Welding, Cutting & Allied Processes
and
Arc Welding Power Sources (Welding Machines)

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The information contained in this booklet represents a significant collection of technical information about welding, cutting, allied processes and arc welding power sources. This information will help to achieve increased reliability at a decreased cost. Assemblage of this information will provide a single point of reference that might otherwise be time consuming to obtain. Most of information given in this booklet is mainly derived from literature on the subject from sources as per the reference list given at the end of this booklet. For more information, please refer them. All information contained in this booklet has been assembled with great care. However, the information is given for guidance purposes only. The ultimate responsibility for its use and any subsequent liability rests with the end user. Please view the disclaimer uploaded on http://www.practicalmaintenance.net.

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Content

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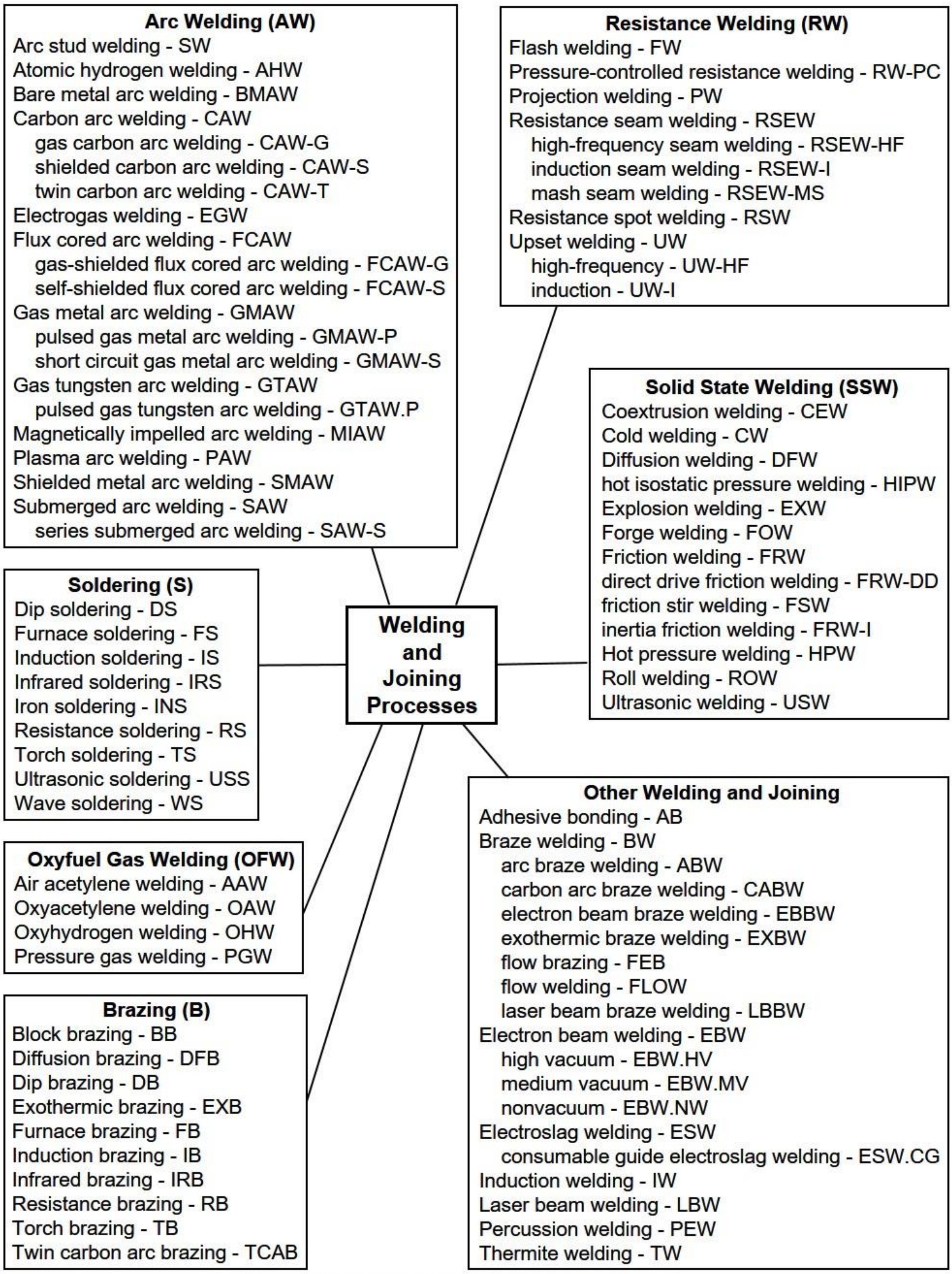
Introduction

There are numerous joining and cutting processes available for use in the fabrication of metal products. The term joining is generally used for welding, brazing, soldering, and adhesive bonding, which form a permanent joint between the parts - a joint that cannot be easily separated. The term assembly usually refers to mechanical methods of fastening parts together. Cutting can be carried out by mechanical means like sawing, turning, filing, grinding etc. and by thermal cutting methods like arc cutting, fuel cutting, etc.

Information about various welding and joining processes; thermal cutting methods; energy sources for welding, welding arc and arc welding; transformers, rectifiers and inverters; arc welding power sources; and safety during welding and cutting is given in this booklet.

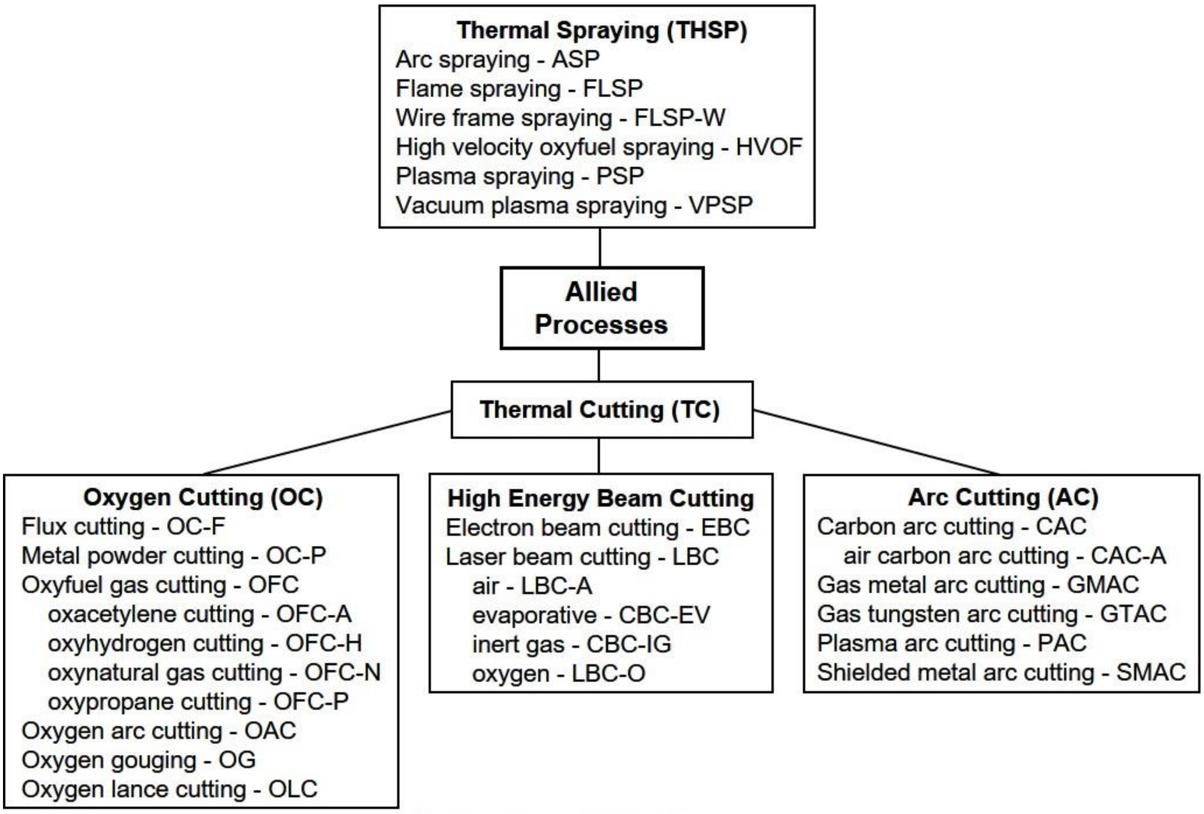
Welding, Cutting and Allied Processes

Information about various welding, cutting and allied processes is given in this chapter.



Master Chart of Welding and Joining Processes

Today, there are many welding and joining processes available. Above figure, Master Chart of Welding and Joining Processes provides a list of processes used in modern metal fabrication and repair. This list, published by the American Welding Society (AWS), also shows the official abbreviations for each process. For example, SMAW stands for shielded metal arc welding.



Master Chart of Allied Processes

Above figure, Master Chart of Allied Processes published by the American Welding Society (AWS) lists the allied processes related with welding and joining processes.

Welding and Joining Processes

According to AWS, a weld is, "a localized coalescence of metals or nonmetals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler metal." Coalescence means "joining together." Therefore, welding refers to the operations used to accomplish this joining operation. Many welding processes are accomplished by heat alone, with no pressure applied; others by a combination of heat and pressure; and still others by pressure alone, with no external heat supplied. In some welding processes a filler material is added to facilitate coalescence. Welding is most commonly associated with metal parts, but the process is also used for joining plastics. Information about some of the more common welding and joining processes is given in this section.

Arc Welding (AW)

The term arc welding applies to welding processes that use an electric arc as the source of heat. Arc welding processes do not usually involve pressure but may utilize a filler metal. In an arc welding, an arc is struck between the work piece and the tip of the electrode. The intense heat produced by the arc quickly melts a portion of the base metal, resulting in the formation of a weld.

Resistance Welding (RW)

Resistance welding achieves joining of faying surfaces using heat from electrical resistance to the flow of welding current passing between the faying surfaces held together under pressure.

Solid-State Welding (SSW)

The solid-state welding (SSW) refers to joining processes in which joining is accomplished by application of pressure at a temperature below the melting point of the base and filler metals.

The solid-state processes have the capability to join dissimilar metals that cannot be successfully joined with processes involving molten metal.

Oxyfuel Gas Welding (OFW)

Oxyfuel gas welding processes utilize the heat produced by an oxyfuel gas (such as a mixture of oxygen and acetylene) flame for melting the base metal and filler metal, if one is used to create a weld.

Brazing (B) and Soldering (S)

Brazing and soldering are liquid-solid state processes as they involve molten filler metal and solid base metal, which do not melt or mix. In brazing and soldering, the joints are designed for capillary action and the metallurgical bonds are produced by mutual diffusion rather than by fusion. The temperature required to effect joining determines whether the diffusion process is considered brazing or soldering. Brazing takes place when the metal is heated to above 840°F (450°C), while soldering occurs below this temperature.

Braze Welding (WB)

Braze welding is a joining process that accomplishes joining using a filler metal with a liquidus above 840°F (450°C) and below the solidus of the metal. Braze welding is different from brazing in that the filler metal is not distributed throughout the joint by means of capillary action.

Adhesive Bonding (AB)

Adhesive bonding is a joining process in which nonmetallic adhesive material is placed between the faying surfaces of the pieces to be joined, followed by a curing procedure to complete the bond. The bonding agent placed between the faying surfaces consists of an adhesive in the form of a liquid, paste, or tacky solid. Although natural organic and inorganic adhesives are available, synthetic organic polymers are usually employed to join metal assemblies.

Though many processes are used in industry, very few processes (shielded metal arc welding, gas tungsten arc welding, oxyacetylene welding, soldering, torch brazing, oxyacetylene cutting, plasma arc cutting and carbon arc cutting) are used in erection and maintenance. For detail information on various welding, joining and allied processes used in erection and maintenance, please see www.practicalmaintenance.net.

Welding and Allied Processes - Nomenclature as per ISO 4063

ISO 4063: Welding and allied processes - Nomenclature of processes and reference numbers establishes a nomenclature for welding and allied processes, with each process identified by a reference number. It covers the main groups of processes (one digit), groups (two digits) and sub-groups (three digits). The reference number for any process has a maximum of three digits. This system is intended as an aid in computerization, drawings, the drafting of working papers, welding procedure specifications, etc. Salient information about the standard is given in this section.

Following table shows main group reference number (one digit) and the main groups of welding and allied processes.

Main Group Reference Number (one digit)	Nomenclature of Main Group Processes
1	Arc Welding
2	Resistance Welding
3	Gas Welding
4	Welding with Pressure
5	Beam Welding
7	Other Welding Processes
8	Cutting and Gouging
9	Brazing, Soldering and Braze Welding

Above main groups (one digit) are divided into groups (two digits) relying on the same method of heating, which may themselves have sub-groups (three digits), for example:

1	**Arc Welding**
13	**Gas-shielded metal arc welding**
131	MIG welding with solid wire electrode

Following table shows the reference numbers for the main groups, groups and some sub-groups. For information on other sub-groups, please see ISO 4063.

Reference Numbers	Nomenclature of Processes
1	**Arc Welding**
11	Metal arc welding without gas protection
111	Manual metal arc welding (metal arc welding with covered electrode); Shielded metal arc welding, USA
112	Gravity (arc) welding with covered electrode; Gravity feed welding, USA
114	Self-shielded tubular cored arc welding
12	Submerged arc welding
121	Submerged arc welding with solid wire electrode
122	Submerged arc welding with strip electrode
124	Submerged arc welding with metallic powder addition
125	Submerged arc welding with tubular cored electrode
126	Submerged arc welding with cored strip electrode
13	Gas-shielded metal arc welding; Gas metal arc welding, USA
131	MIG welding with solid wire electrode; Gas metal arc welding using inert gas and solid wire electrode, USA
132	MIG welding with flux cored electrode; Flux cored arc welding, USA
133	MIG welding with metal cored electrode; Gas metal arc welding using inert gas and metal cored wire, USA
135	MAG welding with solid wire electrode; Gas metal arc welding using active gas with solid wire electrode, USA
136	MAG welding with flux cored electrode; Gas metal arc welding using active gas and flux cored electrode, USA

138	MAG welding with metal cored electrode; gas metal arc welding using active gas and metal cored electrode
14	Gas-shielded arc welding with non-consumable tungsten electrode; Gas tungsten arc welding, USA
141	TIG welding with solid filler material(wire/rod); Gas tungsten arc welding using inert gas and solid filler material (wire/rod), USA
15	Plasma arc welding
151	Plasma MIG welding
152	Powder plasma arc welding
18	Other arc welding processes
185	Magnetically impelled arc welding
2	**Resistance welding**
21	Resistance spot welding; Spot welding, USA
22	Resistance seam welding; Seam welding, USA
23	Projection welding
24	Flash welding
25	Resistance butt welding; Upset welding, USA
26	Resistance stud welding
27	HF resistance welding (high-frequency resistance welding); High-frequency upset welding, USA
29	Other resistance welding processes
3	**Gas welding; Oxyfuel gas welding, USA**
31	Oxyfuel gas welding
311	Oxyacetylene welding
312	Oxypropane welding
313	Oxyhydrogen welding
4	**Welding with pressure**
41	Ultrasonic welding
42	Friction welding
43	Friction stir welding
44	Welding by high mechanical energy
45	Diffusion welding
47	Oxyfuel gas welding pressure; Pressure gas welding, USA
48	Cold pressure welding; Cold welding, USA
49	Hot pressure welding
5	**Beam welding**
51	Electron beam welding
52	Laser welding; Laser beam welding, USA
7	**Other welding processes**
71	Aluminothermic welding; Thermite welding, USA
72	Electroslag welding
73	Electrogas welding
74	Induction welding
75	Light radiation welding
78	Arc stud welding
8	**Cutting and gouging**
81	Flame cutting; Oxygen cutting, Oxyfuel cutting, USA
82	Arc cutting
821	Air arc cutting; Air carbon arc cutting, USA
822	Oxygen arc cutting
83	Plasma cutting; Plasma arc cutting, USA
84	Laser cutting; Laser beam cutting, USA
86	Flame gouging; Thermal gouging, USA
87	Arc gouging
88	Plasma gouging
9	**Brazing, soldering and braze welding**
91	Brazing with local heating

912	Flame brazing; Torch brazing, USA
92	Brazing with global heating
921	Furnace brazing
922	Vacuum brazing
923	The Dip brazing bath
924	Salt-bath brazing
925	Flux-bath brazing
926	Immersion brazing
93	Other brazing processes
94	Soldering with local heating
942	Flame soldering; Torch soldering, USA
943	Soldering with soldering iron
95	Soldering with global heating
953	Furnace soldering
96	Other soldering processes
97	Weld brazing; Braze welding, USA
971	Gas weld brazing; Gas braze welding, USA
972	Arc weld brazing; Arc braze welding, USA
973	Gas metal arc weld brazing; Gas metal arc braze welding, USA
974	Gas tungsten arc weld brazing; Gas tungsten arc braze welding, USA
975	Plasma arc weld brazing; Plasma arc braze welding, USA
976	Laser weld brazing; Laser braze welding, USA
977	Electron beam weld brazing; Electron beam braze welding, USA

Process Marking/Designation

The marking/designation of the welding process must have the following structure: the number of this standard (ISO 4063), separated by a hyphen from the reference number of the process as shown in the example below.

Example: Marking for friction welding, reference number 42 should be ISO 4063-42.

Process Variations

For welding processes where different transfer modes are possible, the transfer mode may be indicated in accordance with following designation:

D - short-circuit transfer
G - globular transfer
S - spray (jet) transfer
P - pulsed transfer

For example: MIG welding with solid wire electrode using short-circuiting transfer is designated as ISO 4063-131-D

If more than one electrode is used, it may be indicated by number.

For example: MIG welding with two solid electrodes is designated as ISO 4063-131-2

If additional filler material is used, it is indicated in accordance with following designation:

C - cold wire
H - hot wire

For example: Submerged arc welding with a single solid wire electrode and additional cold wire is designated as ISO 4063-121-C

When more than one welding process is used simultaneously in one process area, the processes may be describes using the designation for each process separated by a plus symbol ("+"). For example: The joint use of laser welding and plasma welding together would be designated as ISO 4063-522 + 15.

ISO/DIS 4063

The fifth edition of ISO 4063, ISO/DIS 4063 Welding, brazing, soldering, cutting, mechanical joining and adhesive bonding - Nomenclature of processes and reference numbers cancels and replaces the fourth edition (ISO 4063:2009), which has been technically revised.

The main change in the fifth edition is the incorporation of processes and reference numbers for welding (thermal joining) of plastics, for mechanical joining and for adhesive bonding.

Because of the intrinsic limits of the three-digits system, it became necessary to adopt a four-digits system, where the first digit corresponds to the main type of technology (i.e.: 1xxx for mechanical joining and 2xxx for adhesive bonding), and the three following digits to the main process, sub-processes and sub-sub-processes.

