
316	CF-8M	ER316, ER308Mo
316H	CF-12M	ER316H, ER16-8-2
316L	CF-3M	ER316L, ER316LSi, ER308MoL
316LN		ER316L, ER316LSi
316N		ER316
317	CG-8M	ER317
317L		ER317L
321		ER321
321H		ER321
329		ER312
330	HT	ER330
330HC		ER330
332		ER330
347	CF-8C	ER347, ER347Si
347H		ER347, ER347Si
348		ER347, ER347Si
348H		ER347, ER347Si
Nitronic 33		ER240
Nitronic 40		ER219
Nitronic 50		ER209
Nitronic 60		ER218
254SMo		ERNiCrMo-3
AL-6XN		ERNiCrMo-10

From AWS Filler Metal Specifications: A5.4, A5.9, A5.22

TABLE 18 — Solid, Metal-Cored Wires for Welding Ferritic Stainless Steels

ELECTRODES

Base Stainless Steel		Recommended Solid, Metal-Cored Stainless Steel GMAW Wire
Wrought	Cast	
405		ER410NiMo, ER430
409		ER409, AM363, EC409
429		ER409Cb
430	CB-30	ER430
430F		ER430
430FSe		ER430
434		ER434
442		ER442
444		ER316L
446	CC-50	ER446
26-1		ER26-1

From AWS Filler Metal Specifications: A5.4, A5.9, A5.22

TABLE 19 — Solid, Metal-Cored Wires for Welding Martensitic and Duplex Stainless Steels

ELECTRODES

Base Stainless Steel		Recommended Solid, Metal-Cored Stainless Steel GMAW Wire
Wrought	Cast	
403		ER410
410	CA-15	ER410, ER410NiMo
410S		ER410NiMo
414		ER410
416		ER312, ER410
416Se		ER312
416PlusX		ER312
420	CA-90	ER420, ER410
420F		ER312
431	CB-30	ER410
440A		Not recommended for Arc Welding
440B		Not recommended for Arc Welding
440C		Not recommended for Arc Welding
	CA-6NM	ER410NiMo
	CA-15	ER430
2205		ER2209
2304		ER2209
255		ER2553

From AWS Filler Metal Specifications: A5.4, A5.9, A5.22

STAINLESS STEEL PRODUCT SELECTION GUIDE

Stainless Steel		Nickel-Based Alloy	
AWS Classification	Lincoln Product Name	AWS Classification	Lincoln Product Name
ER308LSi	Blue Max® MIG 308LSi	ERNiCrMo-3	Blue Max LNM NiCro 60/20
ER308Si	Blue Max MIG 308Si	ERNiCr-3	Blue Max LNM NiCro 70/19
ER309LSi	Blue Max MIG 309LSi		
ER309Si	Blue Max MIG 309Si		
ER316LSi	Blue Max MIG 316LSi		
ER316Si	Blue Max MIG 316Si		
ER347Si	Blue Max LNM 347Si		
ER2209	Blue Max LNM 4462		
ER385	Blue Max LNM 4500		

Request publications C6.10 and C6.1 for more information on Blue Max stainless steel premium GMAW electrode wires.

TABLE 20 — Solid, Metal-Cored Wires for Welding Precipitation-Hardening Stainless Steels

ELECTRODES

Designation	UNS No.	Bare Welding Wire	Dissimilar PH Stainless Steels
Martensitic Types			
17-4PH and 15-5 PH	S17400 S15500	AMS 5826 (17-4 PH) or ER308	E or ER309, E or ER309 Cb
Stainless W	S17600	AMS 5805C (A-286) or ERNiMo-3[b]	E or ERNiMo-3, E or ER309
Semiaustenitic Types			
17-7PH	S17700	AMS 5824A (17-7 PH)	E or ER310, ENiCrFe-2, or ERNiCr-3
PH 15-7Mo	S15700	AMS 5812C (PH 15-7Mo)	E or ER309, E or ER310
AM350	S35000	AMS 5774B (AM350)	E or ER308, E or ER309
AM355	S35500	AMS 5780A (AM355)	E or ER308, E or ER309
Austenitic Types			
A-286	K66286	ERNiCrFe-6 or ERNiMo-3	E or ER309, E or ER310

TABLE 21 — Standard Sizes for Stainless Steel Electrodes

ELECTRODES

Form	Diameter, in.	Diameter, mm,
Electrode in coils, with or without support	0.045, 1/16, 5/64, 3/32, 7/64 1/8, 5/32, 3/16, 1/4	1.2, 1.6, 2.0, 2.4, 2.8 3.2, 4.0, 4.8, 6.4
Electrode wound on standard 12-in. O.D. spools	0.030, 0.035, 0.045, 1/16 5/64, 3/32, 7/64	0.8, 0.9, 1.2, 1.6 2.0, 2.4, 2.8
Electrodes wound on lightweight 1-1/2 and 2-1/2 lb., 4-in O.D. spools	0.020, 0.025, 0.030 0.035, 0.045	0.5, 0.6, 0.8 0.9, 1.2

GMAW of Stainless Steel

If the production application involves long joints in relatively thick material or a large number of parts, the GMAW process with solid or metal cored electrodes may be the best choice.

Solid or metal cored electrodes will provide the fastest deposition rates with the GMAW process but wire feeding equipment, power supplies and the requirement for inert gas shielding add to the cost of using these fillers. However, there is little need to remove slag between passes. Solid and metal cored electrodes can be used in short-circuiting, globular and spray modes of arc operation which gives a wide range of deposition rates and heat input levels. Solid and metal cored electrodes can therefore be used for welding a wide range of thicknesses.

Gas metal arc welding with spray transfer is used to join sections thicker than about 1/4” (6.4 mm) because deposition rates are higher than with other transfer modes. Welding procedures are similar for conventional austenitic and PH stainless steels.

The shielding gas is generally argon with 1 to 2% oxygen added for arc stability. Mixtures of argon and helium are employed if a hotter arc is desired. A small oxygen addition can be added to provide a stable arc, but some aluminum or titanium can be lost from certain PH filler metals during transfer across the arc as a result of oxidation. Response of the weld metal to heat treatment might be less because of this action.

Stainless steels may be welded by the gas metal arc process, using either spray arc, short-circuiting or pulsed arc transfer. For flat position welding, spray transfer is usually preferred. For other welding positions, short-circuiting transfer is often used with helium-rich gas such as 90% He, 7.5% Ar, 2.5% CO_2. Pulsed spray transfer can be employed using argon or an argon/helium mixture with a small addition of oxygen or carbon dioxide.

Copper backup strips are necessary for welding stainless steel sections up to 1/16” (1.6 mm) thick. Backup is also needed when welding 1/4” (6.4 mm) and thicker plate from one side only. No air must be permitted to reach the underside of the weld while the weld puddle is solidifying.

Oxygen picked up by the molten metal may reduce the corrosion resistance and ductility of the stainless steel as it cools. To prevent this, the underside of the weld should be shielded by an inert gas such as argon. The shielding gas source can be built into the welding fixture(s).

Electrode diameters as large as 3/32" (2.4 mm), but usually less than 1/16" (1.6 mm), are used with relatively high currents to create the spray arc transfer. A current of approximately 300 - 350 amps is required for a 1/16" (1.6 mm) electrode, depending on the shielding gas and type of stainless wire being used. The degree of spatter is dependent upon the composition and flow rate of the shielding gas, wire feed speed and the characteristics of the welding power supply. DC+ is used for most stainless steel GMAW and an argon with 1-2% oxygen gas mixture is recommended. Suggested welding guidelines for 200 and 300 series stainless steels in the spray transfer mode are given below. On square butt welds, a backup strip should be used to prevent weld metal drop-through. When fitup is poor or copper backing cannot be used, drop-through may be minimized by short-circuiting transfer welding the first pass.

When welding with a semiautomatic gun, forehand ("pushing") techniques are beneficial. Although the operator's hand is exposed to more radiated heat, better visibility is obtained.

For welding plate 1/4" (6.4 mm) and thicker, the welding gun should be moved back and forth in the direction of the joint and at the same time moved slightly from side to side. On thinner metal, only back and forth motion along the joint is used. The more economical short-circuiting transfer process for thinner material should be employed in the overhead and horizontal position for at least the root and first passes. Although some operators use a short digging spray arc to control the puddle, the weld may be abnormally porous.

Power supply units with slope, voltage and inductance controls are recommended for the welding of stainless steel with short-circuiting transfer. Inductance, in particular, plays an important part in obtaining proper puddle fluidity.

The shielding gas often recommended for short-circuiting welding of stainless steel contains 90% helium, 7.5% argon and 2.5% carbon dioxide. The gas gives the most desirable bead contour while keeping the CO_2 level low enough so that is does not influence the corrosion resistance of the metal. High inductance in the power supply output is beneficial when using this gas mixture.

Single pass welds may also be made using argon/oxygen and argon/CO_2 gas mixes. However, arc voltage for steady short-circuiting transfer may be as much as 6 volts lower than for the helium based gas. The colder arc may lead to lack of fusion defects. The CO_2 in the shielding gas will affect the corrosion resistance of multi-pass welds made with short-circuiting transfer due to carbon pickup.

Wire extension or CTWD (contact tip to work distance) should be kept as short as possible. Backhand welding is usually easier on fillet welds and will result in a neater weld. Forehand welding should be used for butt welds. Outside corner welds may be made with a straight motion.

A slight backward and forward motion along the axis of the joint should be used. The following charts summarize the welding guidelines recommended for stainless steel.

Short-circuiting transfer welds on stainless steel made with a shielding gas of 90% He, 7.5% Ar, 2.5% CO_2 show good corrosion resistance and coalescence. Butt, lap and single fillet welds in material ranging from 0.060 inch to 0.125 inch in 304, 310, 316, 321, 347, 410 and similar stainless steels can be made successfully.

The pulsed arc process, as normally used, is a spray transfer process wherein one small drop of molten metal is transferred across the arc for each high current pulse of weld current. The high current pulse must be of sufficient magnitude and duration to cause at least one small drop of molten metal to form and be propelled by the pinch effect from the end of the electrode to the weld puddle. During the low current portion of the weld cycle, the arc is maintained and the wire electrode is heated, but the heat developed is not adequate to transfer any metal. For this reason, the time duration at the low current value must be limited otherwise metal would be transferred in the globular transfer mode.

Wire diameters of 0.035" and 0.045" (0.9 and 1.1 mm) are most commonly used with this process. Gases for spray pulsed arc welding, such as argon with 1% oxygen are popular, the same as used for axial spray arc welding. These and other electrode sizes can be welded in the spray transfer mode at a lower average current with pulsed current than with continuous weld current. The advantage of this is that thin material can be welded in the spray transfer mode which produces a smooth weld with less spatter than the short-circuiting transfer mode. Another advantage is that for a given average current, spray transfer can be obtained with a larger diameter wire than could be obtained with continuous currents. Larger diameter wires are less costly than smaller sizes, and the lower ratio of surface to volume reduces the amount of deposit contamination.

The electrode diameters for gas metal arc welding are generally between 0.030" and 3/32" (0.8 and 2.4 mm). For each electrode diameter, there is a certain minimum welding current that must be exceeded to achieve spray transfer. For example, when welding stainless steel in an argon/oxygen atmosphere with 0.045" (1.1 mm) diameter stainless steel electrode, spray transfer will be obtained at a welding current of about 220 amp DC+. Along with the minimum current, a minimum arc voltage must also be obtained. This is generally between 22 and 30 volts.

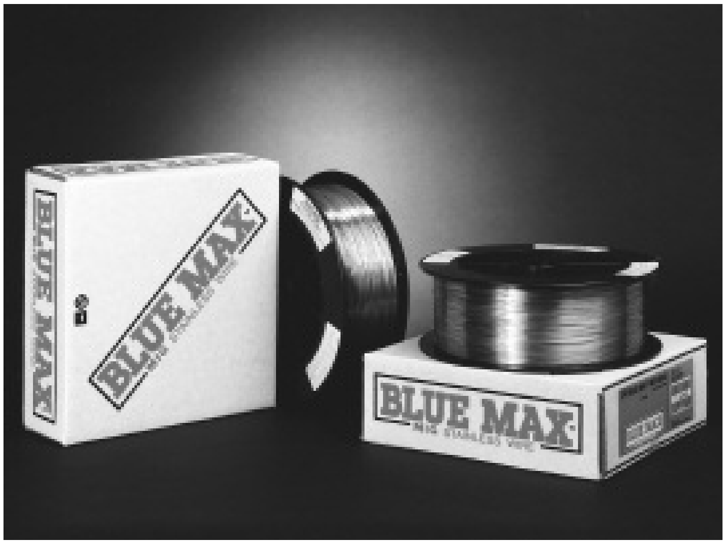
Electrodes come on spools varying in weight between 2 and 60 lbs. Also available are electrodes for welding the straight chromium stainless steels and austenitic electrodes that contain more than the usual amount of silicon. The latter have particularly good wetting characteristics when used with the short-circuiting transfer process.

Some stainless steel weld metals during welding have a tendency toward hot cracking or tearing when they contain little or no ferrite — Type 347, for example. When welding these, more welding passes than indicated in the procedures may be needed. Stringer bead techniques are also recommended rather than weaving or oscillating from side to side. Hot cracking may be eliminated by stringer bead techniques since there is a reduction in contraction stresses, hence cooling is more rapid through the hot short temperature range. A procedure that tends to produce a more convex bead than normal can be very helpful, and care should be taken to fill craters.

Weld metal hot cracking may be reduced by short-circuiting transfer welding, because of the lower dilution from the base metal. Excessive dilution may produce a completely austenitic weld metal having strong cracking characteristics.

When welding magnetic stainless steels (ferritic and martensitic types) to the relatively non-magnetic types (austenitic types), it is desirable to:

1. Use a single bevel joint to obtain minimum joint reinforcement.
2. Use low heat input short-circuiting transfer to minimize the arc deflection encountered when welding magnetic to non-magnetic steels.
3. For uniform fusion, be sure the wire is kept centered over the non-beveled edge of the joint.



Blue Max® Stainless Steel GMAW Electrode

GMAW of Aluminum Alloys

Keywords:

Thermal Conductivity

Axial Spray Transfer

Pulsed Spray Transfer

Properties of Aluminum

The engineering use of wrought and cast aluminum base materials continues to increase, and it does so because of the basic properties of this unique material. The more prominent features of aluminum and its alloys are:

- Aluminum is lightweight – it weighs about one third that of steel. A cubic inch of aluminum weighs 0.098 lbs./in.^{3} compared to steel, which weighs 0.283 lbs/in^3.
- Aluminum has a wide range of strength properties that vary from 13,000 tensile for pure aluminum up to 90,000 tensile for the heat treatable aluminum alloys.
- Aluminum provides excellent corrosion resistance in many environments. The thin refractory oxide that forms on the surface of aluminum provides a protective barrier.
- Aluminum is an excellent conductor of heat. It is up to five times more thermally conductive than steel.
- Aluminum is reflective of radiant heat, and the surface finish of aluminum is frequently used to take advantage of this feature.
- Aluminum is widely available in either extruded shapes or wrought sheet in an equally wide range of alloy compositions.
- Aluminum is widely available as a die cast base material.

For welding purposes, an important consideration for welding aluminum is its thermal conductivity. This property has an important facet:

- To compensate for the high rate of thermal conductivity, aluminum requires the use of higher energy modes of metal transfer. Axial Spray and Pulsed Spray are the two accepted and recommended GMAW modes of metal transfer for Aluminum. The use of the lower energy forms of metal transfer will usually result in incomplete fusion defects.

Aluminum GMAW Modes of Metal Transfer

Keywords

Short-Circuit Transfer

Axial Spray Transfer

Pulsed Spray Transfer

Nearly all of the same modes of metal transfer that are described earlier in this document for carbon steel, stainless steel, and nickel alloys apply to the application of aluminum solid wire electrode. What is important to note when welding aluminum base material is that the thermal conductivity of the aluminum base material is higher than it is for carbon steel, and because of this the lower energy modes of metal transfer are unable to provide sufficient melting of the base material to ensure good fusion.

Axial spray and pulsed spray metal transfers are the preferred metal transfer modes for aluminum, each of these are capable of providing the required energy levels for base metal melting to assure good fusion.

Table 22 supplies the typical axial spray transfer transition currents related to specific aluminum electrode diameters (note that argon gas is the shielding gas associated with the transition currents). In those cases where helium additions are made to the argon, the required watt energy level (current x voltage) to achieve the transition to axial spray will have to increase. Axial spray is the higher energy transfer mode for GMAW, and aluminum requires the use of higher energy modes of transfer to compensate for the higher thermal conductivity. Because of these two central facts, axial spray is generally applied to aluminum base materials 0.125” (3.2 mm) or greater in material thickness.

TABLE 22

AXIAL SPRAY TRANSITION CURRENT

Aluminum Electrode Diameter Inches	(mm)	Shielding Gas	Transition Current
0.030	(0.8)	100% Argon	90 ± 5 Amps
0.035	(0.9)	100% Argon	110 ± 5 Amps
0.047	(1.2)	100% Argon	135 ± 5 Amps
0.062	(1.6)	100% Argon	180 ± 5 Amps

If available, GMAW-P is able to join thin and thick sections of aluminum. For those materials that are less than or equal to 0.125” (3 mm), pulsed spray transfer is the preferred choice. Pulsed spray transfer is more easily able to join materials less than 0.125” (3.2 mm), and this is due to the fact that the average current is lower in magnitude for GMAW-P than axial spray transfer welding current. When compared to axial spray transfer GMAW-P has the following advantages when used for welding aluminum:

- Lower heat input – less distortion.
- Ability to handle poor fit-up.
- Ability to handle thinner materials.
- The lower heat input of GMAW-P reduces the size of the heat affected zone.
- Out-of-position welding is greatly enhanced.

Power Supplies and Wire Drives for Aluminum GMAW

Keywords:

Constant Current (CC)
Constant Voltage (CV)
Synergic
Push-Pull System
Push System

The history of the development of power sources for aluminum GMAW welding relates to the development of CC, constant current, or CV, constant voltage output characteristics. Prior to the development of CV power sources the use of CC or "drooper" type power sources were used exclusively for welding aluminum. Special techniques were required for arc striking and special variable speed wire drives were developed as a solution for the unstable arc length associated with CC.

Constant current power sources provided excellent penetration uniformity, and they reacted slowly to changing conditions. The slower dynamic response to changes in arc length were desirable for welding thicker sections of aluminum with electrodes diameters 3/32" (2.4 mm) and larger. The primary disadvantage of CC power sources is arc starting and the ability to regulate arc length.

In the late 1950s, when selenium rectifiers were employed to provide the CV output characteristic, many aluminum fabricators soon realized there was a problem. The output of the early CV power sources produced wide welding current fluctuations due to changes in arc length, and this was compounded by changes in output due to fluctuations in input power. Because of the higher thermal conductivity of aluminum the current changes that occurred produced variations in weld penetration. Incomplete fusion defects often accompanied the penetration problems. Because of this, many aluminum fabricators went back to CC power supplies for consistent penetration. As a result of these early difficulties, much of the available aluminum welding literature continues to advocate the use of CC supplies.

Constant voltage power supplies produced since the 1990s demonstrate more consistent output. These newer CV power sources are line voltage compensated, which assures consistent delivery of output. CV enjoys widespread use, and is highly recommended for aluminum gas metal arc welding.

GMAW-P Power Supplies for Aluminum Welding

Pulsed arc power supplies have become much more sophisticated than those of only a few years ago. Early pulsed power supplies had a fixed pulsing frequency based upon multiples of input frequencies, and they usually were 60 and 120Hz. These systems were non-synergic, and they were difficult to set up.

The 1990s introduced newer pulsed power sources that provided synergic control (one knob control) with a high speed amplifier used to control output. (See Waveform Control Technology™ Section on page 18). In the newer pulsed arc power sources, either an inverter transformer or related Chopper Technology™ provide power for the arc, and software is used to direct the output of the power source.

The software developed specifically for these newer power sources provides a wide selection for a range of filler types, diameters, and shielding gas compositions. In most cases the newer power sources provide a wide selection of pulsed spray transfer, synergic CV, and special Pulse on Pulse™ programs for use with aluminum electrodes.

Wire Drives and Controls

Reliable feeding of the softer aluminum solid wire electrodes through a welding torch presents more of a challenge than feeding carbon steel electrodes. First of all, the aluminum is much less rigid than steel wire and it is harder to push through a GMAW torch. Special wire drives and GMAW guns are available to enhance the feedability of aluminum electrode. They fall into four main categories:

1. Push Type Feeders

Standard wire feeders, employed for carbon steel solid wire electrodes, can also be referred to as "push type feeders." In this type of equipment, a spool of wire electrode is mounted on a spindle located to the rear of the drive. A shielding gas pre-flow and post-flow timer/control should be available. There is a set of drive rolls (two-roll or four-roll), on the feeder which pushes the wire through from the spool mounting device through the torch cable and then through the contact tip. **For aluminum electrode the use of highly polished "U" groove drive rolls, is recommended**. In all of the ensuing scenarios the use of hard shell nylon or Teflon type liners is strongly recommended. This type of system, with some modifications described below, can also be used to feed softer aluminum wire under the following circumstances:

- The gun cable must be kept short. 10 - 12 ft. (3.0 - 3.6 m) is the practical maximum length – the shorter the GMAW gun cable the better the overall performance. Teflon or hard shelled nylon electrode liners must also be employed.
- If 1/16” (1.6 mm) diameter wire is used, either 4043 or 5356 filler alloys can be pushed. The thicker electrodes have higher column strength. Again, Teflon or hard shell nylon electrode liners must be employed.
- 3/64” (1.2 mm) 5356 filler metal can generally be pushed, but 3/64” (1.2 mm) 4043 filler metal will usually result in wire feeding problems if pushed.
- Plastic or aluminum specific inlet and outlet guides and special aluminum contact tips are highly recommended.
- U-grooved type drive rolls should be used. See optional accessories for wire drive systems on page 27.

2. Push–Pull Type Feeders

A solution to the problem of feeding either small diameter or softer aluminum wire is to use a "push–pull" feeder. These feeders combine a push motor in the cabinet which holds the wire spool with a pull motor in the handle of the welding torch.

Figure 37 shows the feeder cabinet and slave type push drive system. Figure 38 shows a push-pull torch. The bulged area houses the pull drive motor. Wire feed speed is controlled by the motor on the torch handle, and the cabinet contains a slave motor system designed to provide a slack wire reducing effect on the electrode. The push-pull type of aluminum wire drive provides the most consistent daily performance when compared to the other type systems.

The push-pull systems handle aluminum diameters from 0.030" to 1/16" (0.8 - 1.6 mm), and they reliably feed aluminum wire electrode up to 50 ft. (15.2 m) from the control cabinet.

FIGURE 37: Complete Push Drive System

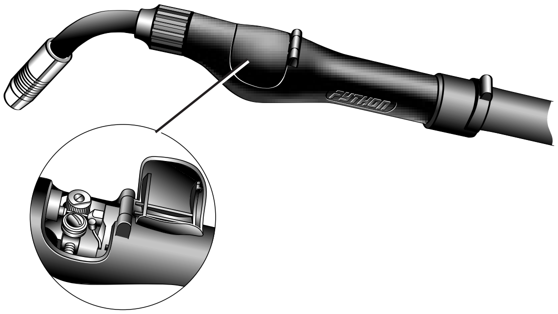


FIGURE 38: Push-Pull GMAW Aluminum Torch

3. Special Push–Pull GMAW Torches for Aluminum

There are a few "after market" push-pull GMAW aluminum torches, which will retrofit onto most standard wire drives. This permits the use of a more integrated approach for feeding aluminum. The motor in the torch handle is variable torque, constant speed, which permits the use of the wire feed speed control at the standard drive. Figure 38 details one of these.

These add–on torches usually function such that the pull torch in the gun is the slave and the push motor in the feeder is the master. There is evidence that the gun (master) and feeder (slave) arrangement gives more consistent results, but these add–on pull torches have also been shown to be effective.

4. Spool Guns

Another solution for lighter duty welding is the spool gun shown in Figure 39. In this system, a 1 lb. (0.5 kg) spool of filler wire is mounted directly on the rear of the GMAW gun, so that it is only pushed a few inches past the drive rolls. These torches are usually air-cooled, so they are not recommended for higher current or higher duty cycle welding.

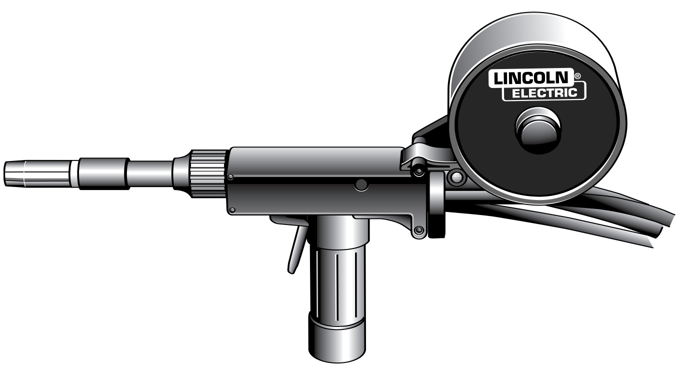


FIGURE 39: Spool Gun

Aluminum Feeding Enhancements

- Drive Rolls should always be highly polished "U" groove type for aluminum. The 'U" groove is designed to cradle the softer electrode without altering its shape and the high polish prevents the accumulation of aluminum oxide in the drive roll groove. Steel electrodes use either knurled rolls or a "V" groove configuration. Drive rolls designed for carbon steel electrodes should not be used for feeding aluminum
- Inlet and outlet guides for steel wire are usually made from steel. These should not be used to feed aluminum. Inlet and outlet guides to feed aluminum should be made from teflon, nylon, or other suitable plastic which will not scrape the wire.
- Both push and push–pull torches are available in air- and water-cooled versions. It is recommended that water-cooled torches be used for applications calling for welding current greater than 150 amps or when higher volume production is a factor.
- Torches are available in straight barrel pistol grip, curved barrel pistol grip, or gooseneck styles. All are acceptable for welding aluminum. However, if angled barrels are used, anything greater than 45° should be avoided. They will contribute to wire feeding difficulties.
- Liners for torches made to feed steel are usually made from spirally wound small diameter steel wire. These types of liners should not be used for feeding aluminum wire. They will shave the aluminum wire and then quickly clog the path. Instead, consider the use of either teflon or nylon liners for aluminum electrode. Some of these types of aluminum liners will have a short coiled brass liner section located at the front of the plastic liner.
- Contact tips for welding steel are not suitable for welding aluminum. Aluminum readily expands as it absorbs the heat of the arc. Aluminum contact tips for a given size aluminum wire are designed to accommodate the thermal expansion of the electrode – the inside diameter of the contact tip is slightly larger than those for the same size steel wire. Most manufacturers make contact tips specifically for aluminum wire.
- The contact tip should be positioned either flush with the end of the gas nozzle or slightly recessed [approximately 1/8" (3 mm)]. The contact tip should never extend beyond the gas nozzle.

Shielding Gas for Aluminum GMAW

The shielding gas section of this document provides a more expansive presentation of shielding gases for aluminum and other filler alloys (see Shielding Gas section on page 12).

The recommended shielding gas for welding aluminum up to approximately 1/2” (12 mm) in thickness is 100% argon. Above this thickness, where additional energy is needed to melt the material, it is common to use gas mixtures of 75% argon + 25% helium or 75% helium + 25% argon. The use of helium in the arc provides additional energy used to accommodate heavier section thickness welding. It also expands the cross sectional shape of the finished weld giving it a more rounded appearance. Shielding gas flow rates range from 30 to 100 cubic feet/hour (cfh), (14 to 47 L/min). Higher flow rates are employed for wider diameter gas nozzles and when using higher helium two-part blends.

Shielding gas components such as oxygen, hydrogen, or CO_2 should never be employed for aluminum GMAW, even in trace amounts these gases will adversely affect the weld.

Filler Alloys for Aluminum GMAW

It is critical to aluminum GMAW that the filler alloy is of high quality. It provides not only the material that forms the finished weld, but it also conducts the electrical current necessary to form the welding arc. The surface of the wire must be smooth and free from scratches, metal laps, excessive surface oxides, and contaminants that might add hydrogen to the weld.

Filler Alloy Electrode Surface Contaminants

All aluminum wire must be lubricated during the process of its manufacture. It is the job of the wire manufacturer to assure that the lubricants used in wire drawing manufacture are removed before the electrode is packaged. Usually, this is not a problem, but occasionally, some spools of wire are found that have unacceptable levels of residual lubricant on them. Excessive residual lubricant may result in an erratic arc performance or produce hydrogen porosity within the weld.

Storage of Aluminum Electrode

Care must be taken in the storage of spooled filler wire. It is best to store it between uses in its original packing in a low humidity environment. Some users assure low humidity in the storage area by installing a 100 watt light bulb in a closed cabinet. A heated cabinet or an air conditioned environment that removes humidity from the vicinity of the electrode is critical. Wire stored in this manner can be stored for several years without deterioration.

Storage of Aluminum Electrode Mounted on the Wire Drive

Some wire feeders incorporate a cover for the wire spool while on the wire drive. If the feeder has no such cover, the wire should be removed and stored when it is between uses, otherwise shop dust, dirt, and airborne oil can contaminate the electrode.

Aluminum GMAW Welding Technique

Keywords:

Aluminum Oxide
Hydrated Aluminum Oxide
Hydrogen Porosity
Smut (Soot)
Contact Tip to Work Distance (CTWD)
Hot Start
Push Angle
Drag Angle
Arc Decay
Feathering Technique

Aluminum Oxides and Base Material Contaminants

Before the onset of welding any weld joint configuration it is important to understand that the surface of aluminum, in all cases, is comprised of a hard, thin, tightly bonded layer of aluminum oxide (Al_2O_3). The oxide film, in high humidity environments, because it is porous will absorb moisture. Aluminum oxide can have an affect on the finished weld appearance, and the hydrated aluminum oxide, under the heat of the arc, will contribute to the formation of hydrogen porosity within the finished weld. The characteristics of aluminum oxide are as follows:

- The melting point for aluminum oxide is higher, 3725°F, (2042°C), than the base aluminum alloy. The melting point of aluminum is 1220°F (660°C).
- Aluminum oxide normally continues to grow in thickness over time – usually this occurs at a very slow rate, but it accelerates under higher ambient temperatures coupled with higher humidity.
- Aluminum oxide forms immediately following cleaning, and over time, it will nearly regain its former density. It is advisable to weld aluminum soon after it is brushed.

It is for those reasons that aluminum oxide should be removed from the weld joint prior to welding. Stainless steel power brushes or hand brushes will remove the heavier oxides, but care should be taken not to burnish the surfaces to be welded — burnishing will drive the oxide into the base material. Prior cleaning is not always required, but the removal of the oxide will contribute to improved finished weld quality.

The 5XXX base alloys usually have heavier aluminum oxide films than other base materials. Generally, the thicker oxide layer is made up of finely divided oxides of both magnesium and aluminum. Because of the heavy oxide layer the surface of the 5XXX series base alloy is more prone to hydration, and care must be taken with respect to storing it in a low humidity environment.

Welding through residual oils, those that remain on the surface of aluminum parts after shearing, stamping, or machining operations, will also contribute to hydrogen porosity. It is important that the surfaces of the aluminum base materials are clean: free of oil, shop dust, airborne oils, and moisture. Preparing the weld joint prior to welding should include the following:

- Remove oils from the surface using non-petroleum based solvents first. Then wipe the parts dry using a clean (unused) shop towel. Acetone is commonly used.
- Remove the oxides from the weld joint using a stainless steel power or hand brush. If the brush is air driven, be certain that the compressed air used to clean the material does not contain oil. Never use stainless steel brushes that have been previously used on carbon steels, and never use carbon steel brushes for removing aluminum oxide.

Welding Techniques
The formation of black soot on the surface, or the adjacent areas of a weld, is referred to as smut. It is made up of finely divided oxides of aluminum and magnesium. They usually indicate that adjustments in technique are necessary.

At the onset of learning to weld using aluminum GMAW the most common mistake made is to hold too long a contact tip to work distance (CTWD). Shorter CTWDs, 1/2" to 5/8" (13 - 16 mm), are required when welding aluminum. If the CTWD is too long, then the gas shielding will be insufficient. In the absence of adequate shielding gas the weld will become gray, and in the most severe case, the arc may bore into the work piece.

At the start of an aluminum weld it is not uncommon to get a cold looking weld bead for the first 1/2" (13 mm). This is due to the high thermal conductivity of aluminum. This condition can be minimized by using a power supply with a hot start. A common alternative used in the absence of a hot start control is to strike the arc about 1" (25 mm) ahead of the nominal weld starting point, and quickly maneuver the arc back to the desired starting point. This action has the effect of providing preheat to the aluminum base material, and it provides improved fusion at the beginning of the weld.

While welding, the torch must be held with a push angle of 5° to 10° (also known as a leading torch angle). If the torch is applied using a drag angle (also known as a lagging torch angle), then the gas shielding will be absent from the molten puddle and the finished weld will appear gray or black.

Care must be taken in extinguishing the arc. Terminating the arc abruptly will result in a deep weld crater that may contain a shrinkage crack in the crater. There are a number of ways to minimize the size and depth of the crater.

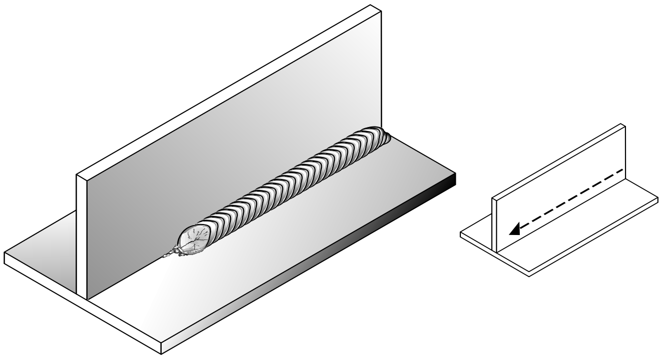


FIGURE 40: Straight Progression Weld

- Weld tabs can be used and the weld may be started and terminated on them.
- A power supply with an arc decay control allows the electrode and current to tail off for a predetermined wire feed speed per unit of time. This permits a controlled fill of the aluminum weld crater.
- Near the end of the weld, progressively increase the travel speed. The effect here is to reduce the size of the weld bead and diminish the overall size of the crater. This is known as a "feathering" or "back step" technique.
- At the end of the weld, reverse the direction of the torch to place the crater within the body of the weld bead.

Some welders learn aluminum GMAW by keeping a very steady, constant motion in the travel direction to make a very smooth weld with a minimum of weld ripples, this is known as a straight progression type weld bead, see Figure 40. Other welders learn to weld by using the back step technique, see Figure 41. Each of these techniques produce a weld with distinct, evenly spaced ripples. Each technique produces acceptable finished welds.

The finished weld should be bright and free from oxides and smut. A "frost line" or cleaning stripe approximately 1/16" to 1/8" (1.6 to 3.2 mm) wide should be visible along each edge of the weld. These stripes show the area where the reverse polarity arc has removed the oxide from the aluminum surface. If the weld metal is black or gray, or if the cleaning stripes are not present, something is wrong. The most likely causes are either the arc length is too long or the torch angle is wrong. If some weld smut is present outside these areas - this is expected. There will also be some weld smut present at weld starts, stops and at internal and external corners. More smut will be present when using 5XXX filler than with 4XXX filler.

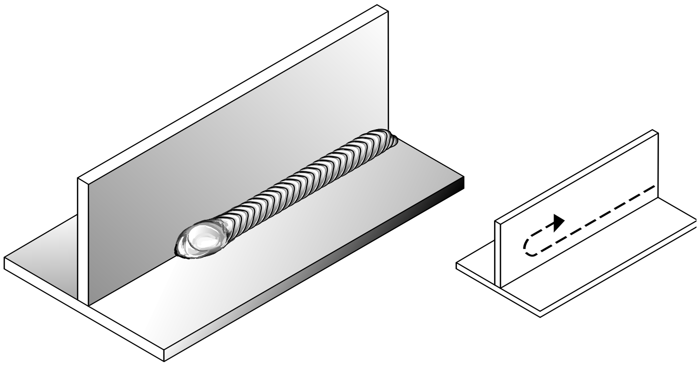


FIGURE 41: A Back Step Technique Weld

Filler Metal Selection
Most common aluminum filler alloys fall into the 4XXX and 5XXX families, with a few coming from the 1XXX, 2XXX, and the casting alloys. The chemical composition of the common aluminum filler alloys is shown in Table 23 on page 64.

There are a number of characteristics which determine the best filler metal choice for a given base material, or combination of base materials. Among these are:

- Freedom from hot cracking.

- Weld metal ductility.
- Weld metal corrosion resistance.
- Weld metal shear strength in fillet and lap joints.
- Ease of welding (i.e., weldability).
- Wire electrode feedability.
- For applications requiring postweld anodizing, color matching with parent metal.

There are a number of filler metal selection charts which take these variables into account, and they provide recommendations for filler metal selection. A composite of these charts covering most alloy combinations are shown on Table 24 on page 65.

In general, filler alloy recommendations for the various alloy families of base materials can be summarized as follows

1XXX alloys – These base materials are usually used for their electrical conductivity and/or corrosion resistance. Their tendency to hot cracking is very low. They are usually welded using 1100 or 1188 fillers, but matching filler metals are also available for specialized alloys such as 1350. If electrical conductivity of the finished weld joint is not of primary importance, then 4043 may be used

2XXX alloys – Many base materials in this series are not recommended for arc welding. Those that are weldable include: 2219, 2014, 2519, 2008, and 2036. Alloy 2319 is a matching filler alloy for 2219 and 2519 and can also be used on the other weldable alloys. Alloys 4043 and 4145, which contain copper, can also be used. 5XXX fillers should not be used to weld 2XXX parent materials; otherwise weld cracking will result.

3XXX alloys – These moderate strength aluminum-manganese base materials are relatively crack resistant and can be welded easily using either 4043 or 5356 filler alloys.