However, since any change of a given existing process and reference number can have a very strong and negative impact in the industry, it was decided to keep the three-digits numbering system for all the processes already covered in previous editions.

Energy Sources for Welding, Welding Arc and Arc Welding

All welding processes require some form of energy. Information about power/energy density, energy sources for welding, plasma, welding arc and arc welding is given in this chapter.

Power Density

Although several coalescing mechanisms are available for welding, fusion is by far the most common means. To accomplish fusion, welding processes must produce sufficient heat to achieve localized melting of the base metals. Most fusion welding processes apply high-density heat energy from an external source to the weld joint to produce the weld bond. If a filler metal is added, the heat density must be high enough to melt it also. The transferred power/energy is the rate at which energy is delivered per unit time from the heat source to the work piece and is typically expressed in watts. Heat/power density can be defined as the power/energy transferred to the work piece per unit surface area, generally expressed in watts per square millimeter, W/mm^2 (or watts per square inch).

The heat produced by a welding heat source such as an arc gets transferred to the work piece in two stages. First, heat is transferred from the source to the surface of the work piece. Then, heat is transferred within the work piece from the contact area to colder regions of the materials to be joined. The time to melt the metal is inversely proportional to the power density. At low power densities, a significant amount of time is required to cause melting. If power density is too low, the heat is conducted into the work as rapidly as it is added at the surface, and melting never occurs. It has been found that the minimum power density required to melt most metals in welding is about 10 W/mm^2. As heat density increases, melting time is reduced. If power density is too high - above around 10^5 W/mm^2 - the localized temperatures vaporize the metal in the affected region. Thus, there is a practical range of values for power density within which welding can be performed. Following table shows power densities for the major fusion welding processes.

Power Densities for Fusion Welding Processes	
Welding Process	**Approximate Power Density, W/mm^2**
Oxyfuel welding	10
Arc welding	50
Resistance welding	1000
Laser beam welding	9000
Electron beam welding	10000

Oxyfuel gas welding is capable of developing large amounts of heat, but the power density is relatively low because it is spread over a large area. Oxyacetylene gas, the hottest of the OFW fuels, burns at a top temperature of around 3500°C (6300°F). By comparison, arc welding produces high energy over a smaller area, resulting in local temperatures of 5500°C to 6600°C (10000°F to 12000°F). With a very high energy density heat source, such as an electron beam, energy can be delivered to the contact area so rapidly that local melting occurs before there is any significant loss of heat by conduction. For metallurgical reasons, it is desirable to melt the metal with minimum energy, and high power densities are generally preferable.

Energy Sources for Welding

A welding process requires some form of energy. In many welding processes, the energy source provides the heat necessary for melting and joining. However, there are some welding processes that do not utilize heat, but require some form of energy to produce a bond. Based on type of energy source used, welding processes are grouped into five categories: electrical sources, chemical sources, focused sources, mechanical sources, and solid state sources.

Electrical Sources

Many welding processes for example arc welding and resistance welding use energy from electrical sources. In arc welding, an electric arc is used as the source of heat to accomplish fusion. In the resistance welding processes, heat and pressure are used to produce welds.

Chemical Sources

In case of chemical sources, chemical energy stored in the source is converted to useful heat. The temperature and the rate of reaction are two major characteristics that determine the application of the various energy sources. Oxyfuel gas welding and thermite welding are examples of processes that use chemical heat sources.

Focused Sources

The laser beam and the electron beam are two focused sources of welding energy that are governed by the laws of optics. The laser beam produces coalescence in a weldment with the heat from a laser beam impinging on the joint. In the electron beam welding process, coalescence is achieved with the heat from a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint.

Mechanical Sources (Solid-State)

Friction welding, ultrasonic welding, and explosion welding use mechanical sources of energy. All these processes involve some type of mechanical movement that produces the energy for welding. These are classified as solid-state processes because no melting of the base metals occurs in these processes.

Solid State Sources

Solid-state sources provide energy that drives the macroscopic or microscopic coalescence of materials in the solid state. Diffusion welding (DFW) is a solid-state welding process that relies almost solely on microscopic atomic diffusion to create a solid-state bond.

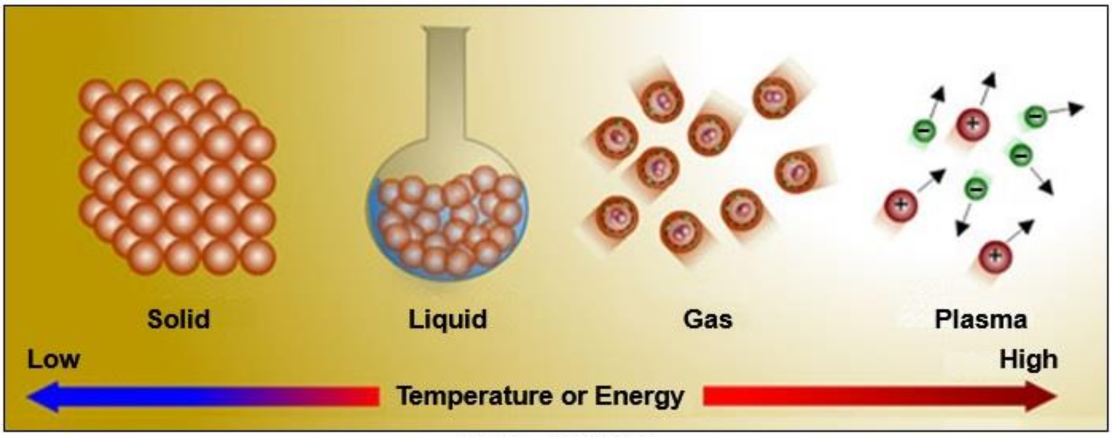
In diffusion welding, the energy for welding is provided by furnaces. The furnaces may be electrical or chemical. In the diffusion welding, localized deformation of the faying surfaces and diffusion of atoms across the interface occurs due to application of pressure at elevated temperature. As the diffusion welding process is not like arc, resistance, oxyfuel or thermite welding; it has not been included in the electrical or chemical sources for welding energy.

It may be noted that in diffusion welding, a solid-state bond is created by atomic motion whereas in case of mechanical sources, a solid-state bond is created by some type of mechanical movement.

Plasma

The different states of matter generally found on earth are solid, liquid, and gas. Sir William Crookes, an English physicist, identified a fourth state of matter, now called plasma, in 1879. The word "PLASMA" was first applied to ionized gas by Dr. Irving Langmuir, an American chemist and physicist, in 1929.

The first state is a solid and it is the coldest state of matter. As we heat up a solid it becomes liquid. Liquid is the second state of matter. As we heat up liquid, the liquid turns to gas. Gas is the third state of matter. As we heat up the gas, atoms break apart into a collection of free moving electrons and ions (atoms that have lost electrons) turning the gas into plasma.



States of Matter

Above figure shows various states of matter - Credits: NASA / UC Regents.

It may be noted that energy is needed to strip electrons from atoms to make plasma. The energy can be of various origins: thermal (heat), electrical, or light (ultraviolet light or intense visible light from a laser). With insufficient sustaining power, plasmas recombine into neutral gas.

Welding Arc

The use of electricity to weld metals together began with Sir Humphrey Davy and his student, Michael Faraday. In the first decade of the 19th century, Davy investigated the nature of electricity. At one point, he touched two carbon electrodes together and passed a current through them from a large battery. When the electrodes were drawn apart, the current jumped the gap, forming an electrical discharge. Its path from one electrode to the other was curved, not straight, hence the name arc.

The electric arc is extensively used heat source for fusion welding processes because the heat of the arc can be effectively concentrated and controlled. A welding arc can be considered a gaseous conductor that changes electrical energy into heat. The arc current is carried by plasma, the ionized state of a gas composed of nearly equal numbers of electrons and ions of gas atoms and molecules.

All gases are insulators and thus sufficient voltage needs to be available to strip electrons from atoms to make conducting path or plasma. Once this conducting path has been created, a lower voltage can normally maintain the arc though this will vary depending on the length of the arc gap. The voltage required to initiate the arc is termed the open circuit voltage or OCV requirement of the process/consumable. Voltage that maintains the arc is termed the welding or arc voltage. It may be noted that to begin the welding, first the electrode must always be touched on to the work since the smallest air gap will not conduct a current (at the open circuit voltage) unless the air gap is first ionized or made conducting.

The length of the arc is proportional to the voltage across the arc. If the arc length is increased beyond a certain point, the arc will suddenly go out. This means that there is a certain current necessary to sustain an arc of different lengths. If a higher current is used, a longer arc can be maintained.

The main function of the arc is to produce heat. However, at the same time, it produces a bright light, noise and bombardment. Bombardment may help remove surface oxides/films from the base metal.

The arc column is normally round in cross section and is made up of an inner core of plasma and an outer flame. The plasma carries most of the current. The plasma of a high current arc can reach a temperature of 5,000 to 50,000° Kelvin. The outer flame of the arc is much cooler and tends to keep the plasma in the center. The temperature and the diameter of the central plasma depend on the amount of current passing through the arc, the shielding atmosphere, and the electrode size and type.

The power of an arc may be expressed in electrical units as the product of the current passing through the arc and the voltage drop across the arc. Given the typical values of 400 A and 25 V for current and voltage, respectively, 10000 W of electrical power is dissipated as heat. Because all the heat generated in the arc can't be effectively utilized in arc welding processes due to heat losses in convection, conduction, radiation and spatter, the heat transfer (arc) efficiency, varies from 50 to 90 percent. Heat transfer efficiency (from arc to work piece) is generally low for GTAW, intermediate for SMAW, and high for SAW.

Many kinds of welding arcs have been conceived, each with a unique application in the field of metal joining. In some cases, the welding arc is operated in a steady state. More frequently, it is intermittent, subjected to interruptions by electrical short-circuiting, or it is continuously unsteady, influenced by the alternating directional flow of the current with ac operation.

Plasma Arc

In plasma arc heating sources, the arc is forced through a nozzle to constrict its diameter. Because a higher voltage is required to drive the arc through the nozzle and because the constriction reduces the diameter of the arc cylinder, the temperature of the arc and the energy density are significantly greater than those available with other nonconsumable electrode welding processes. The arc exits from the nozzle in the form of a high-velocity, intensely hot columnar plasma jet. This plasma jet is referred to as a plasma arc. Due to its high energy density, the plasma arc is used for welding, cutting and metal spraying.

Arc Welding

The term arc welding applies to a large group of welding processes that use an electric arc as the source of heat. The creation of a weld using these processes does not usually involve pressure but may utilize a filler metal. For welding, arc is struck between the work piece and the tip of the electrode. The intense heat produced by the arc quickly melts a portion of the base metal, resulting in the formation of a weld. Movement of the electrode relative to the work is accomplished by either a human welder (manual welding) or by mechanical means (called machine welding or robotic welding).

Arc welding operations are performed by conducting the welding current through electrodes. Two types of electrodes used in welding operations are: consumable electrodes, which take the form of a wire or rod; and nonconsumable electrodes, consisting of tungsten rods (or sometimes carbon rods). The consumable electrodes provide the source of the filler metal in the arc welding operation. They may also produce a slag covering to protect the molten metal from oxidation. Because the nonconsumable electrode serves only to sustain the arc, in case of welding operation that utilize nonconsumable electrodes, any filler metal required in the operation must be supplied by means of a separate wire that is fed into the weld pool.

Resistance, Reactance and Impedance

DC circuits are relatively easy to analyze, due to current flowing in one direction, with resistance being the main element of the circuit. AC circuits, on the other hand, are more complex, since voltage and current alternate direction with a given frequency. Whereas DC circuits have resistance, AC circuits often have resistance and another property, known as reactance. Impedance is the combination of resistance and reactance. As a ready reference, information about resistance, reactance, impedance, inductor and capacitor is given in this chapter.

Impedance

Impedance (symbol Z) is a measure of the overall opposition of a circuit to current, in other words: how much the circuit impedes the flow of charge. It is like resistance, but it also takes into account the effects of capacitance and inductance. Impedance is measured in ohms (Ω).

Impedance is more complex than resistance because the effects of capacitance and inductance vary with the frequency of the current passing through the circuit and this means impedance varies with frequency. The effect of resistance is constant regardless of frequency.

Impedance, $Z = \frac{V}{I}$ and

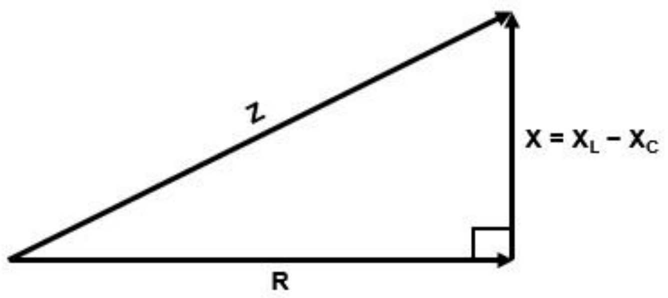
Resistance, $R = \frac{V}{I}$

Where,

Z = impedance in ohms (Ω)
R = resistance in ohms (Ω)
V = voltage in volts (V)
I = current in amps (A)

Impedance (Z) can be split into two parts:

- Resistance (R), the part which is constant regardless of frequency
- Reactance (X), the part which varies with frequency due to capacitance and inductance



Impedance

The capacitance and inductance cause a phase shift between the current and voltage which means that the resistance and reactance cannot be simply added up to give impedance. Instead they must be added as vectors with reactance at right angles to resistance as shown in above figure.

Reactance

Reactance is a property that opposes a change in current and is found in both inductors and capacitors. Because it only affects changing current, reactance is specific to AC power and depends on the frequency of the current. When reactance is present, it creates a 90° phase shift between voltage and current, with the direction of the shift depending on whether the component is an inductor or a capacitor.

Reactance (symbol X) is a measure of the opposition of inductance and capacitance to current. Reactance varies with the frequency of the electrical signal. Reactance is measured in ohms (Ω).

There are two types of reactance: inductive reactance (X_L) and capacitive reactance (X_C).

The total reactance (X) is the difference between the two: $X = X_L - X_C$

Inductive Reactance, X_L

Reactance that occurs in an inductor is known as inductive reactance. When inductive reactance is present, energy is stored in the form of a changing magnetic field, and the current waveform lags the voltage waveform by 90°. Inductive reactance is caused by devices in which wire is wound circularly - such as coils reactors, chokes, and transformers.

Inductive Reactance, $X_L = 2\pi fL$

Where,
X_L = reactance in ohms (Ω)
f = frequency in hertz (Hz)
L = inductance in henrys (H)

Hence, inductive reactance, X_L is small at low frequencies and large at high frequencies. For steady DC (frequency zero), X_L is zero (no opposition), which means that inductors pass DC but block high frequency AC.

Capacitive Reactance X_C

Reactance that occurs in a capacitor is known as capacitive reactance. Capacitive reactance stores energy in the form of a changing electrical field and causes current to lead voltage by 90°. Capacitance is created when two conducting plates are placed parallel to one another with a small distance between them, filled with a dielectric material (insulator).

Capacitive Reactance, $Xc = \frac{1}{2\pi fC}$

Where,
X_C = reactance in ohms (Ω)
f = frequency in hertz (Hz)
C = capacitance in farads (F)

Hence, capacitive reactance (X_C) is large at low frequencies and small at high frequencies. For steady DC which is zero frequency (f = 0 Hz), X_C is infinite (total opposition), which means that capacitors pass AC but block DC.

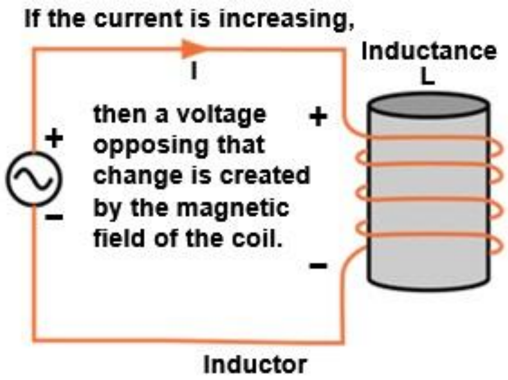
Resistors

Components known as resistors prevent current from flowing - in other words, they have the property of resistance. Resistors are found in both AC and DC circuits, and the energy that is prevented from flowing is expelled as heat. Mathematically, resistance is simply voltage divided by current.

$$R = \frac{V}{I}$$

Where,
R = resistance in ohms (Ω)
V = voltage in volts (V)
I = current in amps (A)

Inductors



As shown in above figure, in its most basic form, an inductor is simply a coil of wire. The schematic symbol for an inductor is that of a coil of wire. Inductors are categorized according to the type of inner core (for example air, iron, ferrite, etc.).

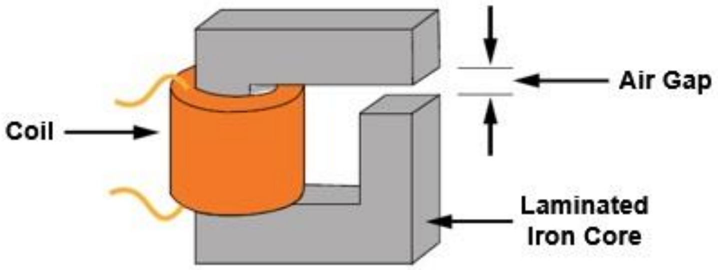
When a current (I) is flowing through an inductor, it produces a magnetic flux which is proportional to the flow of the electrical current. As per Faraday's law of electromagnetic induction, an electromotive force (voltage) is induced into the coil by this magnetic flux and it opposes or resists any changes in the electrical current flowing through it.

Inductance (Symbol L) is defined as the property of inductor (an electric circuit) that opposes any change in current flowing through it. To increase inductance, an inductor may have an iron core as it greatly increases the strength of the magnetic field. When they are used in AC (Alternating Current) circuits, they are called reactors. An inductor freely allows an unchanging current (for example Direct Current) but opposes a rapidly changing one.

The property of inductors makes them very useful in various applications. For example, inductors oppose any changes in current. Therefore, inductors can be used to protect circuits from surges of current. Inductors are also used to stabilize direct current and to control or eliminate alternating current. Inductors used to eliminate alternating current above a certain frequency are called chokes.

From Faraday's law, the inductance L may be defined in terms of the emf generated to oppose a given change in current: $\text{emf} = -L\frac{\Delta I}{\Delta t}$.

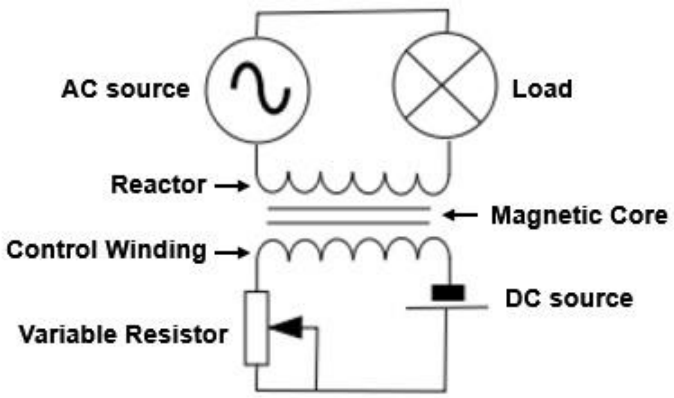
Unit for L: $\frac{\text{Volt Second}}{\text{Ampere}} = \text{Henry}$



Iron Core Inductor with Air Gap

As shown in above figure, some iron core inductors have air gap in their magnetic path so the magnetic flux lines must cross the gap. This action produces an Inductor with more linear properties then an un-gapped inductor. Ferromagnetic materials without an interruption in their magnetic path exhibit non-linear behavior.

Saturable Reactor



Saturable Reactor

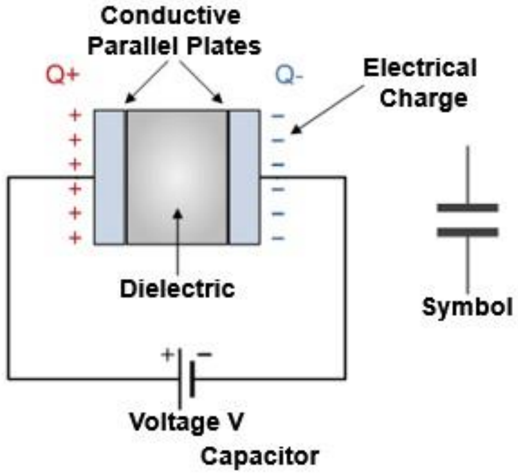
A saturable reactor is a special form of reactor (inductor) where the magnetic core can be deliberately saturated by a direct electric current in a control winding. Once saturated, the inductance of the saturable reactor drops dramatically. This decreases inductive reactance and allows increased flow of the alternating current (AC).

Saturable reactors provide a very simple means to remotely and proportionally control the AC through a load such as an incandescent lamp, the AC current is roughly proportional to the direct current (DC) through the control winding.

The reactor (power) windings, the control winding/s, and the magnetic core/s are arranged so that the control winding/s is well isolated from the power windings. The power windings (two reactors connected in series) are also usually configured so that they self-cancel any AC voltage that might otherwise be induced in the control winding/s.

Capacitors

A capacitor, sometimes referred to as a condenser is a device which stores electrical energy in the form of an electrostatic field producing a potential difference (static voltage) across its plates. In its basic form a capacitor consists of two parallel conductive (metal) plates that do not touch and are electrically separated either by air or some form of insulating material such as paper, mica or ceramic called the dielectric.



As shown in above figure, if a DC voltage is applied to the capacitor plates, current flows charging up the plates with electrons giving one plate a positive charge and the other plate an equal and opposite negative charge. This flow of electrons to the plates is known as the charging current and continues to flow until the voltage across both plates (and hence the capacitor) is equal to the applied voltage V. At this point the capacitor is said to be fully charged. The strength of this charging current will be at its maximum when the plates are fully discharged and will slowly reduce in value to zero as the plates charge up to a potential difference equal to the applied supply voltage.

Thus, when used in a direct-current or DC circuit, a capacitor blocks the flow of current through it, but when it is connected to an alternating-current or AC circuit, the current appears to pass straight through it with little or no resistance (due to continuously charging and discharging).

The parallel plate capacitor is the simplest form of capacitor and its capacitance value is fixed by the surface area of the conductive plates and the distance or separation between them.

By applying a voltage to a capacitor and measuring the charge on the plates, the ratio of the charge Q to the voltage V will give the capacitance value of the capacitor and capacitance is therefore given as: $C = \frac{Q}{V}$.

Where C is the capacitance in farads (symbol F, named after Michael Faraday) is a measure of a capacitor's capacity to store charge, Q is the magnitude of charge stored in coulombs on each plate and V is the voltage applied to the plates.

It may be note that capacitors return their stored energy to the circuit. They do not 'use up' electrical energy by converting it to heat as a resistor does. The energy stored by a capacitor is much smaller than the energy stored by a battery so they cannot be used as a practical source of energy for most purposes.

Transformers, Rectifiers and Inverters

All types of arc welding processes utilizes the transfer of electrical energy to heat energy, and to understand this transfer, a basic knowledge of electricity and welding power sources is necessary. In view of this, information about transformers, rectifiers, transistor and inverters is given in this chapter as they are utilized for making a welding power source (welding machine). Information about arc welding power sources is given in the next chapter.

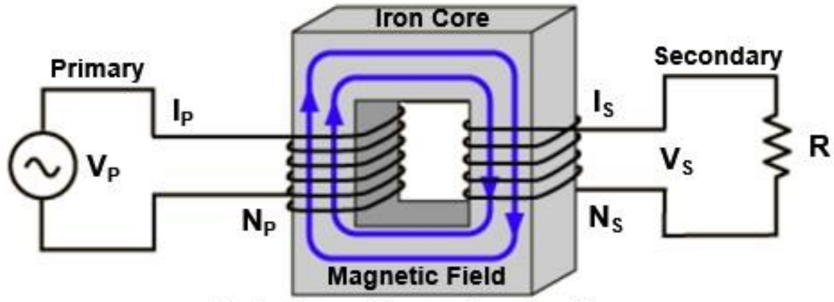
Relation Between Magnetism and Electricity

Whenever an electric current flows through a conductor, a magnetic field is immediately brought into existence in the space surrounding the conductor. It can be said that when electrons are in motion, they produce a magnetic field. The converse of this is also true i.e. when a magnetic field embracing a conductor moves relative to the conductor, it produces a flow of electrons in the conductor. This phenomenon whereby an electromotive force, emf and hence current (i.e. flow of electrons) is induced in any conductor which is cut across or is cut by a magnetic flux is known as electromagnetic induction. In 1831, Michael Faraday formulated basic laws underlying the phenomenon of electromagnetic induction (known after his name), upon which is based the operation of most of the commercial apparatus like motors, generators, transformers, etc.

Transformers

A transformer is a static (or stationary) device by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit, usually with a change in voltage. Transformers work only with a varying electric current, such as alternating current (AC).

Construction and Working



Typical Transformer Construction

Above figure shows construction of a typical transformer. In the above figure,

N_P = Number of turns in the primary coil/winding
N_S = Number of turns in the secondary coil/winding
V_P = Voltage in the primary coil/winding
V_S = Voltage in the secondary coil/winding
I_P = Current in the primary coil/winding
I_S = Current in the secondary coil/winding

As shown in above figure, a transformer consists of two or more coils (insulated wire windings) placed on the same iron core magnetic path. Thus, these coils are electrically separated but magnetically linked. The iron core is made up of sheets of rolled iron. This iron is of high silicon content so that it has a high magnetic conducting quality (high permeability).

The eddy current (which cause heating of the core) loss is minimized by laminating the core, the laminations being insulated from each other by a light coat of core-plate varnish on their surface.

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance and there is no magnetic leakage (and hence it is a transformer which has no resistance loss and core loss). In other words, an ideal transformer consists of two purely inductive coils wound on a loss-free core. It may, however, be noted that it is impossible to realize such a transformer in practice. Consider an ideal transformer whose secondary is open and whose primary (the primary is the coil which receives the energy) is connected to alternating voltage V_P. This potential difference causes an alternating current to flow in the primary. Since the primary coil (winding) is purely inductive and there is no output (secondary being open) the primary draws the magnetizing current I_μ only. The function of this current is merely to magnetize the iron core and it is small in magnitude. This alternating current I_μ produces an alternating magnetic flux (field) φ which is, at all times, proportional to the current. This changing magnetic flux (field) φ links both with the primary and the secondary coils. This changing magnetic flux (field) φ produces self-induced emf in the primary. This self-induced emf E_P is, at every instant, equal to and in opposition to V_P. It is also known as counter emf or back emf of the primary. This self-induced emf E_P is proportional to the alternating magnetic flux (field) φ and the number of primary turns. Similarly, there is produced in the secondary an induced emf E_S which is known as mutually induced emf. This emf is proportional to the alternating magnetic flux (field) φ and the number of secondary turns. This induced emf E_S is, at every instant, equal to and in opposition to V_S.

As per Faraday's Laws of Electromagnetic Induction, $\mathbf{emf} = -\mathbf{N}\frac{\Delta\boldsymbol{\varphi}}{\Delta \mathbf{t}}$ where,
N = Number of turns
∆ = Change
φ= Magnetic flux
t = Time

The negative sign in Faraday's Laws signify the fact that the induced emf sets up current in such a direction that magnetic effect produced by it opposes the very cause producing it.

Hence,
$E_P = V_P = -N_P\frac{\Delta\varphi}{\Delta t}$
$E_S = V_S = -N_S\frac{\Delta\varphi}{\Delta t}$

As magnetic flux (field) φ is same in both the primary coil and the secondary coil,

$$\frac{\mathbf{V_P}}{\mathbf{V_S}} = \frac{\mathbf{N_P}}{\mathbf{N_S}}$$

Thus the ratio of the number of turns in the primary coil to the number of turns in the secondary coil, the **turns ratio**, determines the ratio of the voltages in the two coils. For example, if there is one turn in the primary and ten turns in the secondary coil, the voltage in the secondary coil will be 10 times that in the primary. Such a transformer is called **a step-up transformer**. If there are ten turns in the primary coil and one turn in the secondary the voltage in the secondary will be one-tenth that in the primary. This kind of transformer is called a **step-down transformer**.

Again, for an ideal transformer, electrical power input (input voltage multiplied by input amperage) equals the electric power output (output voltage multiplied by output amperage).

Hence, Primary Power = Secondary Power, $V_P I_P = V_S I_S$ and $\frac{V_P}{V_S} = \frac{I_S}{I_P}$

Thus, the voltage ratio and the current ratio are inversely proportional. Therefore, if the voltage level is increased, the current level is decreased.

The greater the current, the larger size the wire leads are on the transformer. From this information we can determine the high and low voltage sides as under.

Higher voltage = lower current therefore smaller wire size
Lower voltage = higher current therefore larger size wire

Primary Loading with Secondary Loading

The current in the secondary controls the current in the primary. When the secondary circuit is completed by placing a load (R) across it, the secondary emf causes a current to flow. This builds up a magnetic flux (field) in opposition to the primary flux (field). This opposing, or demagnetizing, action reduces the effective flux of the primary flux, which in turn reduces the primary emf, thereby permitting more current to flow in the primary. The greater the current flow in the secondary, the greater is the flux produced by the secondary. This results in more reduced primary flux; resulting in a more reduction in primary emf produced. This condition permits greater current flow in the primary. This entire process will repeat itself whenever there is any change in the value of the current in either the primary or the secondary. A transformer adjusts itself readily to any normal change in secondary load. However, if a direct short is placed across the secondary, the abnormally great amount of current flowing causes the primary current to rise in a like manner, resulting in damage to, or complete burn-out of the transformer, if it is not protected properly.

Efficiency

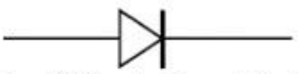
In general, transformer efficiency is about 97 percent. Only three percent of the total voltage at the secondary winding is lost through the transformation. The loss in voltage is due to core losses and copper losses. The core loss is the result of hysteresis (magnetic friction) and eddy currents (induced currents) in the iron core. The copper loss is power lost in the wire (resistance) of the windings.

% Efficiency = [Watts output (secondary) / Watts input (primary)] × 100

Rectifiers

A rectifier is an electrical device that converts an Alternating Current (AC) into a Direct Current (DC) by using one or more diodes.

Diode



Circuit Symbol for a Diode

A diode is made by two layers of semiconductor (p-type and n-type) sandwiched together to produce a junction. A diode is a one-way electrical valve. When placed in an electric circuit, a diode allows current to flow in one direction only (when the anode of the diode is positive with respect to the cathode). Using a proper arrangement of diodes, it is possible to convert alternating current to direct current. Above figure shows the circuit symbol for a diode. The arrow of the circuit symbol shows the direction in which the current can flow.

Labeling of a Diode

Diodes must be connected in the correct way. A diode may be labelled **a** or **+** for anode and **k** or **-** for cathode (yes, it really is k, not c, for cathode!) as shown in above figure.

Small **signal diodes** can be damaged by heat when soldering, but the risk is small unless you are using **germanium diodes** (codes beginning OA...) in which case one should use a heat sink clipped to the lead between the joint and the diode body. A standard crocodile clip can be used as a heat sink.

Rectifier diodes are quite robust and no special precautions are needed for soldering them. Rectifier diodes are used in power supplies to convert alternating current (AC) to direct current (DC). They are used where a large current must pass through the diode. In earlier times, rectifier diodes were made from selenium. Today, all rectifiers are made of silicon diodes for reasons of economy, current-carrying capacity, reliability, and efficiency.

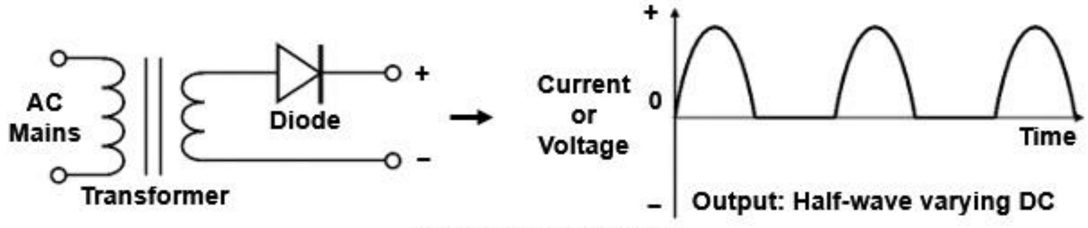
Transformer-rectifier or alternator-rectifier welding machines (power sources) rely on rectifiers to convert AC to DC. The resistance to current flow through a diode results in a voltage drop across it and generates heat within the diode. Unless this heat is dissipated, the diode temperature can increase enough to cause failure. Therefore, diodes are normally mounted on heat sinks (aluminum plates) to remove the heat.

Diodes have limits as to the amount of voltage they can block in the reverse direction (anode negative and cathode positive). This is expressed as the voltage rating of the device. Welding power source diodes are usually selected with a blocking rating at least twice the open circuit voltage in order to provide a safe operating margin.

A diode can accommodate current peaks well beyond its normal steady state rating, but a high, reverse voltage transient could damage it. Hence, most rectifier power sources for welding have a resistor, capacitor, or other electronic device to suppress voltage transients that could damage the rectifiers.

There are several ways of connecting diodes to make a rectifier to convert AC to DC. Two of them are as under.

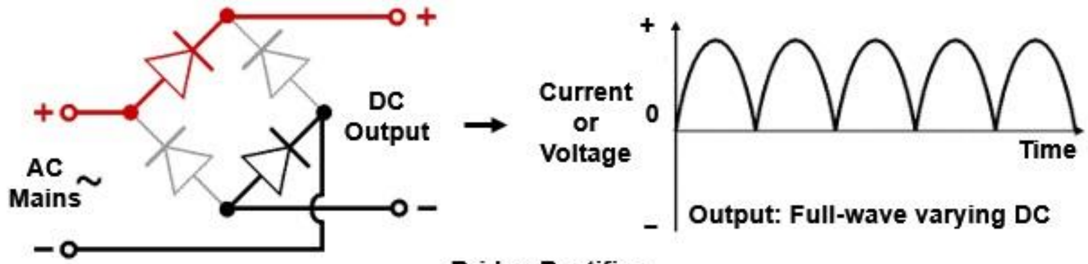
Single Diode Rectifier



Single Diode Rectifier

As shown above figure, a single diode can be used as a rectifier but it only uses the positive (+) parts of the AC wave (only half of the AC wave) to produce **half-wave** varying DC which has gaps (when the AC is negative).

Bridge Rectifier



Bridge Rectifier

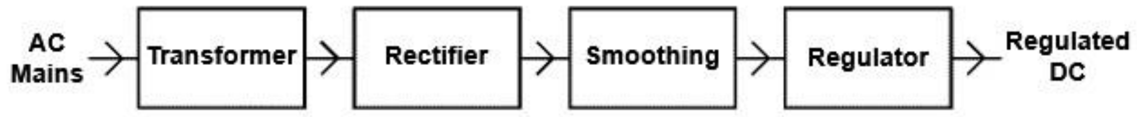
A bridge rectifier produces **full-wave** varying DC. As shown in above figure, a bridge rectifier can be made using four individual diodes. It may be noted that + and - labelled to AC Mains in above figure shows the positive (+) section of the AC wave.

It is called a full-wave rectifier because it uses the AC wave fully (both positive and negative sections). There are always two diodes conducting (alternate pairs of diodes) as shown in above figure. They change over the connections every half cycle such that alternating directions of AC are converted to the one direction of DC.

They have four leads or terminals: the two DC outputs are labelled + and -, the two AC inputs are labeled by a sine wave. Bridge rectifiers are rated by the maximum current they can pass and the maximum reverse voltage they can withstand.

Electric Power Supply

There are many types of electric power supply. Most are designed to convert the high voltage AC mains electricity to a suitable low voltage supply for electronic circuits and other applications like welding machines. A power supply can by broken down into a series of blocks, each of which performs a particular function as shown in the following figure.

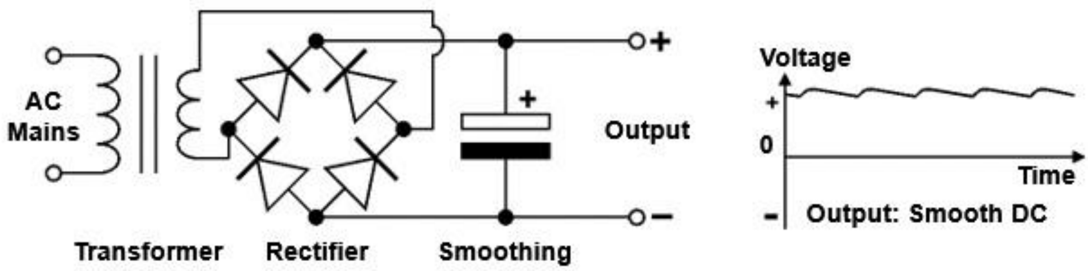


Block Diagram of a Regulated Power Supply System

A **transformer** steps down the high voltage AC mains to a low voltage AC.