4XXX alloys – These base materials are usually found as welding or brazing fillers. In the rare event they are encountered as parent materials, 4047 is usually the best choice as a filler metal

5XXX alloys – These higher strength aluminum-magnesium base materials, are the most commonly found structural aluminum sheet and plate alloys. The general rule, except for 5052, is to choose a 5XXX filler metal with slightly higher magnesium content than the parent material being welded. For all alloys except 5052, 5XXX alloys should not be welded using 4XXX filler alloys. The high Mg content of the parent material when combined with the high silicon content of the 4XXX fillers will result in a high level of Mg_2Si (magnesium silicide), a brittle intermetallic compound that will cause the weld to have very poor ductility and toughness. In choosing filler alloys for 5XXX alloys, there are several specific recommendations as follows:

- 5052 – The magnesium content of this alloy contributes to its high crack sensitivity. If it is welded with 5052 filler alloy, it will often crack. In order to avoid the tendency to crack, 5052 is usually welded with a filler alloy of much higher Mg content, such as 5356. The result is that the weld metal, which is an alloy of the 5356 and 5052, has magnesium contents high enough to be crack resistant. Additionally, the magnesium content of 5052 is low enough so that it can be successfully welded using 4043.
- For high temperature applications the Al-Mg alloys with Mg content over 3% are unsuitable for service temperatures over 150°F (66°C). They are susceptible to stress corrosion cracking at higher temperatures. This is also true for the filler alloys, and should be taken into account when selecting the proper filler alloys
- 5454 – This alloy is a lower Mg alloy specifically developed to be immune to the stress corrosion cracking noted above. Filler alloy 5554 is designed as a matching filler alloy for the 5454 base alloy and it should be used whenever possible.
- 5083 and 5456 – These high Mg, high strength alloys can be successfully welded using 5356. However, most structural welding codes require that the tensile strength of these welds have a minimum ultimate tensile strength of 40 ksi. When welded using 5356, welds in these alloys often will not meet this requirement. For this reason, 5183 or 5556 are the recommended filler materials for these alloys

6XXX alloys – These Al-Mg-Si alloys are primarily used for extrusion alloys, although they can also often be found as sheet and plate. The chemistry of these alloys makes them very sensitive to hot cracking. Autogenous welds (i.e., welds made without adding filler metal) are susceptible to cracking. But, these alloys are readily weldable using either 4043 or 5356 filler metal. The chemistry of 4043, aluminum with 5% silicon, or 5356 aluminum with 5% magnesium, when combined with 6061, provide a crack resistant chemistry.

- The decision whether to use 4043 or 5356 depends upon a number of factors. Below is a comparison of these two common filler metals and shows the advantages and disadvantages of each:

Comparison of 4043 and 5356

ER4043	ER5356
• Smooth Bead, Good Wetting	• Black Smut, Distinct Ripples
• Low Column Strength	• Best Feedability
• Higher Penetration	• Lower Penetration
• Lower Ductility	• Higher Ductility
• Lower Tensile	• Higher Tensile
• Less Prone to Porosity	• More Prone to Porosity
• Anodizes a Dark Gray	• Anodizes w/good Colormatch
• Much Lower Shear Strength	• Higher Cracking Sensitivity
• Lower Cracking Sensitivity	• Higher Melting Point
• Lower Melting Point	• Wider Melting Range
• Narrower Melting Range	

To summarize, ER4043 is easier for the welder to use than ER5356, it is more fluid and therefore it wets into the base material better. It is also more crack resistant. ER5356 feeds better and gives welds that are both stronger, especially in lap welds and fillet welds, and more ductile. While 5356 should be used to weld the 6XXX alloys to any of the 5XXX alloys, 4043 should be used to weld the 6XXX alloys to the common 3XXX casting alloys.

One other point worth making here is the recommendation to use 5356 for making welds in 6XXX alloys that are to be anodized. If 4043 is used in these applications, it will turn dark grey on anodizing. Since the 6XXX parent materials anodize to a clear color, a 4043 weld is very visible and not desirable. 5356 will anodize to a color very similar to the parent material and is therefore the filler alloy of choice.

7XXX alloys – as mentioned previously, most of these alloys are not arc weldable. However, 7005, 7003, and 7039 are weldable, and they should be welded using a 5356 filler alloy.

SuperGlaze® Aluminum GMAW Wire

TABLE 23

WIRE CHEMICAL COMPOSITION FOR ALUMINUM WIRES

AWS A5.10-92 ASME SFA-5.1 Classification	%Mn	%Si	%Fe	%Mg	%Cr	%Cu	%Ti	%Zn	%Be	%Others(1)	%Al
ER1100 & Alloy 1050	0.05	—	—	—	—	0.05-0.20	—	0.10		0.05	99.0
ER2319	0.20-0.40	0.20	0.30	0.02	—	5.8-6.8	0.10-0.20	0.10	(2)	0.05(3)	Balance
ER4043	0.05	4.5-6.0	0.8	0.05	—	0.30	0.20	0.10	(2)	0.05	Balance
ER4047	0.15	11.0-13.0	0.8	0.10	—	0.30	—	0.20	(2)	0.05	Balance
ER4643	0.05	3.6-4.6	0.8	0.10-0.30	—	0.10	0.15	0.10	(2)	0.05	Balance
Alloy 5052	0.10	0.25	0.40	2.2-2.8	0.15-0.35	0.10	—	0.10	(2)	0.05	Balance
Alloy 5056	0.05-0.20	0.30	0.40	4.5-5.6	0.05-0.20	0.10	—	0.10	(2)	0.05	Balance
Alloy 5087	0.6-1.0	0.25	0.40	4.3-5.2	0.05-0.25	0.05	0.15	0.25	(2)	0.10-0.20	Balance
Alloy 5154	0.10	0.25	0.40	3.1-3.9	0.15-0.35	0.10	0.20	0.20	(2)	0.05	Balance
ER5183	0.50-1.0	0.40	0.40	4.3-5.2	0.05-0.25	0.10	0.15	0.25	(2)	0.05	Balance
ER5356	0.05-0.20	0.25	0.40	4.5-5.5	0.05-0.20	0.10	0.06-0.20	0.10	(2)	0.05	Balance
ER5554	0.50-1.0	0.25	0.40	2.4-3.0	0.05-0.20	0.10	0.05-0.20	0.25	(2)	0.05	Balance
ER5556	0.50-1.0	0.25	0.40	4.7-5.5	0.05-0.20	0.10	0.05-0.20	0.25	(2)	0.05	Balance
ER5654	0.01	—	—	3.1-3.9	0.15-0.35	0.05	0.05-0.15	0.20	(2)	0.05	Balance
Alloy 5754	—	0.25	0.40	2.6-3.6	0.05-0.30	0.05	0.15	0.20	(2)	0.05	Balance

NOTE: Single values are maximum, except aluminum.

(1) Total of "others" shall not exceed 0.15%. (2) Beryllium shall not exceed 0.0008%.
(3) Vanadium content shall be 0.05 - 0.15% and Zirconium content shall be 0.10 - 0.25%.

ALUMINUM PRODUCT SELECTION GUIDE

Aluminum AWS Classification	Lincoln Product Name
ER1100	SuperGlaze® 1100
ER4043	SuperGlaze 4043
ER4047	SuperGlaze 4047
ER5183	SuperGlaze 5183
ER5356	SuperGlaze 5356
ER5554	SuperGlaze 5554
ER5556	SuperGlaze 5556

Request publication C8.05 for more information on SuperGlaze aluminum GMAW electrode wires.

TABLE 24: Aluminum Filler Metal Guide

Base Metal	319.0 333.0 354.0 355.0 380.0	356.0 357.0 359.0 413.0 444.0 443.0	511.0 512.0 513.0 514.0	7005 k 7039 710.0 711.0 712.0	6070	6061 6063 6101 6201 6151 6351 6951	5456	5454	5154 5254 a	5086	5083	5052 5652 a	5005 5050	3004	2219 2519	2014 2036	1100 3003	1060 1070 1080 1350
1060 1070 1080 1350	4145 c, i	4043 i, f	5356 c,e,i	5356 c,e,i	4043 i	4043 i	5356 c	4043 i	5356 c,e,i	5356 c	5356 c	4043 i	1100 c	4043	4145	4145	1100 c	1188 j
1100 3003	4145 c,i	4043 i,f	5356 c,e,i	5356 c,e,i	4043 i	4043 i	5356 c	4043 e,i	5356 c,e,i	5356 c	5356 c	4043 e,i	4043 e	4043 e	4145	4145	1100 c	
2014 2036	4145 g	4145			4145	4145									4145 g	4145 g		
2219 2519	4145 g,c,i	4145 c,i	4043 i	4043 i	4043 f,i	4043 f,i	4043	4043 i	4043 i	4043	4043	4043 i	4043	4043	2319 c,f,i			
3004	4043 i	4043 i	5654 b	5356 e	4043 e	4043 b	5356 e	5654 b	5654 b	5356 e	5356 e	4043 e,i	4043 e	4043 e				
5005 5050	4043 i	4043 i	5654 b	5356 e	4043 e	4043 b	5356 e	5654 b	5654 b	5356 e	5356 e	4043 e,i	4043 d,e					
5052 5652	4043 i	4043 b,i	5654 b	5356 e	5356 b,c	5356 b,c	5356 b	5654 b	5654 b	5356 e	5356 e	5654 a,b,c						
5083		5356 c,e,i	5356 e	5183 e	5356 e	5356 e	5183 b	5356 e	5356 e	5356 e	5183 e							
5086		5356 c,e,i	5356 e	5356 e	5356 e	5356 e	5356 e	5356 b	5356 b	5356 e								
5154 5254 a		4043 b,i	5654 b	5356 b	5356 b,c	5356 b,c	5356 b	5654 a	5654 a,b									
5454	4043 i	4043 b,i	5654 b	5356 b	5356 b,c	5356 b,c	5356 b	5554 c,e										
5456		5356 c,e,i	5356 e	5556 e	5356 e	5356 e	5556 e											
6061 6063 6101 6201 6151 6351 6951	4145 c,i	4043 f,i	5356 b,c	5356 b,c,i	4043 b,i	4043 b,i												
6070	4145 c,i	4043 f,i	5356 c,e	5356 c,e,i	4043 e,i													
7005 k **7039 710.0 711.0 712.0**	4043 i	4043 b,i	5356 b	5356 e														
511.0 512.0 513.0 514.0		4043 b,i	5654 b,d															
356.0 357.0 359.0 413.0 444.0 443.0	4145 c,i	4043 d,i																
319.0 333.0 354.0 355.0 380.0	4145 d,c,i																	

Notes: All filler materials are listed in AWS specification A5.10.

a. Base metal alloys 5652 and 5254 are used for hydrogen peroxide service, 5654 filler metal is used for welding both alloys for low temperature [150°F (65°C)] service.

b. 5183, 5356, 5454, 5556 and 5654 may be used. In some cases they provide improved color match after anodizing, highest weld ductility and higher weld strength. 5554 is suitable for elevated temperature service.

c. 4043 may be used for some applications.

d. Filler metal with the same analysis as the base metal is sometimes used.

e. 5183, 5356 or 5556 may be used.

f. 4145 may be used for some applications.

g. 2319 may be used for some applications.

i. 4047 may be used for some applications.

j. 1100 may be used for some applications.

k. This refers to 7005 extrusions only.

ADDITIONAL GUIDELINES

1. Service conditions such as immersion in fresh or salt water, exposure to specific chemicals, or exposure sustained high temperature [over 150°F (65°C)] may limit the choice of filler metals. Filler alloys 5356, 5183, 5556 and 5654 are not recommended for sustained elevated temperature service.
2. Guide lines in this table apply to gas shielded arc welding processes.
3. Where no filler metal is listed, the base metal combination is not recommended for welding.

Current vs Wire Feed Speed

FIGURE 42: Typical Melting Rates for Carbon and Low Alloy Steel Electrodes

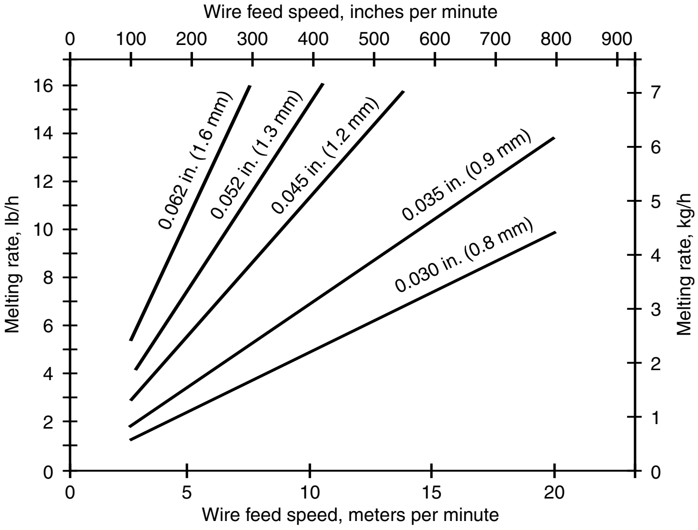


FIGURE 43: Welding Current vs WFS for Carbon Steel and Low Alloy Electrodes at a Fixed Stickout

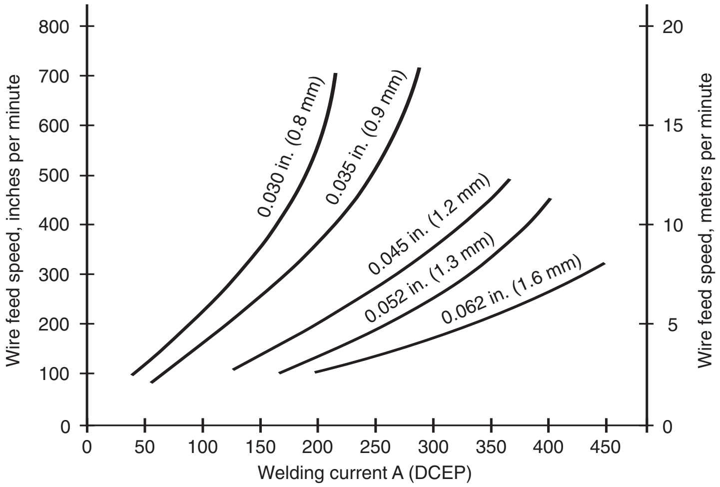


FIGURE 44: Typical Melting Rates for Aluminum Electrodes

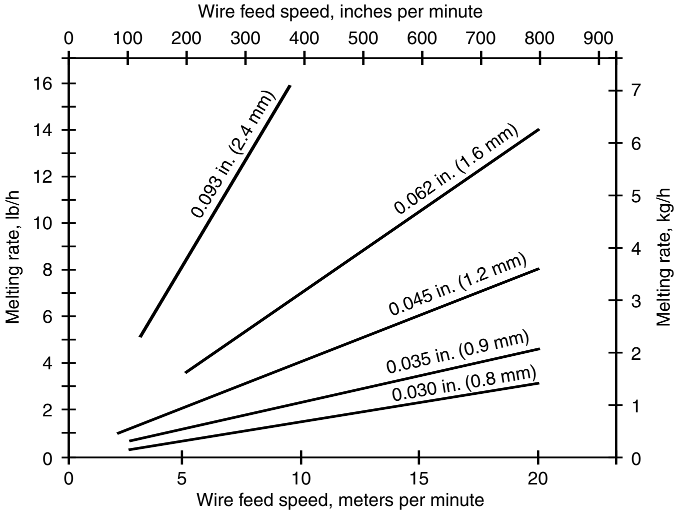


FIGURE 45: Welding Current vs WFS for ER4043 Aluminum Electrodes at a Fixed Stickout

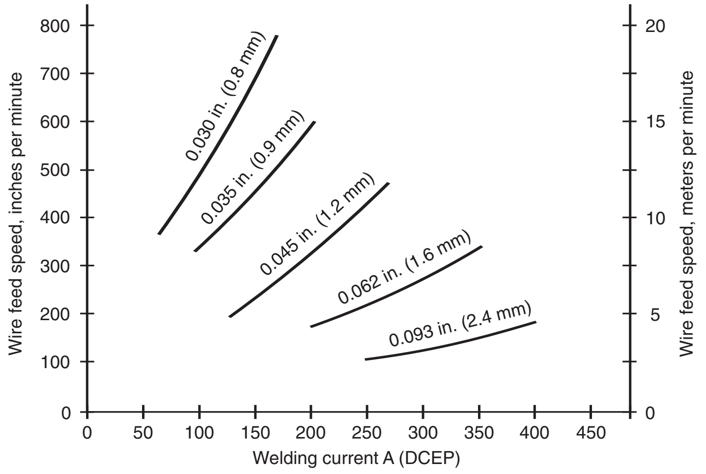


FIGURE 46: Welding Current vs WFS for ER5356 Aluminum Electrodes at a Fixed Stickout

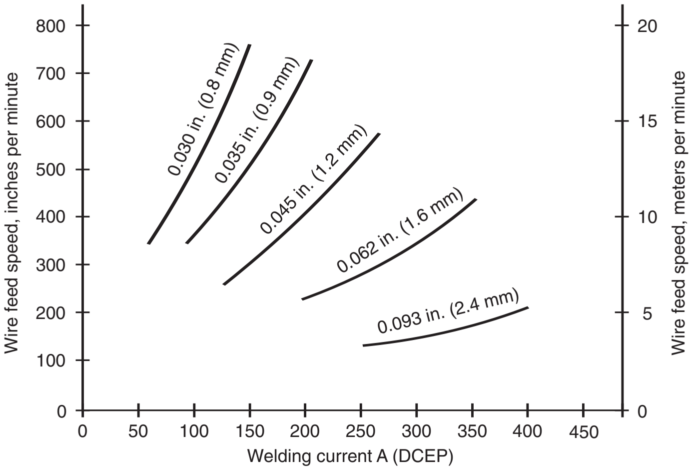


FIGURE 47: Typical Melting Rates for 300 Series Stainless Steel Electrodes

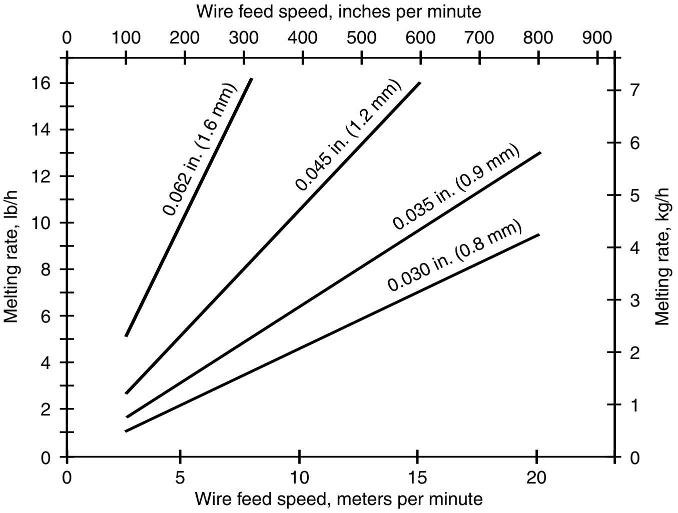


FIGURE 48: Welding Current vs WFS for 300 Series Stainless Steel Electrodes at a Fixed Stickout

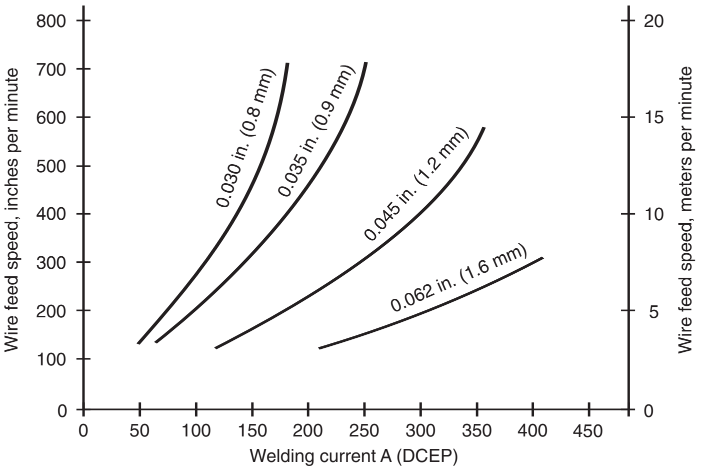


FIGURE 49: Welding Current vs WFS for Carbon Steel Composite Electrodes

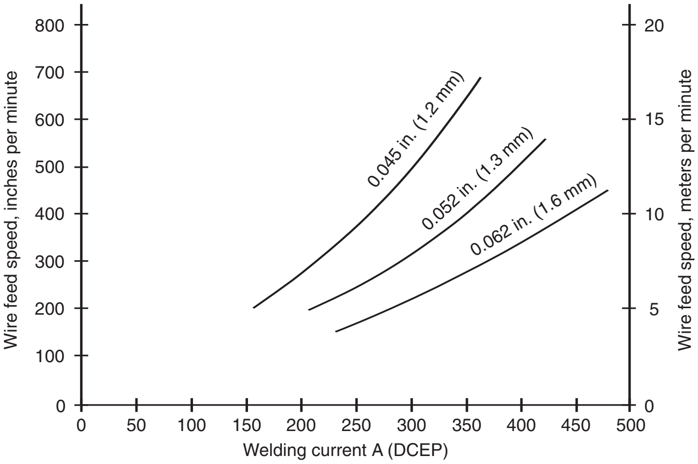
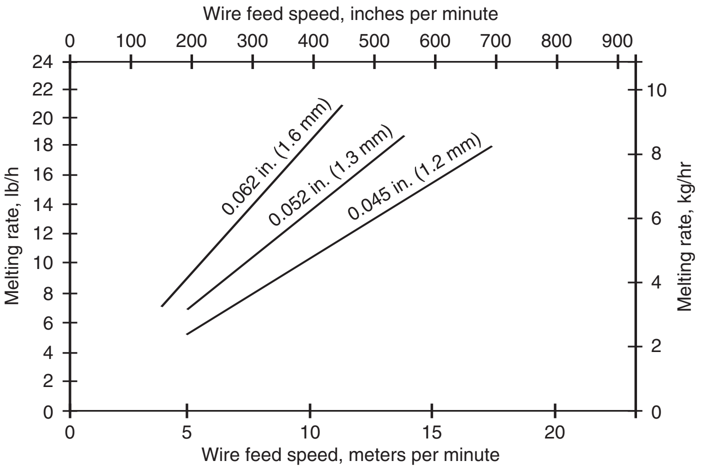


FIGURE 50: Typical Melting Rates for Carbon Composite Steel Electrodes



Welding Guidelines for Carbon and Low Alloy Steel

Welding Guidelines for Carbon and Low Alloy Steel
Short-Circuiting Transfer — Horizontal Fillets and Flat Butt Joints

CTWD[1] : 1/2" (13mm)
Gas: 100% CO_2
Gas flow: 25 to 35 cfh
(12 to 17 L/min.)

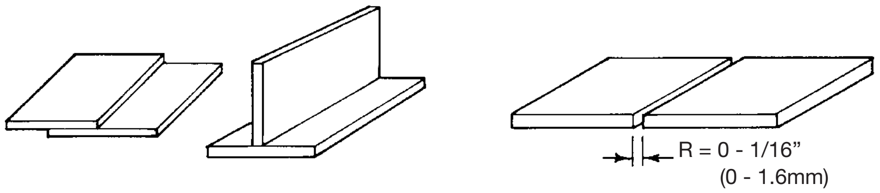


Plate Thickness - (mm)	24 ga (0.6)		20 ga (0.9)		16 ga (1.5)		14 ga (2)		12 ga (3)		10 ga (4)			3/16" (5)	1/4" (6)
Electrode Dia. - in.	0.025	0.030	0.030	0.035	0.030	0.035	0.030	0.035	0.030	0.035	0.030	0.035	0.045	0.045	0.045
(mm)	(0.6)	(0.8)	(0.8)	(0.9)	(0.8)	(0.9)	(0.8)	(0.9)	(0.8)	(0.9)	(0.8)	(0.9)	(1.1)	(1.1)	(1.1)
WFS - in./min	100	75	125	100	175	150	225	175	275	225	300	250	125	150	200
(M/min.)	(2.5)	(1.9)	(3.2)	(2.5)	(4.4)	(3.8)	(5.7)	(4.4)	(7.0)	(5.7)	(7.6)	(6.4)	(3.2)	(3.8)	(5.0)
Amps (Approximate)	35	35	55	80	80	120	100	130	115	160	130	175	145	165	200
Travel Speed - in./min	10	10	14	13	13	20	18	18	20	20	17	20	18	15	13
(M/min.)	(0.25)	(0.25)	(0.35)	(0.33)	(0.33)	(0.50)	(0.45)	(0.45)	(0.50)	(0.50)	(0.43)	(0.50)	(0.45)	(0.38)	(0.33)
Voltage [2] (DC+)	17	17	18	18	19	19	20	20	21	21	22	22	18-20	19-21	20-22

[1] Contact Tip to Work Distance
[2] Decrease 2 volts for Argon/CO_2 blend.

Welding Guidelines for Carbon and Low Alloy Steel
Short-Circuiting Transfer — Vertical Down Fillets and Square Butt Joints

CTWD[1] : 1/2" (13mm)
Gas: 100% CO_2
Gas flow: 25 to 35 cfh
(12 to 17 L/min.)

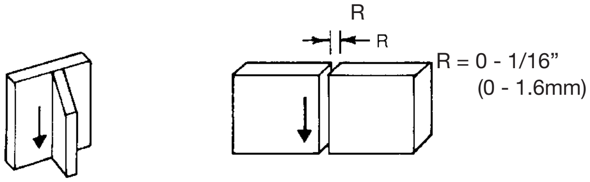
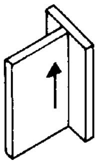


Plate Thickness - (mm)	24 ga (0.6)		18 ga (1)		14 ga (2)		10 ga (4)			3/16" (5)	1/4" (6)
Electrode Dia. - in.	0.025	0.030	0.030	0.035	0.030	0.035	0.030	0.035	0.045	0.045	0.045
(mm)	(0.6)	(0.8)	(0.8)	(0.9)	(0.8)	(0.9)	(0.8)	(0.9)	(1.1)	(1.1)	(1.1)
WFS - in./min	100	75	150	125	225	175	300	250	125	150	200
(M/min.)	(2.5)	(1.9)	(3.8)	(3.2)	(5.7)	(4.4)	(7.6)	(6.4)	(3.2)	(3.8)	(5.0)
Amps (Approximate)	35	35	70	100	100	130	130	175	145	165	200
Travel Speed - in./min	10	10	15	19	20	20	20	20	20	17	17
(M/min.)	(0.25)	(0.25)	(0.38)	(0.48)	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)	(0.43)	(0.43)
Voltage [2] (DC+)	17	17	18	18	20	20	22	22	19	20	21

[1] Contact Tip to Work Distance
[2] Decrease 2 volts for Argon/CO_2 blend.

Welding Guidelines for Carbon and Low Alloy Steel
Short-Circuiting Transfer — Vertical Up Fillets

CTWD[1]: 1/2" (13mm)
Gas: 75% Argon, 25% CO_2
Gas flow: 25 to 35 cfh
(12 to 17 L/min.)



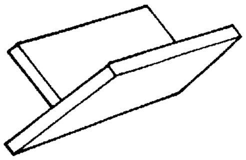
Technique:
Use vee weave or triangle weave

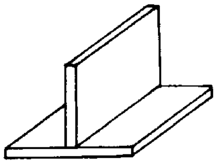
Plate Thickness - in. (mm)	5/16 (8)		3/8 (10)	
Leg Size - in. (mm)	1/4 (6.4)		5/16 (7.9)	
Electrode Dia. - in. (mm)	.035 (0.9)	.045 (1.1)	.035 (0.9)	.045 (1.1)
WFS - in./min (M/min.)	225 (5.7)	150 (3.8)	250 (6.4)	150 (3.8)
Amps (Approximate)	160	165	175	165
Travel Speed - in./min (M/min.)	5 - 6 (0.13 - 0.15)	4 - 5 (0.10 - 0.13)	4 - 4.5 (0.10 - 0.11)	4 - 5 (0.10 - 0.11)
Voltage (DC+)	18	19	20	19

[1] Contact Tip to Work Distance

Welding Guidelines for Carbon and Low Alloy Steel
Axial Spray Transfer — Flat and Horizontal Fillets

CTWD[1]: 5/8"-3/4" (16-19mm)
Gas: 90% Argon, 10% CO_2
Gas flow: 35 to 45 cfh
(17 to 21 L/min.)





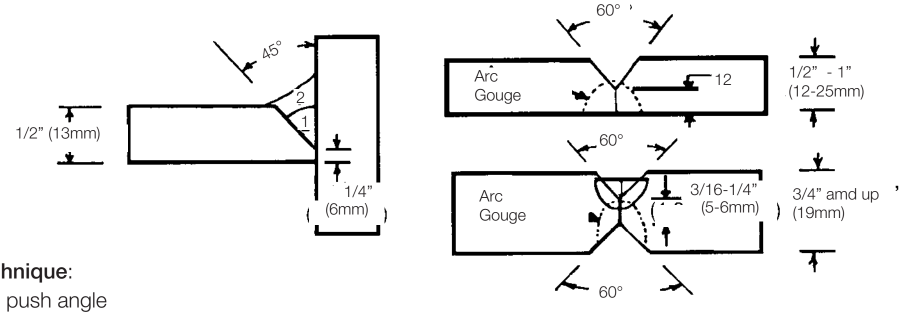
Technique:
Use push angle

Plate Thickness - in. (mm)	3/16 (5)	1/4 (6)		5/16 (8)				3/8 (10)			1/2 (13)	
Leg Size - in. (mm)	5/32 (4.0)	3/16 (4.8)		1/4 (6.4)				5/16 (7.9)			3/8 (9.5)	
Electrode Dia. - in. (mm)	0.035 (0.9)	0.035 (0.9)	0.045 (1.1)	0.035 (0.9)	0.045 (1.1)	0.052 (1.3)	1/16 (1.6)	0.035[2] (0.9)	0.045 (1.1)	1/16 (1.6)	0.052 (1.3)	1/16 (1.6)
WFS - in./min (M/min.)	375[3] (9.5)	400[3] (10)	350 (8.9)	500 (12.7)	375 (9.5)	320 (8.1)	235 (6.0)	600 (15.2)	475 (12)	235 (6.0)	485 (12.3)	235 (6.0)
Amps (Approximate)	195	200	285	230	300	320	350	275	335	350	430	350
Travel Speed - in./min (M/min.)	24 (0.60)	19 (0.48)	25 (0.63)	14 (0.35)	18 (0.45)	18 (0.45)	19 (0.48)	10 (0.25)	13 (0.33)	12 (0.30)	13 (0.33)	9 (0.23)
	Voltage (DC+)	23	24	27	29	28	29	27	30	30	27	32

[1] Contact Tip to Work Distance
[2] Flat position only.
[3] Not a true spray transfer.

Welding Guidelines for Carbon and Low Alloy Steel
Axial Spray Transfer — Flat Butt Joints

CTWD[1]: 5/8”-3/4” (16-19mm)
Gas: 90% Argon, 10% CO_2
Gas flow: 40 to 45 cfh
(19 to 21 L/min.)



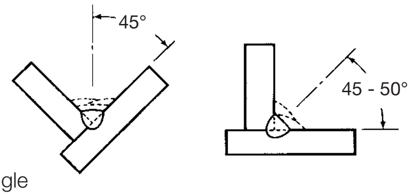
Technique:
Use push angle

Electrode Dia. - in. (mm)	0.035 (0.9)	0.045 (1.1)	0.052 (1.3)	1/16 (1.6)
WFS - in./min (M/min.)	500 - 600 (12.7 - 15.2)	375 - 500 (9.5 - 12.7)	300 - 485 (7.6 - 12.3)	210 - 290 (5.3 - 7.4)
Amps (Approximate)	230 - 275	300 - 340	300 - 430	325 - 430
Travel Speed - in./min (M/min.)	10 - 15 (0.25 - 0.38)	12 - 18 (0.30 - 0.45)	14 - 24 (0.35 - 0.60)	14 - 23 (0.35 - 0.58)
Voltage (DC+)	29 - 30	29 - 30	30 - 32	25 - 28
Deposit Rate - lb/hr (kg/hr)	8.0 - 9.6 (3.6 - 4.4)	9.9 - 13.2 (4.5 - 6.0)	10.6 - 17.1 (4.8 - 7.8)	10.7 - 14.8 (4.8 - 6.7)

(1) Contact Tip to Work Distance

Welding Guidelines for Carbon and Low Alloy Steel
Pulsed Spray Transfer — Flat or Horizontal Fillets

CTWD[1]: 5/8”-3/4” (16-19mm)
Gas: See below
Gas flow: 30 to 40 cfh
(17 to 19 L/min.)



Technique:
Use push angle

Electrode Dia. - in. (mm)		0.045 (1.1)		
Plate Thickness - in. (mm)		1/4 (6)	5/16 (8)	3/8 (10)
Leg Size - in. (mm)		3/16 (4.8)	1/4 (6.4)	5/16 (7.9)
WFS - in./min (M/min.)		300 (7.6)	325 (8.3)	375 (9.5)
Travel Speed - in./min (M/min.)		13 - 14 (0.33 - 0.36)	14 - 15 (0.35 - 0.38)	10 - 11 (0.25 - 0.28)
Voltage (DC+)	95% Ar/5% CO_2[2]	23 - 24	24 - 25	27 - 28
	90% Ar/10% CO_2[2]	24.5 - 25.5	25.5 - 26.5	28 - 29
	75-80%Ar/25-20% CO_2	28 - 29	28.5 - 30	30 - 31
Deposit Rate - lb/hr (kg/hr)		8.1 (3.6)	8.8 (4.0)	10.1 (4.5)

(1) Contact Tip to Work Distance
(2) For use on descaled plate only.

Welding Guidelines for Carbon and Low Alloy Steel
Pulsed Spray Transfer — Vertical Up Fillets - Using PowerWave® 455 Power Source

CTWD(1): 5/8”-3/4” (16-19mm)
Gas: 90% Argon, 10% CO_2
Gas flow: 30 to 40 cfh
(17 to 19 L/min.)

Trim nominally set at 1.0(2)

Technique:
Use push angle

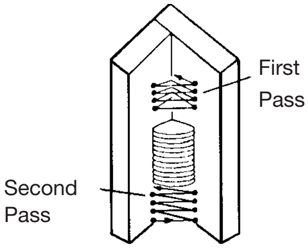


Plate Thickness - in. (mm)	3/8 (10)	1/2 (13) and up
Leg Size - in. (mm)	5/16 (7.9)	pass 2 and up
Electrode Dia. - in. (mm)	0.045 (1.1)	0.045 (1.1)
WFS - in./min (M/min.)	125 (3.2)	130 - 145 (3.3 - 3.7)
Deposit Rate - lb/hr (kg/hr)	3.4 (1.5)	3.5 - 3.9 (1.6 - 1.8)

(1) Contact Tip to Work Distance

(2) Trim can be a function of travel speed, weld size and quality of work connection. Adjusting the Trim Value controls the arc length, thus values set below 1.0 produce shorter arc lengths than those above 1.0.

Welding Guidelines for Stainless Steels

Welding Guidelines for Blue Max® GMAW ERXXXLSi Stainless Steel Electrodes

Diameter, in (mm) Polarity, CTWD[1] Shielding Gas Electrode Weight	Wire Feed Speed		Approximate Current	Arc Voltage	Deposition Rate	
	(in/min)	(M/min.)	(Amps)	(Volts)	(lbs/hr)	(kg/hr)
Short-Circuit Transfer						
0.035 (0.9) DC+, 1/2" (13mm) 90% He/7-1/2% Ar/2-1/2% CO_2 0.279 lbs/1000" (5.11 g/m)	120	3.0	55	19 - 20	2.0	0.9
	150	3.8	75	19 - 20	2.5	1.2
	180	4.6	85	19 - 20	3.0	1.4
	205	5.2	95	19 - 20	3.4	1.6
	230	5.8	105	20 - 21	3.9	1.8
	275	6.9	110	20 - 21	4.6	2.1
	300	7.6	125	20 - 21	5.0	2.3
	325	8.3	130	20 - 21	5.4	2.5
	350	8.9	140	21 - 22	5.9	2.7
	375	9.5	150	21 - 22	6.3	2.9
	400	10.2	160	22 - 23	6.7	3.1
	425	10.8	170	22 - 23	7.1	3.3
0.045 (1.1) DC+, 1/2" (13mm) 90% He/7-1/2% Ar/2-1/2% CO_2 0.461 lbs/1000" (7.63 g/m)	100	2.5	100	19 - 20	2.8	1.1
	125	3.2	120	19 - 20	3.5	1.5
	160	3.8	135	21	4.2	1.7
	175	4.4	140	21	4.8	2.0
	220	5.6	170	22	6.1	2.6
	250	6.4	175	22 - 23	6.9	2.9
	275	7.0	185	22 - 23	7.6	3.2
Axial Spray Transfer						
0.035 (0.9) DC+, 5/8" (16mm) 96% Ar/2% O_2 0.279lbs/1000", (5.11 g/m)	400	10.2	180	23	6.7	3.1
	425	10.8	190	24	7.1	3.3
	450	11.4	200	24	7.5	3.5
	475	12.1	210	25	8.0	3.7
0.045 (1.1) DC+, 3/4" (19mm) 98% Ar/2% O_2 0.461 lbs/1000", (7.63 g/m)	240	6.1	195	24	6.6	2.8
	260	6.6	230	25	7.2	3.0
	300	7.6	240	25	8.3	3.5
	325	8.3	250	26	9.0	3.8
	360	9.1	260	26	10.0	4.2
1/16 (1.6) DC+, 3/4" (19mm) 98% Ar/2% O_2 0.876 lbs/1000", (16.14 g/m)	175	4.4	260	26	9.2	4.3
	200	5.1	310	29	10.5	4.9
	250	6.4	330	29	13.1	6.2
	275	4.0	360	31	14.4	6.8
	300	7.6	390	32	15.8	7.4

(1) Contact Tip to Work Distance.

Welding Guidelines for 200 and 300 Series Stainless Steel
Short-Circuiting Transfer — Butt and Lap Joints

CTWD[1]: 3/8"-1/2" (9.5-12.7mm)
Gas: Helium, + 7-1/2% Argon,
+2-1/2% CO_2
Gas flow 15 to 20 cfh
(7.1 - 9.4 L/min.)

Electrode Dia: 0.030 in. (0.8mm)

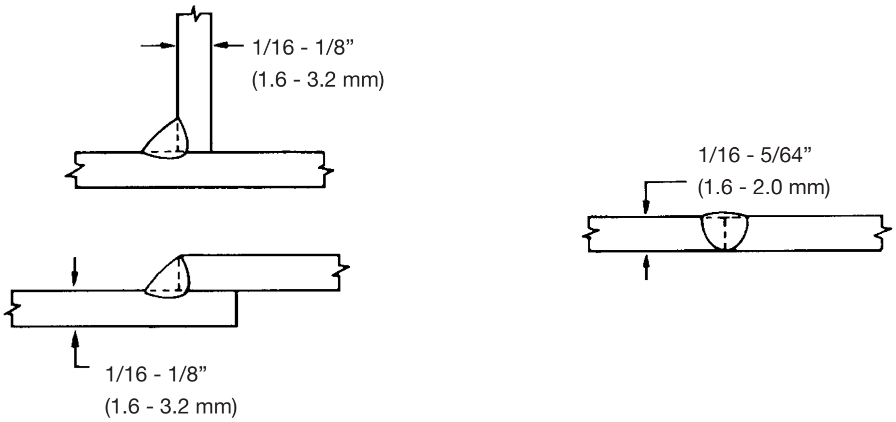


Plate Thickness in.	0.063	0.078	0.093	0.125	0.063	0.078
(mm)	(2)	(2)	(2)	(3)	(2)	(2)
Electrode Diameter in.	0.030	0.030	0.030	0.030	0.030	0.030
(mm)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Current (DC+)	85	90	105	125	85	90
Voltage	21 - 22	21 - 22	21 - 22	21 - 22	21 - 22	21 - 22
Wire Feed Speed - ipm	184	192	232	280	184	192
(mm/sec.)	(78)	(81)	(98)	(119)	(78)	(81)
Welding Speed - ipm	17 -19	13 - 15	14 - 16	14 - 16	19 - 21	11.5 - 12.5
(mm/sec.)	(7.2 - 8.0)	(5.5 - 6.3)	(5.9 - 6.8)	(5.9 - 6.8)	(8.0 - 8.9)	(4.9 - 5.3)
Electrode Required - lb/ft.	0.025	0.034	0.039	0.046	0.023	0.039
(kg/mm)	(0.037)	(0.051)	(0.058)	(0.069)	(0.034)	(0.058)
Total Time - hr/ft of weld	0.0111	0.0143	0.0133	0.0133	0.0100	0.0167
(hr/m of weld)	(0.0364)	(0.0469)	(0.0436)	(0.0436)	(0.0328)	(0.0548)

[1] Contact Tip to Work Distance.