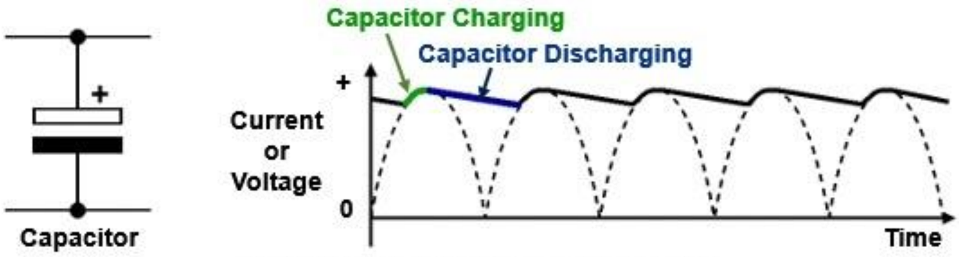
A **rectifier** converts AC to DC, but the DC output is varying.

Smoothing smoothies the DC from varying greatly to a small ripple. The varying DC output of rectifier is smoothened by a capacitor connected across the DC supply as shown in the following figure.



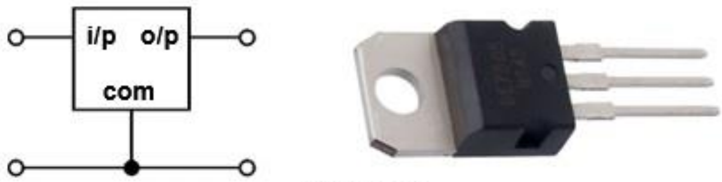
Smoothing of DC Output from Rectifier

Smoothing is performed by a large value electrolytic capacitor connected across the DC supply (DC output from the rectifier) to act as a reservoir, supplying current to the output when the varying DC voltage from the rectifier is falling as shown in the following figure.



Smoothing of Varying DC by Capacitor

Above diagram shows the unsmoothed varying DC (dotted line) and the smoothed DC (solid line). The capacitor charges quickly near the peak of the varying DC, and then discharges as it supplies current to the output. Smoothing is not perfect since the capacitor voltage falls a little as it discharges, giving a small **ripple voltage**. A larger capacitor will give less ripples.

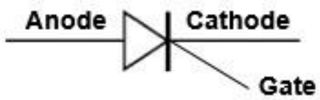


Regulator

A **regulator** eliminates ripple by setting DC output to a fixed voltage. Voltage regulator ICs are available with fixed (typically 5, 12 and 15V) or variable output voltages. They are also rated by the maximum current they can pass. Most regulators include some automatic protection from excessive current (overload protection) and overheating (thermal protection). They include a hole for attaching a heatsink if necessary.

Silicon Controlled Rectifiers (SCR) - Thyristors

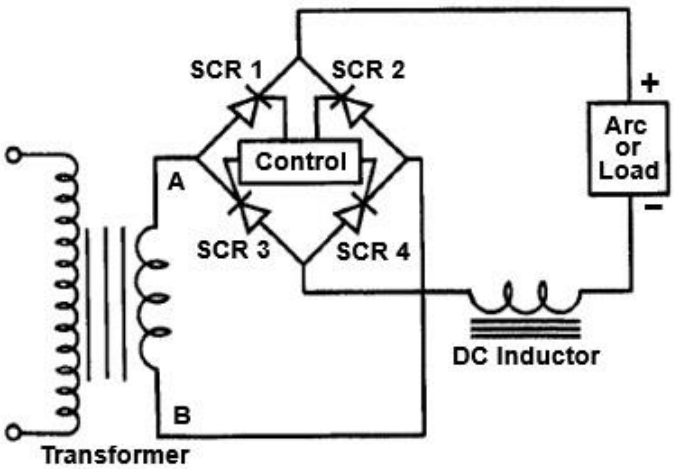
Solid-state (electronic) devices (devices without any moving parts) with special characteristics can be used to directly control welding power by altering the welding current or voltage wave form. Such solid-state devices have now replaced saturable reactors, moving shunts, moving coils, etc., formerly used to control the output of welding power sources (welding machines). The silicon controlled rectifier (SCR), sometimes called a thyristor is one of the most important of these devices. A silicon controlled rectifier is a brand name that General Electric introduced to describe one particular kind of thyristor that it made.



Circuit Symbol for a SCR

As shown above figure, a SCR is a variation of a diode (two junction diodes connected in series) with a trigger called a gate. A thyristor is like two transistors (an n-p-n and a p-n-p) that are connected together so the output from one forms the input to the other. The gate serves as a kind of "starter motor" to activate them. A SCR is non-conducting until a positive electrical signal is applied to the gate. When a positive electrical signal is applied to the gate, the device becomes a diode, and will conduct current as long as the anode is positive with respect to the cathode. However, once it conducts, the current cannot be turned off by a signal to the gate. Conduction will stop only if the voltage applied to the anode becomes negative with respect to the cathode. Conduction will not take place again until a positive voltage is applied to the anode and another gate signal is received.

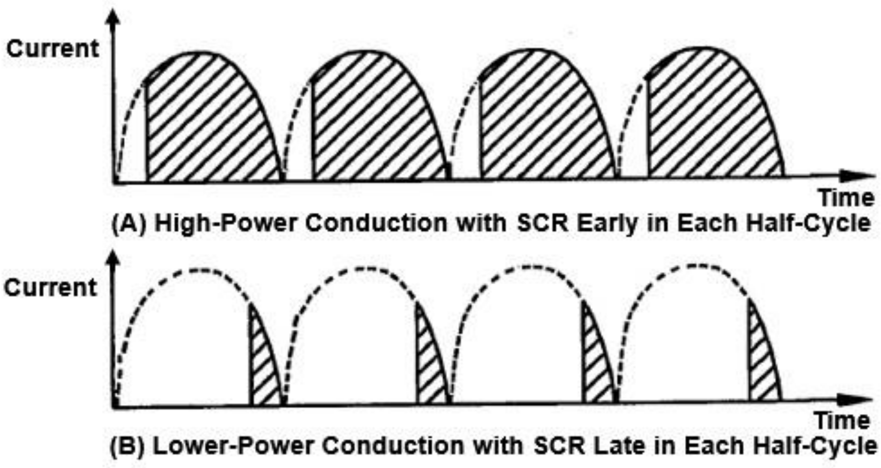
Silicon controlled rectifiers are used in phase-control mode with transformers and sometimes in inverter configurations. The output of a welding power source can be controlled by giving a gate signal to selectively turn on a SCR. Following figure shows a typical single-phase DC power source using an SCR bridge circuit for control.



Single Phase DC Power Source using an SCR Bridge for Control

In above figure, during the time when point A is positive with respective to point B, no current will flow until both SCR 1 and SCR 4 receives gate signals to turn them on. On receiving gate signals, current will flow through the load. At the end of the half-cycle, when the polarity of A and B reverses, a negative voltage will be impressed across SCR 1 and SCR 4, and they will turn off. With point B positive relative to point A, if gate signals are given now to SCR 2 and SCR 3 by the control, it will cause these two SCR to conduct, and current will flow through the load circuit again. To adjust power in the load, it is necessary to precisely time when, in any given half-cycle, the gate signals the SCR into conduction.

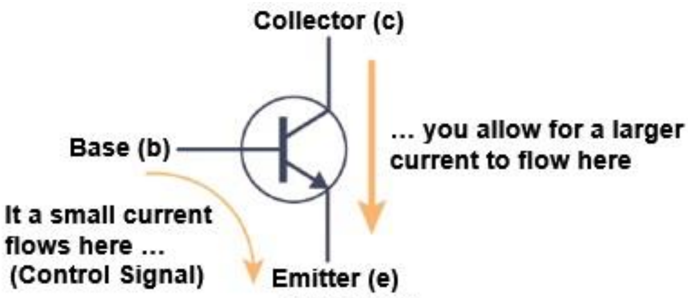
A DC inductor with a large inductance is used in the power source to smooth out the voltage and current pulses.



Use of SCR Bridge for Phase Control

As shown at (A) in above figure, when high power is required, conduction is started early in the half-cycle. If low power is required, conduction is delayed until later in a half-cycle, as shown at (B) in above figure. This type of control is known as phase control. The resulting power is supplied in pulses to the load and is proportional to the shaded areas in above figure under the wave form envelopes.

Transistors



Transistor

A transistor is also a solid-state device used in welding power sources. In a transistor, we have three layers of semiconductor arranged alternately (either p-n-p or n-p-n), giving two junctions. In a transistor, the base-to-emitter part of it works like a diode.

Using a transistor, one can use a small current or voltage to control a much larger current and voltage. A transistor differs from a SCR in many ways. In a transistor, conduction through it is proportional to the control signal applied. With no signal, there is no conduction. When a small signal is applied, there is a corresponding small conduction and with a large signal, there is a correspondingly large conduction. Unlike the SCR, the control can turn off the device without waiting for polarity reversal or an "off" time. In welding power supplies, they are used for frequency modulation and pulse width modulation.

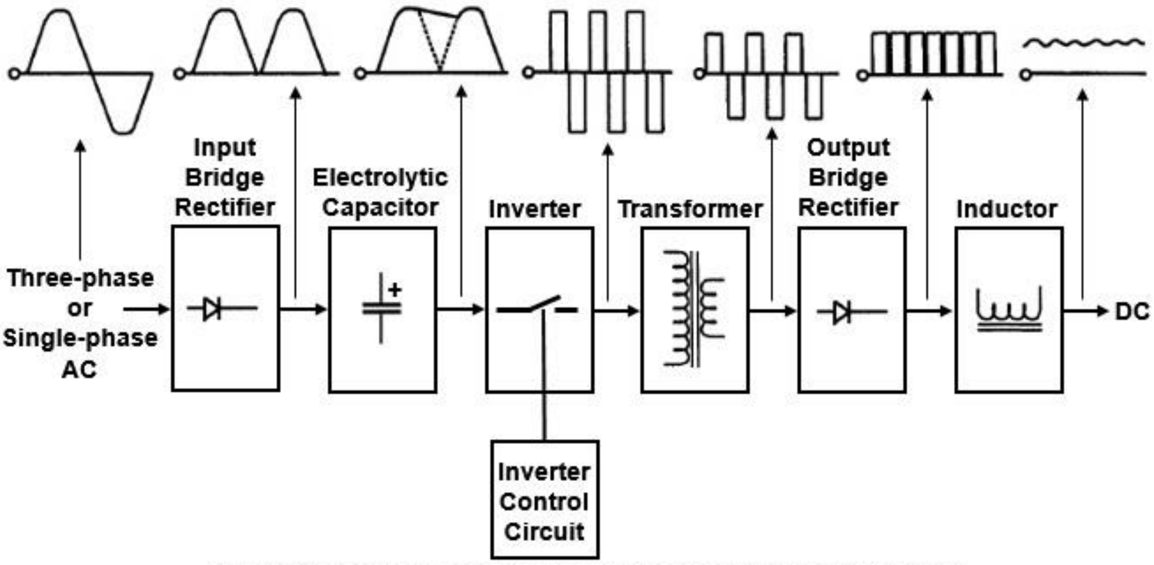
A transistor is also used as an electronic switch, an electronic (solid-state) version of relays (electromagnetic switches).

It may be noted that while a transistor generally deals with tiny electronic currents (milliamps), a thyristor can handle electric power currents (at several hundred volts).

Inverters

The primary contributors to weight/mass in any power source are its magnetic components (main transformer and filter inductor). The use of an inverter circuit can produce significant reductions in size and weight of these components as well as decrease their electrical losses. Thus an inverter based power source is smaller, more compact, requires less electricity than conventional welding power sources, and offers a faster response time.

An inverter is a circuit which uses solid-state devices called metal oxide semiconductor field effect transistors (MOSFETs), or integrated gate bi-polar transistors (IGBTs) to convert DC into high-frequency AC, usually in the range of 20 kHz to 100 kHz before stepping down the voltage. Conventional welding power sources use transformers operating from a line frequency of 50 or 60 Hz. Since transformer size is inversely proportional to line or applied frequency, reductions of up to 75 percent in power source size and weight are possible using inverter circuits.



Block Diagram of Power Source Using Inverter for DC Welding

Above figure shows a block diagram of power source sections and voltage wave forms using inverter with pulse-width modulation control to produce DC for welding. As shown in above figure, first the incoming three-phase or single-phase 50/60 HZ power is converted to DC by a full wave rectifier. This DC is applied to the inverter which, using semiconductor switches, inverts it into high frequency square wave AC or sine waves (for welding application) in a resonant technology, with frequency modulation control. The switching of the semiconductors takes place between 1 kHz and 50 kHz depending on the component used and method of control. This high frequency voltage allows the use of a smaller step down transformer. After being transformed, the AC is rectified to DC for welding.

Arc Welding Power Sources

The power source (welding machine) is the heart of all arc welding processes. Selecting the correct power source depends upon the process requirements. Many types of power sources are available to meet the unique electrical requirements of the various arc welding processes. In view of this, information about the technical aspects of various power sources is given in this article.

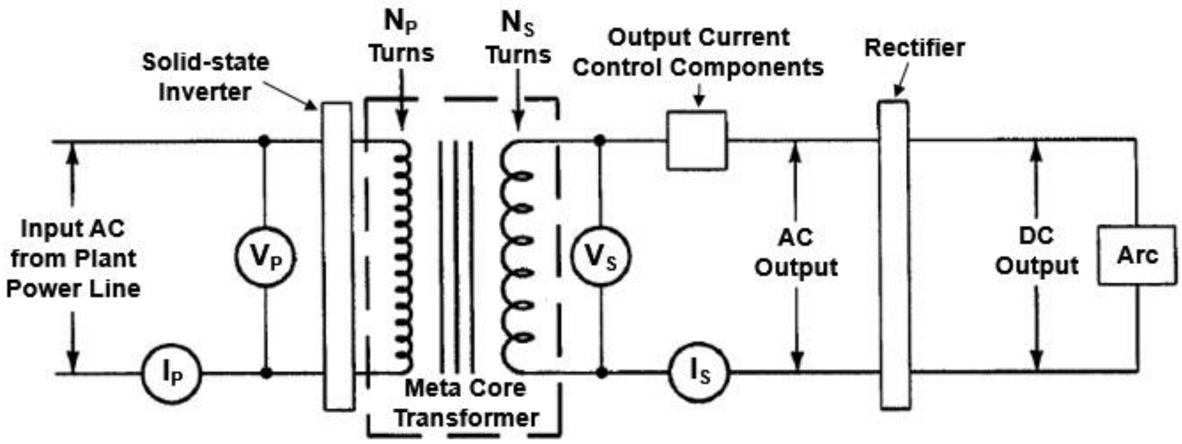
Introduction

Arc welding involves the use of low-voltage, high-current arc between an electrode and the workpiece to produce the heat needed for melting the base plate. The voltage supplied by power (utility) companies is too high for using it directly in an arc welding. Therefore, the function of arc welding power sources is to reduce the high input or line voltage to a suitable output voltage range (usually 20 to 80 volts). A transformer or an electric motor-generator can be used to reduce the utility power to terminal or open circuit voltage appropriate for arc welding. Alternatively, a power source for arc welding may derive its power from a prime mover such as an internal combustion engine. The mechanical power from an internal combustion engine cab be used to rotate a generator or an alternator for the source of electrical current.

Welding transformers or generator/alternators provide high-amperage welding current, generally ranging from 30 amperes (A) to 1500 A. The output of a power source may be alternating current (AC), direct current (DC) or both. It may be constant current, constant voltage, or both. Welding power sources may also provide pulsed output of voltage or current.

Power source designs deliver only certain types of current. Transformer power sources deliver AC only. Transformer-rectifier power sources can deliver either AC or DC, as selected by the operator. Electric motor-generator power sources deliver DC output. A motor-alternator delivers AC, or when equipped with rectifiers, DC.

Construction and Working of Transformer Power Sources for Welding



Components of a Transformer Power Source for Welding

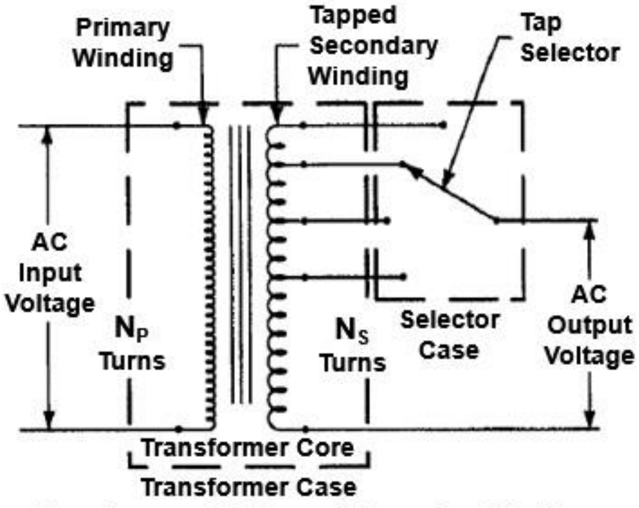
Above figure shows components of a transformer power source for welding. A transformer is a magnetic device that operates on alternating current. The primary winding, with N1 turns of wire is energized by an alternating current input voltage V_P, thereby magnetizing the core. The core couples the alternating magnetic field into the secondary winding, with N2 turns of wire, producing an output voltage V_S.

For a transformer, the relationships between winding turns, voltages and currents in the primary and secondary windings is as follows:

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_P}{I_S}$$

Where,
N_P = Number of turns in the primary winding
N_S = Number of turns in the secondary winding
V_P = Voltage in the primary winding = Input voltage
V_S = Voltage in the secondary winding = Output voltage
I_P = Current in the primary winding = Input current
I_S = Current in the secondary winding = Output (load) current

As shown in above equation, because the primary to secondary current ratio is inversely proportional to the primary to secondary voltage ratio, large secondary welding currents can be obtained from relatively low line input currents.



Transformer with Tapped Secondary Winding

A tapped transformer permits the selection of number of turns, N_S, in the secondary winding of the transformer. Hence, as shown in above figure, taps in the transformer secondary winding may be used to change the number of turns in the secondary winding to vary the open circuit (no-load) output voltage.

Rectifier

A rectifier converts alternating current (AC) to direct current (DC). In AC/DC welding power sources incorporating a rectifier, the rectifier is located between the output current control components and the output terminal. If a single rectifying element called a diode is placed in an electrical circuit, it allows current to flow in one direction only. Using a proper arrangement of diodes called a bridge rectifier, it is possible to convert alternating current to direct current. Silicon controlled rectifier (SCR) or thyristor is a variation of a diode. A proper arrangement of silicon controlled rectifiers can be used to control welding power by altering the welding current or voltage wave form. Transformer-rectifier arc welding power sources usually include a stabilizing inductance, or choke, located in the dc welding circuit to improve arc stability by smoothing out the voltage and current pulses.