Welding guidelines for Stainless Steel
Short-circuit transfer — Vertical up fillets
(Using Blue Max MIG Stainless Steel Electrode)

CTWD[1]: 1/2" (13mm)
Gasflow 30 cfh (14 L/min.)
90% He lium, +7-1/2% Argon,
+2-1/2% CO_2
DC+

Technique:
Use push angle - 5° - 10°

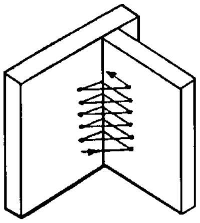


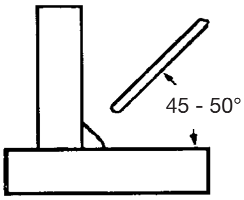
Plate Thickness, in. (mm)	**1/4**	**(6)**
Electrode Dia., in. (mm)	.035	(0.9)
Wire Feed Speed, in/min (M/min.)	175	(4.4)
Voltage	21.5	
Current (Amps)	90	
Travel Speed, in/min (M/min.)	4	(0.10)

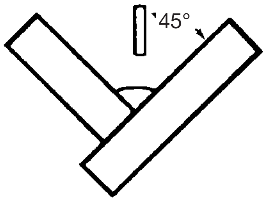
[1] Contact Tip to Work Distance.

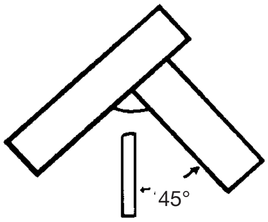
Welding Guidelines for Stainless Steel
Short-circuit transfer — Horizontal, flat and vertical down fillets
(Using Blue Max MIG Stainless Steel Electrode)

CTWD[1]: 1/2” (13mm)
Gas: 90% Helium, +7-1/2% Argon +2-1/2% CO_2
Gas flow 30 cfh (14 L/min.)
DC+

Technique:
Use push angle - 5° - 20°







.035” (0.9mm) Electrode Dia.

Plate Thickness	**18 ga (1 mm)**	**16 ga (1.5 mm)**	**14 ga (2 mm)**	
Wire Feed Speed, in/min (M/min.)	120 - 150 (3.0 - 3.8)	180 - 205 (4.6 - 5.2)	230 - 275 (5.8 - 7.0)	
Voltage	19 - 20	19 - 20	20 - 21	
Current (Amps)	55 - 75	85 - 95	105 - 110	
Travel Speed, in/min (M/min.)	10 - 16 (0.25 - 0.41)	15 - 22 (0.38 - 0.56)	18 - 21 (0.46 - 0.53)	
Plate Thickness	**12 ga (3 mm)**	**10 ga (4 mm)**	**3/16 (5 mm)**	**1/4” (6 mm)**
Wire Feed Speed, in/min (M/min.)	300 - 325 (7.6 - 8.3)	300 - 325 (7.6 - 8.3)	350 - 375 (8.9 - 9.5)	400 - 425 (10.2 - 10.8)
Voltage	20 - 21	20 - 21	21 - 22	22 - 23
Current (Amps)	125 - 130	125 - 130	140 - 150	160 - 170
Travel Speed, in/min (M/min.)	15 - 21 (0.38 - 0.53)	14 - 20 (0.36 - 0.51)	18 - 22 (0.46 - 0.56)	12 - 13 (0.30 - 0.33)

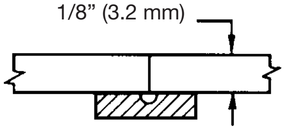
.045” (1.1mm) Electrode Dia.

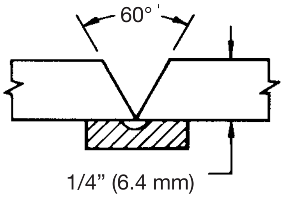
Plate Thickness, in. (mm)	**12 ga (3 mm)**	**10 ga (4 mm)**	**3/16” (5 mm)**	**1/4” (6 mm)**
Wire Feed Speed, in/min (M/min.)	100 - 125 (2.5 - 3.2)	150 - 175 (3.8 - 4.4)	220 - 250 (5.6 - 6.4)	250 - 275 (6.4 - 7.0)
Voltage	19 - 20	21	22	22 - 23
Current (Amps)	100 - 120	135 - 150	170 - 175	175 -185
Travel Speed, in/min (M/min.)	14 - 21 (0.36 - 0.53)	19 - 20 (0.48 - 0.51)	20 - 21 (0.51 - 0.53)	13 - 14 (0.33 - 0.36)

[1] Contact Tip to Work Distance.

Welding Guidelines For 200 and 300 Series Stainless Steels
Axial Spray Transfer — Butt Joints

CTWD[1]: 5/8”-3/4” (16-19mm)
Gas-Argon + 1% Oxygen.
Gas flow 35 cfh (16.5L/min.)





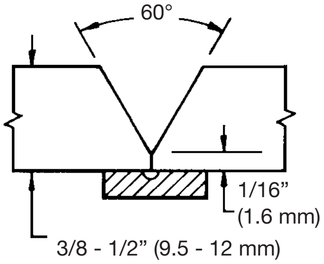


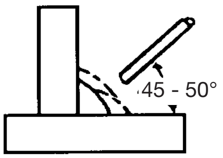
Plate Thickness (in.)	1/8	1/4	3/8	1/2
mm.	3	6	10	13
Electrode Dia. (in.)	1/16	1/16	1/16	3/32
mm.	1.6	1.6	1.6	2.4
Pass	1	2	2	4
Current DC (+)	225	275	300	325
Wire Feed Speed in/min.	140	175	200	225
(M/min.)	(3.6)	(4.4)	(5.8)	(5.7)
Arc Speed - in.min	19 - 21	19 - 21	15 - 17	15 - 17
(M/min.)	(0.48 - 0.53)	(0.48 - 0.53)	(0.38 - 0.43)	(0.38 - 0.43)
Electrode Required (lb/ft)	0.075	0.189	0.272	0.495
kg/m	0.112	0.282	0.405	0.737
Total Time (hr/ft of weld)	0.010	0.020	0.025	0.050
hr/m of weld.	0.033	0.066	0.082	0.164

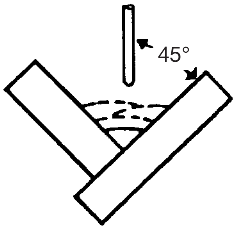
[1] Contact Tip to Work Distance

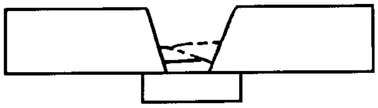
Welding Guidelines for Stainless Steel
Axial Spray Transfer — Horizontal or Flat Fillets and Flat Butt Joints
(Using Blue Max GMAW Stainless Steel Electrode)

CTWD[1]: 5/8”-3/4” (16-19mm)
Gas: 90% Argon, + 2% Oxygen
Gas flow 30 to 40 cfh
(14 to 19 L/min.)
DC+

Technique:
Use push angle - 5°







	.035” (0.9 mm) Electrode Dia.			
Plate Thickness, in. (mm)	**3/16 (5)**	**1/4 (6)**	**5/16 (8) and up**	
Wire Feed Speed, in/min (M/min.)	400 - 425 (10.2 - 10.8)	450 - 475 (11.4 - 12.1)	475 (12.1)	
Voltage	23 - 24	24 - 25	25	
Current (Amps)	180 - 190	200 - 210	210	
Travel Speed, in/min (M/min.)	18 - 19 (0.46 - 0.48)	11 - 12 (0.28 - 0.30)	10 - 11 (0.25 - 0.28)	

	.045” (1.1 mm) Electrode Dia.			
Plate Thickness, in. (mm)	**3/16 (5)**	**1/4 (6)**	**5/16 (8) and up**	
Wire Feed Speed, in/min (M/min.)	240 - 260 (6.1 - 6.6)	300 - 325 (7.6 - 8.3)	360 (9.1)	
Voltage	24 - 25	25 - 26	26	
Current (Amps)	195 - 230	240 - 250	260	
Travel Speed, in/min (M/min.)	17 - 19 (0.43 - 0.48)	15 - 18 (0.38 - 0.46)	14 - 15 (0.36 - 0.38)	

	1/16” (1.6 mm) Electrode Dia.			
Plate Thickness, in. (mm)	**3/16 (5)**	**1/4 (6)**	**5/16 (8) and up**	**3/8 (10) and up**
Wire Feed Speed, in/min (M/min.)	175 (4.4)	200 - 250 (5.1 - 6.4)	275 (7.0)	300 (7.6)
Voltage	26	29	31	32
Current (Amps)	260	310 - 330	360	390
Travel Speed, in/min (M/min.)	19 - 23 (0.48 - 0.58)	23 - 25 (0.58 - 0.64)	16 (0.41)	16 (0.41)

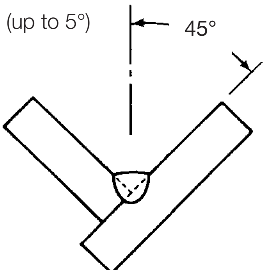
[1] Contact Tip to Work Distance.

Welding Guidelines for Stainless Steel
Pulsed Spray Transfer — Flat or Horizontal Fillets
(For Use with PowerWave 455)

Electrode Dia: 0.045” (1.1mm)
CTWD[1]: 5/8”-3/4” (16-19mm)
Gas: 98% Argon, + 2% Oxygen
Gas flow 25 to 40 cfh
(12-19 L/min.)
Drag Angle 0 - 5 Degrees
Use Push Angle

Trim Value Nominally set at 1.0[2]

Technique:
Use push angle (up to 5°)



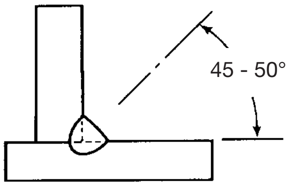


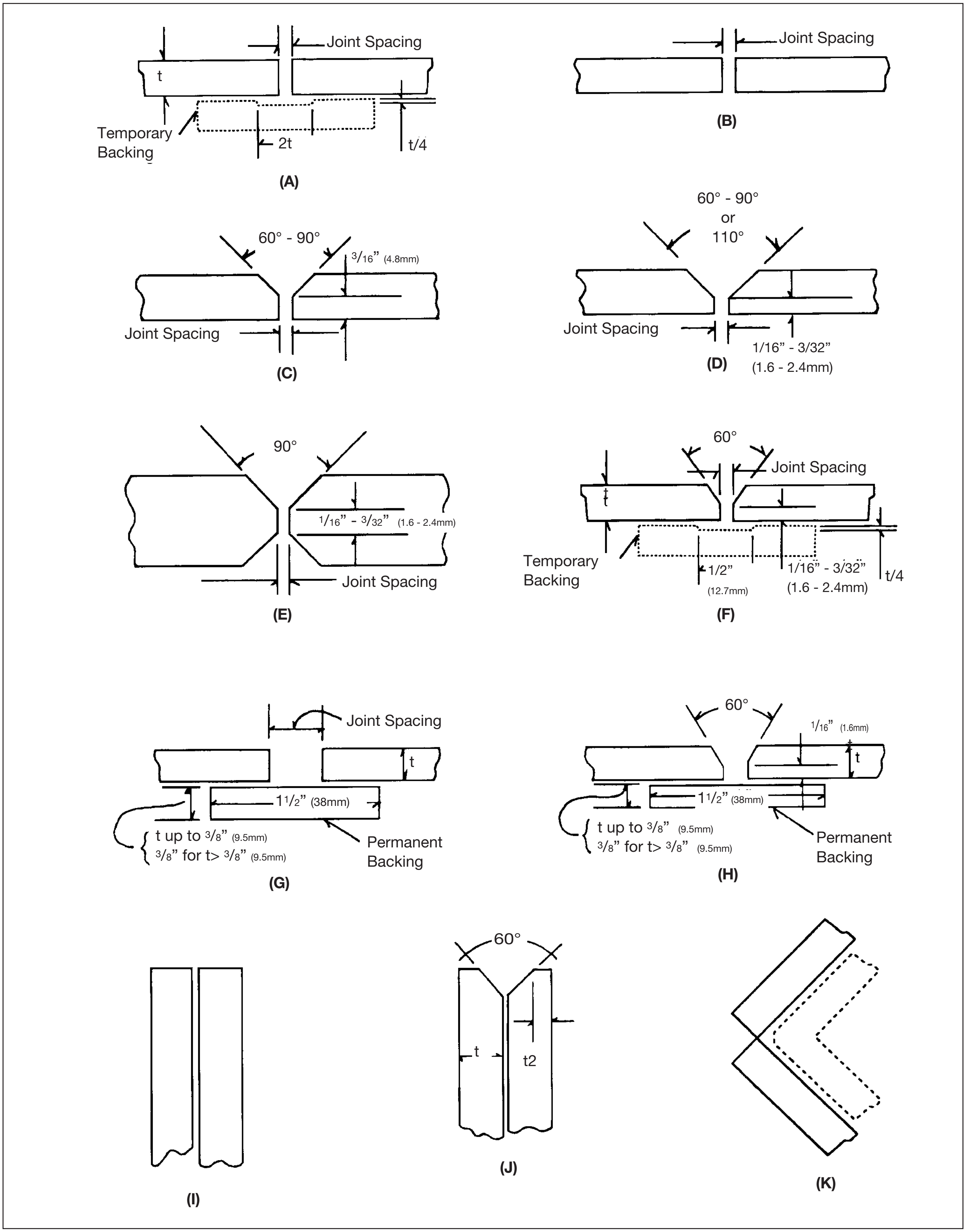
Plate Thickness	14 ga (2 mm)	12 ga (3 mm)	3/16” (5 mm)	1/4” (6 mm)	5/16” (8 mm)
Leg Size, in. (mm)	—	—	—	3/16 (4.8)	1/4 (6.4)
Wire Feed Speed, ipm (M/min.)	150 (3.8)	180 (4.6)	200 (5.0)	275 (7.0)	300 (7.6)
Mode Selector	62	63	65	66	67
Deposition Rate, lbs/hr (kg/hr)	4.2 (1.9)	5.0 (2.3)	5.5 (2.5)	7.6 (3.4)	8.3 (3.8)

For out-of-position welding, start with settings for one thickness smaller.

[1] Contact Tip to Work Distance
[2] Trim can be a function of travel speed, weld size and quality of work connection. Adjusting the Trim Value controls the arc length, thus, values set below 1.0 produce shorter arc lengths than those above 1.0.

Welding Guidelines for Aluminum

Welding Joint Designs for Aluminum MIG Welding
Groove Welding — Flat, Horizontal, Vertical and Overhead



Welding Guidelines for Aluminum GMAW
Groove Welding — Flat, Horizontal, Vertical and Overhead

Plate Thickness	Weld Position(1)	Edge Prep(2)	Joint Spacing In. (mm)	Weld Passes	Electrode Diameter In. (mm)	Welding Current(3) (Amps) (DC+)	Arc Voltage(3) (Volts)	Argon Gas Flow CFH (L/min.)	Travel Speed ipm (M/min.)	Approx. Electrode Consump. (lbs/100 ft)
1/16” (2 mm)	F	A	None	1	0.030 (0.8)	70-110	15-20	25 (12)	25 - 45 (0.64 - 1.14)	1.5
	F	G	3/32 (2.4)	1	0.030 (0.8)	70-110	15-20	25 (12)	25 - 45 (0.64 - 1.14)	2
3/32” (2 mm)	F	A	None	1	0.030-3/64 (0.8 - 1.2)	90-150	18-22	30 (14)	25 - 45 (0.64 - 1.14)	1.8
	F, V, H, O	G	1/8 (3.2)	1	0.030 (0.8)	110-130	18-23	30 (14)	25 - 30 (0.64 - 0.76)	2
1/8” (3 mm)	F, V, H	A	0 - 3/32 (0 - 2.4)	1	0.030 - 3/64 (0.8 - 1.2)	120-150	20-24	30 (14)	24 - 30 (0.60 - 0.76)	2
	F, V, H, O	G	3/16 (4.8)	1	0.030 - 3/64 (0.8 - 1.2)	110-135	19-23	30 (14)	18 - 28 (0.45 - 0.71)	3
3/16” (5 mm)	F, V, H	B	0 - 1/16 (0 - 1.6)	1F, 1R	0.030 - 3/64 (0.8 - 1.2)	130-175	22-26	35 (16)	24 - 30 (0.60 - 0.76)	4
	F, V, H	F	0-1/16 (0 - 1.6)	1	3/64 (1.2)	140-180	23-27	35 (16)	24 - 30 (0.60 - 0.76)	5
	O	F	0-1/16 (0 - 1.6)	2F	3/64 (1.2)	140-175	23-27	60 (28)	24 - 30 (0.60 - 0.76)	5
	F, V	H	3/32 - 3/16 (2.4 - 4.8)	2	3/64 - 1/16 (1.2 - 1.6)	140-185	23-27	35 (16)	24 - 30 (0.60 - 0.76)	8
	H, O	H	3/16 (4.8)	3	3/64 (1.2)	130-175	23-27	60 (28)	25 - 35 (0.63 - 0.89)	10
1/4” (6 mm)	F	B	0 - 3/32 (0 - 2.4)	1F, 1R	3/64-1/16 (1.2 - 1.6)	175-200	24-28	40 (19)	24 - 30 (0.60 - 0.76)	6
	F	F	0 - 3/32 (0 - 2.4)	2	3/64-1/16 (1.2 - 1.6)	185-225	24-29	40 (19)	24 - 30 (0.60 - 0.76)	8
	V, H	F	0 - 3/32 (0 - 2.4)	3F, 1R	3/64 (1.2)	165-190	25-29	45 (21)	25 - 35 (0.63 - 0.89)	10
	O	F	0 - 3/32 (0 - 2.4)	3F, 1R	3/64, 1/16 (1.2 - 1.6)	180-200	25-29	60 (28)	25 - 35 (0.63 - 0.89)	10
	F, V	H	1/8 - 1/4 (3.2 - 6.4)	2 - 3	3/64-1/16 (1.2 - 1.6)	175-225	25-29	40 (19)	24 - 30 (0.60 - 0.76)	12
	O, H	H	1/4 (6.4)	4 - 6	3/64-1/16 (1.2 - 1.6)	170-200	25-29	60 (28)	25 - 40 (0.63 - 1.02)	12
3/8” (10 mm)	F	C - 90°	0 - 3/32 (0 - 2.4)	1F, 1R	1/16 (1.6)	225-290	26-29	50 (24)	20 - 30 (0.51 - 0.76)	16
	F	F	0 - 3/32 (0 - 2.4)	2F, 1R	1/16 (1.6)	210-275	26-29	50 (24)	24 - 35 (0.60 -0.89)	18
	V, H	F	0 - 3/32 (0 - 2.4)	3F, 1R	1/16 (1.6)	190-220	26-29	55 (26)	24 - 30 (0.60 - 0.76)	20
	O	F	0 - 3/32 (0 - 2.4)	5F, 1R	1/16 (1.6)	200-250	26-29	80 (38)	25 - 40 (0.63 - 1.02)	20
	F, V	H	1/4 - 3/8 (6.4 - 9.5)	4	1/16 (1.6)	210-290	26-29	50 (24)	24 - 30 (0.60 - 0.76)	35
	O, H	H	3/8 (9.5)	8 - 10	1/16 (1.6)	190-260	26-29	80 (38)	25-40 (0.63 - 1.02)	50
3/4” (19 mm)	F	C-60°	0 - 3/32 (0 - 2.4)	3F, 1R	3/32 (2.4)	340-400	26-31	60 (28)	14 - 20 (0.36 - 0.51)	50
	F	F	0 - 1/8 (0 - 3.2)	4F, 1R	3/32 (2.4)	325-375	26-31	60 (28)	16 - 20 (0.41 - 0.76)	70
	V, H, O	F	0 - 1/16 (0 - 1.6)	8F, 1R	1/16 (1.6)	240-300	26-30	80 (38)	24 - 30 (0.60 - 0.76)	75
	F	E	0 - 1/16 (0 - 1.6)	3F, 3R	1/16 (1.6)	270-330	26-30	60 (28)	16 - 24 (0.41 - 0.61)	70
	V, H, O	E	0 - 1/16 (0 - 1.6)	6F, 6R	1/16 (1.6)	230-280	26-30	80 (38)	16 - 24 (0.41 - 0.61)	75

(1) F = Flat; V = Vertical; H = Horizontal; O = Overhead. (2) See joint designs on page 75. (3) For 5xxx series electrodes, use a welding current in the high side of the range and an arc voltage in the lower portion of the range. 1XXX, 2XXX and 4XXX series electrodes would use the lower currents and higher arc voltages.

Welding Guidelines for Aluminum GMAW
Fillet and Lap Welding — Flat, Horizontal, Vertical and Overhead

Plate Thickness[1]	Weld Position[2]	Weld Passes[3]	Electrode Diameter In. (mm)	Welding Current[4] (Amps) (DC+)	Arc Voltage[4] (Volts)	Argon Gas Flow CFH (L/min.)	Travel Speed ipm (M/min.)	Approx. Electrode Consump. (lbs/100 ft)
3/32” (2 mm)	F, V, H, O	1	0.030 (0.8)	100-130	18-22	30 (14)	24 - 30 (0.60 - 0.76)	1.8
1/8” (3 mm)	F	1	0.030 - 3/64 (0.8 - 1.2)	125-150	20-24	30 (14)	24 - 30 (0.60 - 0.76)	2
	V, H	1	.030 (0.8)	110-130	19-23	30 (14)	24 - 30 (0.60 - 0.76)	2
	O	1	0.030 - 3/64 (0.8 - 1.2)	115-140	20-24	40 (19)	24 - 30 (0.60 - 0.76)	2
3/16” (5 mm)	F	1	3/64 (1.2)	180-210	22-26	30 (14)	24 - 30 (0.60 - 0.76)	4.5
	V, H	1	0.030 - 3/64 (0.8 - 1.2)	130-175	21-25	35 (16)	24 - 30 (0.60 - 0.76)	4.5
	O	1	0.030 - 3/64 (0.8 - 1.2)	130-190	22-26	45 (21)	24 - 30 (0.60 - 0.76)	4.5
1/4” (6 mm)	F	1	3/64 - 1/16 (1.2 - 1.6)	170-240	24-28	40 (19)	24 - 30 (0.60 - 0.76)	7
	V, H	1	3/64 (1.2)	170-210	23-27	45 (21)	24 - 30 (0.60 - 0.76)	7
	O	1	3/64 - 1/16 (1.2 - 1.6)	190-220	24-28	60 (28)	24 - 30 (0.60 - 0.76)	7
3/8” (10 mm)	F	1	1/16 (1.6)	240-300	26-29	50 (24)	18 - 25 (0.46 - 0.64)	17
	H, V	3	1/16 (1.6)	190-240	24-27	60 (28)	24 - 30 (0.60 - 0.76)	17
	O	3	1/16 (1.6)	200-240	25-28	85 (40)	24 - 30 (0.60 - 0.76)	17
3/4” (19 mm)	F	4	3/32 (2.4)	360-380	26-30	60 (28)	18 - 25 (0.46 - 0.64)	66
	H, V	4-6	1/16 (1.6)	260-310	25-29	70 (33)	24 - 30 (0.60 - 0.76)	66
	O	10	1/16 (1.6)	275-310	25-29	85 (40)	24 - 30 (0.60 - 0.76)	66

[1] Metal thickness of 3/4” or greater for fillet welds sometimes employ a double vee bevel of 50° or greater included vee with 3/32” to 1/8” land thickness on the abutting member. [2] F = Flat; V = Vertical; H = Horizontal; O = Overhead. [3] Number of weld passes and electrode consumption given for weld on one side only. [4] For 5xxx series electrodes, use a welding current in the high side of the range and an arc voltage in the lower portion of the range. 1xxx, 2xxx and 4xxx series electrodes would use the lower currents and higher arc voltages.

STT® II Welding Guidelines

STT II Welding Guidelines

The ensuing procedure guidelines are intended to provide a starting point for the development of welding procedures using the STT II power source and STT 10 wire drive and control. The use of pre-flow, post-flow, and run-in speed are variables that are established based upon the needs of the application. Vertical down fillets are set at the suggested guideline setting, but require an additional 30% to the travel speed.

Background Current controls penetration and is responsible for the overall heat input of the weld.

Peak Current provides arc length – a shorter arc length is required for higher travel speeds. The peak current also provides preheat and melts the surface of the base material prior to a return to background current.

Tail-out Current is applied to add energy to the molten droplet. Adding tail-out may result in faster travel speeds and improved toe wetting.

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout (1)	Travel Speed in/min	(M/min.)	Average Current
0.030" (0.8 mm), ER70S-3,	10	3.2	250	(6.4)	250	75	0 - 3	10	(0.3)	110
ER70S-4, ER70S-6	12	2.4	240	(6.1)	245	70	0 - 3	10	(0.3)	107
3/8" (9 mm)	14	2.0	225	(5.7)	245	70	0 - 3	12	(0.3)	105
80% Ar + 20 %CO_2	16	1.6	180	(4.6)	225	60	0 - 3	13	(0.3)	85
Lap, T-Joints,	18	1.1	160	(4.1)	215	55	0 - 3	14	(0.4)	75
Horizontal Fillets	20	0.9	135	(3.4)	200	50	0 - 3	15	(0.4)	65

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout (1)	Travel Speed in/min	(M/min.)	Average Current
0.035" (0.9 mm), ER70S-3,	7	5.0	245	(6.2)	340	90	0 - 5	8	(0.2)	150
ER70S-4, ER70S-6	10	3.2	230	(5.8)	330	90	0 - 5	10	(0.3)	145
3/8" (9 mm)	12	2.4	200	(5.1)	320	80	0 - 5	12	(0.3)	135
80%Ar + 20%CO_2	14	2.0	190	(4.8)	300	75	0 - 5	13	(0.3)	125
Lap, T-Joints,	16	1.6	150	(3.8)	260	50	0 - 5	14	(0.4)	95
Horizontal Fillets	18	1.1	125	(3.2)	250	45	0 - 5	15	(0.4)	80
	20	0.9	100	(2.5)	220	40	0 - 5	15	(0.4)	65

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout (1)	Travel Speed in/min	(M/min.)	Average Current
0.035" (0.9 mm), ER70S-3,	7	5.0	205	(5.2)	310	85	0 - 6	12	(0.3)	125
ER70S-4, ER70S-6	10	3.2	175	(4.4)	300	75	0 - 6	10	(0.3)	110
3/8" (9 mm)	12	2.4	145	(3.7)	265	60	0 - 7	12	(0.3)	90
54%He + 38%Ar + 8%CO_2	14	2.0	130	(3.3)	240	55	0 - 8	12	(0.3)	85
Lap, T-Joints,	16	1.6	120	(3.0)	235	50	0 - 8	11	(0.3)	75
Horizontal Fillets	18	1.1	110	(2.9)	230	45	0 - 8	12	(0.3)	65
	20	0.9	100	(2.5)	225	40	0 - 8	15	(0.4)	55

(1) Tail-out is adjusted according to end-user acceptance requirements. Increasing tail-out can result in an increase in travel speed and improved wetting at the toes of a weld.

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness		Wire Feed Speed		Peak Amps	Background Amps	Tailout (1)	Travel Speed		Average Current
	Gauge	(mm)	in/min	(M/min.)				in/min	(M/min.)	
0.035” (0.9 mm), ER70S-3,	7	5.0	215	(5.5)	300	80	0 - 3	7	(0.2)	145
ER70S-4, ER70S-6	10	3.2	210	(5.3)	300	80	0 - 3	11	(0.3)	140
3/8” (9 mm)	12	2.4	190	(4.8)	290	70	0 - 3	12	(0.3)	120
100% CO_2	14	2.0	175	(4.4)	270	60	0 - 3	12	(0.3)	105
Lap, T-Joints,	16	1.6	120	(3.0)	250	55	0 - 3	16	(0.4)	85
Horizontal Fillets	18	1.1	100	(2.5)	220	30	0 - 3	15	(0.4)	70
	20	0.9	100	(2.5)	220	30	0 - 3	15	(0.4)	70

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness		Wire Feed Speed		Peak Amps	Background Amps	Tailout (1)	Travel Speed		Average Current
	Gauge	(mm)	in/min	(M/min.)				in/min	(M/min.)	
0.045” (1.1 mm), ER70S-3,	7	5.0	190	(4.8)	400	85	0 - 6	10	(0.3)	155
ER70S-4, ER70S-6	10	3.2	140	(3.6)	330	75	0 - 6	12	(0.3)	145
3/8” (9 mm)	12	2.4	125	(3.2)	300	65	0 - 6	13	(0.3)	125
80%Ar + 20%CO_2	14	2.0	115	(2.9)	270	60	0 - 6	12	(0.3)	115
Lap, T-Joints,	16	1.6	100	(2.5)	250	55	0 - 6	12	(0.3)	90
Horizontal Fillets										

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness		Wire Feed Speed		Peak Amps	Background Amps	Tailout (1)	Travel Speed		Average Current
	Gauge	(mm)	in/min	(M/min.)				in/min	(M/min.)	
0.045” (1.1 mm), ER70S-3,	7	5.0	150	(3.8)	350	90	0 - 8	12	(0.3)	155
ER70S-4, ER70S-6	10	3.2	135	(3.4)	330	80	0 - 6	12	(0.3)	130
3/8” (9 mm)	12	2.4	120	(3.0)	295	70	0 - 6	12	(0.3)	120
54%He + 38%Ar + 8%CO_2	14	2.0	115	(2.9)	285	65	0 - 6	12	(0.3)	110
Lap, T-Joints,	16	1.6	100	(2.5)	275	60	0 - 6	12	(0.3)	100
Horizontal Fillets	18	1.1	75	(1.9)	260	55	0 - 5	12	(0.3)	90
	20	0.9	65	(1.7)	250	50	0 - 5	14	(0.4)	75

Carbon Steel Sheetmetal - Uncoated

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness		Wire Feed Speed		Peak Amps	Background Amps	Tailout(1)	Travel Speed		Average Current
	Gauge	(mm)	in/min	(M/min.)				in/min	(M/min.)	
0.045” (1.1 mm), ER70S-3,	7	5.0	175	(4.4)	390	75	0 - 5	9	(0.2)	170
ER70S-4, ER70S-6	10	3.2	145	(3.7)	350	55	0 - 5	10	(0.3)	150
3/8” (9 mm)	12	2.4	120	(3.0)	320	50	0 - 5	11	(0.3)	125
100% CO_2	14	2.0	110	(2.8)	270	45	0 - 5	13	(0.3)	115
Lap, T-Joints,	16	1.6	80	(2.0)	250	35	0 - 5	15	(0.4)	95
Horizontal Fillets										

(1) Tail-out is adjusted according to end-user acceptance requirements. Increasing tail-out can result in an increase in travel speed and improved wetting at the toes of a weld.

Stainless Steel Guidelines for STT II

Stainless Steel Sheetmetal

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.035” (0.9 mm), Blue Max	7	5.0	170	(4.3)	210	60	3 - 7	9	(0.2)	95
308LSi, 309LSi, 316LSi	10	3.2	160	(4.1)	200	55	3 - 7	10	(0.3)	85
3/8” (9 mm)	12	2.4	140	(3.6)	200	55	2	11	(0.3)	80
90%He+ 7.5%Ar+ 2.5%CO$_2$	14	2.0	130	(3.3)	190	50	2	14	(0.4)	70
Lap, T-Joints,	16	1.6	120	(3.0)	180	45	2	14	(0.4)	65
Horizontal Fillets	18	1.1	110	(2.8)	170	40	2	13	(0.3)	55
	20	0.9	100	(2.5)	165	35	2	15	(0.4)	50

Stainless Steel Sheetmetal

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.035” (0.9 mm), Blue Max	10	3.2	190	(4.8)	200	80	9	9	(0.2)	115
308LSi, 309LSi, 316LSi	12	2.4	165	(4.2)	190	70	7	10	(0.3)	100
3/8” (9 mm)	14	2.0	155	(3.9)	180	65	7	10	(0.3)	95
98%Ar + 2%O$_2$	16	1.6	140	(3.6)	160	65	7	14	(0.4)	85
Lap, T-Joints,	18	1.1	115	(2.9)	150	55	7	14	(0.4)	70
Horizontal Fillets	20	0.9	100	(2.5)	145	45	7	14	(0.4)	60

Stainless Steel Sheetmetal

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.035” (0.9 mm), Blue Max	7	5.0	180	(4.6)	235	90	3	18	(0.5)	140
308LSi, 309LSi, 316LSi	10	3.2	150	(3.8)	225	85	3	14	(0.4)	130
3/8” (9 mm)	12	2.4	140	(3.6)	225	80	3	17	(0.4)	130
90%He+ 7.5%Ar+ 2.5%CO$_2$	14	2.0	130	(3.3)	200	75	3	18	(0.5)	115
Lap, T-Joints,	16	1.6	120	(3.0)	190	70	3	21	(0.5)	100
Horizontal Fillets	18	1.1	100	(2.5)	170	60	3	16	(0.4)	85
	20	0.9	90	(2.3)	160	50	3	17	(0.4)	80

Stainless Steel Sheetmetal

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.045” (1.1 mm), Blue Max	7	5.0	170	(4.3)	230	95	5	14	(0.4)	140
308LSi, 309LSi, 316LSi	10	3.2	160	(3.8)	220	90	5	15	(0.4)	140
3/8” (9 mm)	12	2.4	150	(4.1)	220	90	5	18	(0.5)	135
55%He+ 42.5%Ar+ 2.5%CO$_2$	14	2.0	140	(3.6)	210	80	5	17	(0.4)	125
Lap, T-Joints,	16	1.6	120	(3.0)	200	70	5	20	(0.5)	105
Horizontal Fillets	18	1.1	100	(2.5)	180	60	5	15	(0.4)	95
	20	0.9	90	(2.3)	170	60	5	14	(0.4)	85

Nickel Alloy STT II Welding Guidelines

C276 Nickel Alloy Sheetmetal

Diameter, Wires CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.035” (0.9 mm)										
C-22, 625, C2000	10	3.2	180	(4.6)	220	75	5	13	(0.3)	90
3/8” (9 mm)	12	2.4	170	(4.3)	210	70	5	14	(0.4)	85
90%He + 7.5%Ar + 2.5%CO_2	14	2.0	160	(4.1)	200	65	5	12	(0.3)	80
Lap, T-Joints,	16	1.6	150	(3.8)	190	60	5	15	(0.4)	70
Horizontal Fillets										

Silicon Bronze STT II Welding Guidelines

Carbon Steel Sheetmetal

Diameter, Wire CTWD Shielding Gas Joint Types	Material Thickness Gauge	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Amps	Background Amps	Tailout	Travel Speed in/min	(M/min.)	Average Current
0.035” (0.9 mm)										
Silicon Bronze Filler	14	2.0	180	(4.6)	190	60	4	13	(0.3)	90
3/8” (9 mm)	16	1.6	170	(4.3)	180	55	2	13	(0.3)	80
100% Ar	18	1.1	170	(4.3)	180	55	2	15	(0.4	80
Lap Joints										

STT II Pipe Root Welding Guidelines

Carbon Steel Pipe - Root Pass Procedures

Diameter, Wire CTWD Shielding Gas Root, Land Included Angle	Wall Thickness Inches	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Current	Background Current	Tailout
0.045” (1.1 mm), L-56	1/8	(3.2)	125	(3.2)	380	35	0
1/2” (12.7 mm)	3/16	(4.8)	135	(3.4)	380	45	0
100% CO_2	1/4	(6.4)	135	(3.4)	380	45	0
3/32” (2.4 mm),	5/16	(7.9)	135	(3.4)	380	45	0 - 2
1/16” (1.6 mm)	3/8	(9.5)	145	(3.7)	380	45	0 - 3
60°	1/2	(12.7)	145	(3.7)	400	50	0 - 3

Stainless Steel Pipe - Root Pass Procedures

Diameter, Wire CTWD Shielding Gas Root, Land Included Angle	Wall Thickness Inches	(mm)	Wire Feed Speed in/min	(M/min.)	Peak Current	Background Current	Tailout
.0.045” (1.1 mm), Blue Max							
308LSi, 309LSi, 316LSi	1/8	(3.2)	115	(2.9)	190	50	5
1/2” (12.7 mm)	3/16	(4.8)	120	(3.0)	215	55	5
90%He + 7.5%Ar + 2.5%CO_2	1/4	(6.4)	120	(3.0)	215	55	5
	5/16	(7.9)	120	(3.0)	215	55	5
3/32” (2.4 mm),	3/8	(9.5)	130	(3.3)	220	62	5
1/16” (1.6 mm)	1/2	(12.7)	130	(3.3)	220	62	4
60°							

Rapid Arc® Welding Guidelines

Rapid Arc Welding Guidelines

The ensuing guidelines provide procedure settings for the use of Rapid Arc programs available on the Power Wave® 455. Rapid Arc™ is a higher travel speed GMAW-P program set developed for use with hard automation and robotic applications. It may be applied to semiautomatic applications, but the travel speeds will be far less than those employed with automated applications.

Welding Guidelines for Super Arc® L-56 solid wire.