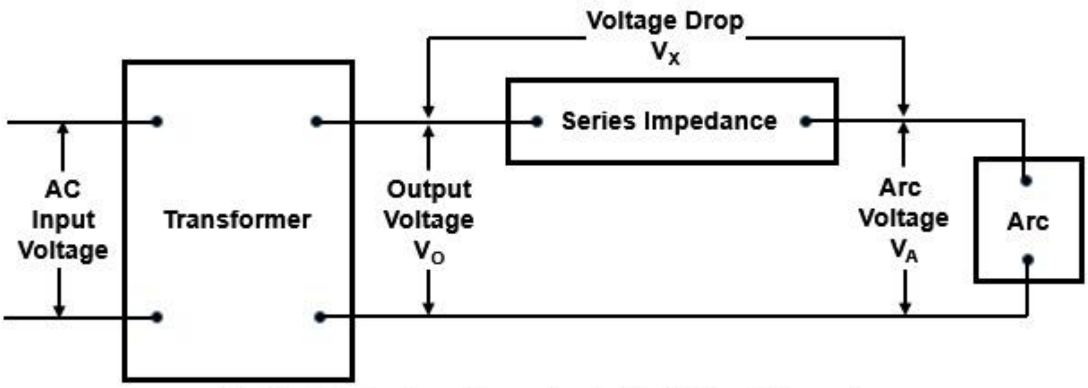
Solid-state Inverter

An inverter is a circuit that uses solid-state devices to convert (invert) direct current into high frequency AC, usually in the range of 20 kHz to 100 kHz. Conventional welding power sources use transformers operating from a line frequency of 50 Hz or 60 Hz.

In an inverter power source, first a full-wave rectifier converts incoming 50-Hz or 60-Hz power to direct current. Then this direct current is applied to the inverter, which inverts it into high-frequency alternating current. This high-frequency voltage allows the use of a smaller step-down transformer. After being transformed, the alternating current is rectified to direct current for welding.

Inverter welding power sources are smaller, more efficient and they offer better performance than their line-frequency counterparts because the size and weight of iron-core components (transformer and the filter inductor, called choke) are reduced when operating at higher frequencies.

Output Current Control Components



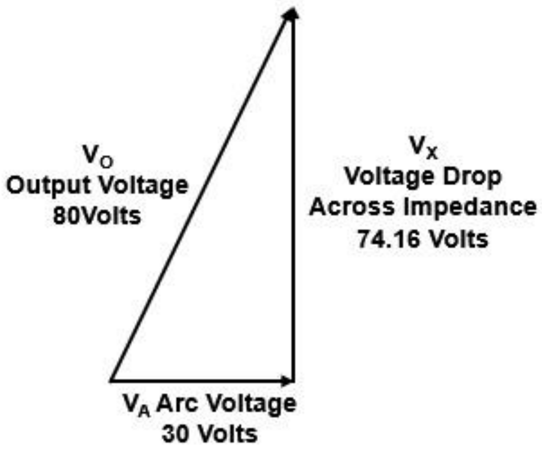
Typical Series Impedance Control of Output Current

As shown in above figure, to adjust the output volt-ampere characteristics, often an impedance source is inserted in series with the transformer secondary winding. The impedance is usually a magnetic device and is called a reactor when used in an AC welding circuit and an inductor when used in a DC welding circuit.

In constant current power sources, the voltage drop across the impedance, V_X increases greatly as the load current is increased. This increase in voltage drop, V_X, causes a large reduction in the arc voltage, V_A. Adjustment of the value of the series impedance controls the V_A voltage drop and the relation of load current to load voltage. This is called current control, or in some cases, slope control. The no-load (open circuit) voltage of the power source equals to the output voltage of the transformer, V_O.

The series impedance in constant voltage power sources is typically small, and the transformer output voltage, V_O is very similar to that required by the arc. The voltage drop, V_X, across the impedance (reactor) increases only slightly as the load current increases and the reduction in load voltage is small. Adjustment in the value of reactance gives slight control of the relation of load current to load voltage.

Following figure shows a vector diagram for the relationship of the alternating voltages for above circuit when a reactor is used as an impedance device. Vector addition is necessary because the alternating load and impedance voltages are not in time phase.



Vector Diagram Showing Alternating Voltages when reactor is used to control output

As shown in above figure, when added vectorially, the output voltage of the transformer, V_O (no-load voltage) equals the voltage drop across the impedance, V_X plus the arc (load) voltage, V_A. As shown in above figure, if the open circuit voltage of the transformer is 80 V and the voltage drop across the reactor is 74.16 V, then the arc load voltage will be 30 V.

By varying the voltage drop across the impedance, the load or arc voltage may be changed. Though both reactance and resistances may be used to produce a drooping voltage characteristic, an advantage of using a reactor is that it consumes little or no power, even though a current flows through it and a voltage is developed across it. When series resistor is used, power is lost and the temperature of the resistor rises. It may be noted that in a purely resistive circuit (no reactance), the voltage drop across the resistor could be added arithmetically to the load voltage to equal the output voltage of the transformer because the voltage and current are in phase in the resistive circuit.

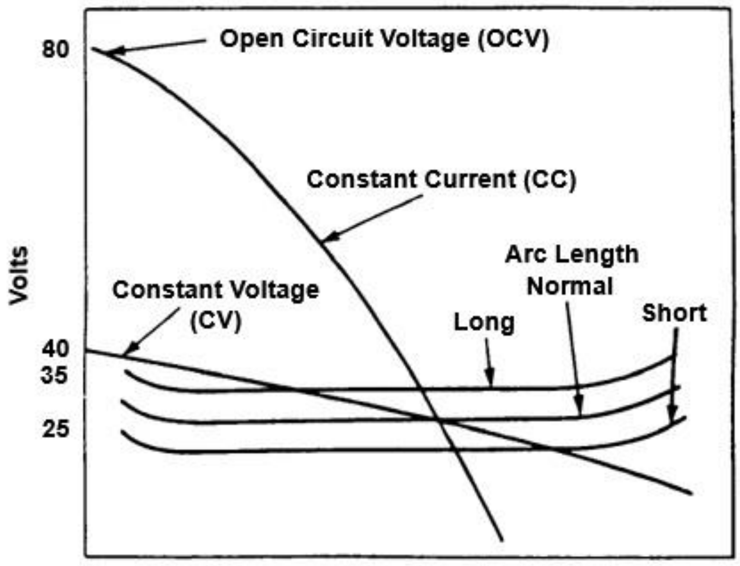
Another advantage of inductive reactance is that the phase shift produced in the alternating current by the reactor improves AC arc stability for a given open circuit voltage. This is an advantage with the GTAW and SMAW processes.

The inductive reactance of a reactor can be varied by various means. One way is by changing taps on a coil or by mechanical/electrical schemes like movable core reactor and saturable reactor. In addition to adjusting series reactance, the mutual inductance between the primary and secondary coils of a transformer can also be adjusted. This can be done by moving the coils relative to one another or by using a movable magnetic shunt that can be inserted or withdrawn from between the primary and secondary windings. These methods change the magnetic coupling of the coils to produce adjustable mutual inductance, which is similar to series inductance.

Volt-Ampere Characteristics

The effectiveness of welding power sources is determined by two kinds of operating characteristics - the static characteristics and dynamic characteristics. Both affect arc stability, but in different ways depending on the welding process.

The static output characteristic curves (volt-ampere curves) of a welding power source (welding machine) are obtained by measuring and plotting the output voltage and the output current under steady-state conditions while the power source is loaded using resistive loads. Volt-ampere curves show graphically how welding current changes when arc voltage changes while power source settings remain unchanged. Static volt-ampere characteristics are generally published by the power supply manufacturer. Two basic types of welding power sources expressed by their volt-ampere output characteristics are constant current power source and the constant voltage power source.



Characteristic Curves for Welding Power Sources

Above figure shows typical static output characteristic curves produced by both type of welding power sources. A constant current power source varies its output voltage to maintain a steady current while a constant voltage power source fluctuates its output current to maintain a set voltage. The term constant is true only in a general sense. In a constant current power source, output current gradually increases as the arc length and arc voltage decrease whereas in a constant voltage power source, output voltage actually reduces or droops slightly as the arc current increases.

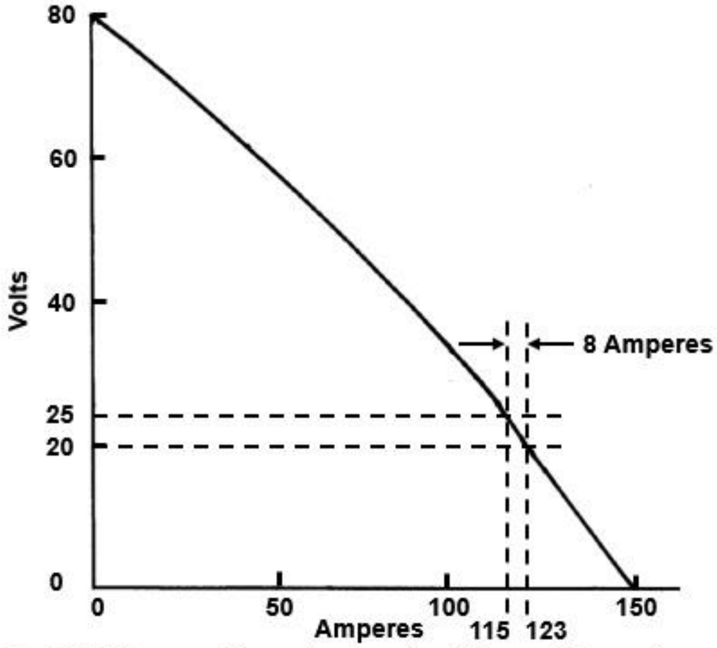
Arc voltage is potential difference between the electrode tip and workpiece surface when there is flow of current. Any fluctuation in arc length affects the resistance to flow of current through plasma and hence arc voltage is also affected. Increase in arc length or electrode extension increases the arc voltage. It may be noted that the no-load, or open circuit voltage (OCV) of constant current arc welding power sources is considerably higher than the arc voltage. Constant current power sources are also known as variable voltage power sources, and constant voltage power sources are often referred to as constant potential power sources.

Constant Current Power Sources

The conventional arc welding power source known as constant current welding power source is one which has means for adjusting (controlling) the arc current. Each current setting yields a separate volt-ampere curve when tested under steady conditions.

The constant current output characteristic describes a power source that will produce a relatively small change in output current when a relatively large change in arc voltage occurs. These characteristics are such that if the arc length varies because of external influences which result in slight changes in arc voltage, the welding current remains substantially constant.

In view of above, constant current power sources are usually used with welding processes which use manually held electrodes (continuously fed consumable electrodes or nonconsumable electrodes) such as shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW), or plasma arc cutting (PAC), where variations in arc length are unavoidable because of the human element.

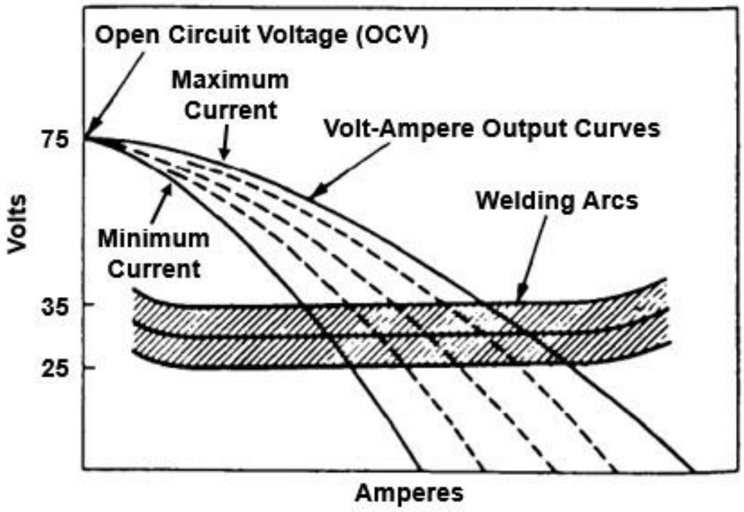


Typical Volt-Ampere Curve for Constant Current Power Sources

Above figure shows typical volt-ampere output curves for a constant current power source. Constant current welding power sources are sometimes called droopers because of the substantial downward (negative) slope of the volt-ampere curves they produce.

It can be seen that in the volt-ampere curve shown in above figure, which has an 80 V open circuit voltage, a steady increase in arc voltage from 20 V to 25 V (25%) would result in a decrease in current from 123 A to 115 A (6.5%). The change in current is relatively small. Therefore, with a consumable electrode welding process, the electrode melting rate would remain relatively constant with a slight change in arc length.

There are two control systems for constant current welding power sources (welding machines): the single control welding machines and the dual control welding machines.

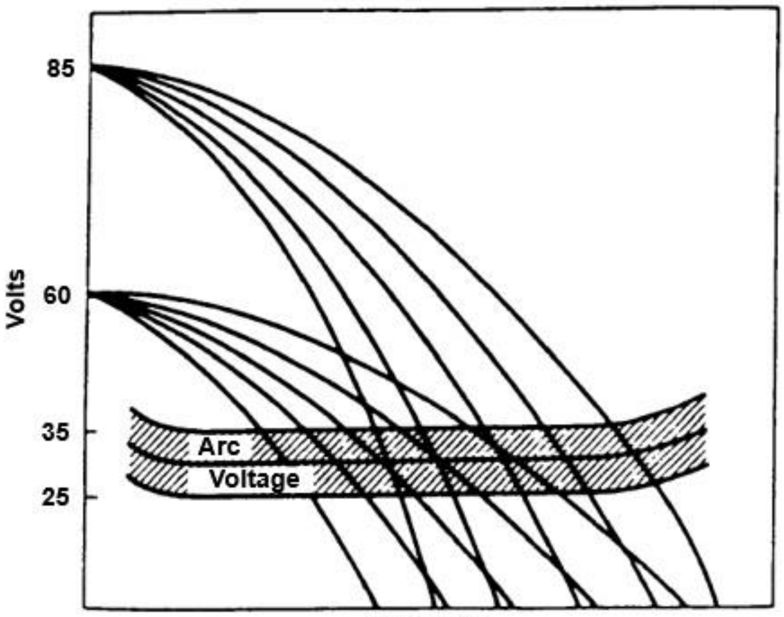


Typical Volt-Ampere Output Curves for Single Control Welding Machines

Above figure shows typical volt-ampere output curves for single control welding machines. These welding machines have one adjustment which changes the current output from minimum to maximum. The maximum current is usually greater than the rated output of the welding machines.

The shaded area in above figure is the normal arc voltage range. By adjusting the current control, a large number of output curves can be obtained. The dotted lines show intermediate adjustments of the machine. With tap or plug-in machines, the number of covers will correspond to the number of taps or plug-in combinations available. Most transformer and transformer-rectifier machines are single control welding machines.

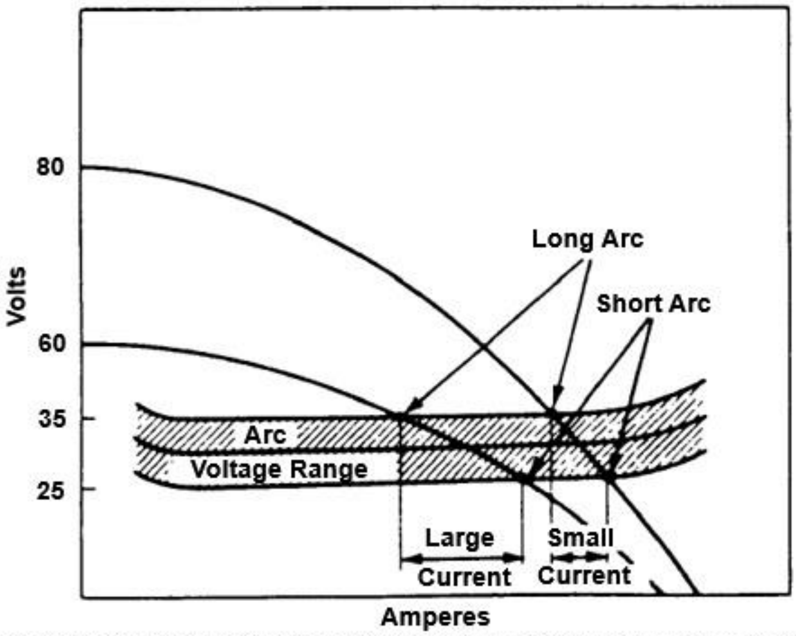
Dual control machines have both current and voltage controls. They have two adjustments, one for coarse-current control and the other for fine-current control, which also acts as an open circuit voltage adjustment. They offer the welder the most flexibility for different welding requirements.



Typical Volt-Ampere Output Curves for Dual Control Welding Machines

Above figure shows some of the different curves that can be obtained by dual control machines. Other curves are obtained with intermediate open circuit voltage settings. The slope is changed by changing the open circuit voltage with the fine-current control adjustment knob. The coarse adjustment sets the current output of the machine in steps from the minimum to the maximum current. The fine-current control will change the open circuit voltage from approximately 55 volts to 85 volts. However, when welding, this adjustment does not change arc voltage. Arc voltage is controlled by the welder by changing the length of the welding arc. The open circuit voltage affects the ability to strike an arc. If the open circuit voltage is much below 60 volts, it is difficult to strike an arc.

The different slopes possible with a dual control machine have an important effect on the welding characteristic of the arc. The arc length can vary, depending on the welding technique. A short arc has lower voltage and the long arc has higher voltage. With a short arc (lower voltage), the power source produces more current, and with a longer arc (higher voltage), the power source provides less welding current. This is illustrated by the following figure, which shows three curves of arcs and two characteristic curves of a dual control welding machine. The three arc curves are for a long arc, a normal arc, and the lower curve is for a short arc.



Typical Volt-Ampere Curve Slops in Dual Control Welding Machines

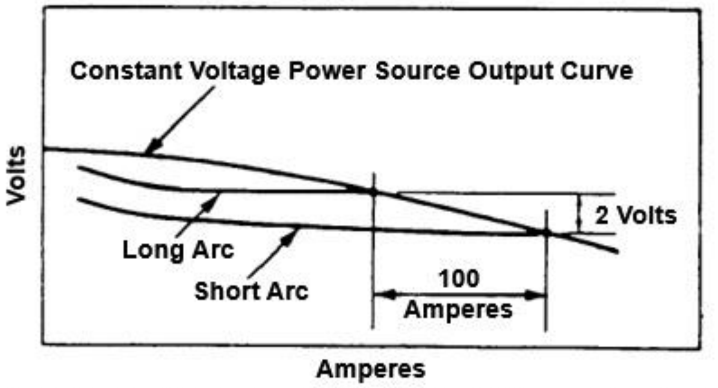
With the dual control machine, the welder can adjust the machine for more or less change of current for a given change of arc voltage. Both curves in above figure are obtained on a dual control machine by adjusting the fine control knob. The top curve shows an 80 volt open circuit voltage and the bottom curve shows a 60 volt open circuit voltage. With either adjustment, the voltage and current relationship will stay on the same curve or line. Consider first the 80 volts open circuit curve which produces the steeper slope. When the arc is long with 35 volts and is shortened to 25 volts, the current increases. This is done without touching the machine control. The welder manipulates the arc. With the flatter, 60 volts open circuit curve, when the arc is shortened from 35 volts to 25 volts, the welding current will increase almost twice as much as it did when following the 80 volts open circuit curve. The flatter slope curve provides a digging arc where an equal change in arc voltage produces a greater change in arc current. The steeper slope curve has less current change for the same change in arc length and provides a softer arc. There are many characteristic curves between the 80 and 60 open circuit voltage curves, and each allows a different current change for the same arc voltage change. This is the advantage of a dual control welding machine over a single control type, since the slope of the curve through the arc voltage range is adjustable only on a dual control machine. This ability to control the current in the arc over a fairly wide range is extremely useful in manual welding. In manual welding, the flatter volt-ampere curve would give a skilled welder the opportunity to substantially vary the output current by changing the arc length through eye-hand coordination called electrode manipulation (shortening or lengthening the arc). This is useful for out-of-position welding because a welder can control the electrode melting rate and weld pool size in real time by simply changing the arc length. A flatter slope also provides increased short-circuit current. This helps reduce the tendency of some electrodes to stick to the workpiece during arc starts or times when the arc length is reduced to control penetration.

The difference between alternating and direct current welding is that the voltage and current pass through zero 100 or 120 times per second, according to line frequency or at each current reversal. Reactance designed into the welding machine causes a phase shift between the voltage and current so that they both do not go through zero at the same instant. When the current goes through zero, the arc is extinguished, but because of the phase difference, there is voltage present which helps to re-establish the arc quickly. The degree of ionization in the arc stream affects the voltage required to re-establish the arc and the overall stability of the arc. Arc stabilizers (ionizers) are included in the coatings of electrodes designed for alternating current welding to provide a stable arc.

Constant Voltage Power Sources

The constant voltage electrical system is the basis of operation of the entire commercial electric power system. The electric power delivered to homes and available at every receptacle has a constant voltage. The same voltage is maintained continuously at each outlet whether a small light bulb, with a very low wattage rating, or a heavy-duty electric heater with a high wattage rating, is connected. The current that flows through each of these circuits will be different based on the resistance of the particular item or appliance in accordance with Ohm’s law. The same principle is utilized by the constant voltage power source.

The National Electrical Manufacturers Association (NEMA) standard *Electric Arc - Welding Power Sources*, EW-1: 1988 (R1999), defines a constant voltage arc power source as “A constant-voltage arc welding power source is a power source which has means for adjusting the load voltage and which has a static volt-ampere curve that tends to produce a relatively constant load voltage. The load current, at a given load voltage, is responsive to the rate at which a consumable electrode is fed into the arc.”



Typical Volt-Ampere Curve for Constant Voltage Power Sources

Above figure shows typical volt-ampere curve for constant voltage power sources. It can be seen that for constant voltage power sources, the volt-ampere characteristic curve is essentially flat with a slight droop (negative slope). The curve may be adjusted up and down to change the voltage; however, it will never rise to as high an open circuit voltage for a constant current power source. This is one reason that the constant voltage power source is not used for manual shielded metal arc welding with covered electrodes. This volt-ampere characteristic is suitable for maintaining a constant arc length in constant-speed electrode processes, such as GMAW, SAW and FCAW.

As the volt-ampere characteristic curve is essentially flat in constant voltage power sources, a small change in arc voltage (arc length) results in a relatively large change in welding current. As shown in above figure, for example, if the arc length shortens slightly resulting in a voltage drop of 2 volts, the welding current increases by approximately 100 amperes. The change in arc length greatly increases the melt-off rate and quickly brings the arc length back to normal.

Constant voltage arc welding is generally used with welding processes that include a continuously fed consumable electrode, usually in the form of wire. A slight change in arc length (voltage) causes a relatively large change in welding current. This automatically increases or decreases the electrode melting rate to regain the desired arc length (voltage) because with a higher welding current, the electrode is melted off more rapidly whereas with low current, the electrode melts off slower. This effect is called self-regulation.

A constant voltage power source is continually changing its current output in order to maintain the arc length (arc voltage). Instead of regulating the electrode wire feed rate to maintain the constant arc length, as is done when using a constant current power source, the electrode wire is fed into the arc at a fixed speed. The power source is designed to provide the necessary current to melt off the electrode wire at this same rate.

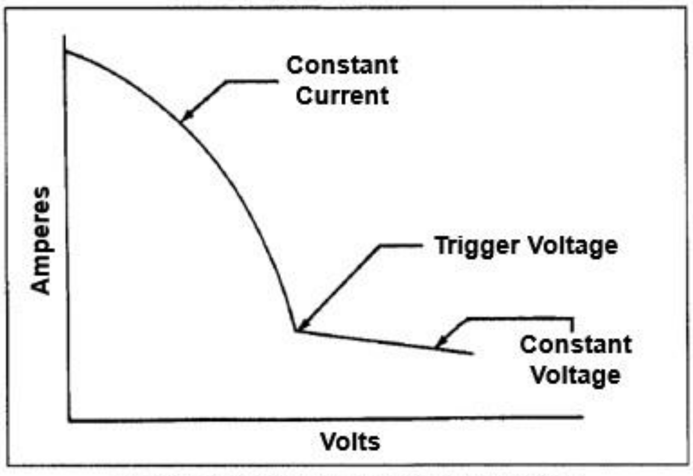
In constant voltage power sources, the arc length is controlled by setting the voltage on the power source. The welding current is controlled by adjusting the wire feed speed.

Constant voltage power sources with alternating current is normally not used. The constant voltage power source should not be used for shielded metal-arc welding because it may overload and damage the power source by drawing too much current too long.

The dynamic characteristics of constant voltage power sources must be carefully engineered. If the voltage changes abruptly with a short circuit, the current will tend to increase quickly to a very high value. This is an advantage in starting the arc but will create unwanted spatter if not controlled. It is controlled by adding reactance or inductance in the circuit. This changes the time factor or response time and provides for a stable arc.

Combined Constant Current and Constant Voltage Characteristics

Electronic controls can be designed to provide either constant current or constant voltage outputs from single power sources, making them useful for a variety of welding processes.



Volt-Ampere Curve for Combination of
Constant Current and Constant Voltage Characteristics

As shown in above figure, electronically controlled outputs can also provide output curves that are a combination of constant current and constant voltage. The top part of the curve is essentially constant current; below a certain trigger voltage, however, the curve switches to constant voltage. This type of curve is beneficial for shielded metal arc welding to assist starting and to avoid electrode stubbing (sticking in the weld pool) if the welder uses an arc length that is too short.

Summary

Constant current power sources are used primarily with coated electrodes. This type of power source has a relatively small change in amperage and arc power for a corresponding relatively large change in arc voltage or arc length, thus the name constant current. In welding with coated electrodes, the output current or amperage is set by the welder/operator while the voltage is designed into the unit. The welder can vary the arc voltage somewhat by increasing or decreasing the arc length. A slight increase in arc length will cause an increase in arc voltage and a slight decrease in amperage. A slight decrease in arc length will cause a decrease in arc voltage and a slight increase in amperage.

Constant voltage power sources are used in welding with solid and flux cored electrodes, and as the name implies, the voltage output remains relatively constant. On this type of power source, the voltage is set at the machine and amperage is determined by the speed that the wire is fed to the welding gun. Increasing the wire feed speed increases the amperage. Decreasing the wire feed speed decreases the amperage.

If a welder attempts to use a constant voltage power source for a shielded metal arc welding (SMAW), the small fluctuations in the arc distance would cause significant fluctuations in the machine's current output. With a constant current power source, the welder can count on a fixed current reaching the workpiece, regardless of how short or long the electric arc gets.

Dynamic Characteristics

The dynamic characteristic of an arc welding power source is determined by measuring the transient variations in output current and voltage that appear in the arc. Dynamic characteristics describe instantaneous variations, or those that occur during very short intervals, such as 0.001 second during which a significant change in ionization of the arc column occurs. The ability of the power source for instantaneous response to rapidly changing conditions at the arc to provide a stable arc is critical for good welding performance. Hence, it is important to control the dynamic characteristics of an arc welding power source. In arc welding, transient variations occur at specific times, such as the following.

- During the striking of the arc
- During rapid changes in arc length
- During the transfer of metal across the arc
- In alternating current welding, during arc extinction and reignition at each half-cycle

Among the arc welding power source design features that do have an effect on dynamic characteristics are those that provide local transient energy storage (for example, parallel capacitance circuits).

Improved arc stability typically results in the following.

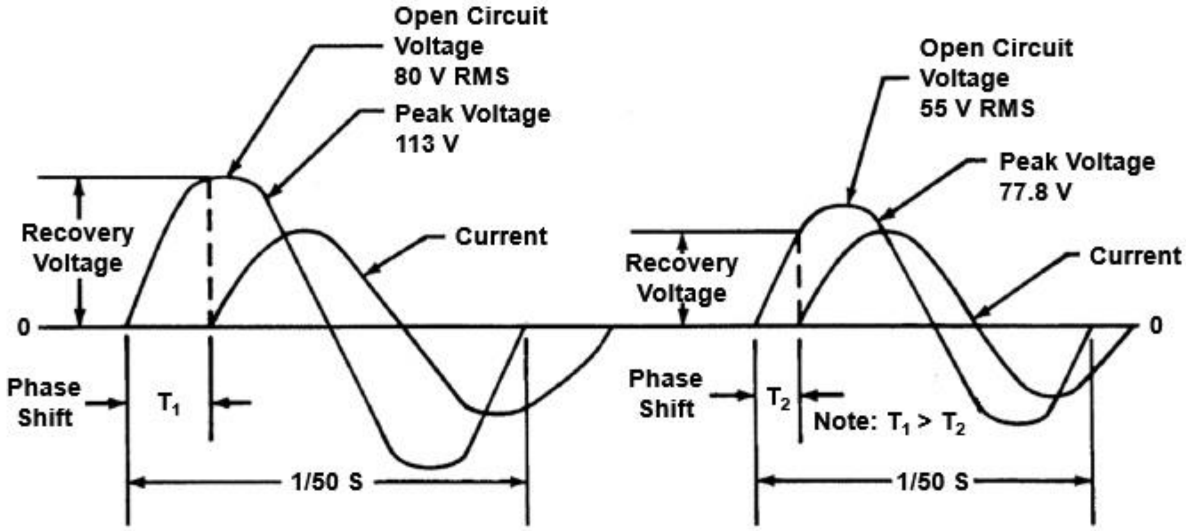
- Improvement in the uniformity of metal transfer
- Reduction in metal spatter
- Reduction in weld-pool turbulence

As no universally recognized method exists by which dynamic characteristics are specified, the user should obtain assurance from the power source manufacturer that both the static and dynamic characteristics of the power source are acceptable for the intended application. It may be noted that arc voltage is affected by arc length and process parameters such as electrode type, shielding gas, and arc current.

Open Circuit Voltage

Open-circuit voltage is the voltage at the output terminals of a welding power source when it is energized but current is not being drawn.

Open circuit voltage is one of the design factors influencing the performance of all welding power sources. Although a high open circuit voltage may be desirable for arc initiation and stability, the electrical hazard prevents the use of higher voltages.



Typical Voltage and Current Waveforms of a Dual Control AC Power Source

Above figure shows typical voltage and current sine waveforms of a dual control 50-Hz ac power source with open circuit voltages of 80 V and 55 V root mean square (RMS). The RMS of alternating current or voltage is the effective current or voltage applied that produces the same heat as that produced by an equal value of direct current or voltage. Since for a sinusoidal alternating voltage, peak voltage = 1.41 × RMS value, peak voltage will be 113 V for 80 V RMS open circuit voltage and 77.8 V for 55 V RMS open circuit voltage. 50-Hz power produces reversals in the direction of current flow each 1/100 second whereas 60-Hz power produces reversals in the direction of current flow each 1/120 second.

The alternating current must change direction after each half cycle. In order for it to do so, the current flow in the arc ceases for an instant at the point at which the current wave form crosses the zero line. An instant later, the current must reverse its direction of flow. However, during the period in which current decreases and reaches zero, the arc plasma cools, reducing ionization of the arc stream.

Welding current cannot be reestablished in the opposite direction unless ionization within the arc length is either adequately maintained or quickly reinitiated. With conventional power sources, ionization may not be sustained adequately depending on the welding process and electrode being used. Reinitiating is improved by providing an appropriately high voltage across the arc, called a recovery voltage. The greater this recovery voltage, the shorter is the period during which the arc is extinguished. If recovery voltage is insufficient, the arc cannot be reestablished without shorting the electrode.

Above figure shows the phase relations between open circuit voltage and equal currents and current for two different open circuit voltages, assuming the same arc voltage (not shown) in each case.

As shown in the figure, the available peak voltage of 113 V is greater with 80 V (RMS) open circuit voltage. The peak voltage of 78 V available with 55 V (RMS) open circuit may not be sufficient to sustain a stable arc. It may be also noted that as compared to 55 V (RMS) open circuit voltage, the greater phase shift ($T_1 > T_2$) that occurs for the 80 V (RMS) open circuit voltage causes a current reversal at a higher recovery voltage because it is near the peak of the open circuit voltage wave form, which is the best condition for reignition.

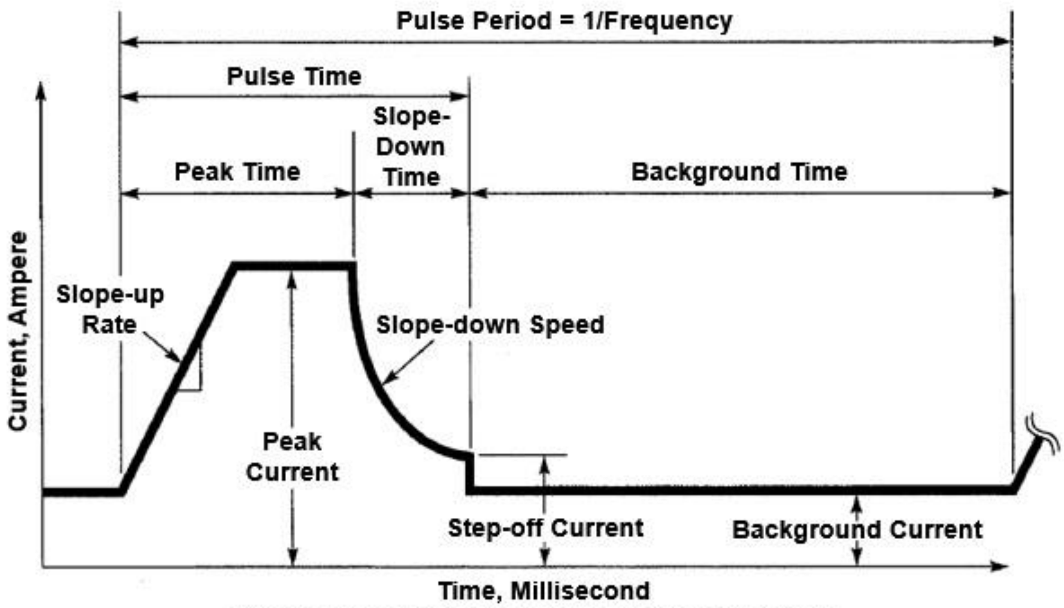
In view of above, for shielded metal arc welding with low voltage open circuit alternating current power sources, it is necessary to use electrodes with ingredients incorporated in the electrode coverings that help to maintain ionization. In a direct current system, once the arc is established, the welding current does not pass through zero. Thus, rapid voltage increase is not critical.

Pulsed Power Sources

Pulsed current power sources are used for GMAW, GTAW, SMAW, FCAW, and SAW. Of these processes, GMAW and GTAW are the most commonly used.

Pulsed-mode welding power sources are used with the GMAW process to reduce heat input, decrease workpiece distortion, and minimize fumes and spatter. The pulse spray transfer process is an advantage when welding thin-gauge and non-ferrous metals. In a shielding gas environment in which argon is predominant, ejection of liquid metal from the tip of the electrode can be achieved when the peak instantaneous current exceeds a critical level, called the transition current. Instantaneously raising the current above the transition current causes the liquid metal to be propelled across the arc. This peak current period is then followed by a lower current period. It is thereby possible to obtain the desirable qualities of spray transfer while reducing the average current significantly, allowing the GMAW process to be used in all positions and for welding sheet metal.

The pulsed current level during the low interval is kept sufficiently low to prevent any metal transfer but high enough to prevent arc loss. Peak current is raised above the transition current for a sufficient time to allow at least one drop to form and transfer. Power sources have been designed with controlled pulsed current outputs for pulsed gas metal arc welding (GMAW-P).



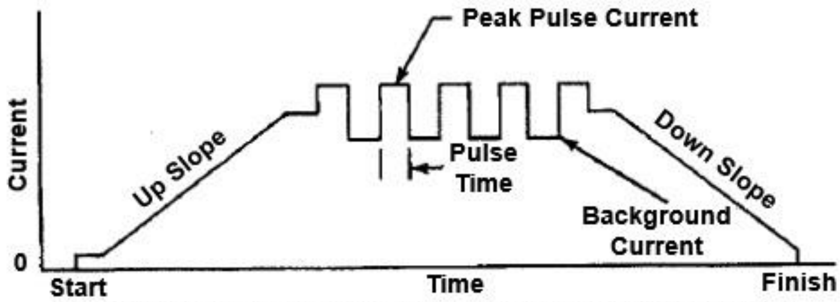
Pulsed-Spray Metal Transfer Wave Form Variables

Above figure shows pulsed-spray metal transfer wave form variables for GMAW-P. Independent settings can be made for peak current, background current, peak time, and background time for the pulse wave form. The slope-up rate defines how fast current rises from background level to peak level. Because of the inductive component in the circuit, current decays exponentially from the peak current to an optional intermediate level called step-off current, at slope-down speed, before it reaches the background current level.

Instead of requiring the user to adjust numerous wave form control parameters, manufacturers preprogram the wave forms for commonly used welding wires and gases. The operator controls usually consist of two knobs, one to adjust wire feed speed (or current) and the other for the voltage adjustment (to refine or trim the voltage). The operator simply turns the wire speed knob to pick one of the preprogrammed wave forms. The term synergic (several things acting as one) is used with pulsed GMAW machines because when the wire feed speed knob is turned, an entire new wave form is selected along with all the parameters defining the wave form.