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	800 (20.3)	30 (0.8)	0.90	24	243
0.035" (0.9 mm) L-56	3/16" (4.8 mm)	800 (20.3)	45 (1.1)	0.85	23	242
5/8" (15.9 mm)	10 Ga. (3.2 mm)	800 (20.3)	55 (1.4)	0.85	23.5	235
90% Ar/10% CO_2	12 Ga. (2.4 mm)	750 (19.1)	60 (1.5)	0.90	23.8	237
	14 Ga. (2.0 mm)	615 (15.6)	60 (1.5)	0.90	22.5	210

3 O'CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	800 (20.3)	40 (1.0)	0.90	24	250
0.035" (0.9 mm) L-56	3/16" (4.8 mm)	780 (19.8)	50 (1.3)	0.90	23.2	240
5/8" (15.9 mm)	10 Ga. (3.2 mm)	740 (18.8)	70 (1.8)	0.90	23	240
90% Ar/10% CO_2	12 Ga. (2.4 mm)	700 (17.8)	80 (2.0)	0.85	21.7	233
	14 Ga. (2.0 mm)	615 (15.6)	90 (2.3)	0.85	20.3	210

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	780 (19.8)	35-40 (0.9-1.0)	0.90	24.4	265
0.035" (0.9 mm) L-56	3/16" (4.8 mm)	780 (19.8)	50 (1.3)	0.90	24	245
5/8" (15.9 mm)	10 Ga. (3.2 mm)	650 (16.5)	50 (1.3)	0.90	23	220
90% Ar/10% CO_2	12 Ga. (2.4 mm)	650 (16.5)	60 (1.5)	0.90	23	221
	14 Ga. (2.0 mm)	600 (15.2)	70 (1.8)	0.90	22.4	200

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min	(M/min.)	Travel Speed in/min	(M/min.)	Trim	Volts	Amps
	1/4” (6.4 mm)	550	(14.0)	40	(1.0)	0.90	23	280
0.045” (1.1 mm) L-56	3/16” (4.8 mm)	525	(13.3)	50	(1.3)	0.85	21.3	276
3/4” (19.1 mm)	10 Ga. (3.2 mm)	500	(12.7)	60	(1.5)	0.85	21.4	280
90% Ar/10% CO_2	12 Ga. (2.4 mm)	450	(11.4)	60	(1.5)	0.80	19.5	260
	14 Ga. (2.0 mm)	375	(9.5)	60	(1.5)	0.80	19	211

3 O’CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min	(M/min.)	Travel Speed in/min	(M/min.)	Trim	Volts	Amps
	1/4” (6.4 mm)	500	(12.7)	45	(1.1)	0.85	21.7	265
0.045” (1.1 mm) L-56	3/16” (4.8 mm)	475	(12.1)	50	(1.3)	0.85	21.2	258
3/4” (19.1 mm)	10 Ga. (3.2 mm)	450	(11.4)	70	(1.8)	0.80	19.5	255
90% Ar/10% CO_2	12 Ga. (2.4 mm)	425	(10.8)	80	(2.0)	0.80	19.4	240
	14 Ga. (2.0 mm)	375	(9.5)	90	(2.3)	0.70	17	236

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min	(M/min.)	Travel Speed in/min	(M/min.)	Trim	Volts	Amps
	1/4” (6.4 mm)	475	(12.1)	35	(0.9)	0.90	22	260
0.045” (1.1 mm) L-56	3/16” (4.8 mm)	475	(12.1)	50	(1.3)	0.95	23.5	274
3/4” (19.1 mm)	10 Ga. (3.2 mm)	400	(10.2)	50	(1.3)	0.95	22	242
90% Ar/10% CO_2	12 Ga. (2.4 mm)	400	(10.2)	60	(1.5)	0.95	22.5	245
	14 Ga. (2.0 mm)	360	(9.1)	70	(1.8)	0.90	20.5	223

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min	(M/min.)	Travel Speed in/min	(M/min.)	Trim	Volts	Amps
	1/4” (6.4 mm)	400	(10.2)	35	(0.9)	0.85	21	320
0.052” (1.3 mm) L-56	3/16” (4.8 mm)	400	(10.2)	45	(1.1)	0.85	21.5	310
3/4” (19.1 mm)	10 Ga. (3.2 mm)	370	(9.4)	55	(1.4)	0.80	19.5	298
90% Ar/10% CO_2	12 Ga. (2.4 mm)	330	(8.4)	60	(1.5)	0.80	18	290
	14 Ga. (2.0 mm)	270	(6.9)	60	(1.5)	0.85	17	250

3 O'CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.052" (1.3 mm) L-56 3/4" (19.1 mm) 90% Ar/10% CO_2	1/4" (6.4 mm)	370 (9.4)	40 (1.0)	0.85	20.6	295
	3/16" (4.8 mm)	360 (9.1)	50 (1.3)	0.85	20.3	293
	10 Ga. (3.2 mm)	330 (8.4)	70 (1.8)	0.80	18.5	280
	12 Ga. (2.4 mm)	310 (7.9)	80 (2.0)	0.85	18.5	273
	14 Ga. (2.0 mm)	280 (7.1)	90 (2.3)	0.80	16.6	252

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.052" (1.3 mm) L-56 3/4" (19.1 mm) 90% Ar/10% CO_2	1/4" (6.4 mm)	360 (9.1)	35-40 (0.9-1.0)	0.90	21.7	289
	3/16" (4.8 mm)	360 (9.1)	50 (1.3)	0.90	21.1	277
	10 Ga. (3.2 mm)	300 (7.6)	50 (1.3)	0.90	19.9	260
	12 Ga. (2.4 mm)	300 (7.6)	60 (1.5)	0.95	20	260
	14 Ga. (2.0 mm)	275 (7.0)	70 (1.8)	0.95	19	250

Welding guidelines for Metalshield® MC-6 metal-cored wire.

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.045" (1.1 mm) MC-6 3/4" (19.1 mm) 90% Ar/10% CO_2	1/4" (6.4 mm)	550 (14.0)	35 (0.9)	0.95	26	300
	3/16" (4.8 mm)	525 (13.3)	50 (1.3)	0.85	22	280
	10 Ga. (3.2 mm)	450 (11.4)	70 (1.8)	0.80	20	241
	12 Ga. (2.4 mm)	375 (9.5)	70 (1.8)	0.80	19.5	214
	14 Ga. (2.0 mm)	350 (8.9)	70 (1.8)	0.90	21	200

3 O'CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.045" (1.1 mm) MC-6 3/4" (19.1 mm) 90% Ar/10% CO_2	1/4" (6.4 mm)	525 (13.3)	40 (1.0)	0.90	24	275
	3/16" (4.8 mm)	500 (12.7)	50 (1.3)	0.85	21	256
	10 Ga. (3.2 mm)	400 (10.2)	70 (1.8)	0.80	19.5	223
	12 Ga. (2.4 mm)	375 (9.5)	80 (2.0)	0.80	19	211
	14 Ga. (2.0 mm)	350 (8.9)	90 (2.3)	0.85	19.5	203

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.045” (1.1 mm) MC-6 3/4” (19.1 mm) 90% Ar/10% CO_2	1/4” (6.4 mm)	500 (12.7)	35-40 (0.9-1.0)	0.95	24	290
	3/16” (4.8 mm)	500 (12.7)	50 (1.3)	0.98	24.5	297
	10 Ga. (3.2 mm)	400 (10.2)	50 (1.3)	0.95	22.5	245
	12 Ga. (2.4 mm)	400 (10.2)	60 (1.5)	0.98	23	245
	14 Ga. (2.0 mm)	360 (19.1)	70 (1.8)	0.98	23	222

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.052” (1.3 mm) MC-6 3/4” (19.1 mm) 90% Ar/10% CO_2	1/4” (6.4 mm)	415 (10.5)	35 (0.9)	1.00	26	336
	3/16” (4.8 mm)	400 (10.2)	45 (1.1)	0.85	21.4	312
	10 Ga. (3.2 mm)	340 (8.6)	65 (1.7)	0.80	19.5	275
	12 Ga. (2.4 mm)	285 (7.2)	70 (1.8)	0.80	18.5	250
	14 Ga. (2.0 mm)	265 (6.7)	70 (1.8)	0.85	18.5	242

3 O’CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.052” (1.3 mm) MC-6 3/4” (19.1 mm) 90% Ar/10% CO_2	1/4” (6.4 mm)	400 (10.2)	40 (1.0)	0.90	23	318
	3/16” (4.8 mm)	375 (9.5)	50 (1.3)	0.85	21.5	287
	10 Ga. (3.2 mm)	300 (7.6)	70 (1.8)	0.85	20.2	242
	12 Ga. (2.4 mm)	285 (7.2)	80 (2.0)	0.85	20	232
	14 Ga. (2.0 mm)	260 (6.6)	90 (2.3)	0.85	19.2	218

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
0.052” (1.3 mm) MC-6 3/4” (19.1 mm) 90% Ar/10% CO_2	1/4” (6.4 mm)	325 (8.3)	35 (0.9)	1.00	24	275
	3/16” (4.8 mm)	325 (8.3)	40 (1.0)	1.00	24.2	277
	10 Ga. (3.2 mm)	300 (7.6)	50 (1.3)	1.00	23.4	254
	12 Ga. (2.4 mm)	285 (7.2)	60 (1.5)	1.00	23.3	246
	14 Ga. (2.0 mm)	260 (6.6)	70 (1.8)	0.95	21	236

HORIZONTAL LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	300 (7.6)	35 (0.9)	1.00	24	351
1/16" (1.6 mm) MC-6	3/16" (4.8 mm)	290 (7.4)	45 (1.1)	0.90	21	327
3/4" (19.1 mm)	10 Ga. (3.2 mm)	240 (6.1)	65 (1.7)	0.85	19.3	292
90% Ar/10% CO_2	12 Ga. (2.4 mm)	210 (5.3)	70 (1.8)	0.85	18	266
	14 Ga. (2.0 mm)	190 (4.8)	70 (1.8)	0.90	18.5	252

3 O'CLOCK LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	300 (7.6)	40 (1.0)	0.90	20.5	347
1/16" (1.6 mm) MC-6	3/16" (4.8 mm)	290 (7.4)	50 (1.3)	0.85	19.5	336
3/4" (19.1 mm)	10 Ga. (3.2 mm)	240 (6.1)	70 (1.8)	0.80	18.5	288
90% Ar/10% CO_2	12 Ga. (2.4 mm)	210 (5.3)	80 (2.0)	0.85	18	260
	14 Ga. (2.0 mm)	190 (4.8)	90 (2.3)	0.90	18	255

VERTICAL DOWN LAP WELD

Diameter, Wires CTWD Shielding Gas	Material Thickness	Wire Feed Speed in/min (M/min.)	Travel Speed in/min (M/min.)	Trim	Volts	Amps
	1/4" (6.4 mm)	215 (5.5)	35 (0.9)	1.00	21.8	275
1/16" (1.6 mm) MC-6	3/16" (4.8 mm)	215 (5.5)	40 (1.0)	1.00	21.5	275
3/4" (19.1 mm)	10 Ga. (3.2 mm)	200 (5.1)	50 (1.3)	1.00	21.4	254
90% Ar/10% CO_2	12 Ga. (2.4 mm)	190 (4.8)	60 (1.7)	1.00	20.5	243
	14 Ga. (2.0 mm)	170 (4.3)	70 (1.8)	1.05	20.5	227

Rapid Arc welding guideline considerations

All listed welding guidelines are starting points and may require some adjustment depending on specific applications. Torch angle, electrode placement, contamination, mill scale, joint fit-up, and joint consistency are factors that may require special consideration depending on the specific application. At higher travel speeds, joint fit-up, wire placement and contamination all become more significant factors. The result of welding at higher travel speeds is a tendency to produce more spatter, less penetration, more undercut, and a less desirable bead shape. Depending on the limitation of the actual application, slower travel speeds and higher trim settings may be required.

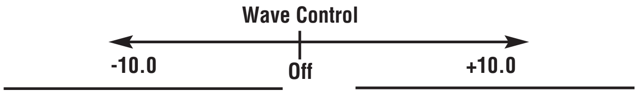
As the travel speed is increased in fast follow applications [1/4" (6.4 mm) to 14 gauge (2.0 mm)], a tighter, shorter arc must be maintained so that the puddle properly follows the arc. Operators typically reduce the arc length control (Trim), to achieve this. At faster travel speeds, the bead shape will not wet as well, and will become very convex and ropey. There is a point at which the arc is set so short that the arc will become unstable and stubbing will occur. This forms a limitation of just how fast the travel speed can be taken. Since Rapid Arc is stable at very low voltages, the travel speed can be significantly increased.

The preferred electrode diameter depends on the application. As a guideline, use the following rule of thumb:

Solid Wire Electrode (Super Arc L-56)
- 0.035” (0.9 mm) diameter for 14 gauge (2.0 mm) and 12 gauge (2.4 mm)
- 0.045” & 0.052” (1.1-1.3 mm) diameter for 10 gauge (3.2 mm) and thicker.

Metal Core Wire (Metalshield MC-6)
- 0.045” (1.1 mm) diameter for 14 gauge (2.0 mm); minimal heat input and good puddle control.
- 0.052” (1.3 mm) diameter for 12 gauge (2.4 mm).
- 1/16” (1.6 mm) diameter for 10 gauge (3.2 mm) and thicker; increases edge wetting and improves fit-up tolerance.
- Metal Core can make smaller weld beads, especially on 10 gauge (3.2 mm) and thinner base materials that tend to be over welded with solid wire electrode.

The improved Rapid Arc program features a modified **wave control** that acts as a fine tune adjustment of the arc. Similar to conventional pulse programs, an increase in wave control will results in a higher frequency and a more focused arc plasma. The results will be especially noticeable in the metal core rapid arc programs. Increasing wave control will improve welding performance in robotic applications.



• Semiautomatic operation.	• Automated operation.
• Reduced travel speeds.	• Increased travel speeds.
• More fluid puddle.	• Tighter arc.

Glossary

Anode The positive end of the welding circuit for a given arc welding process. Anode may reference the particular positive pole of a power source or it may reference the direct current positive region of the welding arc.

Axial Spray Transfer The high-energy mode of metal transfer in GMAW, which is characterized by a fine, axial stream of molten droplets from the end of the electrode.

CAC-A A carbon arc cutting process variation that removes molten metal with a jet of air.

Cathode The negative end of the welding circuit for a given arc welding process. Cathode may reference the negative pole of the power source or it may reference the negative cathode region of the welding arc.

Current Density The electrode current divided by the cross sectional area of the electrode. Important here is the concept that there is maximum current that can be applied to a given electrode diameter. Wire feed speeds beyond the maximum current density result in additional deposition rate.

GMAW American Welding Society acronym for gas metal arc welding. GMAW is an arc welding process that employs an arc between continuous filler metal and the molten weld pool. The electrode is either a solid or a tubular metal-cored electrode. Externally supplied shielding gas is required to protect the molten weld pool.

Globular Transfer A mode of metal transfer in GMAW characterized by large irregularly shaped metal drops from the end of the electrode, and it is commonly associated with high spatter levels. The globular transfer metal transfer mode occurs at arc voltages above those used for short-circuiting transfer, but below axial spray transfer.

GMAW-S Gas metal arc short-circuiting transfer is a low heat input mode of metal transfer in which the molten metal transfers from the electrode to the work piece during repeated short circuiting events. This process variation of GMAW lends itself to the joining of sheet metal range of base material.

GMAW-P Metal transfer modes of GMAW, which uses the advantages of the axial spray transfer mode. The pulsed transfer mode relies on current excursions beyond axial spray, which alternate with low current, to produce an average current. The frequency of the pulsed current cycle occurs many times per second. Designed to overcome lack of fusion defects, reduce weld spatter levels, and weld out-of-position, the pulsed spray transfer provides higher average currents than the short-circuiting mode of metal transfer. The average current is less than is seen in axial spray transfer.

Inert Shielding Gas Shielding gas for GMAW such as argon and helium, which do not react chemically with the molten pool. Aluminum, magnesium, copper, and titanium filler alloys require the use of 100% inert gases. Carbon steel, stainless steel, and nickel alloys usually provide improved arc performance with small additions of reactive gases.

Inductance An essential component for the successful operation of short-circuiting transfer. Inductance provides control of the rate of rise of short-circuit current. Inductance control has the effect of reducing spatter loss and controlling the level of spatter generated by traditional short-circuiting metal transfer. Adding inductance to the arc increase the amount of time that the arc is on, increases the transferred metal droplet size, and adds to the puddle fluidity. The finished weld bead appears flatter, smoother, and exhibits excellent weld toe wetting.

MIG A non-standard term used to describe GMAW or its variants. The acronym refers to Metal Inert Gas welding and it references the use of inert gases such as argon and helium.

Metal-Cored Electrode Composite tubular filler metal electrode consisting of a metal sheath and a core of powdered metals, scavengers, and deoxidizers. The finished weld has the appearance of a gas metal arc weld, but with larger slag islands. External gas shielding is required.

MAG Used to describe GMAW or its variants, the acronym refers to Metallic Active Gas, and it references the use of carbon dioxide shielding gas. The term is common in Europe.

Pinch Current The electromagnetic force relates to the magnitude of the welding current responsible for a given mode of metal transfer. The pinch current is larger in magnitude for axial spray transfer than it is for globular transfer, and globular transfer has a higher pinch current than does short-circuiting transfer.

Power Lead The welding current cable, which carries the welding current to the electrode.

Power Source An electrical apparatus designed to supply current and voltage suitable for welding, thermal cutting, or thermal spraying.

Pulsed Spray Transfer GMAW-P is a metal transfer mode of GMAW, which uses the advantages of the axial spray transfer mode. The pulsed transfer mode relies on current excursions beyond axial spray, which alternate with low current, to produce an average current. The frequency of the pulsed current cycle occurs many times per second. Designed to overcome lack of fusion defects, pulsed spray transfer provides higher average currents than the short-circuiting mode of metal transfer.

Reactive Power Source A power source designed to provide output, based upon feedback from the welding arc. This type of power source design is primary for the Surface Tension Transfer™ welding process. The reactive power source for Surface Tension Transfer is neither constant current nor constant voltage.

Reactive Shielding Gas Shielding gases such as carbon dioxide (CO_2) and oxygen (O_2) are reactive because they have a chemical interaction with the molten weld pool.

Short-Circuit in arc welding, is the physical contact between the electrode and the work piece.

Short-Circuiting Transfer A low heat input mode of metal transfer in which the molten metal transfers from the electrode to the work piece during repeated short-circuit. This process variation of GMAW lends itself to the joining a range of sheet metal base materials.

Spray Arc A non-standard term used to describe the high-energy mode of metal transfer known as axial spray transfer.

Surface Tension The forces that act in a molten droplet of weld metal to prevent it from flowing. The surface tension forces exist at a molecular level below the surface of the molten droplet and act upon those molecules at the surface of the molten drop.

Surface Tension Transfer™ A proprietary process developed by the Lincoln Electric Company, which provides a low heat input form of metal transfer. The process uses a reactive power source, which monitors the arc and is able to respond instantaneously to the changing arc requirements. The process relies on surface tension to transfer the molten metal from the electrode to the work piece.

STT™ The acronym used for Surface Tension Transfer.

Waveform Generator A specific term applied to inverter transfer power sources, which depend upon internal software to modulate the output of the power source. These types of power sources are unique to STT and other modes of GMAW transfer.

Wire Welding A non-standard term used to describe any welding process, which employs continuously fed filler metal. The electrode used may be tubular or solid electrodes.

Work Piece Lead The electrical conductor located between the power source and the work piece. In the GMAW process, the work-piece lead is usually DC-.

SAFE PRACTICES

Introduction. The general subject of safety and safety practices in welding, cutting, and allied processes is covered in ANSI Z49.1[8], "Safety in Welding and Cutting," and ANSI Z49.2[9]. "Fire Prevention in the Use of Welding and Cutting Processes." The handling of compressed gases is covered in CGA P-1[10].

Personnel should be familiar with the safe practices discussed in these documents, equipment operating manuals, and Material Safety Data Sheets (MSDS) for consumables.

In addition to the hazards discussed in the Arc Welding Safety Precautions following this section, be familiar with the safety concerns discussed below.

Safe Handling of Shielding Gas Cylinders and Regulators. Compressed gas cylinders should be handled carefully and should be adequately secured when in use. Knocks, falls, or rough handling may damage cylinders, valves, or fuse plugs and cause leakage or accident. Valve protecting caps, when supplied, should be kept in place (handtight) until the connecting of container equipment.

Cylinder Use. The following should be observed when setting up and using cylinders of shielding gas:

1. Properly secure the cylinder.
2. Before connecting a regulator to the cylinder valve, the valve should momentarily be slightly opened and closed immediately (opening) to clear the valve of dust or dirt that otherwise might enter the regulator. The valve operator should stand to one side of the regulator gauges, never in front of them.
3. After the regulator is attached, the adjusting screw should be released by turning it counter-clockwise. The cylinder valve should then be opened slowly to prevent a too-rapid surge of high pressure gas into the regulator.
4. The source of the gas supply (i.e., the cylinder valve) should be shut off if it is to be left unattended.