When pulsed gas metal arc welding (GMAW-P) is performed using a controlled short-circuiting transfer process, the wave form adapts to the physics of the welding arc and metal transfer. It reduces spatter by reducing the pinch force (current) when the liquid-metal bridge of the short is about to break and establish an arc. Without the energy of a high current, the liquid bridge is then broken by surface tension and fluid-mechanical inertia. The controlled short-circuit process is used for welding thin-gauge materials, open root passes on pipe, single-sided heavy plate, and thin sheet metallic lining (called wallpapering).

Pulsed current has also been used in the gas tungsten arc welding process (GTAW-P). The frequency in GTAW process differs from that of the GMAW process and generally ranges from 2 seconds per pulse to 10 pulses per second, with the lower frequencies most commonly used.



Typical Current Wave Form of a Pulsed GTAW Power Source

Above figure shows typical current wave form of a pulsed GTAW power source. As shown in the figure, current wave form of a pulsed GTAW power source is characterized by a repetitive variation in arc current from a background (low) value to a peak value. The peak current time added to the background current time is equal to the duration of one pulse cycle. The peak current level, peak current duration, background current level and background current duration are independently adjustable.

The purpose of pulsing is to alternately heat and cool the molten weld metal. The heating cycle (peak current) is based on achieving a suitable weld pool size during the peak pulse without excessive groove face fusion or melt-through, depending on the joint being welded. The background current and duration are based on achieving the desired rate of cooling of the weld pool. The purpose of the cooling (background current) portion of the cycle is to speed up the solidification rate and reduce the size of the weld pool without interrupting the arc. Thus, pulsing allows alternately increasing and decreasing the size of the weld pool.

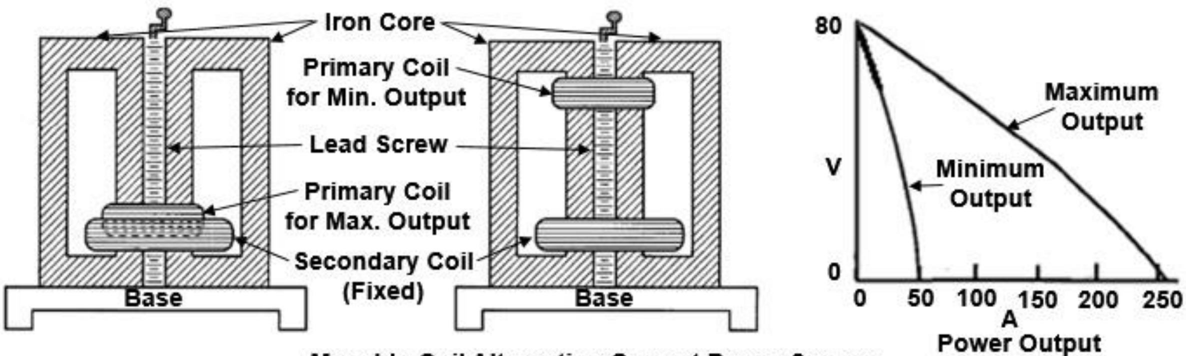
The fluctuation in weld pool size and penetration is related to the pulsing and process variables. Because the size of the weld pool is partially controlled by the current pulsing action, the need for arc manipulation to control the molten metal is reduced or eliminated. Thus, pulsed current is a useful tool for manual out-of-position gas tungsten arc welding.

Pulsed GTAW and GMAW processes require a power source with the ability to deliver precisely shaped current pulses superimposed on a lower background (arc-sustaining) current level. To generate current pulses, in addition to thyristors in phase control, inverters are also used. Add-on "pulse formers" have been also designed as attachment for conventional direct current welding power sources.

Methods to Control Welding Circuit Output

For a welding power source, the high-voltage power delivered by the utility company is converted to the proper welding voltage by transformers. Because various welding applications have different welding power requirements, the means for the control of welding current or arc voltage, or both, must be incorporated within the welding transformer power source. Information about the methods commonly used in transformers to control the welding circuit output is given in this section.

Movable-Coil Control



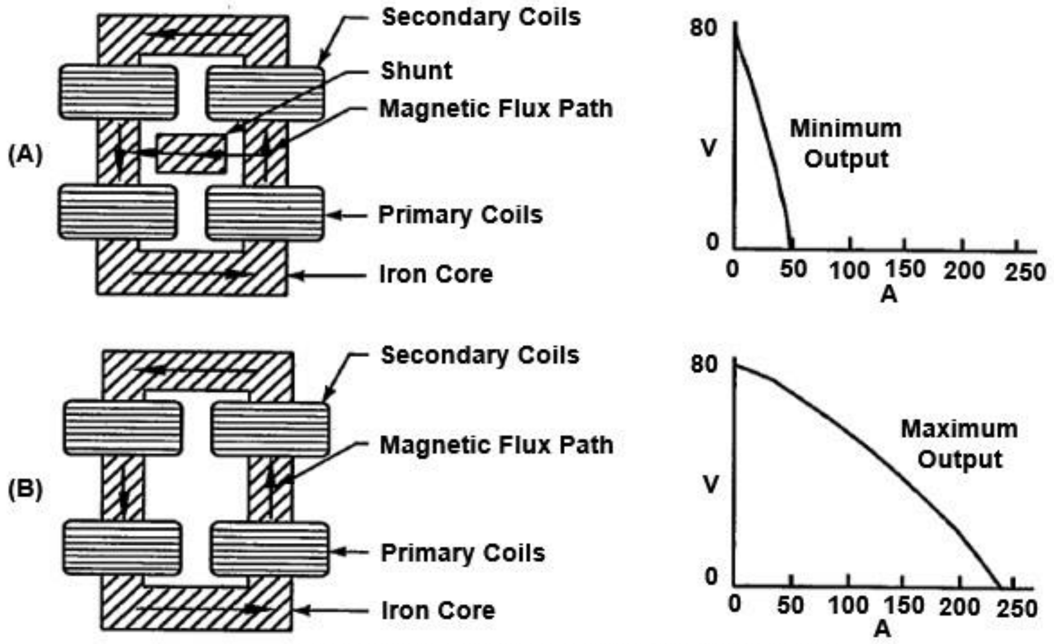
Movable-Coil Alternating Current Power Source

As shown in above figure, a movable-coil transformer consists of an elongated core on which are located primary and secondary coils. Either the primary coil or the secondary coil may be movable, while the other one is fixed in position. Most alternating-current transformers of this design have secondary coil at a fixed-position. As shown in above figure, the primary coil (movable coil) is normally attached to a lead screw, and as the screw is turned, the coil moves closer to the secondary coil or farther from it.

The varying distance between the two coils regulates the inductive coupling of the magnetic lines of force between them. The farther apart the two coils are, the more vertical is the volt-ampere output curve and the lower is the maximum short-circuit current value (minimum output). Conversely, when the two coils are closer together, the maximum short-circuit current is higher and the slope of the volt-ampere output curve is less steep (maximum output).

Movable-Shunt Control

In the movable shunt design, the primary coils and the secondary coils are fixed in position. Output control is achieved with a laminated iron core shunt that is moved between the primary and secondary coils. The movable shunt is made of the same material as that used for making the transformer core.



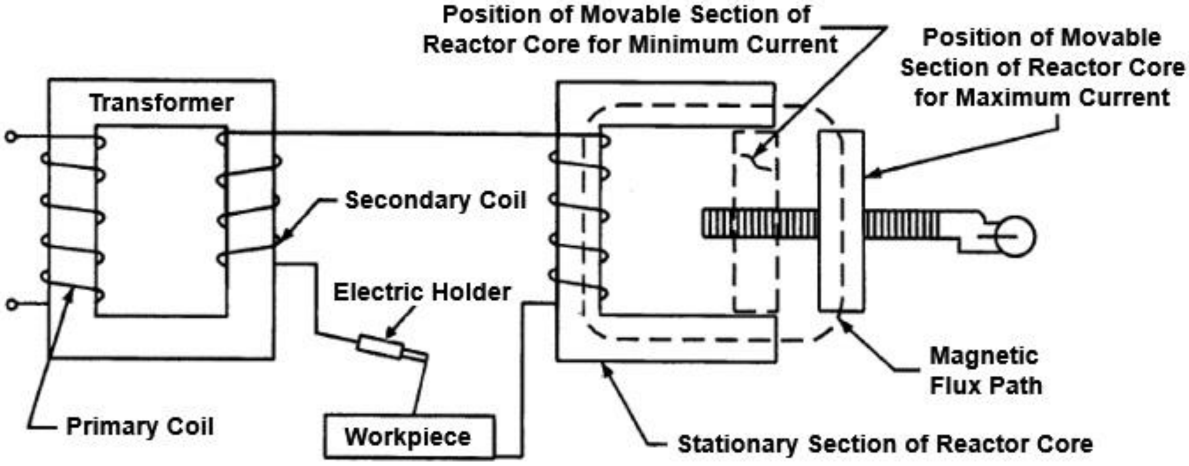
Movable-Shunt Alternating Current Power Source

When the shunt is moved into position between the primary and secondary coils, as shown at (A) in above figure, some magnetic flux or the arrangement of the magnetic lines of force are diverted through the iron shunt rather than to the secondary coils. With the iron shunt between the primary and secondary coils, the slope of the volt-ampere curve increases and the available welding current is decreased. The decrease in welding current depends on the shunt position. Minimum current output is obtained when the shunt is fully in place.

As shown at (B) in above figure, the magnetic flux is unobstructed when the iron shunt is not there between the primary and secondary coils. In this configuration, the output current is at its maximum.

Movable-Core Reactor

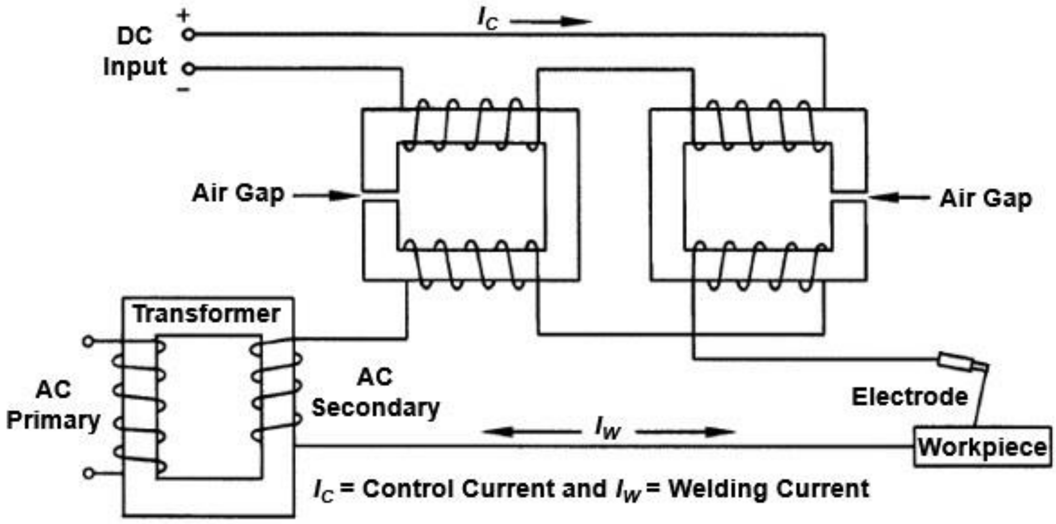
The movable-core reactor type of alternating current welding power source consists of a transformer and a reactor in series. The inductance of the reactor is varied by mechanically moving a section of its iron core.



Movable-Core Reactor Alternating Current Power Source

As shown in above figure, when the movable section of the reactor core is in a withdrawn position, the permeability of the magnetic path is very low because of the air gap. The result is a low inductive reactance that permits a high welding current to flow. When the movable section of reactor core is advanced into the stationary core, as shown by the broken-line rectangle in above figure, the increase in permeability causes an increase in inductive reactance, which reduces the welding current.

Saturable Reactor Control



Saturable Reactor Alternating Current Welding Power Source

A saturable reactor control is an electrical control that uses a low-voltage, low-amperage direct current circuit to change the effective magnetic characteristics of reactor cores. Remote control of output from the power source is relatively easy with this type of control circuit. As with this construction, the main transformer has no moving parts, it normally requires less maintenance compared with mechanical controls. The volt-ampere characteristics are determined by the transformer and the saturable reactor configurations. The direct current control circuit to the reactor system allows the adjustment of the output volt-ampere curve from minimum to maximum.

The amount of current adjustment in a saturable reactor is based on the ampere-turns of the various coils. The term ampere-turns is defined as the number of turns in the coil multiplied by the current in amperes flowing through the coil. In the basic saturable reactor, the law of equal ampere-turns applies. The welding current can be approximated with the following equation:

$$I_W = \frac{I_C N_C}{N_W}$$

where,
I_W = Change in welding current, A
I_C = Change in the control circuit current, A
N_C = Number of turns in the control circuit and
N_W = Number of turns in the welding current circuit.

It may be noted that in above figure, the reactor coils are connected in opposition to the direct current control coils. If this were not done, transformer action would cause high circulating currents to be present in the control circuit. With the opposing connection, the instantaneous voltages and currents tend to cancel out. Saturable reactors tend to cause severe distortion of the sine wave supplied by the transformer. This is not desirable for gas tungsten arc welding (GTAW) because the wave form for that process is important. One method of reducing this distortion is by introducing an air gap in the reactor core. Another is to insert a large choke in the direct current control circuit.

Silicon Controlled Rectifiers (SCR)

In addition to the transformer taps, moving coils, moving shunts and saturable reactors mentioned earlier, there are a number of other means by which output can be controlled. Thyristors, commonly known as silicon controlled rectifiers (SCRs), are frequently employed as control elements, replacing magnetic cores.

Duty Cycle

Internal components of a welding power source tend to heat up as welding current flows through. The amount of heat tolerated is determined by the breakdown temperature of the electrical components and the material used to insulate the transformer windings and other components. The maximum temperatures are specified by component manufacturers and organizations involved with standards in the field of electrical insulation.

The duty cycle is defined as a ratio of the load-on time allowed in a specified test interval time. Observing this ratio is important to prevent the internal windings and components and their electrical insulation system from heating above their rated temperature.

Duty cycle is expressed as a percentage of the maximum time that the power source can deliver its rated output during each of a number of successive test intervals without exceeding a predetermined temperature limit. In the United States, for example, the National Electrical Manufacturers Association (NEMA) specifies duty cycles based on a test interval of 10 minutes in an ambient temperature of 40°C (104°F). Some agencies and manufacturers in other countries use shorter test intervals, such as 5 minutes. Thus, a 60% NEMA duty cycle (a standard industrial rating) means that the power source can deliver its rated output for 6 out of every 10 minutes without overheating. A 100% duty cycle power source is designed to produce its rated output continuously without exceeding the prescribed temperature limits of its components.

Industrial units designed for manual welding are normally rated at a 60% duty cycle. For automatic and semiautomatic processes, the rating is usually a 100% duty cycle. Light-duty power sources usually have a 20% duty cycle.

Manufacturers perform duty cycle tests under what NEMA defines as usual service conditions. Hence, caution should be observed in basing operation on service conditions other than usual. Unusual service conditions such as high ambient temperatures, insufficient cooling air, and low line voltage are among the factors that contribute to performance that is lower than tested or calculated.

Following equation may be used to estimate the duty cycle at other than rated outputs.

$$T_a = \left(\frac{I}{I_a}\right)^2 \times T$$

where,
T_a = Required duty cycle, %
I = Rated current at the rated duty cycle, A
I_a = Maximum current at the required duty cycle, A
T = Rated duty cycle, %

The power source should never be operated above its rated current or duty cycle unless approved by the manufacturer.

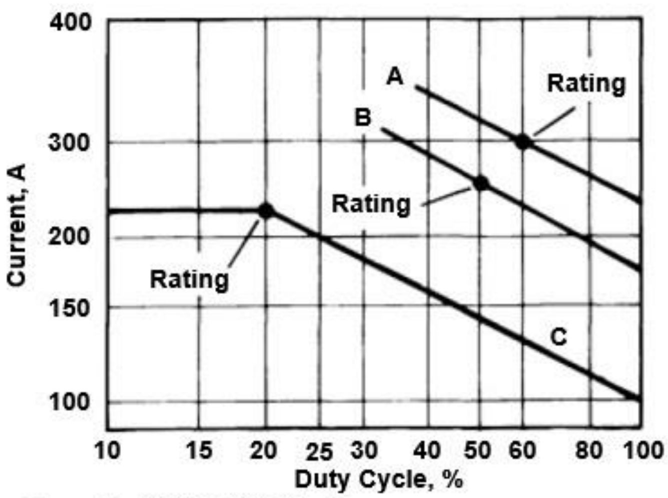
NEMA categorizes arc welding power sources into three classes on the basis of duty cycle as under.

- Class I: Rated output at 60, 80, or 100% duty cycle
- Class II: Rated output at 30, 40, or 50% duty cycle
- Class III: Rated output at 20% duty cycle

In addition to duty cycle, the output ratings and performance capabilities of power sources of each class are specified by NEMA.

Following table shows the output current ratings for NEMA Class I, Class II and Class III arc welding power sources.

Output Currents for NEMA-Rated Arc Welding Power Sources (Amperes)		
Class I	Class II	Class III
200	150	180-230
250	175	235-295
300	200	-
400	225	-
500	250	-
600	300	-
800	350	-
1000	-	-
1200	-	-
1500	-	-



Curve A: 300 A, 60% Machine
Curve B: 250 A, 50% Machine
Curve C: 225 A, 20% Engine Driven Machine

Selected Duty Cycle Curves

Above figure shows selected duty cycle curves. Curve A shows a NEMA class I, 60% duty cycle, 300 A rated machine that is capable of a maximum 375 A at reduced duty cycle (38%) and 232 A at 100% duty cycle (continuous). Curve B represents a NEMA class II, 50% duty cycle, 250 A machine with a continuous duty cycle of 176 A. Curve C represents an engine-driven machine rated at 225 A and 20% duty cycle. It does not offer output in excess of its rating, because of the horsepower limitation of the engine.

NEMA requires most machines to produce a maximum of 125% of rated output current. No minimum current is specified, but 10% (of rating) is typical. Load voltage, E, for class I and II machines is defined by:

$$E = 20 + 0.04 \times I$$

where,
E = Rated load voltage, V
I = Rated load current in amperes, below 600 A

The NEMA-rated load voltage is 44 for output current ratings of 600 A and higher.

Typical efficiencies (that is, ratios of power output to power input) are 68% for line-frequency (50 or 60 Hz) machines and 88% for inverter type.

Nameplate Data

Usual service conditions are temperature that range from 0 to 40°C (32 to 105°F) and altitudes of up to 1000 m (3300 ft). Altitude is a factor because of fuel-air mixtures.

The power source nameplate must include the following specifications.