Metal Fumes. The welding fumes generated by GMAW can be controlled by general ventilation, local exhaust ventilation, or if the exposure cannot be adequately controlled using ventilation, by respiratory protective equipment as described in ANSI Z49.1. The method of ventilation required to keep the level of toxic substances within the welder's breathing zone below acceptable concentrations is directly dependent upon a number of factors. Among these are the material being welded, the size of the work area, and the degree of the confinement or obstruction to normal air movement where the welding is being done. Each operation should be evaluated on an individual basis in order to determine what ventilation, exhaust or personal protective equipment will be required. Legally required exposure limits for hazardous substances are called Permissible Exposure Limits (PEL) and are established by the Occupational Safety and Health Administration (OSHA). Exposure guidelines for hazardous substances are established by the American Conference of Governmental Industrial Hygienists (ACGIH) and are called Threshold Limit Values (TLV). The TLVs® represent conditions under which ACGIH® believes that nearly all workers may be repeatedly exposed without adverse health effects. These values are intended for use in the practice of industrial hygiene as guidelines or recommendations to assist in the control of potential workplace health hazards and are not fine lines between safe and dangerous. Exposure of a worker to harzardous substances can be measured by sampling the atmosphere under the welder's helmet or in the immediate vicinity of the helper's breathing zone. The principle composition or particulate matter (welding fume) which may be present within the welder's breathing zone are listed in the Supplement of Safe Practices. Sampling should be in accordance with ANSI/ AWS F1.1, Method for Sampling Airborne Particulates Generated by Welding and Allied Processes.

Gases. The major toxic gases associated with GMAW welding are ozone, nitrogen dioxide, and carbon monoxide. Phosgene gas could also be present as a result of thermal or ultraviolet decomposition of chlorinated hydrocarbon cleaning agents located in the vicinity of welding operations, such as trichlorethylene and perchlorethylene. DEGREASING OR OTHER CLEANING OPERATIONS INVOLVING CHLORINATED HYDROCARBONS SHOULD BE SO LOCATED THAT VAPORS FROM THESE OPERATIONS CANNOT BE REACHED BY RADIATION FROM THE WELDING ARC.

Ozone. The ultraviolet light emitted by the GMAW arc acts on the oxygen in the surrounding atmosphere to produce ozone, the amount of which will depend upon the intensity and the wave length of the ultraviolet energy, the humidity, the amount of screening afforded by any welding fumes, and other factors. The ozone concentration will generally be increased with an increase in welding current, with the use of argon as the shielding gas, and when welding highly reflective metals. If the ozone cannot be reduced to a safe level by ventilation or process variations, it will be necessary to supply fresh air to the welder either with an air supplied respirator or by other means.

Nitrogen Dioxide. Some test results show that high concentra-tions of nitrogen dioxide are found only within 6 in. (152 mm) of the arc. With normal natural ventilation, these concentrations are quickly reduced to safe levels in the welder's breathing zone, so long as the welder keeps his head out of the plume of fumes (and thus out of the plume of welding-generated gases). Nitrogen dioxide is not thought to be a hazard in GMAW.

Carbon Monoxide. CO shielding used with the GMAW process will be dissociated by the heat of the arc to form carbon monoxide. Only a small amount of carbon monoxide is created by the welding process, although relatively high concentrations are formed temporarily in the plume of fumes. However, the hot carbon monoxide oxidizes to CO so that the concentrations of carbon monoxide become insignificant at distances of more than 3 or 4 in. (76 or 102 mm) from the welding plume.

Under normal welding conditions there should be no hazard from this source. When the welder must work with his head over the welding arc, or with the natural ventilation moving the plume of fumes towards his breathing zone, or where welding is performed in a confined space, ventilation adequate to deflect the plume or remove the fumes and gases must be provided. Because shielding gases can displace air, use special care to insure that breathing air is safe when welding in a confined space. (See ANSI Z49.1.)

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[8] ANSI Z49.1 is available from the American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126, or the AWS website.

[9] ANSI Z49.2 is available from the American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

[10] CGA P-1 is available from the Compressed Gas Association, Inc., 1235 Jefferson Davis Highway, Suite 501, Arlington, VA 22202.

BIBLIOGRAPHY AND SUGGESTED READING

ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection*, American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

Arc Welding and Your Health: A Handbook of Health Information for Welding. Published by The American Industrial Hygiene Association, 2700 Prosperity Avenue, Suite 250, Fairfax, VA 22031-4319.

NFPA Standard 51B, *Cutting and Welding Processes*, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9146, Quincy, MA 02269-9959.

OSHA General Industry Standard 29 CFR 1910 Subpart Q. OSHA Hazard Communication Standard 29 CFR 1910.1200. Available from the Occupational Safety and Health Administration at http://www.osha.org or contact your local OSHA office.

The following publications are published by The American Welding Society, P.O. Box 351040, Miami, Florida 33135. AWS publications may be purchased from the American Welding society at http://www.aws.org or by contacting the AWS at 800-854-7149.

ANSI, Standard Z49.1, *Safety in Welding, Cutting and Allied Processes*. Z49.1 is now available for download at no charge at http://www.lincolnelectric.com/community/safety/ or at the AWS website http://www.aws.org.

AWS F1.1, *Method for Sampling Airborne Particulates Generated by Welding and Allied Processes.*

AWS F1.2, *Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes*.

AWS F1.3, *Evaluating Contaminants in the Welding Environment: A Strategic Sampling Guide*.

AWS F1.5, *Methods for Sampling and Analyzing Gases from Welding and Allied Processes*.

AWS F3.2, Ventilation Guide for Welding Fume Control

AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping That Have Held Hazardous Substances*.

AWS SHF, *Safety and Health Facts Sheets*.

LISTED BELOW ARE SOME TYPICAL INGREDIENTS IN WELDING ELECTRODES AND THEIR TLV (ACGIH) GUIDELINES AND PEL (OSHA) EXPOSURE LIMITS

INGREDIENTS	CAS No.	TLV mg/m^3	PEL mg/m^3
Aluminum and/or aluminum alloys (as Al)*****	7429-90-5	10	15
Aluminum oxide and/or Bauxite*****	1344-28-1	10	5**
Barium compounds (as Ba)*****	513-77-9	****	****
Chromium and chromium alloys or compounds (as Cr)*****	7440-47-3	0.5(b)	1.0(b)
Fluorides (as F)	7789-75-5	2.5	2.5
Iron	7439-89-6	10*	10*
Limestone and/or calcium carbonate	1317-65-3	10	15
Lithium compounds (as Li)	554-13-2	10*	10*
Magnesite	1309-48-4	10	15
Magnesium and/or magnesium alloys and compounds (as Mg)	7439-95-4	10*	10*
Manganese and/or manganese alloys and compounds (as Mn)*****	7439-96-5	0.2	5.0(c)
Mineral silicates	1332-58-7	5**	5**
Molybdenum alloys (as Mo)	7439-98-7	10	10
Nickel*****	7440-02-0	1.5	1
Silicates and other binders	1344-09-8	10*	10*
Silicon and/or silicon alloys and compounds (as Si)	7440-21-3	10*	10*
Strontium compounds (as Sr)	1633-05-2	10*	10*
Zirconium alloys and compounds (as Zr)	12004-83-0	5	5

Supplemental Information:

(*) Not listed. Nuisance value maximum is 10 milligrams per cubic meter. PEL value for iron oxide is 10 milligrams per cubic meter. TLV value for iron oxide is 5 milligrams per cubic meter.

(**) As respirable dust.

(*****) Subject to the reporting requirements of Sections 311, 312, and 313 of the Emergency Planning and Community Right-to-Know Act of 1986 and of 40CFR 370 and 372.

(b) TLV-PEL for water soluble chromium (VI) is 0.05 milligrams per cubic meter. The OSHA PEL is a ceiling value that shall not be exceeded at any time. The TLV for insoluble chromium (VI) is 0.01 milligrams per cubic meter.

(c) Values are for manganese fume. STEL (Short Term Exposure Limit) is 3.0 milligrams per cubic meter. Values are those proposed by OSHA in 1989. Present PEL is 5.0 milligrams per cubic meter (ceiling value).

(****) There is no listed value for insoluble barium compounds. The TLV for soluble barium compounds is 0.5 mg/m^3.

TLV and PEL values are as of 2005. Always check Material Safety Data Sheet (MSDS) with product or on the Lincoln Electric website at http://www.lincolnelectric.com

WARNING

CALIFORNIA PROPOSITION 65 WARNINGS

Diesel engine exhaust and some of its constituents are known to the State of California to cause cancer, birth defects, and other reproductive harm.	The engine exhaust from this product contains chemicals known to the State of California to cause cancer, birth defects, or other reproductive harm.
The Above For Diesel Engines	The Above For Gasoline Engines

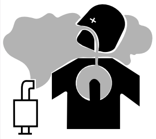
ARC WELDING CAN BE HAZARDOUS. PROTECT YOURSELF AND OTHERS FROM POSSIBLE SERIOUS INJURY OR DEATH. KEEP CHILDREN AWAY. PACEMAKER WEARERS SHOULD CONSULT WITH THEIR DOCTOR BEFORE OPERATING.

Read and understand the following safety highlights. For additional safety information, it is strongly recommended that you purchase a copy of “Safety in Welding & Cutting - ANSI Standard Z49.1” from the American Welding Society, P.O. Box 351040, Miami, Florida 33135 or CSA Standard W117.2-1974. A Free copy of “Arc Welding Safety” booklet E205 is available from the Lincoln Electric Company, 22801 St. Clair Avenue, Cleveland, Ohio 44117-1199.

BE SURE THAT ALL INSTALLATION, OPERATION, MAINTENANCE AND REPAIR PROCEDURES ARE PERFORMED ONLY BY QUALIFIED INDIVIDUALS.

FOR ENGINE powered equipment.

1.a. Turn the engine off before troubleshooting and maintenance work unless the maintenance work requires it to be running.

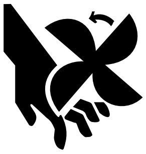


1.b. Operate engines in open, well-ventilated areas or vent the engine exhaust fumes outdoors.

1.c. Do not add the fuel near an open flame welding arc or when the engine is running. Stop the engine and allow it to cool before refueling to prevent spilled fuel from vaporizing on contact with hot engine parts and igniting. Do not spill fuel when filling tank. If fuel is spilled, wipe it up and do not start engine until fumes have been eliminated.

1.d. Keep all equipment safety guards, covers and devices in position and in good repair.Keep hands, hair, clothing and tools away from V-belts, gears, fans and all other moving parts when starting, operating or repairing equipment.

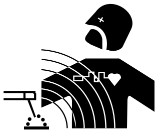
1.e. In some cases it may be necessary to remove safety guards to perform required maintenance. Remove guards only when necessary and replace them when the maintenance requiring their removal is complete. Always use the greatest care when working near moving parts.



1.f. Do not put your hands near the engine fan. Do not attempt to override the governor or idler by pushing on the throttle control rods while the engine is running.

1.g. To prevent accidentally starting gasoline engines while turning the engine or welding generator during maintenance work, disconnect the spark plug wires, distributor cap or magneto wire as appropriate.

1.h. To avoid scalding, do not remove the radiator pressure cap when the engine is hot.



ELECTRIC AND MAGNETIC FIELDS may be dangerous

2.a. Electric current flowing through any conductor causes localized Electric and Magnetic Fields (EMF). Welding current creates EMF fields around welding cables and welding machines

2.b. EMF fields may interfere with some pacemakers, and welders having a pacemaker should consult their physician before welding.

2.c. Exposure to EMF fields in welding may have other health effects which are now not known.

2.d. All welders should use the following procedures in order to minimize exposure to EMF fields from the welding circuit:

2.d.1. Route the electrode and work cables together - Secure them with tape when possible.

2.d.2. Never coil the electrode lead around your body.

2.d.3. Do not place your body between the electrode and work cables. If the electrode cable is on your right side, the work cable should also be on your right side.

2.d.4. Connect the work cable to the workpiece as close as possible to the area being welded.

2.d.5. Do not work next to welding power source.

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ELECTRIC SHOCK can kill.

3.a. The electrode and work (or ground) circuits are electrically "hot" when the welder is on. Do not touch these "hot" parts with your bare skin or wet clothing. Wear dry, hole-free gloves to insulate hands.

3.b. Insulate yourself from work and ground using dry insulation. Make certain the insulation is large enough to cover your full area of physical contact with work and ground.

In addition to the normal safety precautions, if welding must be performed under electrically hazardous conditions (in damp locations or while wearing wet clothing; on metal structures such as floors, gratings or scaffolds; when in cramped positions such as sitting, kneeling or lying, if there is a high risk of unavoidable or accidental contact with the workpiece or ground) use the following equipment:

- **Semiautomatic DC Constant Voltage (Wire) Welder.**
- **DC Manual (Stick) Welder.**
- **AC Welder with Reduced Voltage Control.**

3.c. In semiautomatic or automatic wire welding, the electrode, electrode reel, welding head, nozzle or semiautomatic welding gun are also electrically "hot".

3.d. Always be sure the work cable makes a good electrical connection with the metal being welded. The connection should be as close as possible to the area being welded.

3.e. Ground the work or metal to be welded to a good electrical (earth) ground.

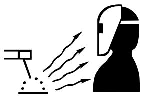
3.f. Maintain the electrode holder, work clamp, welding cable and welding machine in good, safe operating condition. Replace damaged insulation.

3.g. Never dip the electrode in water for cooling.

3.h. Never simultaneously touch electrically "hot" parts of electrode holders connected to two welders because voltage between the two can be the total of the open circuit voltage of both welders.

3.i. When working above floor level, use a safety belt to protect yourself from a fall should you get a shock.

3.j. Also see Items 6.c. and 8.



ARC RAYS can burn.

4.a. Use a shield with the proper filter and cover plates to protect your eyes from sparks and the rays of the arc when welding or observing open arc welding. Headshield and filter lens should conform to ANSI Z87. I standards.

4.b. Use suitable clothing made from durable flame-resistant material to protect your skin and that of your helpers from the arc rays.

4.c. Protect other nearby personnel with suitable, non-flammable screening and/or warn them not to watch the arc nor expose themselves to the arc rays or to hot spatter or metal.

FUMES AND GASES can be dangerous.

5.a. Welding may produce fumes and gases hazardous to health. Avoid breathing these fumes and gases.When welding, keep your head out of the fume. Use enough ventilation and/or exhaust at the arc to keep fumes and gases away from the breathing zone. **When welding with electrodes which require special ventilation such as stainless or hardfacing (see instructions on container or MSDS) or on lead or cadmium plated steel and other metals or coatings which produce highly toxic fumes, keep exposure as low as possible and below Threshold Limit Values (TLV) using local exhaust or mechanical ventilation. In confined spaces or in some circumstances, outdoors, a respirator may be required. Additional precautions are also required when welding on galvanized steel.**

5.b. Do not weld in locations near chlorinated hydrocarbon vapors coming from degreasing, cleaning or spraying operations. The heat and rays of the arc can react with solvent vapors to form phosgene, a highly toxic gas, and other irritating products.

5.c. Shielding gases used for arc welding can displace air and cause injury or death. Always use enough ventilation, especially in confined areas, to insure breathing air is safe.

5.d. Read and understand the manufacturer's instructions for this equipment and the consumables to be used, including the material safety data sheet (MSDS) and follow your employer's safety practices. MSDS forms are available from your welding distributor or from the manufacturer.

5.e. Also see item 1.b.

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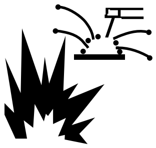


WELDING SPARKS can cause fire or explosion.

6.a. Remove fire hazards from the welding area. If this is not possible, cover them to prevent the welding sparks from starting a fire. Remember that welding sparks and hot materials from welding can easily go through small cracks and openings to adjacent areas. Avoid welding near hydraulic lines. Have a fire extinguisher readily available.

6.b. Where compressed gases are to be used at the job site, special precautions should be used to prevent hazardous situations. Refer to "Safety in Welding and Cutting" (ANSI Standard Z49.1) and the operating information for the equipment being used.

6.c. When not welding, make certain no part of the electrode circuit is touching the work or ground. Accidental contact can cause overheating and create a fire hazard.

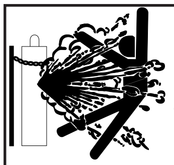
6.d. Do not heat, cut or weld tanks, drums or containers until the proper steps have been taken to insure that such procedures will not cause flammable or toxic vapors from substances inside. They can cause an explosion even though they have been "cleaned". For information, purchase "Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping That Have Held Hazardous Substances", AWS F4.1 from the American Welding Society (see address above 1.a. [Safety]).

6.e. Vent hollow castings or containers before heating, cutting or welding. They may explode.

6.f. Sparks and spatter are thrown from the welding arc. Wear oil free protective garments such as leather gloves, heavy shirt, cuffless trousers, high shoes and a cap over your hair. Wear ear plugs when welding out-of-position or in confined places. Always wear safety glasses with side shields when in a welding area.

6.g. Connect the work cable to the work as close to the welding area as practical. Work cables connected to the building framework or other locations away from the welding area increase the possibility of the welding current passing through lifting chains, crane cables or other alternate circuits. This can create fire hazards or overheat lifting chains or cables until they fail.

6.h. Also see item 1.c.



CYLINDER may explode if damaged.

7.a. Use only compressed gas cylinders containing the correct shielding gas for the process used and properly operating regulators designed for the gas and pressure used. All hoses, fittings, etc. should be suitable for the application and maintained in good condition.

7.b. Always keep cylinders in an upright position securely chained to an undercarriage or fixed support.

7.c. Cylinders should be located:

- Away from areas where they may be struck or subjected to physical damage.

- A safe distance from arc welding or cutting operations and any other source of heat, sparks, or flame.

7.d. Never allow the electrode, electrode holder or any other electrically "hot" parts to touch a cylinder.

7.e. Keep your head and face away from the cylinder valve outlet when opening the cylinder valve.

7.f. Valve protection caps should always be in place and hand tight except when the cylinder is in use or connected for use.

7.g. Read and follow the instructions on compressed gas cylinders, associated equipment, and CGA publication P-l, "Precautions for Safe Handling of Compressed Gases in Cylinders," available from the Compressed Gas Association 1235 Jefferson Davis Highway, Arlington, VA 22202.

FOR ELECTRICALLY powered equipment.

8.a. Turn off input power using the disconnect switch at the fuse box before working on the equipment.

8.b. Install equipment in accordance with the U.S. National Electrical Code, all local codes and the manufacturer's recommendations.

8.c. Ground the equipment in accordance with the U.S. National Electrical Code and the manufacturer's recommendations.

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Notes

CUSTOMER ASSISTANCE POLICY

The business of The Lincoln Electric Company is manufacturing and selling high quality welding equipment, consumables, and cutting equipment. Our challenge is to meet the needs of our customers and to exceed their expectations. On occasion, purchasers may ask Lincoln Electric for advice or information about their use of our products. We respond to our customers based on the best information in our possession at that time. Lincoln Electric is not in a position to warrant or guarantee such advice, and assumes no liability, with respect to such information or advice. We expressly disclaim any warranty of any kind, including any warranty of fitness for any customer's particular purpose, with respect to such information or advice. As a matter of practical consideration, we also cannot assume any responsibility for updating or correcting any such information or advice once it has been given, nor does the provision of information or advice create, expand or alter any warranty with respect to the sale of our products.

Lincoln Electric is a responsive manufacturer, but the selection and use of specific products sold by Lincoln Electric is solely within the control of, and remains the sole responsibility of the customer. Many variables beyond the control of Lincoln Electric affect the results obtained in applying these types of fabrication methods and service requirements.

Subject to Change – This information is accurate to the best of our knowledge at the time of printing. Please refer to www.lincolnelectric.com for any updated information.

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