Manufacturer's detail
NEMA class designation (I, II or III) and duty cycle at rated load
Maximum open circuit voltage
Rated load voltage (V)
Rated load current (A)
Maximum speed in revolutions per minute (rpm) at no-load (generator or alternator)
Frequency of power source (Hz)
Number of phases of power source
Input voltage(s) of power source
Current (A) input at rated load output

The manufacturer also provides other useful data concerning input requirements such as primary conductor size and recommended fuse size.

Proper grounding is a necessary safety consideration.

It may be noted that most power sources are forced-air cooled by internal fans. Thermal sensors will interrupt output if airflow is impeded.

Safety During Welding and Cutting

Arc welding is safe when sufficient measures are taken to protect the welder from potential hazards. When these measures are overlooked or ignored, welders can encounter dangers such as: electric shock, overexposure to radiation, fumes and gases, fire, or explosion, falls, etc. any of which can result in fatal injuries. In view of this, information about safety precautions to be practiced during welding is given in this chapter.

Electric Shock

The human body conducts electricity. Hence, electrical shock can occur when the body becomes part of the electric circuit, either when an individual comes in contact with both wires of an electrical circuit, with the wire of an energized circuit and the ground, or with a metallic part that has become energized by contact with an electrical conductor.

The severity and effects of electrical shock depend on factors such as the path of the current through the body, the amount of current, the length of time of the exposure, and whether the skin is wet or dry. Water readily conducts electricity. Hence, electric current flows more easily in wet conditions and through wet skin. Serious injuries or deaths can also occur if the electrical shock causes the welder to fall from an elevated location. The safe electrical practices should include the following.

Only qualified persons with knowledge and understanding of the principles of electricity and certified training in safe practices should install, test, repair, or perform maintenance of electrical power source (welding machine) and associated welding equipment (cable, electrode holder, etc.).

During repair or replacement of parts, the power source should be turned off, the input power should be disconnected, and the supply circuit locked out and tagged out. Electrolytic capacitors should be discharged using a resistor, such as a 1000-ohm, 25-watt resistor.

If it is necessary to work on an energized unit, a good technique is to work with one hand (if it is safe to do so), keeping the other hand at the side or in a pocket to avoid contact with conductive material and to reduce the possibility of current passing through the chest cavity.

Inverter power sources require special safety considerations. Failed parts or parts installed incorrectly can explode or cause other parts to explode when power is applied to inverters. Hence, the technician should always wear a face shield and long sleeves when servicing inverters.

The condition of electrode holder and electrode cable is very important. The plastic or fiber insulation on the electrode holder protects one from touching the metal “electrically hot” parts inside. Always inspect the electrode holder before turning the welding machine on. Replace the holder if it is damaged. A damaged electrode cable should be replaced or, at minimum, repaired using electrical tape. If the cable has been repaired, check that the tape is secure properly. Do not use cables that are undersized (too small) or poorly spliced. Do not wrap cables around your body. 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. Periodically insure that the terminals of the welding machine are clean and tight. Also insure that the welding machine is properly grounded.

Insulate yourself from the work piece and ground by wearing rubber soled shoes. Use plywood, rubber mats, or other dry insulation to stand or lie on. Keep gloves dry. Don’t rest body, arms, or legs on the workpiece, especially if clothing is wet or bare skin is exposed.

If a person comes in contact with a live electrical conductor, a coworker or attendant should not touch the equipment, input power cable, or the person. The rescuer should immediately disconnect the input power by turning off the disconnect switch at the supply fuse box or circuit breaker panel and when applicable, pull out the plug.

An energized unit must never be left unattended. Turn off power source when not in use. If a welding power source is to be moved, the supply line should be de-energized and the input power conductors disconnected before moving it.

Personal Protective Equipment

Any exposed skin is susceptible to the damaging effects of ultraviolet and infrared rays. Ultraviolet radiation exposure appears as a skin burn (much like sunburn). Weld sparks and spatter landing on the bare skin burns it. Hence, welders must wear protective clothing. The protective clothing must allow freedom of movement while providing adequate coverage against burns from sparks, weld spatter, and arc radiation. Further, sparks catch in open pockets, pant cuffs or down a shirt that isn't completely buttoned so care should be taken to wear them properly.

Because of its durability and resistance to fire, wool clothing is suggested over synthetics (which should never be worn because it melts when exposed to extreme heat) or cotton, unless it is specially treated for fire protection. Keep your clothes clean of grease and oil, as these substances may ignite and burn uncontrollably in the presence of oxygen. Pockets may be eliminated from the front of clothing. When pockets are present, they should be emptied of flammable or readily combustible materials such as matches and butane/gas lighters.

Avoid rolling up your sleeves and pant-cuffs, because sparks or hot metal could deposit in the folds; also, wear your trousers outside your work boots, not tucked in, to keep particles from falling into your boots.

It is suggested to wear high top boots with steel toes (especially when doing heavy work) fully laced to prevent sparks from entering into the boots.

Heavy, flame-resistant gloves, such as leather, should always be worn to protect your hands from burns, cuts, and scratches. In addition, as long as they are dry and in good condition, they will offer some insulation against electric shock.

It is also suggested to wear safety glasses with side shields or goggles when chipping or grinding a work piece. In general, it is recommended to wear safety glasses with side shields in work area at all times to protect eyes from flying particles.

Other protective wear for heavy work or especially hazardous situations (for example overhead welding or cutting) includes: aprons to protect your chest and lap from sparks when standing or sitting, cape sleeves or shoulder covers with bibs made of leather or other flame-resistant material to protect wrists and forearms and caps worn under your helmet, when necessary, to prevent head burns. Hard hats must be worn when working in an environment where there is a risk of objects falling from above.

Arc Rays

It is essential that eyes and skin are protected from radiation exposure. Infrared radiation has been known to cause retinal burning and cataracts. And even a brief exposure to ultraviolet (UV) radiation can cause an eye burn known as “welder’s flash,” "welders' eye," or "arc eye." These names are common names for "conjunctivitis" - an inflammation of the mucous membrane of the front of the eye. While this condition is not always apparent until several hours after exposure, it causes extreme discomfort, and can result in swelling, fluid excretion, and temporary blindness. Normally, welder's flash is temporary, but repeated or prolonged exposure can lead to permanent injury of the eyes. While infrared radiation can usually be felt as heat, there is no real way to know if one is being exposed to UV radiation. Hence, one should not take any chance and always wear eye protection.

Besides not looking at an arc, the only other preventative measure is the use the proper shade filter lens in the helmet. The standard filter lens size is 2 in. by 4-1/4 in. (51 mm by 108 mm), but larger are available. The filter lenses (ANSI/ISEA Z87.1) are marked as to the manufacturer and shade number. The higher the number, the darker the shade. Refer to a lens shade selector chart (for example AWS F2.2, Lens Shade Selector) for the recommended shade numbers for various arc welding processes. The general rule is to choose a filter lens too dark to see the weld, then move to lighter shades without dropping below the minimum protective rating.

Outer cover lenses shall be provided to protect the filter lenses in goggles, helmets, or hand shields from welding spatter, pitting, or scratching. Outer cover lenses shall be of clear glass or self-extinguishing plastic, but need not be impact resistant.

Helmets Helmet with Cap Hand Shield

Typical Welding Helmets and Hand Shield

Welding helmets and hand shields (ANSI/ISEA Z87.1) offer the most complete shading against arc radiation. Helmets and hand shields are made from a hard plastic or fiberglass to protect head, face, ears and neck from electric shock, heat, sparks, and flames. Use of a clear lens made of plastic behind the filter lens will prevent any broken pieces of the filter lens from reaching the eye. When the "lift front" type of welders' helmet is used, there shall be a fixed impact resistant safety lens or plate on the inside of the frame nearest to the eyes to protect the welder against flying particles when the front is lifted. If the welding helmet is not the "lift front" type, the welder should wear safety glasses with side shields beneath his helmet to serve as eye protection during chipping the slag from a previous weld deposit.

A helmet is required for protecting the welder's eyes and face whereas a hand shield is convenient for the use of foremen, inspectors, and other spectators.

The sensors on an auto-darkening helmet (ANSI Z87.1) darken the filter lens in a fraction of a second. Industrial grade helmets react at speeds of 1/10000 to 1/20000 of a second. It is recommended to avoid use of auto-darkening helmets that darken with a reaction time of 1/2000 to 1/3600 of a second as this time is not adequate for industrial applications. Compared to a traditional fixed shade helmet, an auto-darkening helmet reduces neck fatigue because it is usually lighter and welders no longer need to snap their head to drop the hood down.

Nearby personnel also should be protected from splatter, flash and glare with noncombustible protective screens or barriers. 12 m (40 ft) is the recommended minimum distance from which an electric welding arc should be seen by the unprotected eye.

Following table shows the lens shade selector chart as per AWS F2.2 (Source: ANSI Z49.1:2012)

Guide for Shade Numbers
(from AWS F2.2:2001(R2010), Lens Shade Selector)
Shade numbers are given as a guide only and may be varied to suit individual needs.

Process	Electrode Size in. (mm)	Arc Current (Amperes)	Minimum Protective Shade	Suggested* Shade No. (Comfort)
Shielded Metal Arc Welding (SMAW)	Less than 3/32 (2.4)	Less than 60	7	-
	3/32–5/32 (2.4–4.0)	60–160	8	10
	5/32–1/4 (4.0–6.4)	160–250	10	12
	More than 1/4 (6.4)	250–550	11	14
Gas Metal Arc Welding (GMAW) and Flux Cored Arc Welding (FCAW)	-	Less than 60	7	-
		60–160	10	11
		160–250	10	12
		250–500	10	14
Gas Tungsten Arc Welding (GTAW)	-	Less than 50	8	10
		50–150	8	12
		150–500	10	14
Air Carbon Arc Cutting (CAC-A), Light	-	Less than 500	10	12
Air Carbon Arc Cutting (CAC-A), Heavy	-	500–1000	11	14
Plasma Arc Welding (PAW)	-	Less than 20	6	6 to 8
		20–100	8	10
		100–400	10	12
		400–800	11	14
Plasma Arc Cutting (PAC)	-	Less than 20	4	4
		20–40	5	5
		40–60	6	6
		60–80	8	8
		80–300	8	9
		300–400	9	12
		400–800	10	14
Torch Brazing (TB)	-	-	-	3 or 4
Torch Soldering (TS)	-	-	-	2
Carbon Arc Welding (CAW)	-	-	-	14

Process	Plate Thickness		Suggested* Shade No.
	in.	mm	
Oxyfuel Gas Welding (OFW), Light	Under 1/8	Under 3	4 or 5
Oxyfuel Gas Welding (OFW), Medium	1/8 to 1/2	3 to 13	5 or 6
Oxyfuel Gas Welding (OFW), Heavy	Over 1/2	Over 13	6 or 8
Oxygen Cutting (OC), Light	Under 1	Under 25	3 or 4
Oxygen Cutting (OC), Medium	1 to 6	25 to 150	4 or 5
Oxygen Cutting (OC), Heavy	Over 6	Over 150	5 or 6

*As a rule of thumb, start with a shade that is too dark to see the weld zone. Then go to a lighter shade which gives sufficient view of the weld zone without going below the minimum. In oxyfuel gas welding, cutting, or brazing where the torch and/or the flux produces a high yellow light, it is desirable to use a filter lens that absorbs the yellow or sodium line of the visible light spectrum.

Ventilation

One of the major health hazards to welders is the inhalation of fumes and gases emitted during welding. Fume plumes contain solid particles from consumables, base metals and base metal coatings. Most of the shielding gases (argon, helium, and carbon dioxide) are non-toxic, but as they are released they displace oxygen in the breathing air, causing dizziness, unconsciousness, and death if the brain is denied its needed oxygen long enough.

Adequate ventilation shall be provided for all welding, cutting, brazing and related operations. Adequate ventilation shall be enough ventilation such that personnel exposures to hazardous concentrations of airborne contaminants are maintained below the allowable limits specified by the authority having jurisdiction.

Avoiding the fume can be done by positioning of the work, the head, or by ventilation which captures or directs the fume away from the face. If natural ventilation is not sufficient to maintain contaminants below the allowable limits, mechanical ventilation shall be provided.

Mechanical ventilation includes local exhaust, local forced air, and general area mechanical air movement. Local exhaust ventilation is preferred.

Local exhaust ventilation means fixed or moveable exhaust hoods placed as near as practicable to the work and able to maintain a capture velocity sufficient to keep airborne contaminants below the allowable limits. Local forced ventilation means a local air moving system (such as a fan) placed so that it moves the air horizontally across the welder's face. General mechanical ventilation may be necessary in addition to local forced ventilation. Examples of general mechanical ventilation are roof exhaust fans, wall exhaust fans, and similar large area air movers.

Ventilation should not produce more than approximately 100 feet per minute (0.5 meters per second) air velocity at the work (welding or cutting) zone. This is to prevent disturbance of the arc or flame.

When controls such as ventilation fail to reduce air contaminants to allowable levels or when the implementation of such controls are not feasible, respiratory protective equipment shall be used to protect personnel from hazardous concentrations of airborne contaminants.

There are situations when a welder is required to work in a confined space (relatively small or restricted space) such as tanks, boiler, pressure vessel or small compartment. In a confined space, welding fumes can accumulate rapidly, and can force out breathable air, suffocating the welder in the process. It is recommended to use respiratory protective equipment while working in a confined space. One should not use oxygen supplies as it is a very serious fire risk. It is also recommended to have someone trained to handle emergencies positioned outside the confined space to pull the welder out if danger arises.

Fire Prevention and Protection

A fire hazard results from the effects of intense heat upon the work in the form of sparks and molten metals. Hence one should recognize and protect combustible materials from the welding arc, sparks and spatter. It is also important to be sure that the work is not in contact with any combustible materials which it may ignite when heated.

Remove all potential fire hazards from welding area. Where the work and fire hazards are not movable, safeguards (fire-resistant shield) shall be used to protect the immovable fire hazards and nearby personnel from the heat, sparks, and slag.

Particular care must be taken when welding or cutting in dusty locations. Fine combustible dust particles (for example, coal dust) may readily oxidize (burn) and without warning result in a flash fire or even an explosion when exposed to the welding arc or even sparks.

Welding or cutting work shall not be started on a container or piping which had held hazardous substances until it has been prepared (properly cleaned) for hot work. Workers shall be fully familiar with safe practices for the preparation of containers and piping for welding and cutting (like AWS F4.1) prior to the commencement of hot work.

Sufficient fire extinguishing equipment (sand buckets, fire extinguishers, fire-resistant blankets, access to fire hoses, etc.) shall be ready for use where welding and cutting work is being done.

Fire watchers shall be posted where welding or cutting is done and where a large fire might develop. It is recommended to have a fire watcher to see where your sparks are flying if you're welding within 35 feet (distance a spark can travel) or so of flammable materials.

It is recommended that the fire watcher should wait for a half hour after all welding is finished to find and put out any smoldering fires that may have resulted from welding.

Oxyfuel Gas Welding and Cutting Safety

Information about safe practices for users of oxyfuel gas welding, cutting, soldering, brazing, and related materials and equipment is given in this section.

Oxygen cylinders, cylinder valves, regulators and hoses shall be kept free from oil, grease, and other flammable or explosive substances.

All connections shall be checked for leaks after assembly and before lighting the torch.

Before lighting the torch for the first time each day, hoses shall be purged individually. Purging consists of allowing each gas to flow through its respective hose separately, to purge out any flammable mixture in the hose.

To minimize burns of hands and fingers, a friction lighter, stationary pilot flame, or other suitable source of ignition shall be used. Matches, cigarette lighters, or welding arcs, shall not be used for lighting torches.

In confined spaces, the torch valves shall be closed and in addition, the fuel gas and oxygen supply to the torch shall be positively shut off at a point outside the confined area whenever the torch is not to be used, such as during lunch or overnight. This is to minimize the possibility of gas accumulation in confined space due to leaks or improperly closed valves when gas welding or cutting is completed.

Hose showing leaks, burns, worn places, or other defects rendering it unfit for service shall be repaired or replaced. Bending areas at the regulator and torch connections are prone to crack and leak because of additional stress. Damaged hose cannot be repaired with tape.

Flashback arrestors can provide a certain measure of protection against the hazards of flashback. To maintain this protection and to ensure that they have not become damaged or inoperative during use, a routine inspection program should be followed as specified by the manufacturer during its use.

Cylinders shall be stored preferably outdoors, where they will not be exposed to physical damage, tampering, or subject to temperatures which would raise the contents above 125°F (52°C). Hot gases may expand and increase pressures above allowable limits.

Cylinders in storage shall be separated from flammable and combustible liquids and from easily ignited materials such as wood, paper, packaging materials, oil, and grease. Oxygen cylinders in storage shall additionally be separated from fuel gas cylinders, or from reserve stocks of calcium carbide.

Acetylene and liquefied gas cylinders shall be used valve end up to prevents liquid flow into hoses and regulators.

Cylinders shall not be dropped, struck, or permitted to strike objects violently in a manner which may damage the cylinder, valve, or safety device.

Cylinder valves shall be closed before moving cylinders. Valve protection caps, where the cylinder is designed to accept a cap, shall always be in place and hand tight (except when cylinders are in use or connected for use).

When transporting cylinders by a crane or derrick, a cradle or suitable platform shall be used. Slings or electromagnets shall not be used for this purpose. For manual lifting of cylinders, valve protection caps shall not be used for lifting them. It is recommended to move cylinders with appropriate trolley.

When cylinders are to be moved with regulators attached, the cylinders shall be secured in position when moved, and cylinder valve closed.

Before connecting a regulator to a cylinder valve, the valve outlet shall be wiped clean with a clean cloth free of oil and lint, and the valve shall be opened momentarily and closed immediately. This action is intended to clear the valve of dust or dirt that otherwise might enter the regulator. The valve shall be cracked while standing to one side of the outlet, never in front of it. Fuel gas cylinder valves shall not be cracked near other welding work or near sparks, flame, or other possible sources of ignition.

Open the oxygen cylinder valve slightly so that the regulator cylinder-pressure gauge pointer moves up slowly before opening the valve all the way. If oxygen at high pressure is suddenly applied, it is possible to cause ignition of regulator components and injure the operator.

An acetylene cylinder valve shall not be opened more than approximately one and one-half turns and preferably no more than three fourths of a turn, unless otherwise specified by the manufacturer so that it may be closed quickly in case of emergency.

A suitable cylinder trolley/truck, chain, or steadying device shall be used to keep cylinders from being knocked over while in use.

Cylinders shall be kept far enough away from actual welding or cutting operations so that sparks, hot slag, or flame will not reach them, otherwise fire resistant shields shall be provided.

Cylinders shall not be placed where they might become part of an electrical circuit. By fastening cylinders to a work table or to structures, they could become part of an electrical circuit. Do not strike an arc on cylinders because arc damaged cylinders may leak or explode.

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